11 PART: OPERATION, PERFORMANCE CHECK & POST CONSTRUCTION

11.1 Introduction

Operating turbines should frequently be checked if they perform as expected. There can be many reasons for poorer performance than expected when the project was designed. A major reason is that the model calculation had poor quality or wrong data/assumptions, or the short-comings of the model itself But also, operational issues like yaw errors, pitching problems, and unforeseen curtailments (e.g. grid), icing loss, etc. could be the reason.

With the windPRO module PERFORMANCE CHECK, it is possible to analyse the performance in an efficient way and find reasons for under-/over-performance or fine-tune a wind model to be used for new projects in the area.

Also, monthly production and availability figures can be efficiently analysed with the tool.

Since windPRO 3.4, PERFORMANCE CHECK has been divided into three work paths.

- **Post-Construction:**
  - Primary focus, detailed investigation into historic losses, and calculation of Potential Production, Long Term Correction, and Future Net Production reporting.
  - Methodology is based on historic measured SCADA power curve, for when the turbine is in normal operation.
  - Based on 10min SCADA data, and turbine error/event logs for defining losses and their causes.
- **PERFORMANCE CHECK:**
  - Monthly production and long-term correction.
  - Primary focus on wind model validation, to existing wind farm production data.
  - Long term correction of production data, 10min, hourly or monthly data.

- **TR10: Dedicated manual: https://help.emd.dk/knowledgebase User manual Chapter 13.**
  - Primary focus, German wind farms built under FGW17, must evaluate Goodness factor, according the TR10 standard. Model is certified by TÜV SÜD.

This manual is focused on the *Post-Construction* path, explaining in detail every Tab in the module and the workflow. Multiple operations are identical if one uses Performance Check for quantification of error losses or for model validation.

- **1st Chapter** is for *Post-Construction*.
- **2nd Chapter** is for having only monthly production data and wanting to evaluate long-term expected yield.
- **3rd Chapter** is for *model validation* path, where a time-varying PARK calculation is paired to actual production to calibrate a wind model to reality, such that the model can be used for re-powering a wind farm or designing future neighbouring projects.

11.2 Chapter 1: Performance Check & Post Construction Method

The Performance Check module in windPRO allows the user to analyse 10-minute SCADA production data together with wind turbine error/event logs to evaluate the lost production corresponding to individual errors and predict the future long-term corrected production.

The calculation is based on the actual 10-minute SCADA data of the wind turbines, combined with the error/event logs to identify each 10-minute period stop or non-optimal performance, identify the cause of each event, and categorise and assign responsibilities. If error codes are logged in separate files with start/stop times, the information can be synchronised with the 10-minute SCADA time series. This results in a 10-minute time, series of production, wind data, and relevant error codes and their description.

Once all events with errors and/or non-optimal performance have been filtered out, the remaining records describe normal operation which is used to establish the *historic power curve* for each turbine (typically for 0.5 m/s wind speed bins). For periods with faults or stops the nacelle wind speed and the *historic power curves* of the individual WTG are used to derive the *potential production*. The loss categories follow IEC 61400 26-1. In this process, the logged actual production during error (and non-optimal) periods is being replaced with the production found by applying the *historic power curve* to the nacelle wind speed at the relevant time steps. The *potential production* values will tell, what the turbines would have produced on average under normal operation, if it was not affected by an error event or partial performance. It represents 100% availability. The *actual production* from the SCADA data and *potential production* are then compared in periods of irregular operation. The difference results in the *lost production* for each time step.

Please note, that wake losses (internal and from neighbouring wind farms) are inherent in the SCADA data and are not quantified separately. Electrical losses i.e. within the cables from the turbine to the metering point) are handled separately as they appear after the SCADA data are logged.

This potential production is then long-term corrected using a wind energy index based on mesoscale data or other sources and results in the *normalised production*. Subsequently, expected future long-term losses are deducted from the *normalised production* to assess the *expected future net production*. Future losses are either assumed to be identical with previous losses or defined by the user, if for example, changes in the losses are expected. Additionally, electrical losses and losses due to degradation can be included.

This method is primarily used for evaluation of operating wind turbines/farms, as the uncertainty of the net production is typically half of the traditional pre-construction yield estimates based on wind measurement and models. It can also be used for a detailed investigation into the causes of lost production and to evaluate if actions should/could be taken to address the causes of lost production.

11.1.1 Workflow

The most typical application and workflow for post-construction analysis is described in the Quick Guide.

However, since only a few error code logs follow the IEC 61400-26-1 structure, the user can be confronted with various formats. In case of cascading errors and alarms it might be difficult to identify the relevant event. Therefore, iterations in the work process might be necessary. For example, the user might find that some events with a specific fault show no poor production. This could be due to the fact that the time stamp in the SCADA data belongs to the end of the 10-minute period and not the start. Consequently, the user has to revisit the loading of the 10-minute SCADA data, change the setting, load the data again and pair the production data with the right WTGs.

Apart from the pure analysis of SCADA data, the *Performance Check* module can be operated together with *Performance Check* track/work path, such the user can fine-tune and validate a chosen model set-up by comparing real production with modelled production. Specifically, for assets with poor availability, or poor data recovery of the SCADA data, it might be advisable to use *Performance Check* track rather than *Post-Construction* to predict the future production.

There are interfaces between the two methodologies. Please note, that both tracks require running a time-varying PARK calculation. In case of Post-Construction, the nacelle wind speed and historic power curve of the individual WTG will be used to calculate what the WTG should have produced for each time step. The time-varying PARK calculation does not require any flow modelling in this case. It can be started from within the *Performance Check* module.

In the case of the *Performance Check track*, a full flow model must be set-up. It is possible to use local mast data as well as mesoscale data for wind speed information. The model can be queried, for example to find the most suitable scaling factor of the mesoscale data, or to find the best wake parametrisation which reflects the observed wakes best. The actual production data can be prepared in the *Post construction* module and filtered for events with error codes or sub-optimal performance. One of the key parameters to identify the success of a specific model set-up is the Goodness factor which describes how well the model reproduces the measured production.

11.1.2 File Type Overview

By default, all windPRO files are located in the folder \windPRO Data\Projects\…

What	Project file extension
wind base file	*.wbf
Performance Check Error Settings file	*.pfc
Performance Check Import Setup	*.pci

11.3 Data Preparation

Typically, 10-minute SCADA data are used for Post-Construction analysis. The data have to be in form of an ASCII text file, e.g., comma or tab delimited. If they are in MS Excel files (.xls/.xlsx), these must be saved as .txt or .csv or other text file formats. Tab separated text data are recommended.

For the import of the files, it is convenient if the turbine identification in the import files is identical to the ID in the *existing WTG* object (description or user label) in the windPRO project. It is important that the files contain data organized in rows, each row starting with the time stamp, preferably something like dd-mm-yyyy hh:mm. Please note that midnight (00:00) will be empty in Excel, however, there is no reason for concern as this empty time stamp is handled correctly in the data importer in windPRO.

The temporal resolution of SCADA data is typically 10 minutes. windPRO is currently able to handle data with a granularity of 1 minute.

As a minimum, the files must contain production data and wind speed. Both production data in kW and kWh can be handled, as well as accumulated production. Additionally, wind direction and any operational parameter like rpm, pitch angle, etc. can be imported. The direct use of error codes is also possible as long as the error codes come in 10-minute steps. If the error codes are available in a separate file with start/stop times they can be converted to 10-minute steps later in the process (see Section 11.1.12).

Table 1 shows an example for a data structure. Each signal contains the WTG ID. Please note that the data structure is shown transposed! For importing the file structure has to be in rows per time stamp.

	A	B	C
1	PCTimeStamp	01-01-2011	01-01-2011 00:10
2	WEA04_Production LatestAverage Total Active Power Avg. (1)	-545	4950
3	WEA05_Production LatestAverage Total Active Power Avg. (2)	-557	3773
4	WEA06_Production LatestAverage Total Active Power Avg. (3)	-525	4186
5	WEA04_Ambient WindSpeed Avg. (4)	4	4,5
6	WEA05_Ambient WindSpeed Avg. (5)	4,1	4,5
7	WEA06_Ambient WindSpeed Avg. (6)	4,3	4,8
8	WEA04_Ambient WindDir Absolute Avg. (7)	250	248,4
9	WEA05_Ambient WindDir Absolute Avg. (8)	268,4	266,2
10	WEA06_Ambient WindDir Absolute Avg. (9)	293,3	290,9
11	WEA04_Blades PitchAngle Avg. (10)	23,9	-0,6
12	WEA05_Blades PitchAngle Avg. (11)	24	11,6
13	WEA06_Blades PitchAngle Avg. (12)	24	5,1
14	WEA04_Blades PitchAngle Max. (13)	19	-2,3
15	WEA05_Blades PitchAngle Max. (14)	24	-2,4
16	WEA06_Blades PitchAngle Max. (15)	24	-2,4
17	WEA04_Blades PitchAngle Min. (16)	24,1	17,6
18	WEA05_Blades PitchAngle Min. (17)	24	24
19	WEA06_Blades PitchAngle Min. (18)	24,1	25,6
20	WEA04_System Logs First Active Alarm No (19)	0	0
21	WEA05_System Logs First Active Alarm No (20)	0	0
22	WEA06_System Logs First Active Alarm No (21)	0	0
23	WEA04_Nacelle Temp. Avg. (22)	13	12
24	WEA05_Nacelle Temp. Avg. (23)	12	12
25	WEA06_Nacelle Temp. Avg. (24)	13	13
26	WEA04_Generator RPM Avg. (25)	295	1207
27	WEA05_Generator RPM Avg. (26)	278	635
28	WEA06_Generator RPM Avg. (27)	284	847
29	WEA04_Rotor RPM Avg. (28)	2,6	10,6
30	WEA05_Rotor RPM Avg. (29)	2,4	5,5
31	WEA06_Rotor RPM Avg. (30)	2,5	7,4

Table 1: Example SCADA data structure – please note for display reasons the table has been transposed!

11.4 Data

11.1.3 Start Performance Check and Concept Choice

The *Performance Check* module can be found under *Loads & Operation* tab in the main ribbon (Figure 1) under the SCADA Data Analysis group select Performance check. Start with creating a new "session" or open a previously created session.

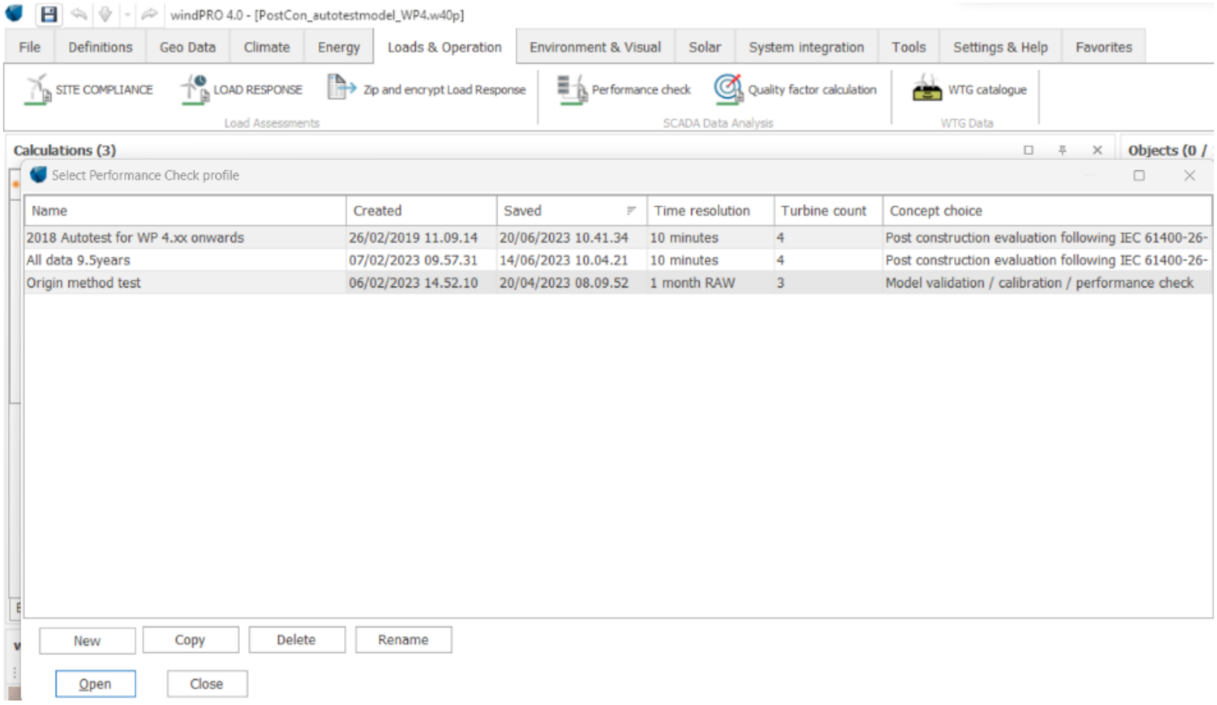


Figure 1: Start Performance Check Module

Performance Check offers different workflows. In this section we explain the workflow and functionalities for *Post construction evaluation* (Figure 2). The process follows the IEC 61400-26-1 structure. The use of this functionality requires a license for Post construction.

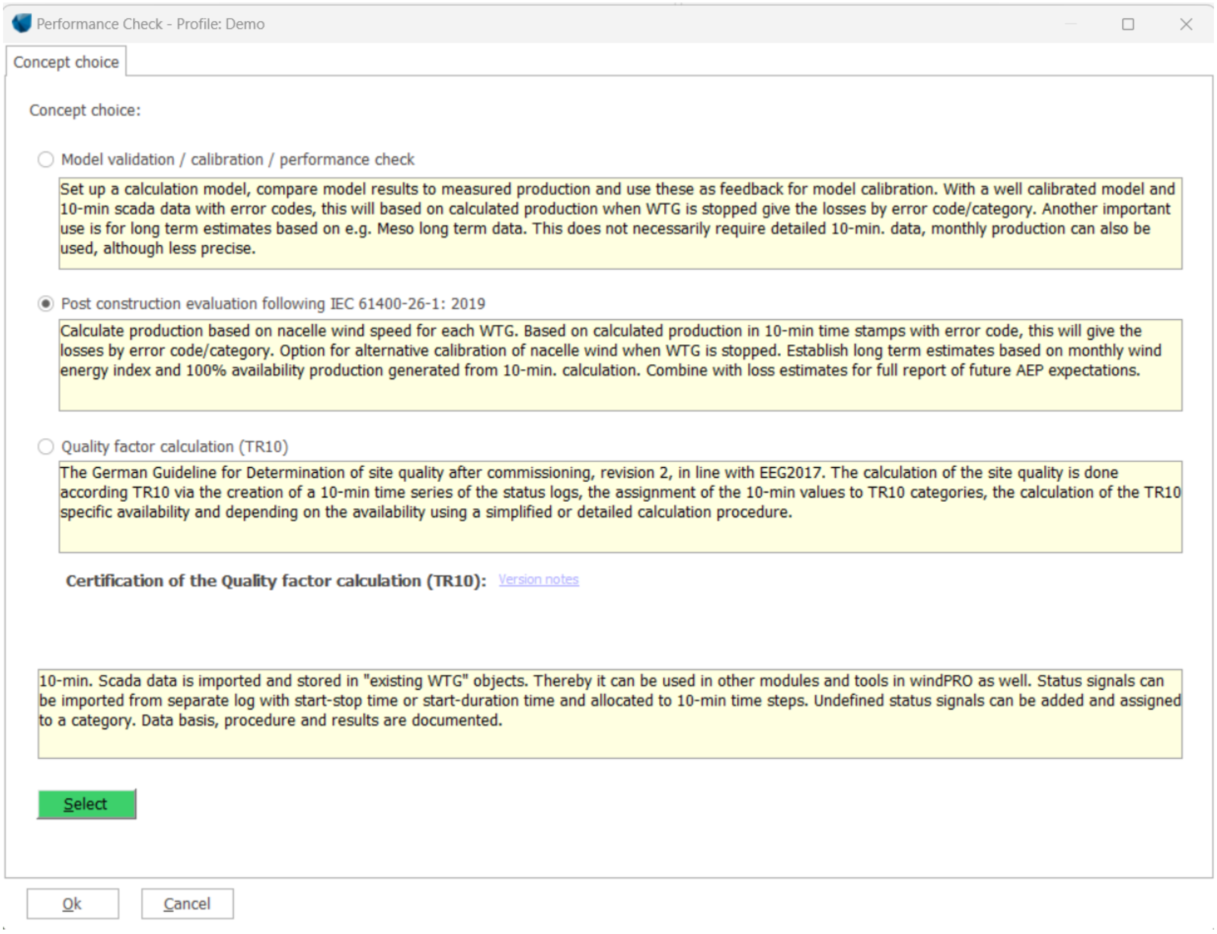


Figure 2: Choice of workflow in Performance Check

11.1.4 Data – Data Source

After having chosen the concept (*post construction evaluation*) the user must define what type of data is imported (Figure 3).

For SCADA data analysis typically 10-minute data are used. This category also handles other temporal resolutions like 1-minute or hourly data.

In case the *existing WTG* object already contains production data, the user can decide to use the already imported production data.

Starting a new session requires the user to decide if new data are to be imported into the *existing WTG* objects, or already imported shall be used. In the latter case, the import process is skipped.

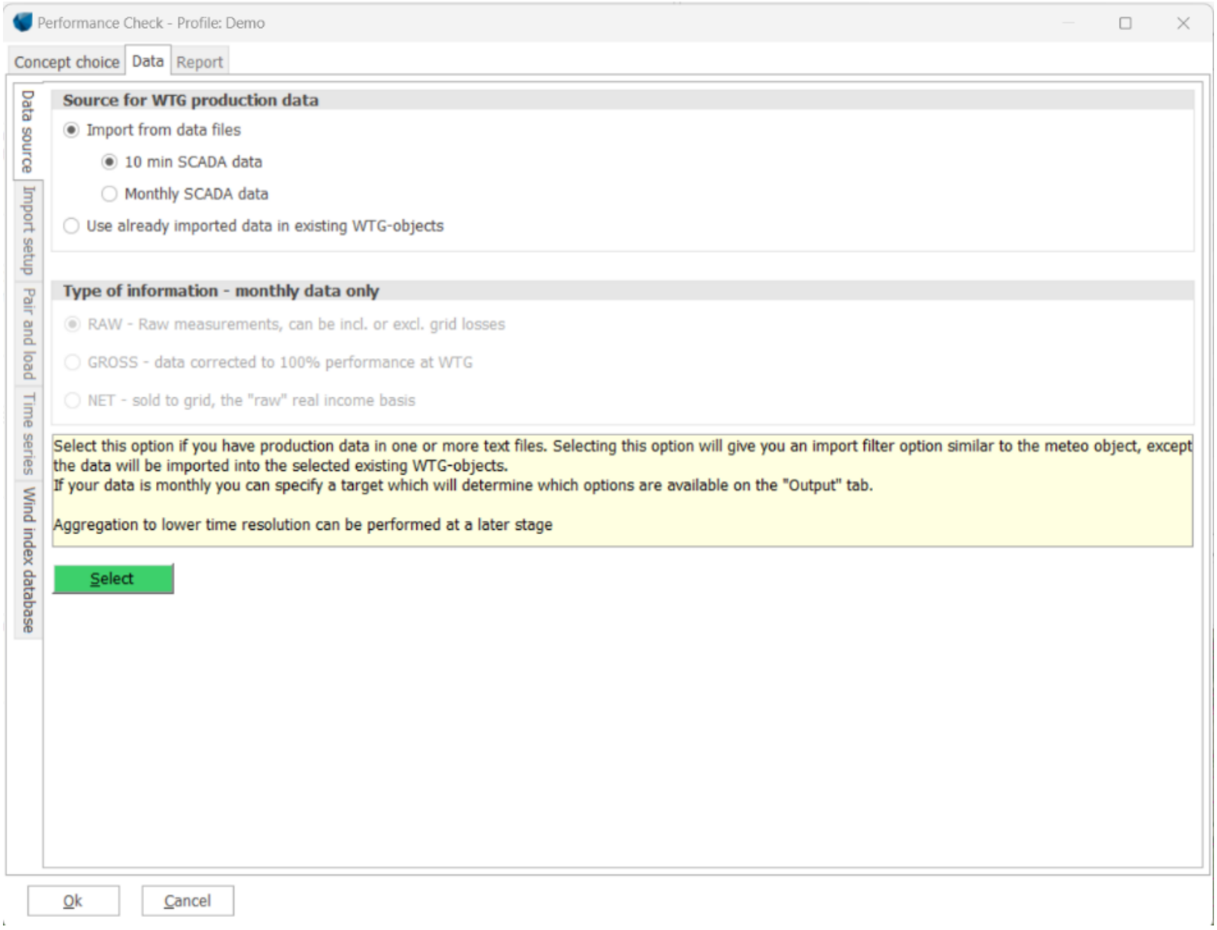


Figure 3: Define type of import data.

11.1.5 Data – Import Setup

The Importer for SCADA data is very similar to the importer in the *Meteo* object. The user has to either directly select text files or a folder which contains the text files.

The time zone has to be specified.

The *Auto detect* button will suggest a structure. This might identify some of the signals, but typically some manual adjustment will be needed. The user has the option to modify the suggested structure and specify the line with the header, the first line with data and field separators. At any step the user can preview the file structure and adjust file formats if required. It is also important to define if the time stamps refer to the start of a 10-minute period or to the end of a 10-minute period. SCADA systems often log the data at the end of a 10-minute period, however this is not a universal/standard practice. The impact of this setting can become important later in the process when the production data is coupled with error codes.

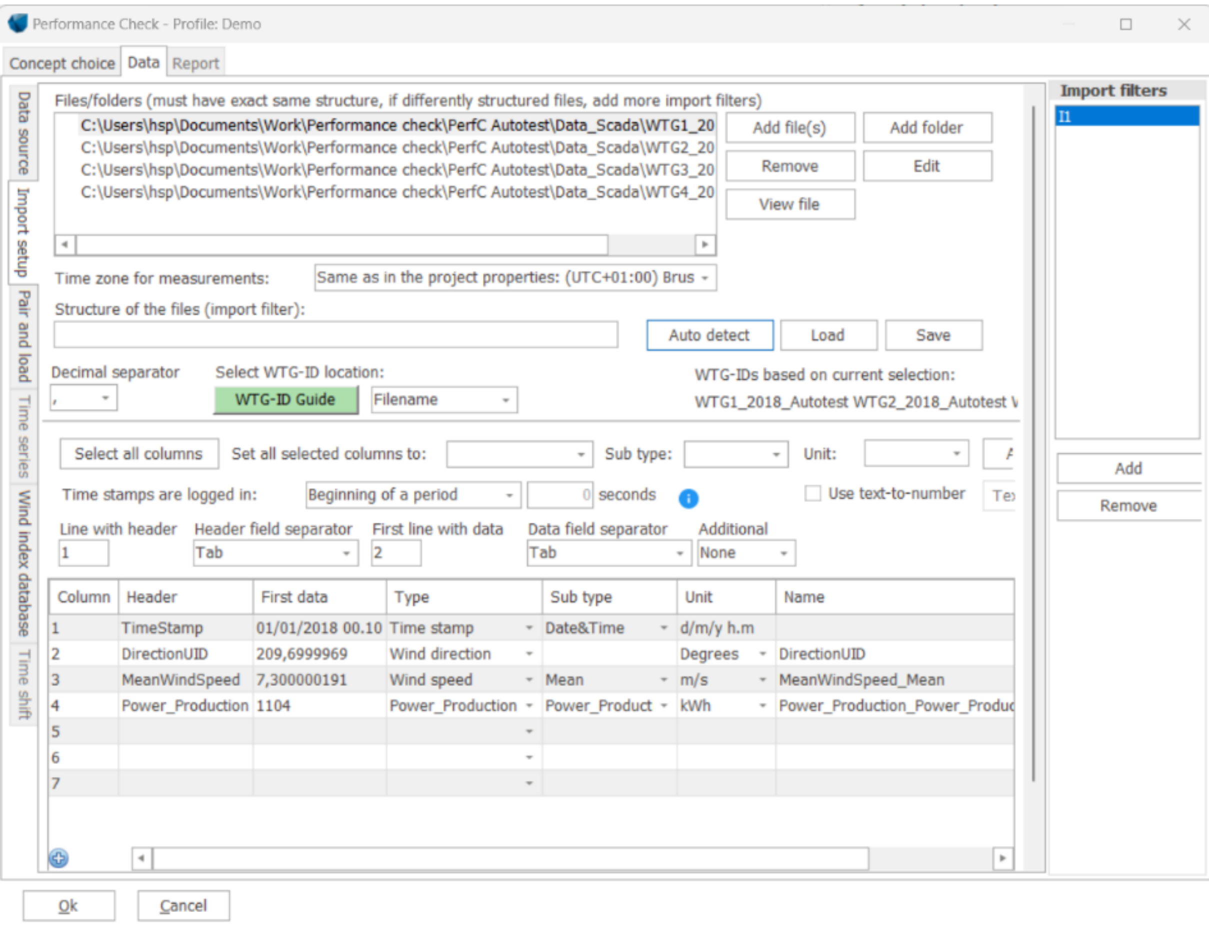


Figure 4: Importer for 10-minute data

For post construction analysis, users are required to have the production and the wind speed as bare minimum. Following additional pre-defined signals are available:

- Wind direction
- Availability
- Error Code
- Temperature
- Pressure
- Pitch angle
- RPM

For some signals it is necessary to define the sub-type: Is the wind speed signal representing the mean, max, min, or std? Is the production signal accumulated production? Once the sub-type is defined, and the units are set, the data are converted and appears in the right-most column. Please note that you also must specify the unit for the time stamp. Specific care must be taken in setting the unit of the power signal correctly. It is, however, at any time possible to return and change the unit.

Please note that all negative production is set to zero. For any selected period, the sum is logged and documented as a total for the selected turbines.

Multi-editing of the signal is possible by marking the signals you want (by dragging the mouse or by “Shift-/control-click”), specify the type and sub-type and finally pressing “*Apply*”.

Further it is possible to change text to numbers. E.g. if your date stamp contains text like DEC, you can translate this into 12. Or if invalid data is marked NAN, you can change it to -999.

It is possible to save the structure as a “.*pci” file and use it for other projects. It is also possible to use several import filters in case the SCADA data has been provided in different formats.

In the next step of the process, it is necessary to assign the production data to a specific WTG. There are two options: In case you do not know where to find the WTG-ID, a *WTG-ID Guide* will help you with the necessary specifications, or alternatively you can directly enter where to find the WTG-ID in the file (Figure 5).

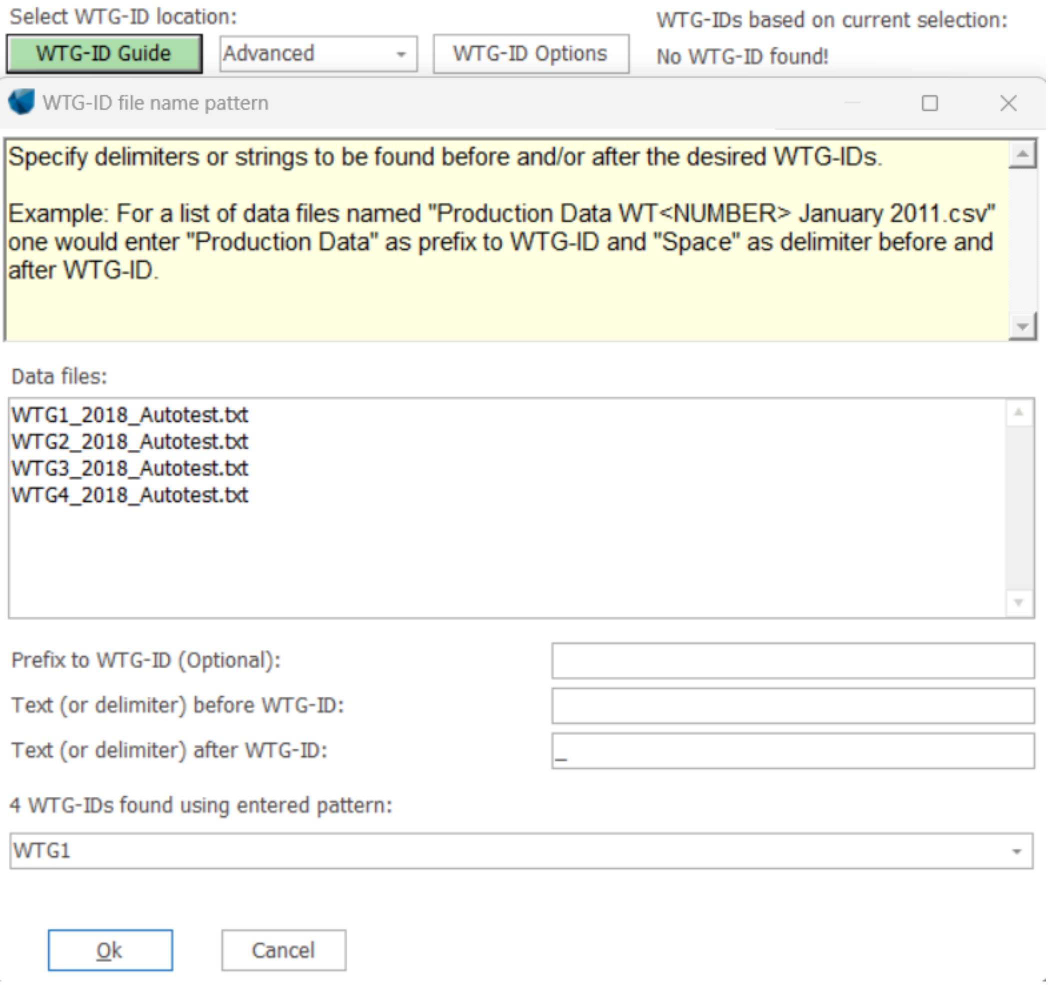


Figure 5: WTG-ID Guide

In first step of the *WTG-ID Guide* you have to specify the number of WTGs you want to analyse. Then, you have to define whether the data are in individual files per WTG, if the WTG-ID is inside each file, or if the WTG-ID is part of the file name. As shown in Figure 5, selecting underscore as delimiter after WTG-ID, windPRO will identify the individual names of each of the turbines.

If the WTG-ID is inside the file, you have to specify if the WTG-ID is part of the column header (e.g. WTG02_Spd as column header) or in a specific column.

In the next step you have to define the first, second WTG-ID, as well as the last WTG-ID by clicking at the top of the columns. This assists the tool to identify the remaining WTGs automatically. You have to specify the delimiter, which separates the WTG-ID from the signal name. If the delimiter is an underscore "_". Sometimes the column name might include several underscores (e.g. WTG03_Spd_1). Therefore, it is possible to define which sub-string includes the WTG-ID, in our example it is the first sub-string that contains the WTG-ID.

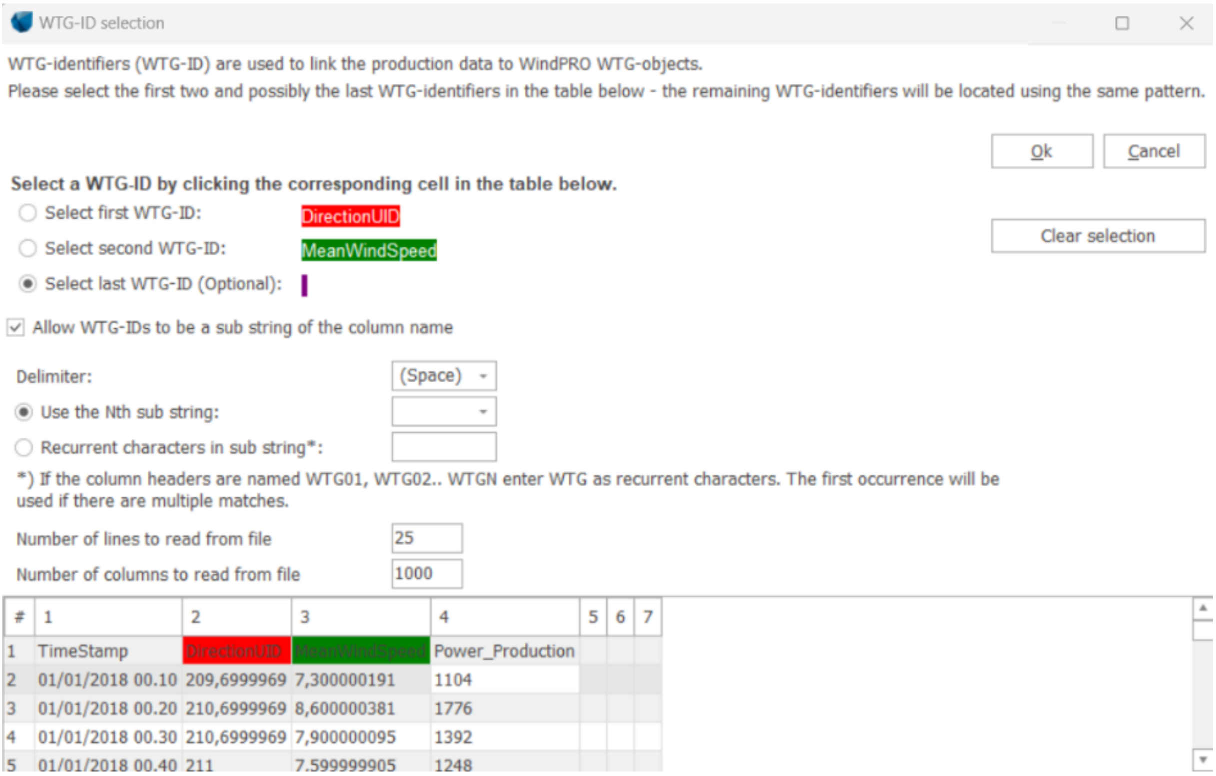


Figure 6: WTG-ID selection GUI Example.

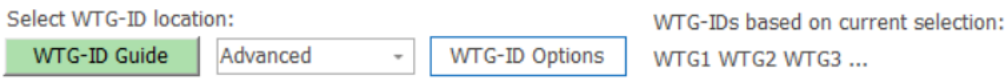


Figure 7: Successful selection of WTG-ID

If the selection has been successful, the WTG-ID will now show up (Figure 7). You now have to pair the production data with *existing WTG* objects.

11.1.6 Data – Pair and Load

The user has to choose which of the existing WTGs to add to the analysis (Figure 8).

In the case where the naming convention of the *existing WTGs* is identical with the WTG-ID used in the SCADA files, windPRO will automatically pair the object with the production data. In the case where the automatic pairing does not work properly, use the drop-down in upper right corner to match the ID in the import filter to the objects.

***IMPORTANT NOTE: the exiting WTG object works as a database of SCADA data loaded. If you load new data into the same layer containing the same existing turbine objects in another Performance Check session, the existing data with all filters and settings will be overwritten. Thus, it's important to clone the object layer containing the existing WTG objects if multiple investigations on different parameters are required.

Once correctly paired, click [Load measured data] and the data will be imported into the WTG objects (Figure 9).

It is possible to re-visit [Load measured data] at a later time. This might be the case, if you have received further data: For example, you started out by only having monthly production data but now you want to add data with a different temporal resolution e.g. 10-minute production data. Depending on the application you might want to load all data, or you might want to load only the new additional data into the *existing WTG* objects, and consequently maintain data that was earlier loaded. Or you want to load production data, which you had loaded directly into the *existing WTG* object into the post-construction calculation.

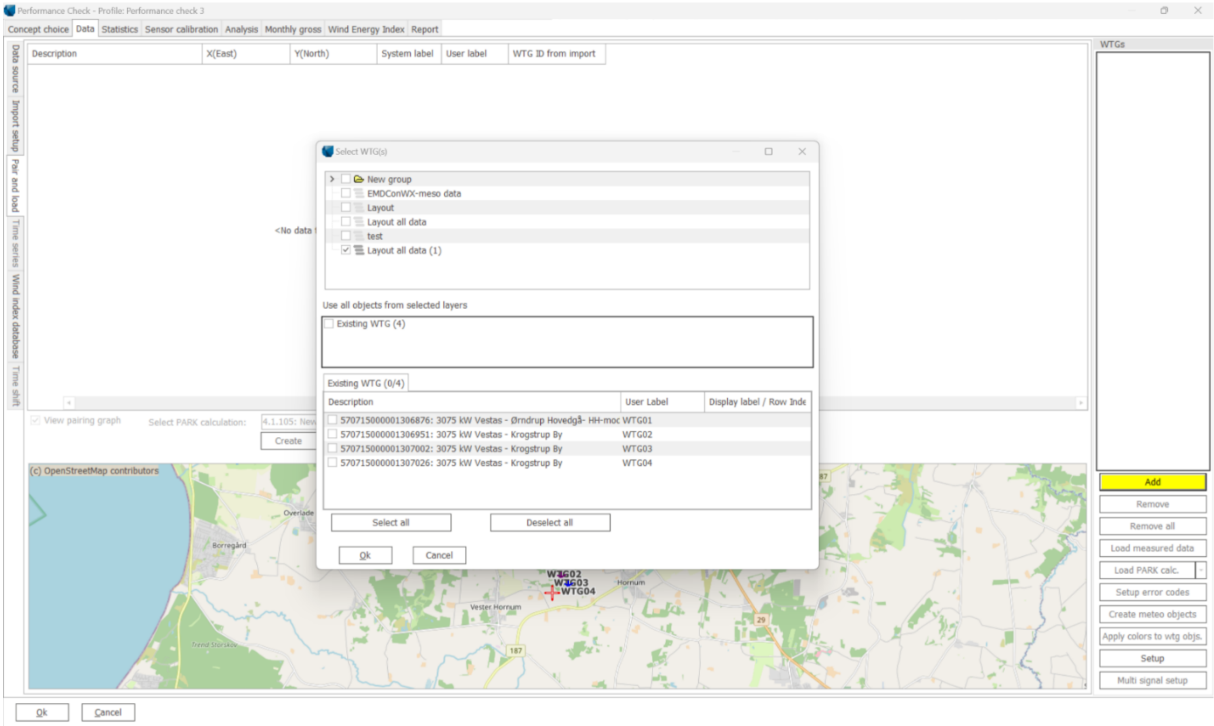


Figure 8: Chose existing WTGs for pairing.

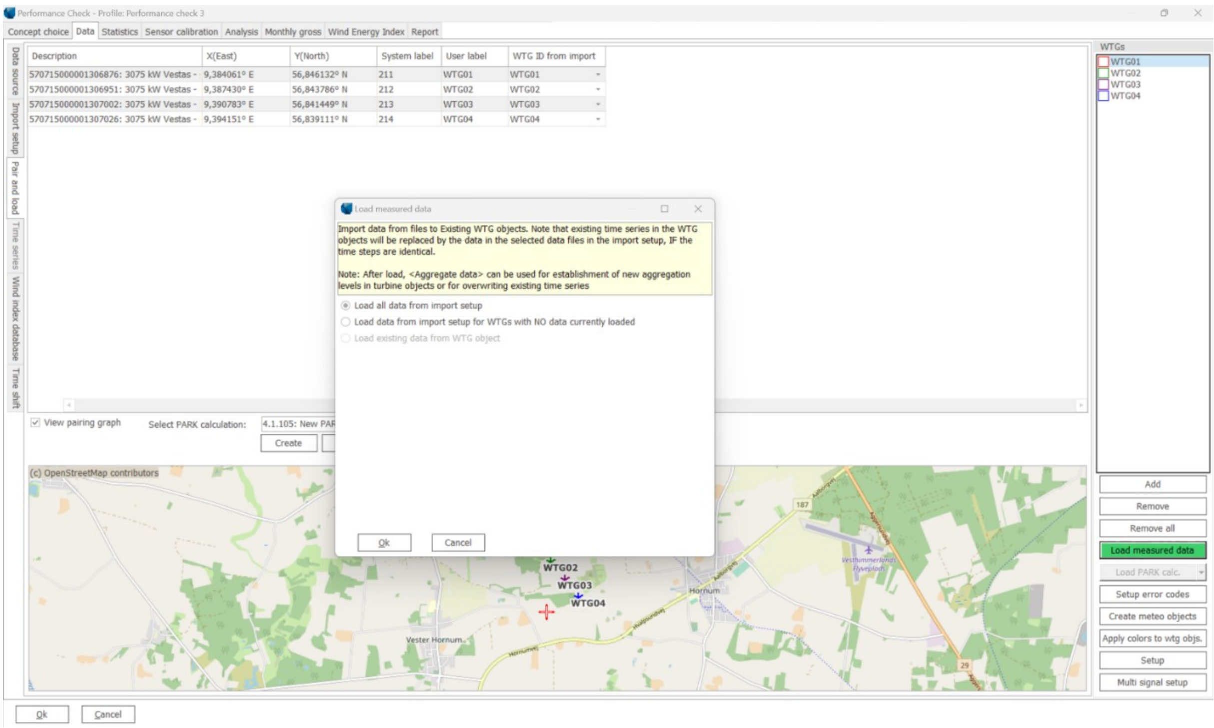


Figure 9: Load measured data

On the tab *Pair and Load* a lot of other functions can be found. Some of them will be treated in a different manual section (as annotated in Figure 10).

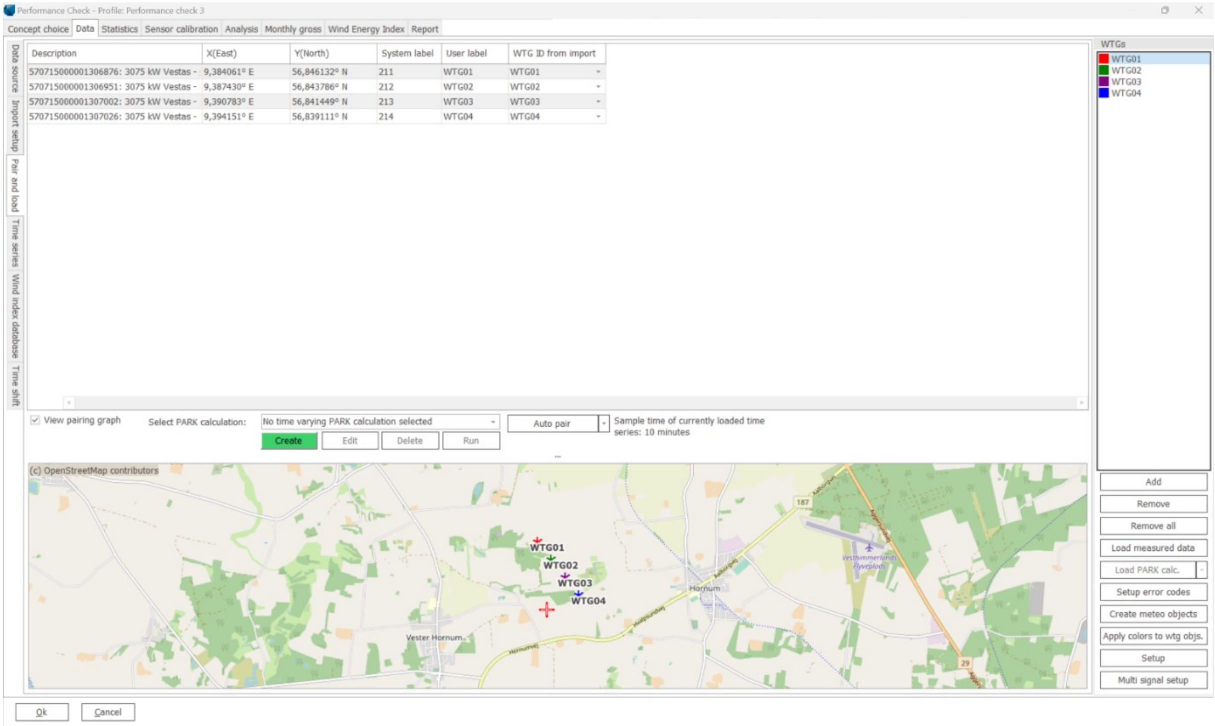


Figure 10: Additional functions on Pair-and-Load tab

Setup error codes is described in Section 11.5. It deals with how to combine the error logs, error descriptions and categories with 10-minute SCADA data.

Sensor calibration is described in Section 11.6. It deals with checking the nacelle wind speed for consistency by comparing with references, and for substituting filtered and/or missing wind speeds.

Create time-varying PARK calculation is described in Section 11.7. It allows the user to run a time-varying PARK calculation.

Additionally, to these larger functionalities following possibilities can be accessed:

Create meteo objects: This button will convert the wind speed signal of each WTG into a *Meteo* object.

Apply colours to WTG objects will give the WTG symbols the same colours as used in the graphics within Performance Check. This is very convenient when evaluating results WTG by WTG.

Setup: Here a number of boundary conditions can be defined (Figure 11). In the first section the user can define which signal should be used for further analysis, e.g. turbulence intensity is only considered for wind speeds above 4 m/s. Turbulence intensities at wind speed lower than this value are automatically disabled. How many samples must be present when aggregating data from e.g. 10-minute data to hourly data, can also be defined.

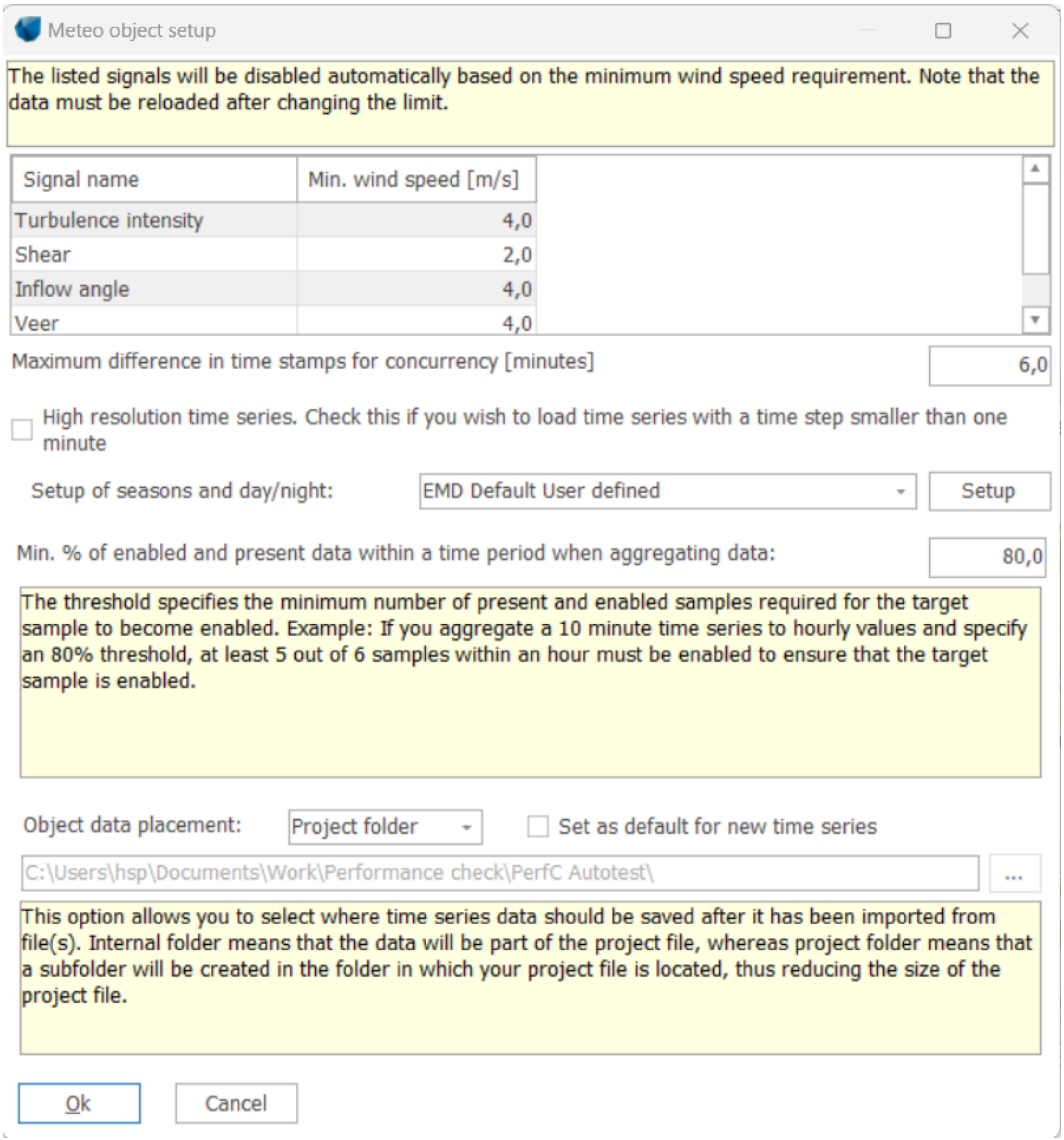


Figure 11: Setup settings

Multi Signal setup defines the handling of several signals of the same type, e.g. there might be two anemometers installed on a nacelle. If both signals are loaded, it can be decided to use the average, maximum, minimum, or sum of the two signals.

Figure 12 shows an example with two wind speeds being imported. The two signals are combined by averaging. The user can further define which of the signals is used in future graphical displays.

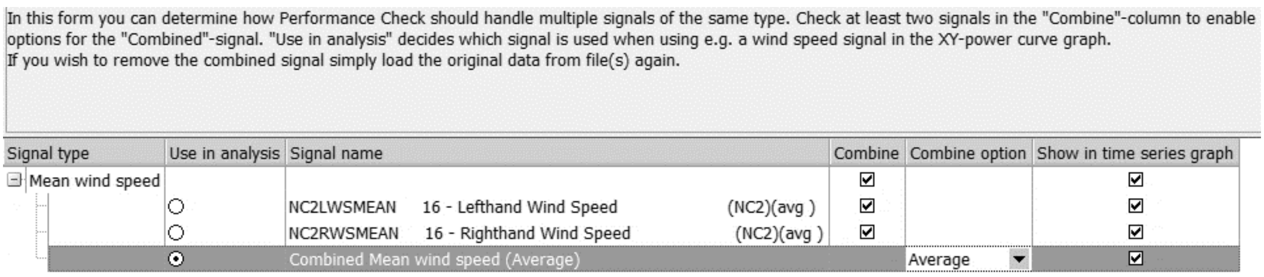


Figure 12: Handling of multiple signals

11.1.7 Data – Time Series

Before moving on, it is a good idea to quality control all choices by visiting the *time series* tab. Here you can inspect your data and perform some basic filtering. Please refer to *Meteo* manual for details as the functions are identical to those in the *Meteo* object.

The data can be sorted by clicking on the top of the column you want to sort by. If data are out of range or there are duplicates, etc., the small arrows will allow you to jump to the specific time step.

The power signal can be investigated for e.g. by sorting the power column values. The maximum power [kW] should be identical to the rating of the WTG. If the maximum power is wrong by a factor of 6, the reason could be the choice of units in the import filter: [kWh] or [kW]. If the maximum power is wrong by a factor of 1000, check if [Wh] or [kWh] should be used. Simply change the unit in the import filter (see Section 11.1.5) and reload the data.

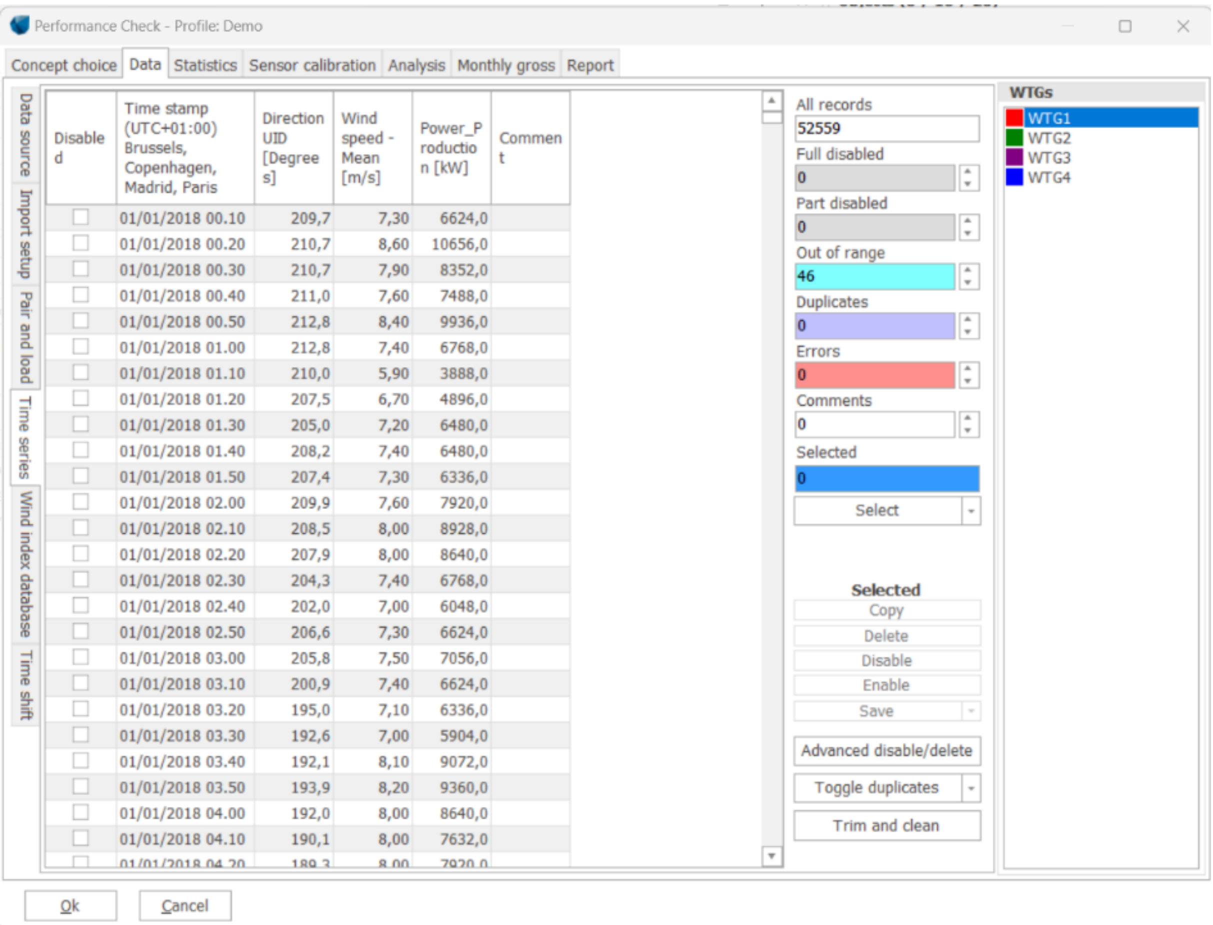
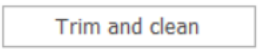


Figure 13: Example resulting time series.

From windPRO 4.0 a new data cleaning tool within the “Trim and Clean” button is introduced.



This is capable of working on all individual turbines in one iteration, where previously the trimming and managing of the loaded SCADA data needed to be dealt with one turbine at a time.

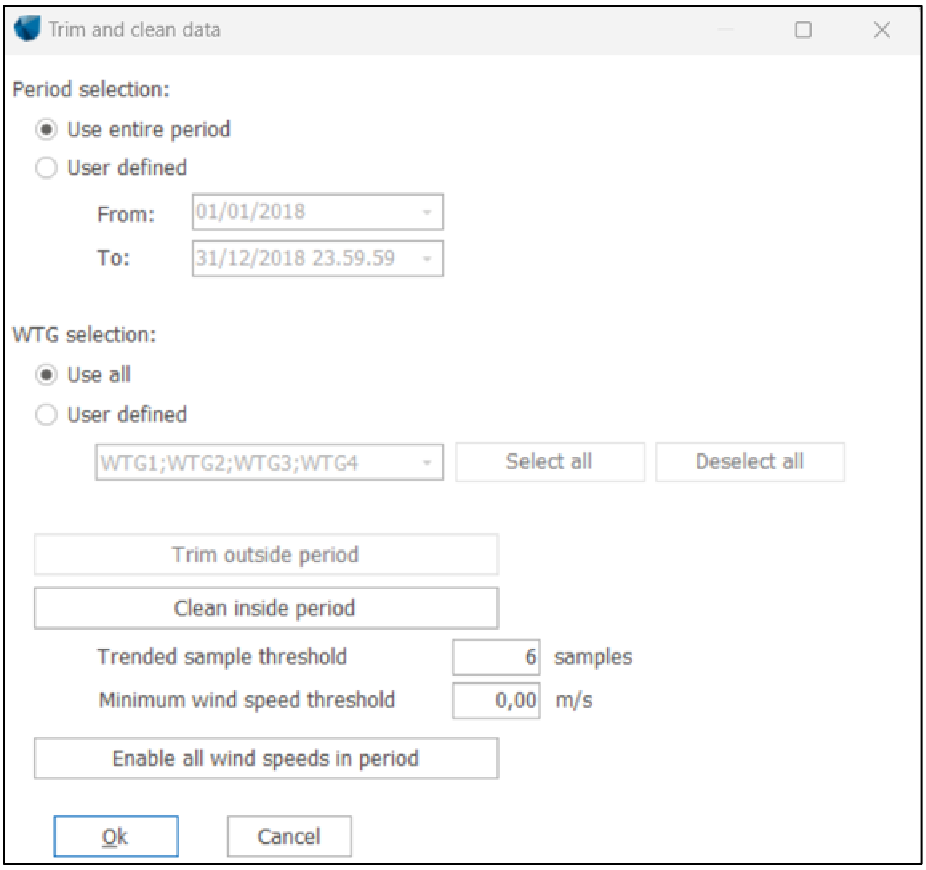


Figure 14 window for Trim and Clean feature, all turbines in one work step.

By selecting the Trim and Clean button, a new window appears, here you can select if you want to work on all loaded SCADA data or a sub section in time.

Further if you want to remove some turbines from the trim and cleaning task, you can de-select the turbines individually.

Hitting the trim outside period button, deletes measurements outside the selected time interval for selected turbines after a confirmation notification. All data can be re-loaded under Pair and Load tab.

Trim option is disabled, as long as entire period is selected.

The Clean inside period button, will start scanning through the selected turbines and time period, for identical wind speed samples following each other of minimum set sample length, for all samples below minimum wind speed threshold, and disable these samples. These are presumed to be faulty data that are “frozen” & trended wind speed signals that should not be used to calculate potential production.

Note for trends of a frozen wind speed signal the first and last sample is disabled for the duration of found samples. For linear/sloped trends, the first and last sample is not disabled. This is due to the assumption that such events represent a logger system where it’s a fixed linear inserted wind speed range, between a gap in the data from last known value and first known value after the gap.

Later these faulty and disabled or missing signals for wind speed readings can be replaced with a calculated windspeed signal following the TR10 “German Standard” methodology, see section 11.6 for further details.

The trend detector is based on a gradually increasing, moving window which considers the difference between each sample. Example:

1) Moving window starts at 05:30. Time to next sample is 10 minutes, so we continue
2) Time to next sample is 10 minutes, so we continue.
3) The sample at 05:50 does not match the trend of the previous two samples. The moving window size is once again decreased to one sample, and we assign the base of the window to the next sample at 05:40.
4) The window is gradually increased again and since the number of samples in the window is greater than or equal to the threshold, we mark all samples in the window to be cleaned - except for the first and last sample as highlighted below:

Disabled	Time stamp (UTC+01:00) Brussels, Copenhagen, Madrid, Paris	DirectionUID [Degrees]	Wind speed - Mean [m/s]	Power_Production [kW]
☐	08-06-2018 05:30	300.0	3.40	96.0
☐	08-06-2018 05:40	299.7	3.20	48.0
☐	08-06-2018 05:50	304.8	3.10	24.0
☐	08-06-2018 06:00	313.8	3.00	72.0
☐	08-06-2018 06:10	315.5	2.90	24.0
☐	08-06-2018 06:20	314.3	2.80	24.0
☐	08-06-2018 06:30	315.9	2.70	0.0
☐	08-06-2018 06:40	317.0	2.60	0.0
☐	08-06-2018 06:50	320.6	2.70	0.0

Figure 15 Example of sloped trend detection

The last button “Enable all windspeeds in period” is to re-load all wind speeds which have been disabled by the cleaning function.

Note, some 10-min SCADA wind speed signals only have one value beyond the decimal point, hence it becomes statistically more and more realistic that at random, three samples following each other will have a 100% linear trend/constant offset for 3 x consecutive time steps. Thus it’s recommended to investigate the time series post running the “Clean inside” method and evaluate if the threshold for your type of SCADA data require a larger threshold for the automatic filter setting for constant or trended data.

11.1.8 Data – Wind Energy Index Database

In order to calculate the long-term expected energy (WCP - wind corrected power), it is necessary to load a minimum of one wind energy index. windPRO has its own file format for storing indices: *.wbf file (wind base file).

Figure 16: Different choices for energy indices

There are several options (Figure 16):

Option 1: You can load an existing *.wbf file (wind base file) which you have created earlier.

Option 2: *Import/update online*: For some countries, there are “official” wind energy indices. So far, this online data includes only the DK-index. While the German BDB index is not included in windPRO and therefore must be added manually, windPRO assists in identifying the relevant region (Figure 17).

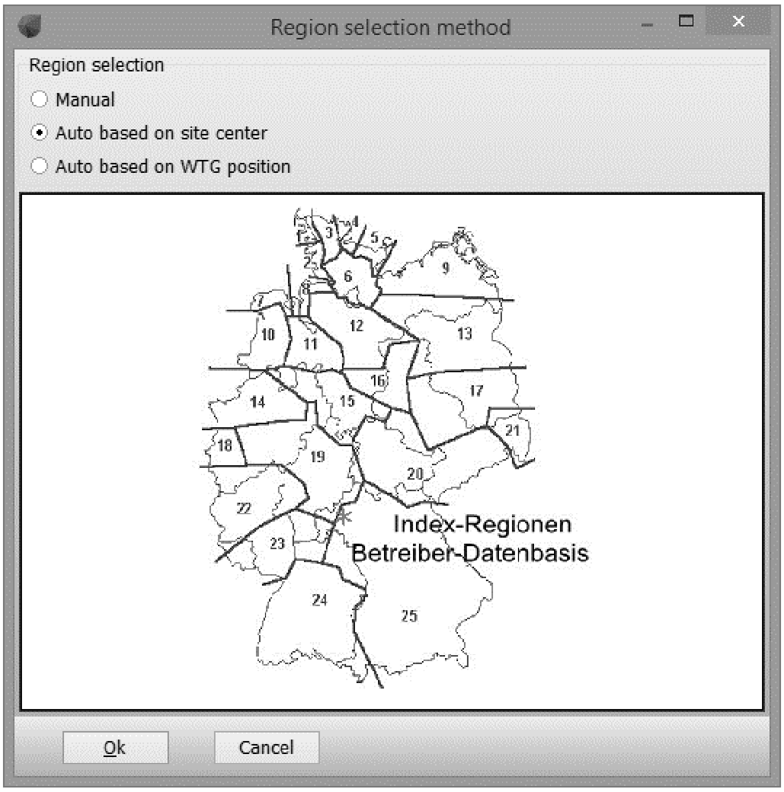


Figure 17: Identification of relevant region BDB index

Option 3: *Add from Meteo object*: You can create an index based on a *Meteo* object and save it either in a local or in a global folder (for later use). Typically, reanalysis data like MERRA-2 or ERA5, or mesoscale data like EMD-WRF Europe+ are used. To convert wind speed to energy, the user can define a power curve and the expected long-term wind speed at hub height. The wind speed from the long-term data is scaled to match the expected long-term wind speed on site. This way the dynamic behaviour of the index reflects the production variations as best as possible, and it becomes possible to use also long-term wind speed data, which may be very different from the site conditions.

In the next step, the relevant *Meteo* object is selected, and the reference period defined.

Finally, the calculated wind energy index can be viewed graphically.

This process can be repeated for different sources and/or settings. All results are written into a Wind Index Database (Figure 19).

Option 4: *Add user index base*: This function allows to create a user index either by manually editing row-by-row or by pasting from the clipboard.

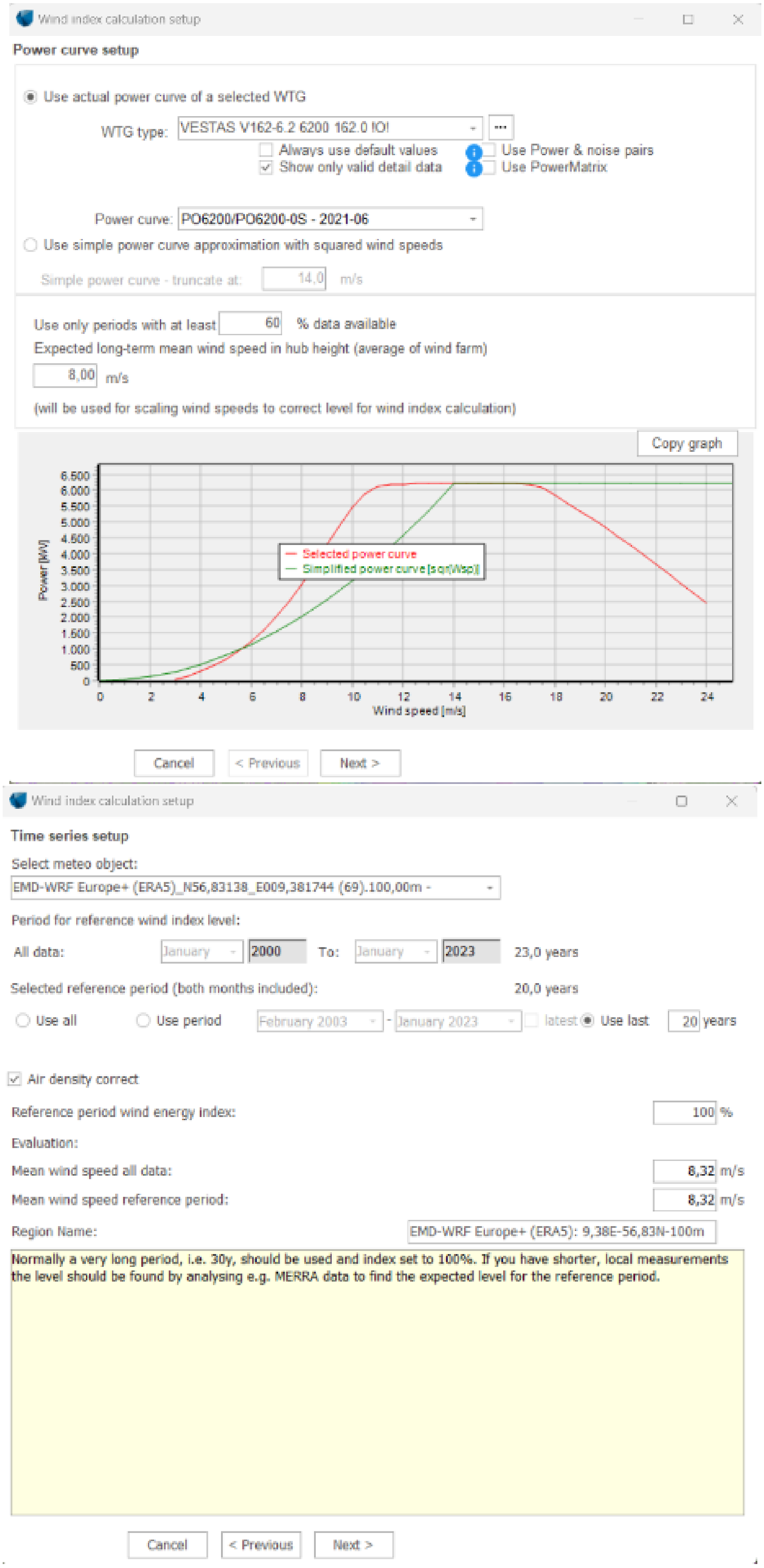


Figure 18: From wind speed to energy index

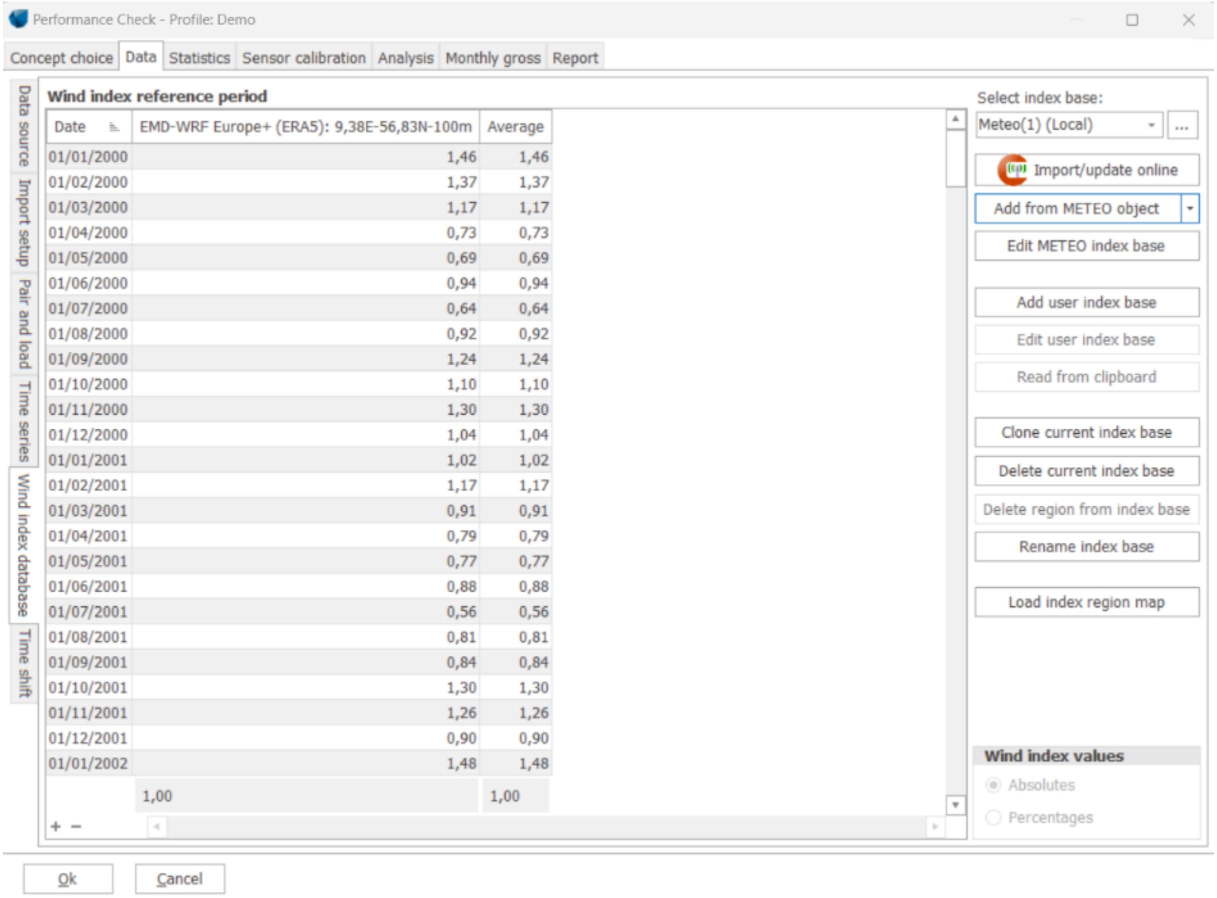


Figure 19: Example Wind Index Database

Option 5: Since WindPRO 4.1 Create Turbine Indices.

Note this option requires that error codes have been loaded and a loss calculation has been performed.

Turbine indices are auto created pr turbine, it uses a solver to fit the reference long term wind speeds such that it on average can predict what was measured. Thus it requires loaded production data to be used for the solver.

The user can choose a Turbine Index, which follows strictly the same process as defined in www.emdenergyindex.com for turbine indices, user can here set the training period and the reference “Index100% period” windPRO will then automatically download all required ERA5t data nodes, and initiate the solver pr wtg and create a unique Turbine Index pr turbine.

Alternative the user can select a meteo object, Note it requires minimum data since January 2004 and windspeed, direction and temperature at 10 and 100m elevation, like ERA5 data points or EMD WRF Mesoscale data time series.

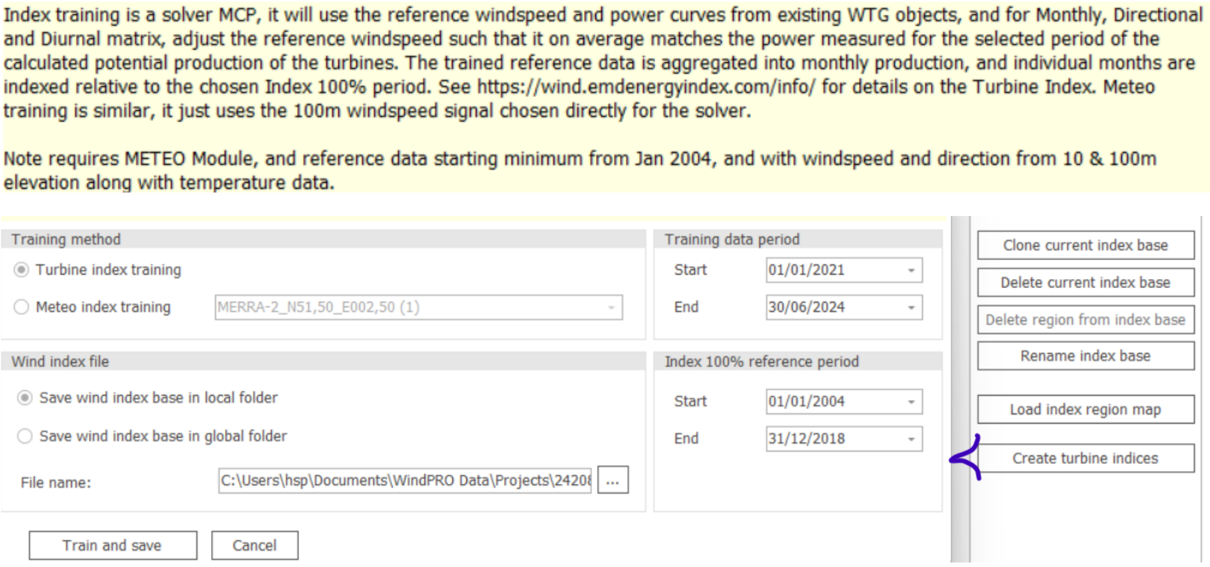


Figure 20 Create turbine Indices

Note with many years of production data for the training and many turbines, the solver and creation of the unique turbine indices can take +30min. “about 2min pr turbine”.

Once the solver is finished, a new monthly energy index is saved pr turbine, and under Wind energy Index tab, the Index will now change if a new turbine is selected as they are fixed together and not as the other types of Indices which are representative to the area excluding wakes and micro site-specific speedups.

Typically, the turbine index, should see a higher fit to the actual production variation over time, as the solver have forced it to do so, eg training the index to know each individual turbines micro site-specific conditions. According to our findings validating the turbine index for a period after the selected training data period, we seen a +40% increased correlation or reduced uncertainty by using the trained turbine Index vs a traditional energy Index.

11.1.9 Data – Time Shift

In the *time shift* tab (Figure 21) time shifts can be applied, either to individual or to all WTGs. Such a time shift might become necessary when you want to compare data with, for example, mesoscale data or production generated from a flow model. The user can add as many lines as necessary. The status column keeps track if the time shift has been performed. By pressing *Load measured data* the time shift is applied.

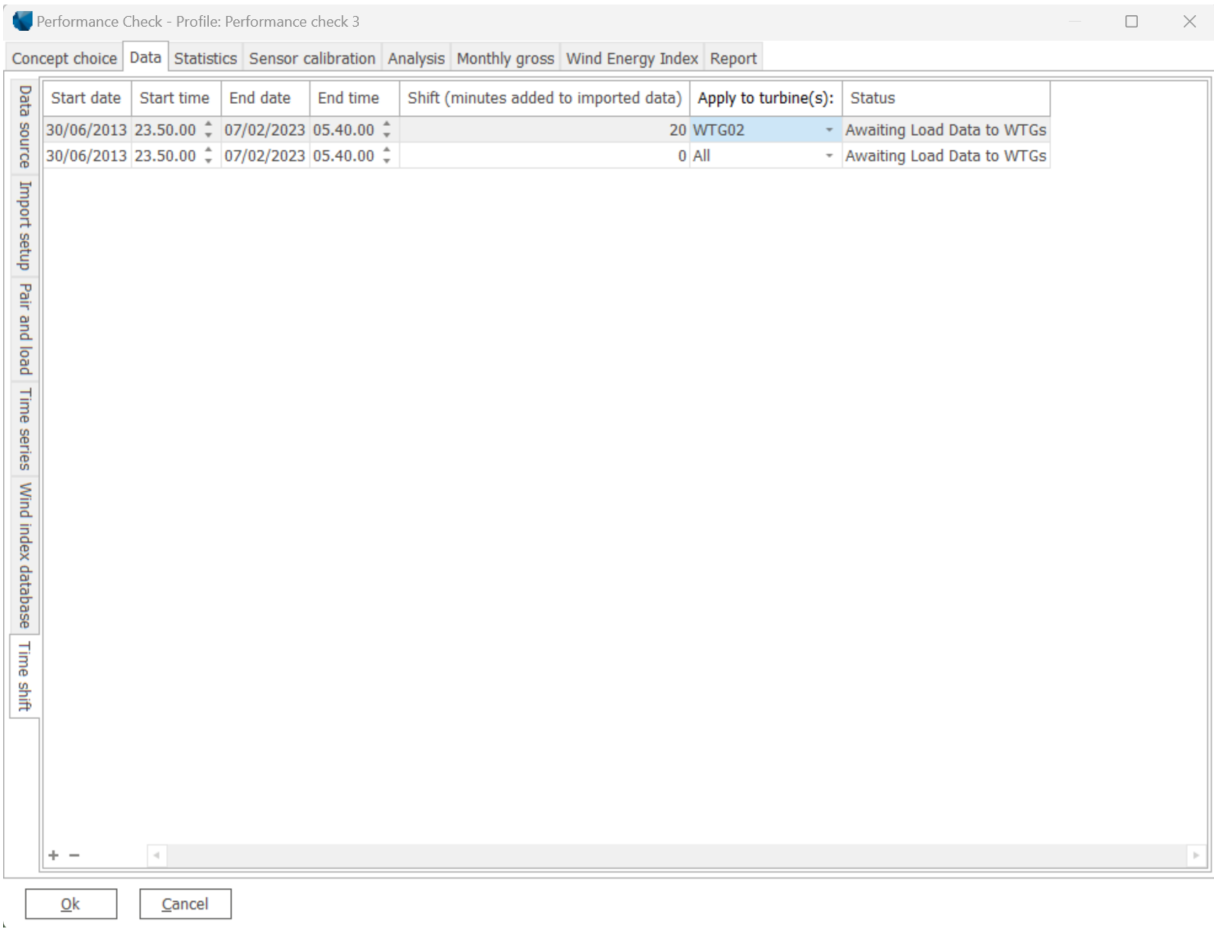


Figure 21: Use of time shift function

11.5 Setup Error Codes

The setup of error codes can be accessed from the *Pair-and-Load* tab. In Section 11.1.4 it is explained how SCADA data are loaded. Some SCADA data might include an error code in the 10-minute time series, but it might not include a description of what that error code means. Also, a category has to be added. This allows the allocation of lost production to different categories. Other SCADA systems do not include error codes at all in the 10-minute time series. Consequently, the SCADA data has to be linked with a separate error log. Besides the error code number (e.g. 309) you might also want to add a description to that specific number and introduce sub-categories based on the description. The user is required to define and add these categories.

In this part of the performance check module, you learn how you can tie all the information together, so in the end you have production data, error code, description of error code, and the category tied together in a 10-minute time series.

The process of setting up error codes and their respective categories or sub-categories can be time intensive and might require a number of iterations. However, the resulting settings can be saved and can be used for other projects with the specific error code structure (*.pfc file).

After loading 10-minute SCADA data you have three concepts to choose from (Figure 22) depending on which information is available and therefore how you want to load and set up the error codes. Depending on which option is chosen the user must run through various steps to load error logs, connect error code numbers with descriptions, categorize the errors, convert them into 10-minute (if they are provided as start/stop time), and connect with the *existing WTG* objects. You can also define whether any lost production related to a specific error code is compensated for or not.

- ***Error codes in the time series***: Here the error codes are already part of the production data and are consequently already imported along with the production data. The next step is to *manage error codes* to assign descriptions and categories.
- ***Separate error code file(s)***: Error codes are available in a separate error log file with start/stop times. This file can be added to the production time series using an advanced interpreter.
- ***No error codes available****:* In case error codes are not available, it is possible to define user error codes based on the scatter plot of the power curve.

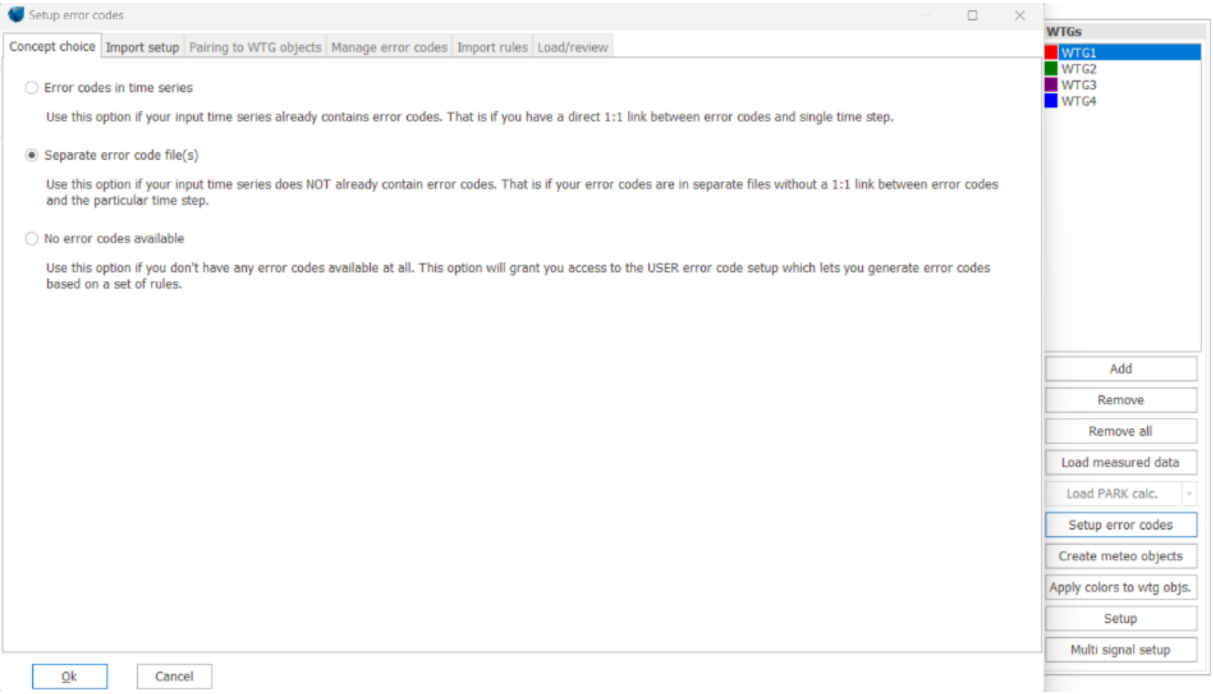


Figure 22: Setup error codes: Concept choice

11.1.10 Error Code in Time Series

Some SCADA systems include an error code in the 10-minute time series, e.g. the manufacturer logs the first error code within each time stamp. In such a case the error code can be imported together with the production data (Figure 23). Information can be found in Section 11.1.5 Data – Import Setup.

Column	Header	First data	Type
22	WTG01_System Logs First Active Alarm No (21)	0	Error code
23	WTG02_System Logs First Active Alarm No (22)	0	Error code
24	WTG03_System Logs First Active Alarm No (23)	0	Error code
25	WTG04_System Logs First Active Alarm No (24)	0	Error code

Figure 23: Loading error codes in Data – Import Setup

It is important to note that only ONE error code column per WTG can be loaded. If there are more columns (e.g. a main and a secondary error code), these must be merged into ONE error code column before loading. This can be done, for example, by multiplying the first error code with 10000 and then adding to the other. This way a unique error code for each sub-category is created.

If an error code is a text string, it must be converted to a number (e.g. in Excel) before loading. Merging two error code numbers is possible in the importer based on a log file, see Section 11.1.13.

Even though the 10-minute time series includes the error code number, you might want to add a description to the error code. Additionally, it can be defined if losses due to curtailments are compensated for or not. Also, the loaded error codes have to be categorised such that the user is able to differentiate between compensated and non-compensated losses. Pressing the top button (*Error Codes in Time Series*) in Figure 22 brings you to *Manage Error Codes*.

11.1.11 Manage Error Codes

The *Load Error Code Translator* allows you to assign categories and descriptions to the already loaded error codes. It is also possible to define curtailments, which can add significant value to the analysis: If a turbine is curtailed, e.g. for flicker or bats, this is an upfront known loss included in the pre-construction AEP expectations. Therefore, this would often be given a special treatment, which is possible to do so by marking this. An example for compensated curtailment could be grid curtailment, where the operator is reimbursed for shutdown due to grid limitations.

Setup is the same as if error logs were from files, see Section 11.1.15

It's now possible under Load/review to ignore pre-loaded error codes, e.g. if they are covering mostly normal operation modes, and are just an alarm that's has been set in the 10-min production time series. You can now choose the individual error codes and ignore them. Note this will change the error code and set it to a 0 value, and it is then considered as normal operation for the 10-min samples it covered.

11.1.12 Separate Error Code File(s)

In this section you learn how you can merge start/stop error logs from separate files with the 10-minute production time series.

Several manufacturers do not store the error codes as part of the 10-minute time series in the SCADA system. The error codes might be available in a separate error log files with the time stamp for start and stop of individual error codes and/or the duration of the error. Often multiple error codes can be present simultaneously, meaning that there are several error codes active within a 10-minute period.

The tool presented here gives the user different options for the interpretation of such data and the possibility to evaluate the consequences of the chosen interpretation.

The error log file has to be in ASCII format. It is advisable to align the naming of the WTG such that it is the same in the SCADA data and the error logs. The error code importer can load two columns of error signals (primary and secondary level). Consequently, it is not necessary to merge primary and secondary error codes before loading. Only numerical values can be imported, any error codes in form of text have to be converted to numbers.

The use of error logs in separate files requires several steps, starting with the *import*. After importing, the error log(s) must be paired with the WTGs. The next step involves *managing the error codes*. *Import rules* can be set and finally the resulting statistics can be *loaded and reviewed*.

11.1.13 Import error codes Set-up

The error log files (in ASCII format) are selected. The format has to be defined, including the line which the header is in, the first line with error code and the delimiter (Figure 24).

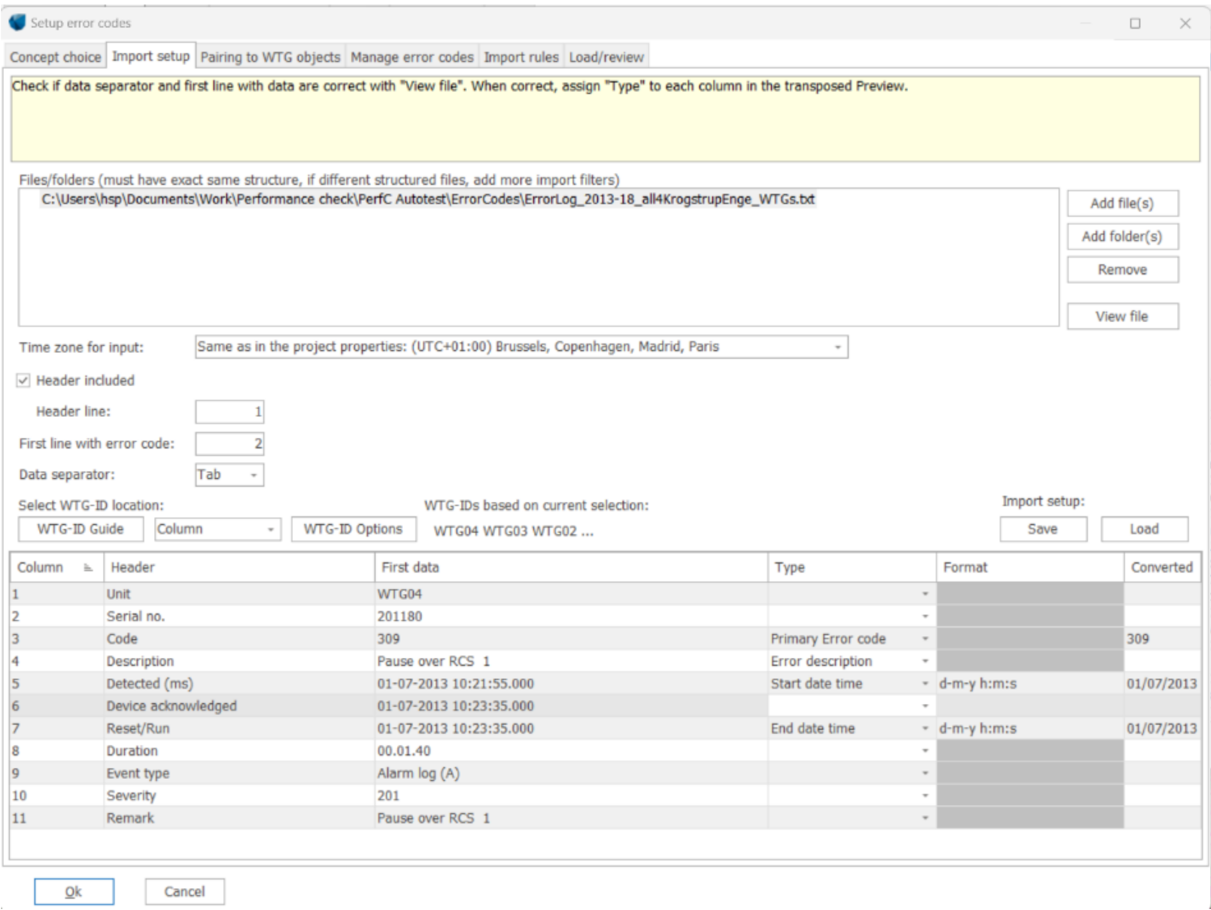


Figure 24: Importing error log file(s)

The concept is similar to the error code translator loader described in Section 11.1.11. However, since error logs normally do not come as 10-minute time series, not only the error code and its description but also the start and stop time/duration have to be defined.

The user has to set the correct format for date and time. If both stop time and duration is available, only one of these can be chosen. Some SCADA systems have neither a duration nor end time in the log. Instead they might have a time stamp with a text, e.g. “incoming” means that the event starts, “reset” or “phasing out” means the end of the event. In such a case the type has to be set to “start/stop text”. An extra box will appear (Figure 25) where you can specify the text which stands for activating the event (e.g. “incoming”) and which text deactivates the event (e.g. “reset” or “phasing out”). It is possible to specify several words, which must be separated with a semicolon. The setup is case sensitive.

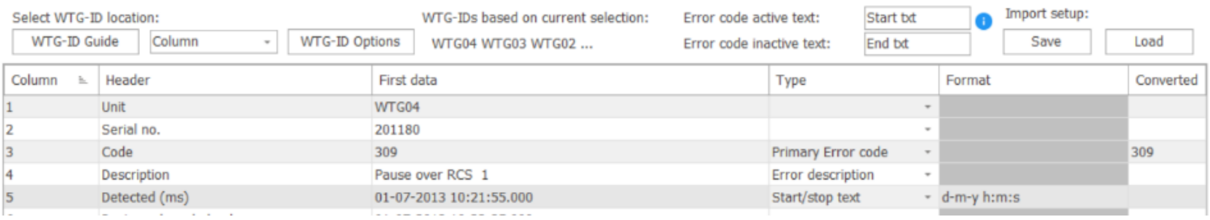


Figure 25: Set-up for start/stop text.

It is essential to assign the error codes to the specific WTGs. In our example the WTG-ID can be found in a column (Figure 26).

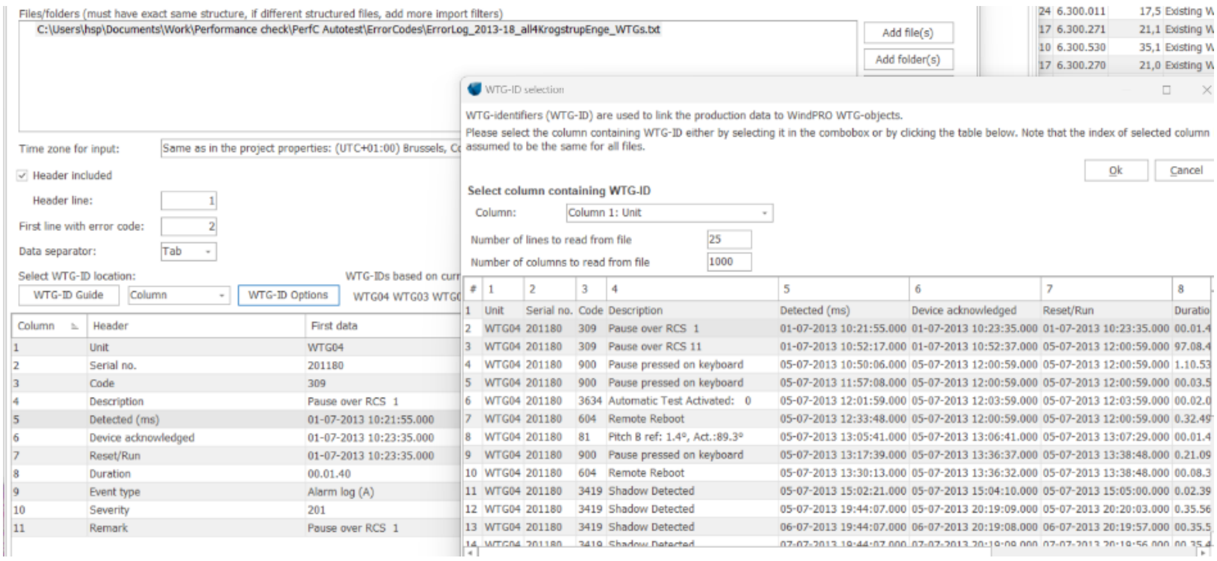


Figure 26: WTG-ID in error log

11.1.14 Pairing to WTG object

After the import of the file the error log has to be paired with the *existing WTG* object similar to Section 11.1.6. If the WTG-ID in the error log is identical with the name of the *existing WTG,* the tool will automatically pair the object with the error log. In case the automatic pairing does not work properly, use the drop-down in upper right corner to match the ID in the import filter to the objects.

11.1.15 Manage Error Codes

Since error logs have various forms, it depends very much on the individual error log how much information is included. The aim is to not only have the error code but also the error description and category connected to the 10-minute time series.

In this tab the error codes are given both descriptions and categories. There are five options on how to connect error codes with their description (if required) and categories.

It is also possible to define curtailments, which can add significant value to the analysis: If a turbine is curtailed, e.g. for flicker or bats, this is an upfront known loss included in the AEP expectations. Therefore, this would often be given a special treatment, which is possible by marking this. An example for compensated curtailment could be grid curtailment, where the operator is reimbursed for shutdown due to grid limitations.

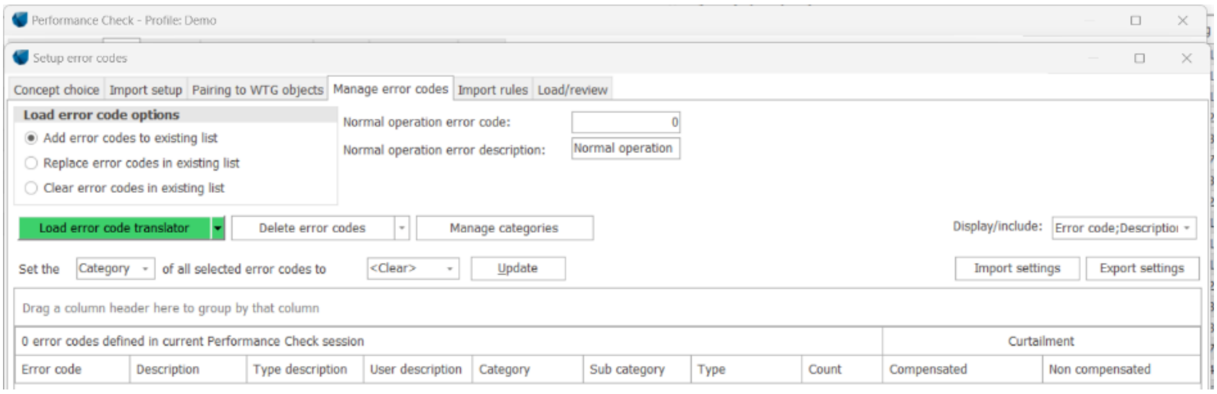


Figure 27: Five options to load error code translator

Option 1: From loaded time series – this transfers the error codes which you have loaded before (Section 11.1.5) into a table. The user now has the possibility to manually assign descriptions and categories to each error code. As modern turbines can have several thousands of error codes, this can become a time-consuming process.

Option 2: From attached error log file(s) – in contrast to Option 1, here the error log file is used to connect the error code numbers with their descriptions. Often categories must be assigned manually.

Option 3: From file – From previous experience you might have built up a directory which connects error codes with their descriptions for a specific SCADA system. The main advantage compared to Option 2 is that you can benefit from your own error code library, which can also include categories.

The user has to specify how the ASCII file is structured (Figure 28), e.g. in which line (row) the header is and what the delimiter is. Via a drop-down menu the user can define the type of data. Normally just the error code and description are needed.

Sometimes files containing error codes, and their descriptions are part of the contract with OEM. The contractual agreement might refer to the error codes the manufacturer is responsible for and thereby is included in the calculated availability guarantees.

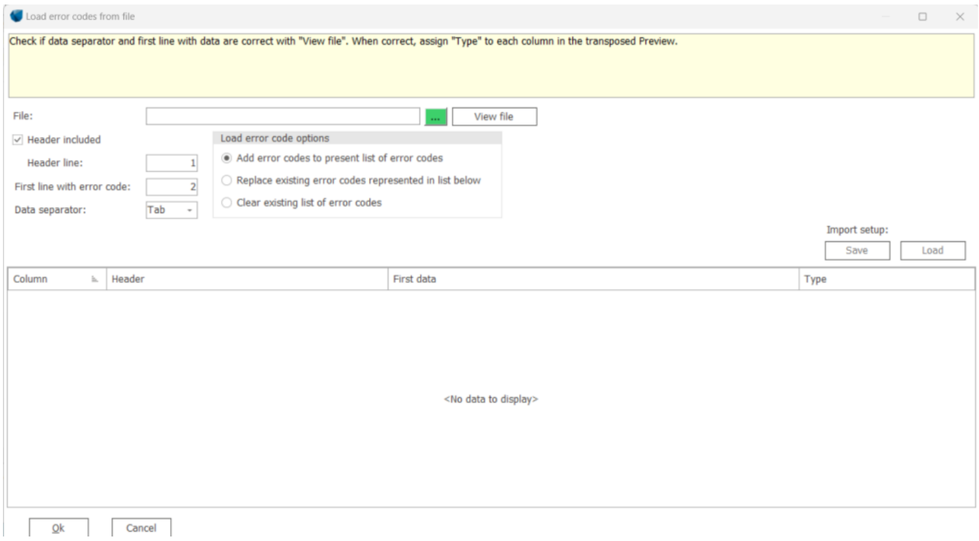


Figure 28: Define types in error code file.

As a special feature it is possible to define both primary and secondary error codes (Figure 29). In such a case an extra item appears: By defining a multiplying factor for the primary (main) or secondary error code it is possible to create a unique error code. It is recommended that you assign a multiplier which exceeds the highest value of the secondary error code to ensure unique codes. In our example the primary error code 309 will be multiplied with 10000 resulting in 3090000 and 201 from the secondary error code will be added. The new, unique error code is 3090201.

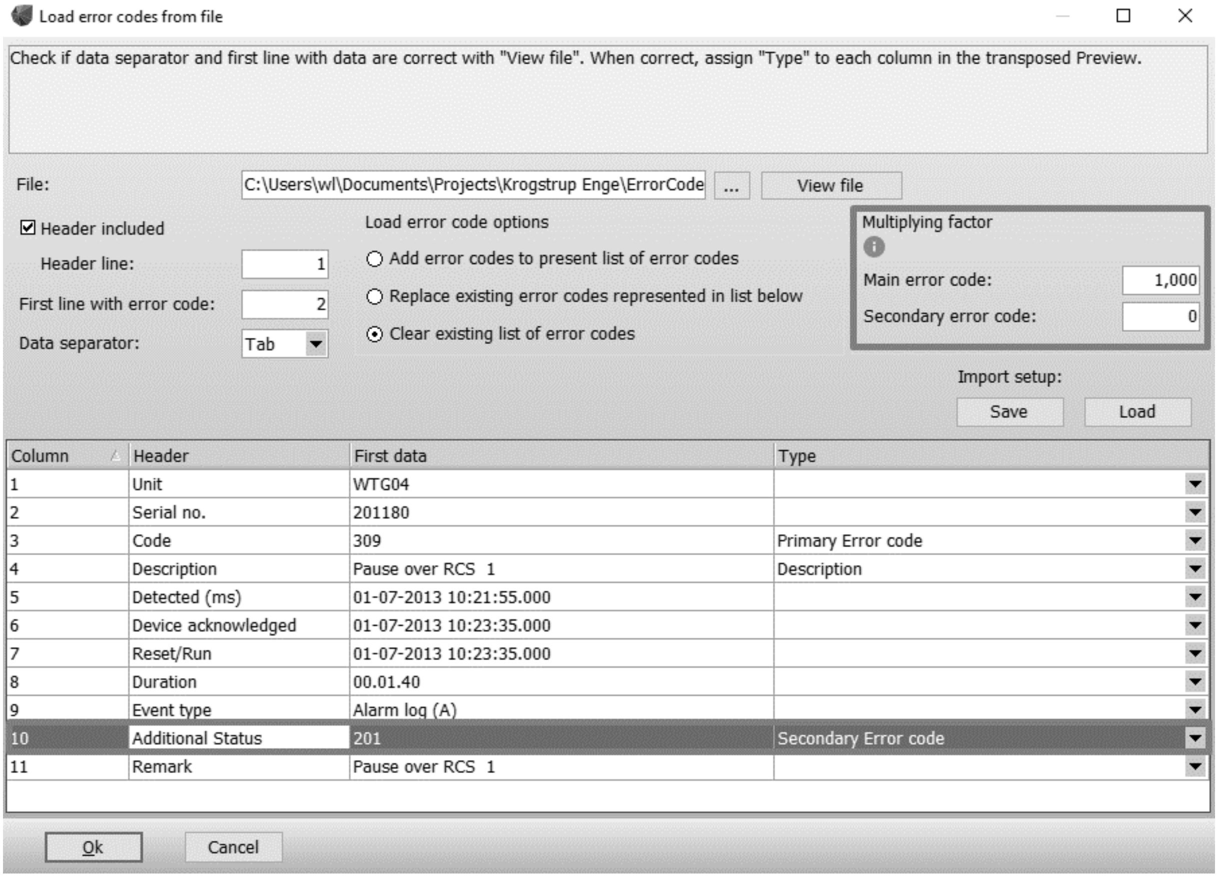


Figure 29: Secondary error codes

Option 4: From Clipboard is like Option 3 but used when the data is in the clipboard e.g. after copying from Excel.

Option 5: From another Performance Check session – This option is only available when you create a new *Performance Check* session within the same windPRO project. To get access to a list from another project, use the Export – Import option.

In general (independent of the chosen option) multi-editing is possible by marking a group of error codes (Figure 30). The list is auto sorted by the most frequent occurring error codes.

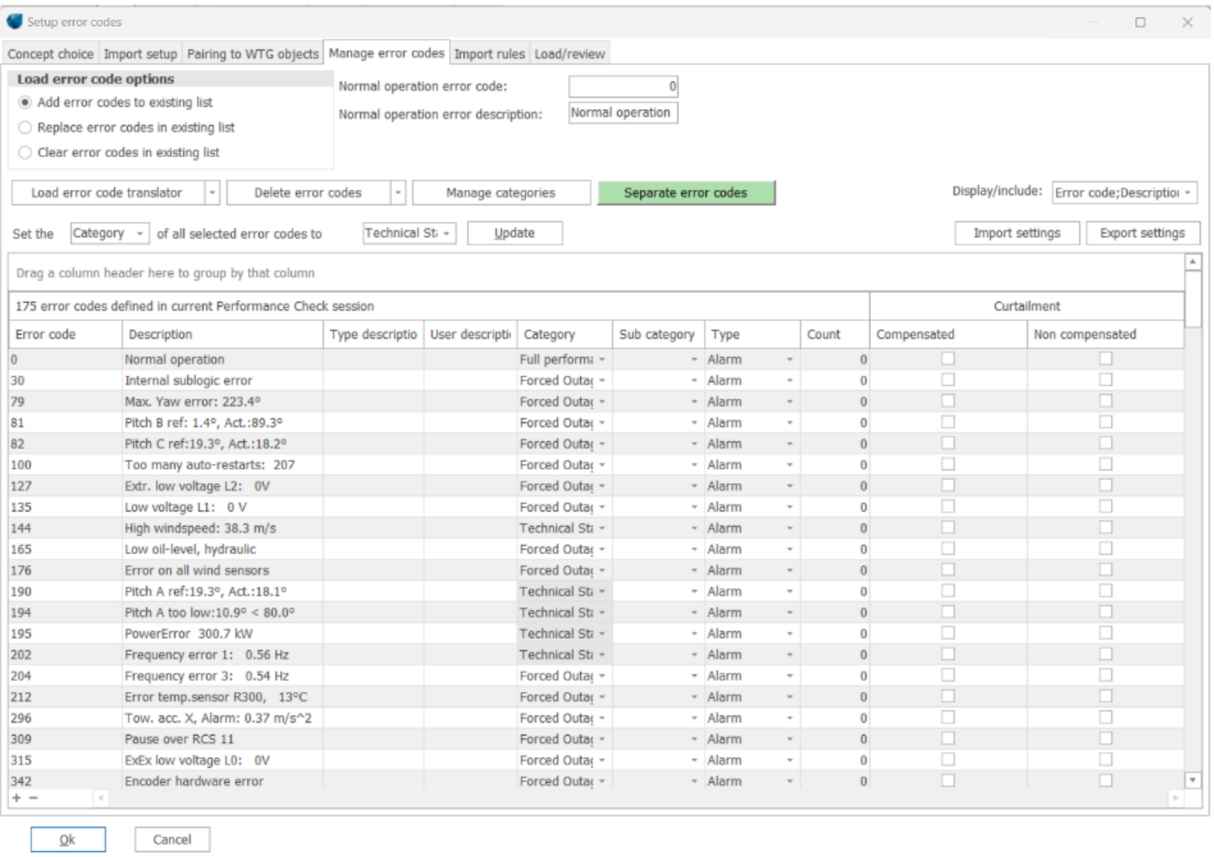


Figure 30: Multi-editing of error code categories

A problem can arise if a unique error code has more meanings. An example is shown in Table 2. In our example error code 309 appear in more variants.

308	System log reestablished	Log	Normal operation
309	Pause over RCS __	Alarm	Manufacturer
309	Pause over RCS __	Alarm	Environmental
309	Pause over RCS __	Alarm	Owner
309	Pause over RCS __	Alarm	Utility
309	Pause over RCS __	Alarm	Normal operation
309	Pause over RCS __	Alarm	Owner
309	Pause over RCS __	Alarm	Owner
309	Pause over RCS __	Alarm	Utility
309	Pause over RCS __	Alarm	Owner
309	Pause over RCS __	Alarm	Manufacturer
309	Pause over RCS __	Alarm	Environmental
310	Run over RCS __	Log	Normal operation

Table 2: Example error code with various meanings

If windPRO identifies an error code with varying descriptions, a green menu "*Separate error codes*" bar will appear. A pop-up window lists all observed error codes, which have varying descriptions. For each description a new error code is suggested. Update error code list all events under error code 309 will be split into sub-events with a new, unique error code and a specific description.

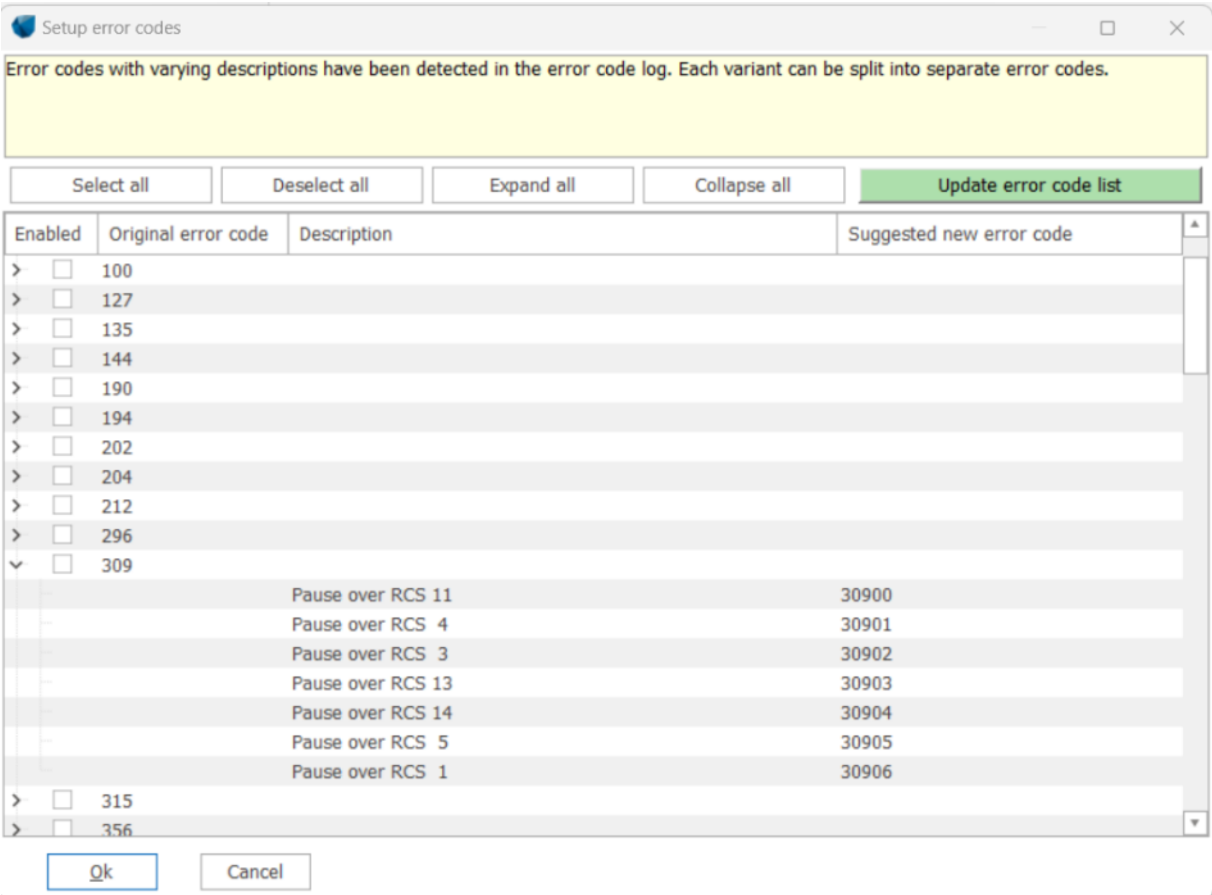


Figure 31: Separate error codes with multiple meanings

After setting up error codes with description and category, the list could look like Figure 32. Some errors are curtailments, of which some are compensated for. In our example “Remote shut down” is a grid curtailment, compensated by the utility.

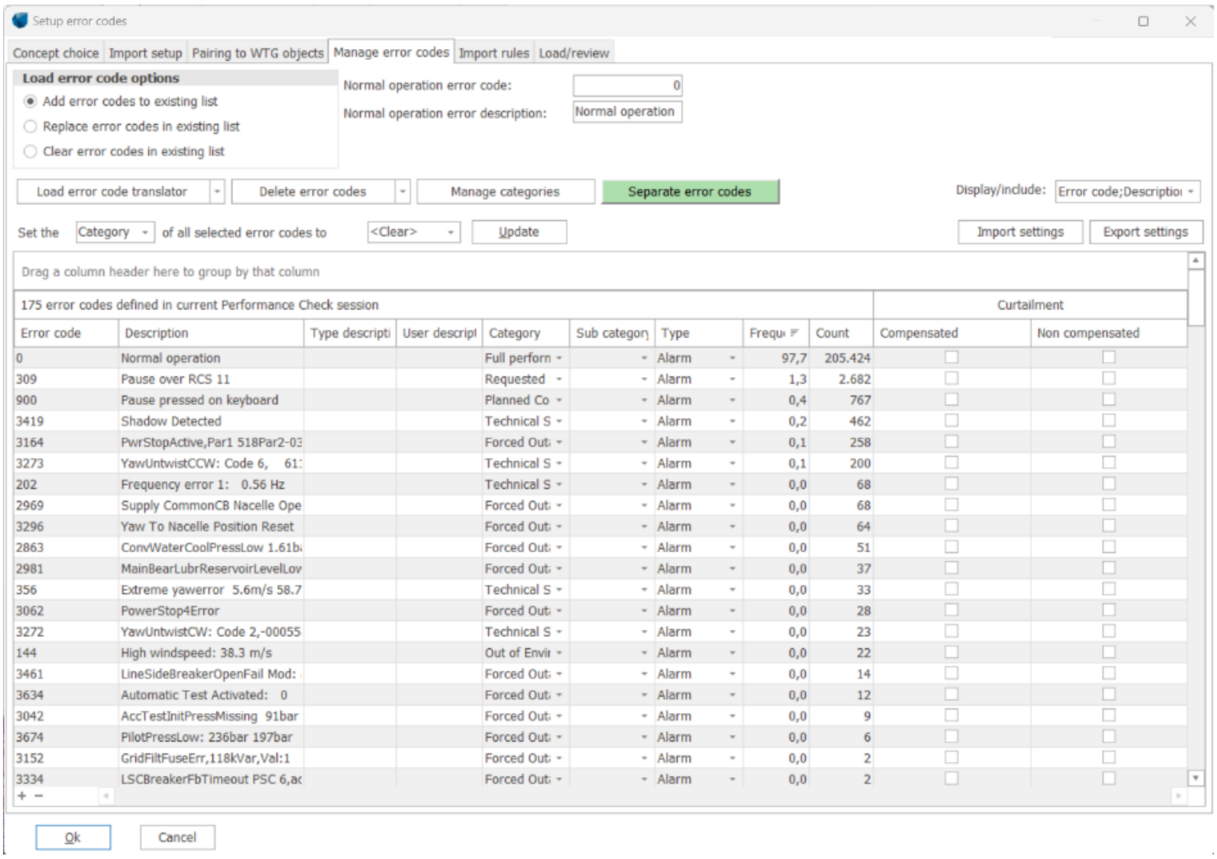


Figure 32: Example of categorized error codes

11.1.16 Import Rules

The tab *Import rules* give different options for handling the import. In most cases it will be ok to choose the default option.

In some cases, the control system uses an error code called “alarm chain activated” independent of the reason. Consequently, all errors will have the same code, which of course will prohibit any meaningful analysis. Therefore, more choices are available.

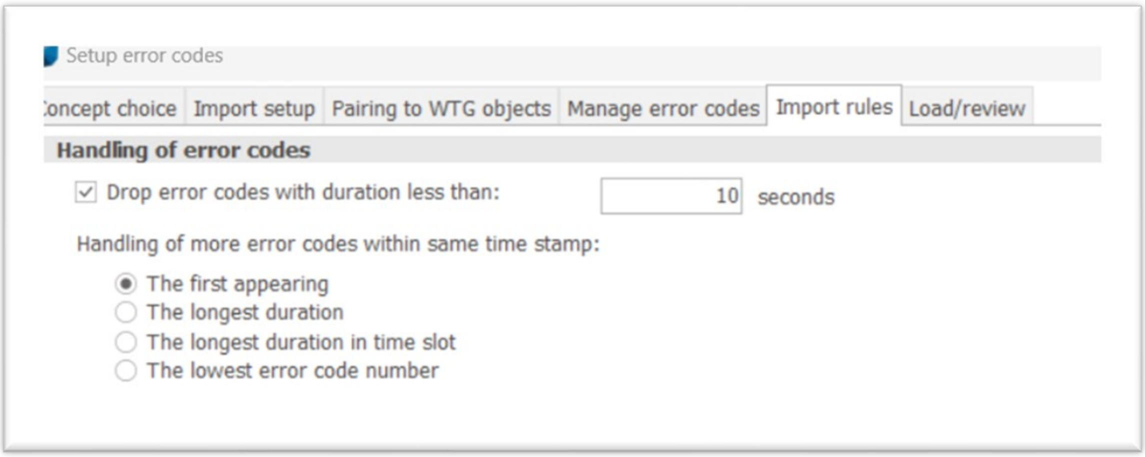


Figure 33: Import rules

11.1.17 Load/Review

Here the error codes are loaded from the error log file(s) into the *existing WTG* objects by pressing the "Load" button. There are two tabs on the left-hand side: *WTG time series* and *Error code frequency*.

In ***WTG time series*** the resulting 10-minute time series is displayed (Figure 34). Please note that only 10-minute periods without any error will fall in the category "Normal operation". If within the 10-minute period, there is one milli-second subject to an error event, the whole 10-minute period will be marked with that specific error code, unless otherwise specified on the Import Rules tab under "Drop error codes with duration less than" field.

Clicking on individual 10-minute time stamps with an error code allows to see in the bottom of the window all error codes that were active in that time stamp. It is possible to manually select (button on the right) another error code within the 10-minute time stamp other than the one selected by the import rules setup.

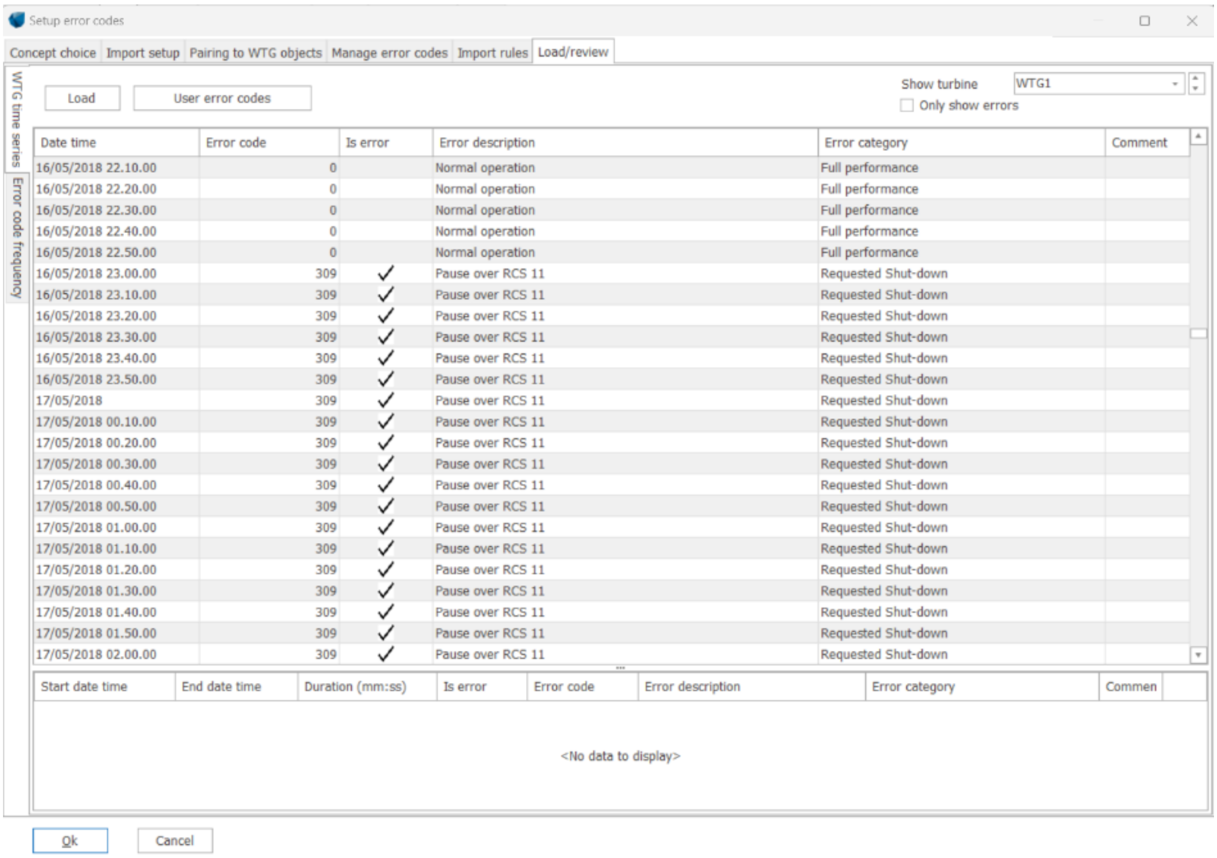


Figure 34: 10-minute time series from error log

On the tab ***WTG time series,*** the user again has access to *user error codes* (see Section 11.1.18), as there might be time stamps remaining, where the WTG clearly does not operate optimally but has no error code. Using *user error codes,* it is possible to manually assign an error code to these events.

On the second tab to the left ***Error Code Frequency,*** the main statistics are shown for each error code together with the description: MTTR (mean time to repair), the period count (how many time steps has this event been logged for), and frequency (how often has the event been logged).

A plausibility check can be performed by pressing the "*Preview*" button. The specific error code can be reviewed. In Figure 35 events for yaw untwist are shown. Luckily the control system untwists the WTG during low wind speeds.

As a second example, the events which belong to error code 309 are shown in Figure 36. Not all events are below the power curve as one might expect, since the error codes description is “remote shutdown”. However, as explained earlier, a 10-minute time stamp is marked with an error code even if the error has been active for a millisecond. This might have been the case in this example, where the shutdown has only been active for a very small part of the time stamp.

However, it could also be the case that the assumptions as to which period the SCADA data refers to were wrong. In the initial data import of the SCADA data, the user had to choose if the time-stamp refers to beginning or the end of the 10-minute period (see Section 11.1.5). If the wrong choice has been made, the 10-minute error table and 10-minute production table do not refer to the same time but are shifted by 10 minutes. In such a case, the user must exit the *error code set-up* and go back to the start. The *data import setup* must be revisited (see Section 11.1.5), the time stamp setting must be changed, and *pair & load* must be repeated. The *Setup Error Codes* must be re-done. After reloading the error logs files and converting them to 10-minute periods, the stop events should now concur with zero production. It can consequently be assumed that the production and error logs are now synchronized.

Finally, in case the user has merged error codes – the merged code can be checked for plausibility.

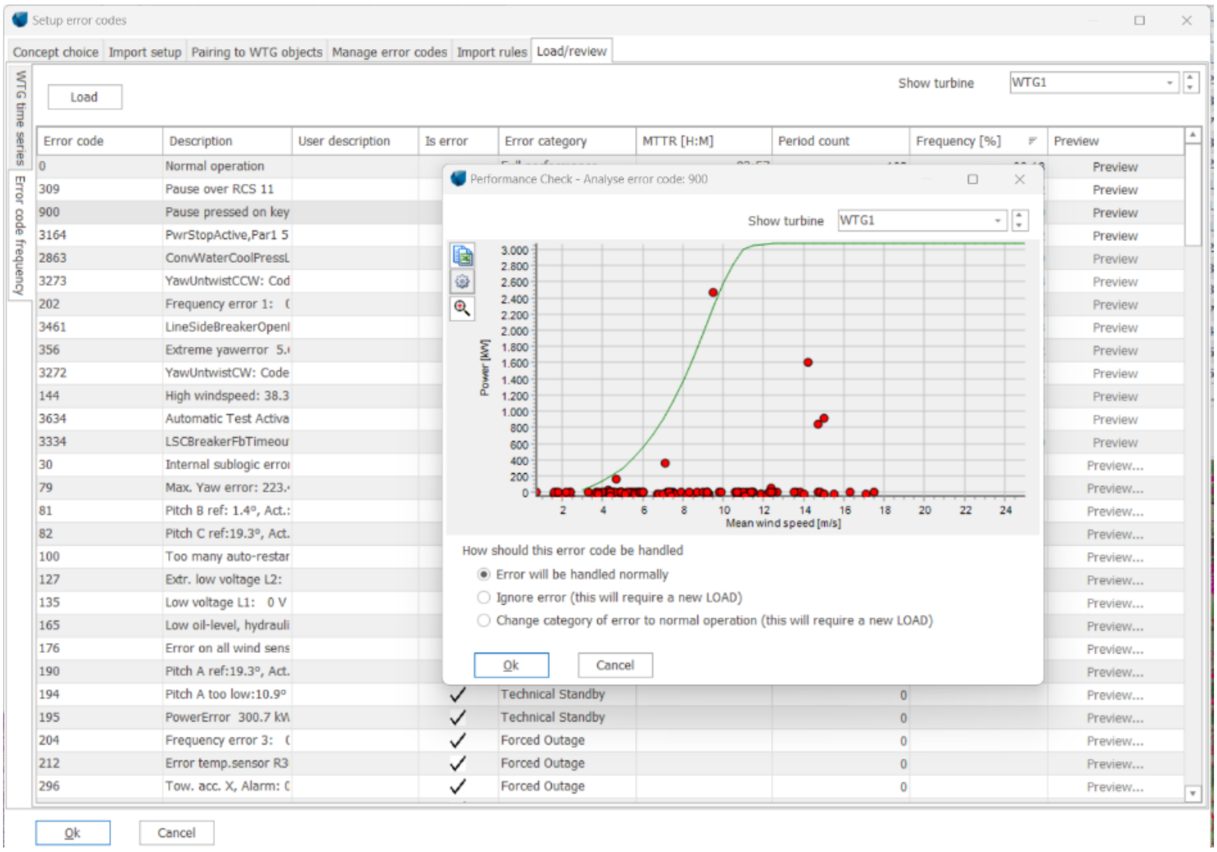


Figure 35: Error code statistics and plausibility check

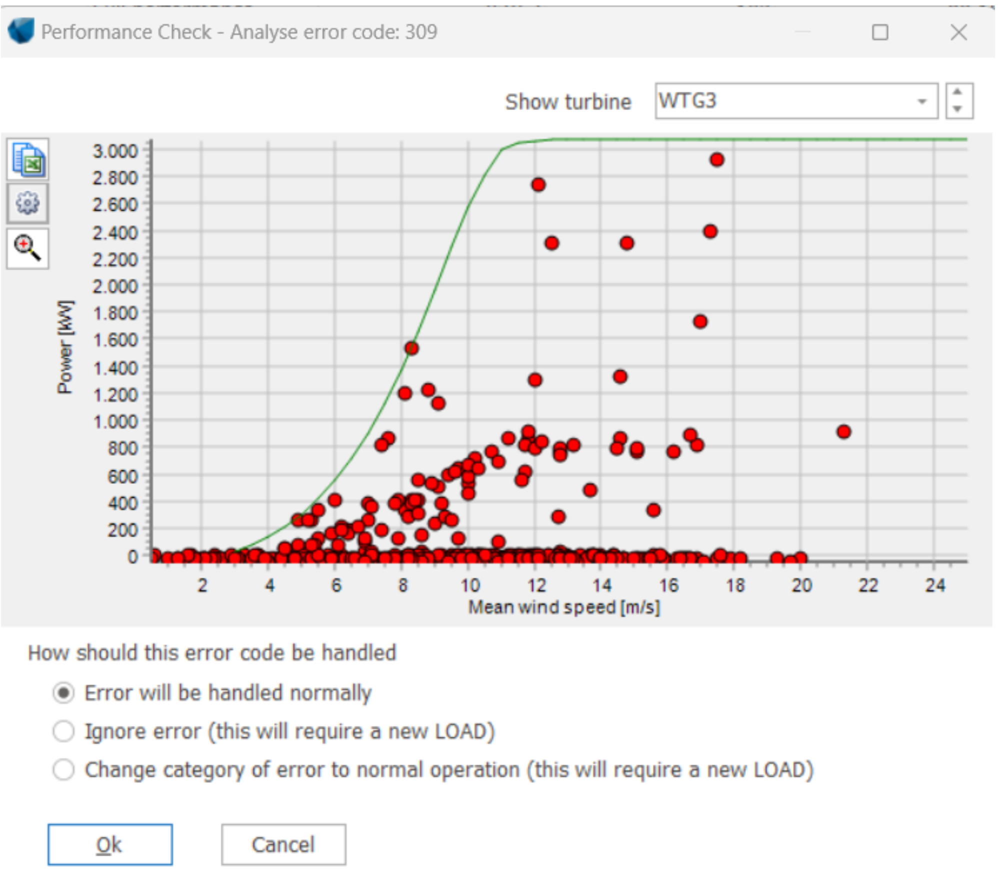


Figure 36: Error code 309 – remote shutdown: Likely wrong import setting for time stamp.

11.1.18 No Error Code Available

This feature can be used when error codes have not been provided. It can also be of use, if the error codes have been provided, but not all events are assigned an error code. E.g. the WTG de-rates, but the operational status shows normal operation. Please note that user error codes will NOT overwrite imported error codes. Figure 37 it is demonstrated, as to how to use this feature where no error codes are available, but it will work similarly if error codes are already loaded.

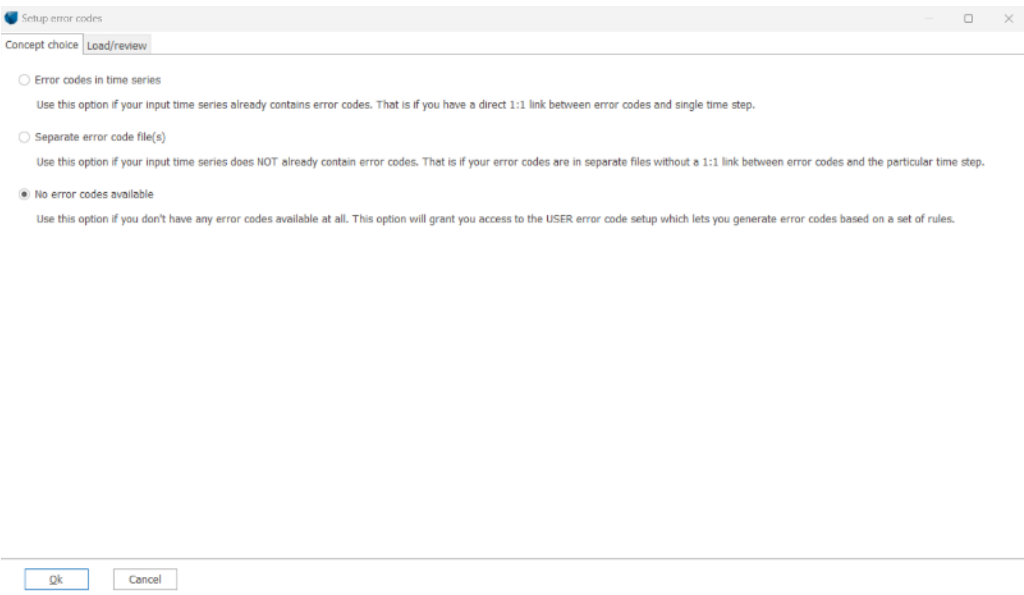


Figure 37: No error codes available

User error codes can be defined in the *Load/review* tab*:* The button "*User error codes*" brings you to the following form (Figure 38).

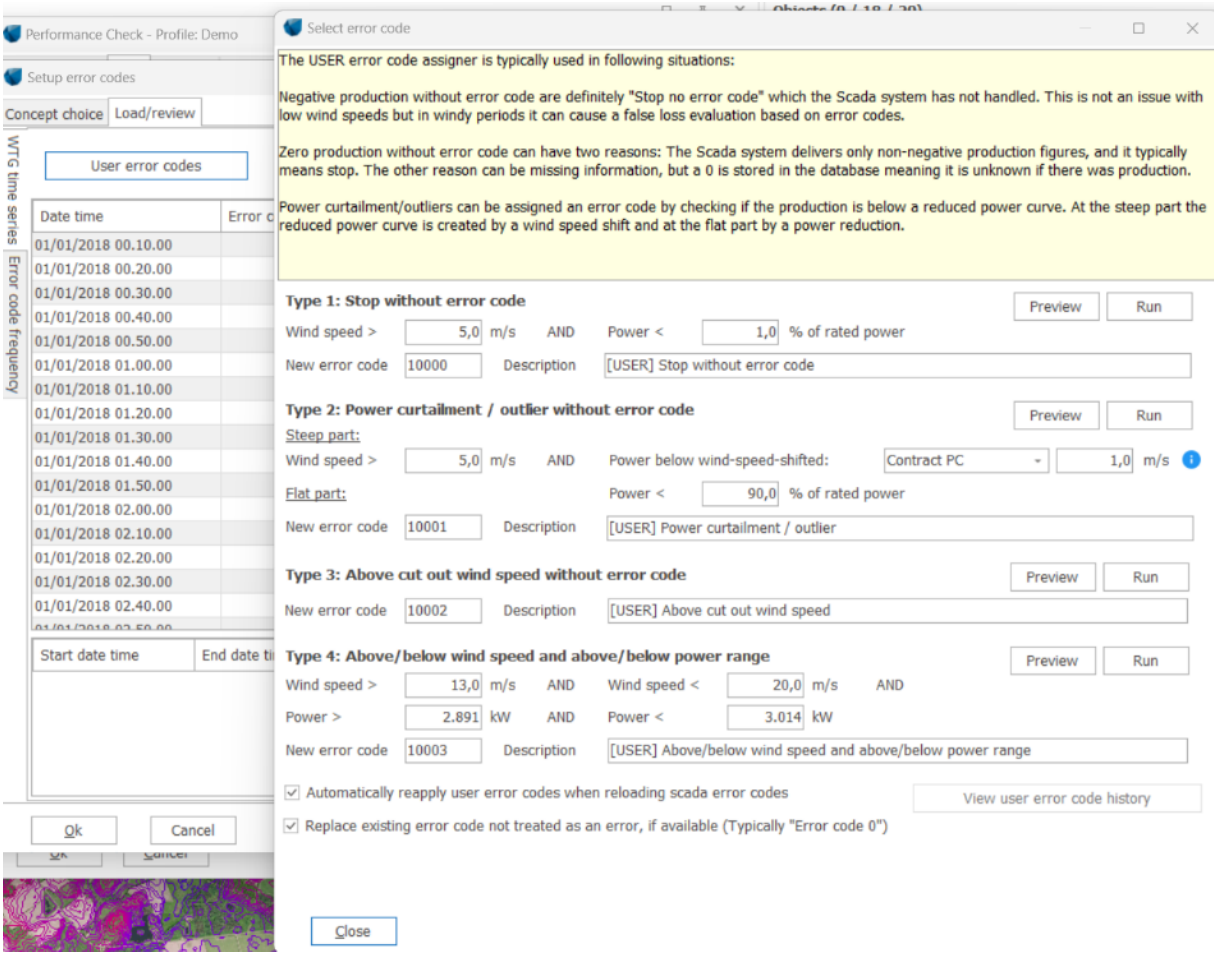


Figure 38: Form for defining user error codes.

Four different types of user-defined error codes are setup. Please note that you can specify from which WTG you will see the scatter plot. The user-defined error codes however will apply to all WTGs.

Type 1 allows to identify events with stops without error code: A combination of wind speed and power is used to find these events. The algorithm is based on that when wind speed is bigger than x m/s (default 5 m/s) and the power is smaller than x% of rated power, one can specify a new error code number for these events. The *Preview* button brings you to the scatter plot and shows the impact of the chosen settings (Figure 39). In the scatter plot the filtered events are shown in a colour. The new, user defined error code becomes effective after you have closed the preview and pressed *Run*. The new error code will then be added to the 10-minute production time series.

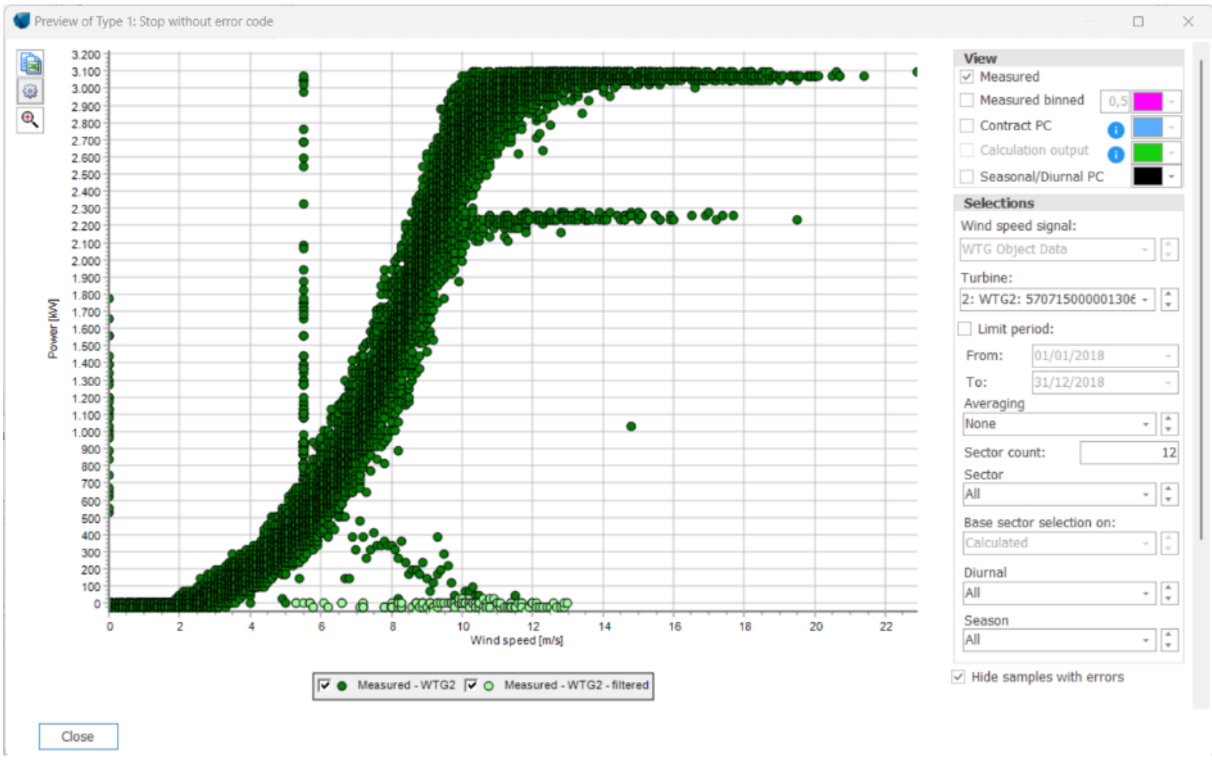


Figure 39: Preview: Stop without error code.

Type 2 addresses power curtailments and outliers without error codes. Two sets of parametrisations are used: one for the steep part of the power curve below rated power and one for the flat part of the power curve above rated wind speed.

For the *steep part* of the power curve events below a fictive, shifted power curve are filtered. The user can specify if the measured, binned SCADA power curve or the contracted power curve from the WTG catalogue is used, which is assigned to the *existing WTG* object. The user can also specify how much the power curve is shifted to the right. Obviously the further the power curve is shifted to the right, the less aggressively it is filtered. Please note that the filtering affects the measured, binned power curve. Consequently, running the same filter once more will pinpoint a few, additional time stamps.

For the *flat part* of the power curve, events with x % of the rated power can be filtered.

It is possible to assign several user-defined error codes e.g. first you might want to isolate the rating at approximately 2300 kW. Once you have found appropriate settings you can run the tool, which will add the error code to the 10-minute time series. You can then re-visit the scatter plot and define new, different error codes.

In the example in Figure 40 the filtering might have been too aggressive, as too many data are filtered out - especially in the knee area of the power curve. In such a case, it is possible to go back and adjust the settings, e.g. a bigger shift of the power curve.

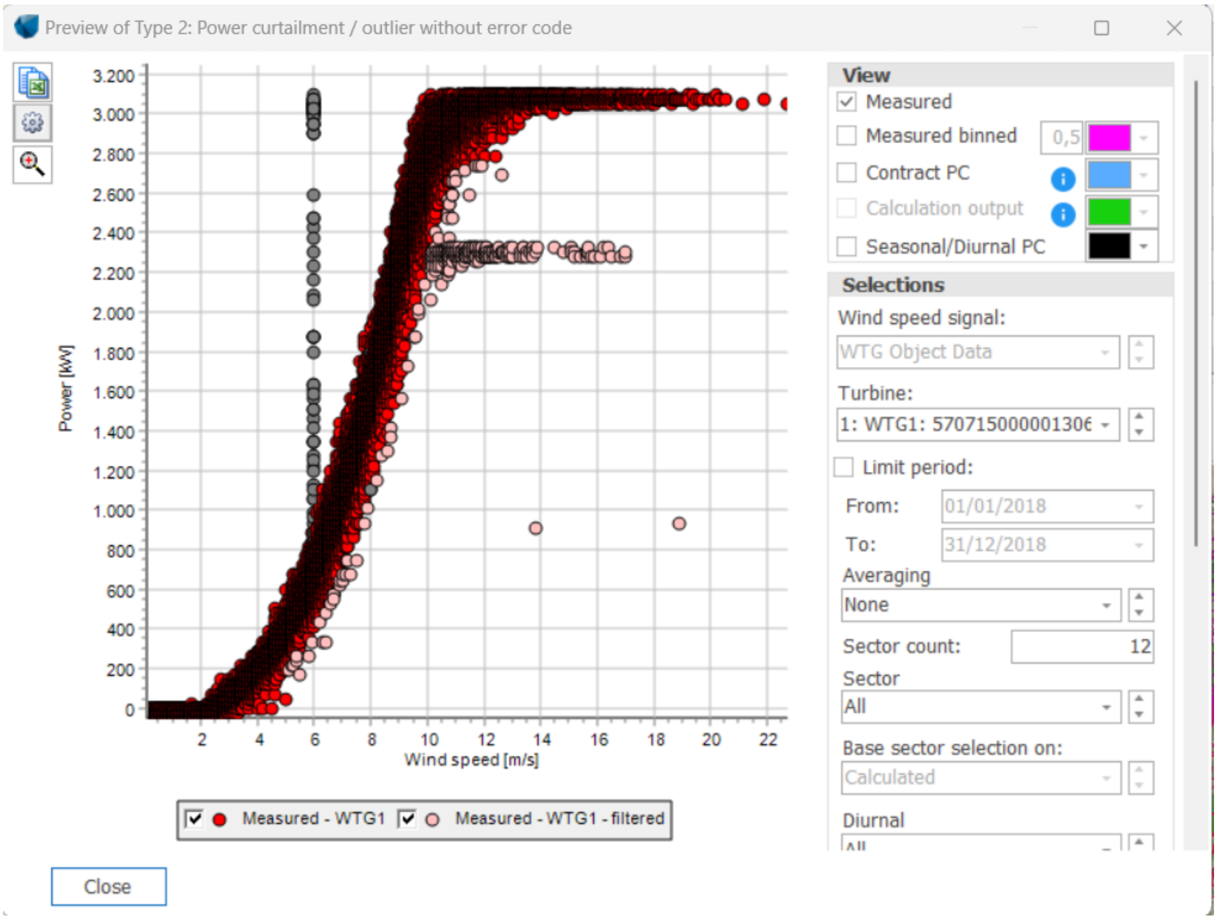


Figure 40: Preview: Filtering for curtailments and non-optimal performance

Type 3 is to establish an error code for operation above cut-out wind speed. The purpose of this option is mainly to avoid these samples disturbing the comparison between measured and modelled production from a time-varying PARK calculation.

Type 4 can be used to catch a specific operating mode which has no error code, by selecting a box parametrised by a wind speed and a power range. Pressing preview allows you to drag & drop a box to mark an area for filter.

The history of the user-defined error codes can be re-visited. The user can see how many samples have been affected by which setting. The user-defined error codes can be deleted.

As mentioned above, the user defined error codes can also be used even though you have the error code in the 10-minute SCADA data. You might want to use this option e.g. if the WTG de-rates, but this de-rating is treated as normal operation in the SCADA system. In the bottom of the form (Figure 38) you have to confirm if you want to replace the existing error code with the user-defined error code.

With the user-error codes established, a rough loss evaluation for each WTG can now be performed (Figure 41). The WTG can be changed in the top-right corner.

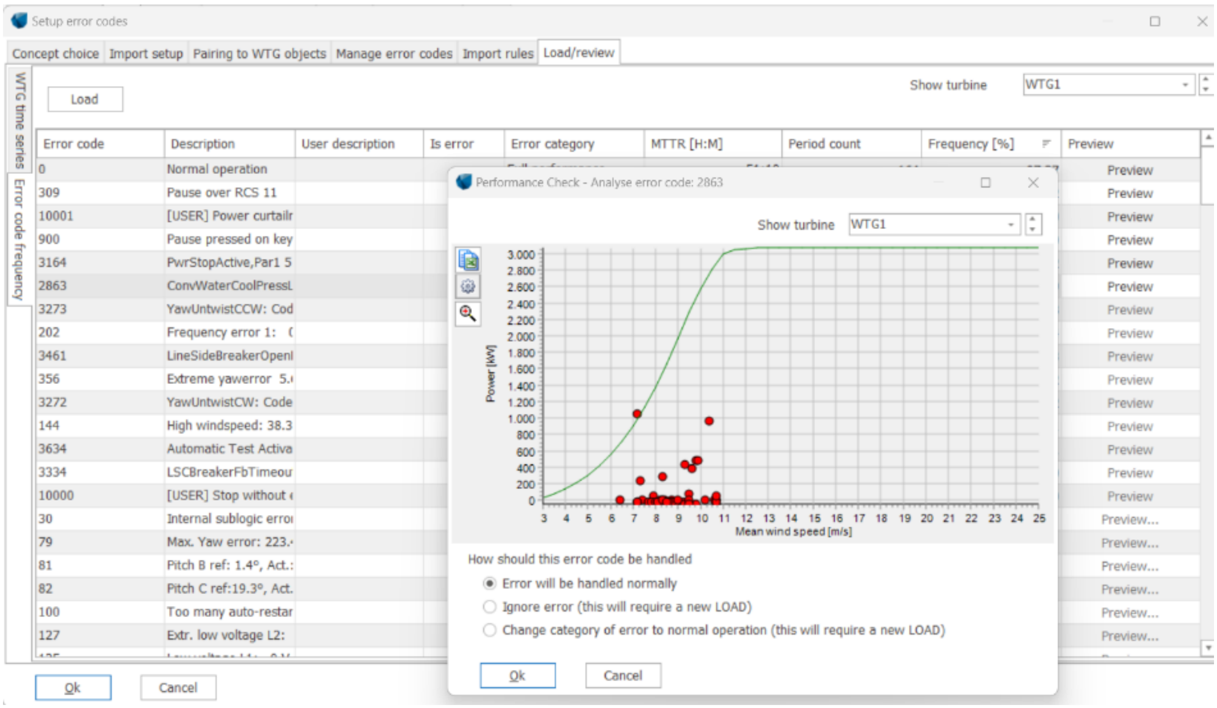


Figure 41: Loss evaluation of user-defined error codes: example user code 10000

As a check, it is possible to see the events which have been assigned to a user error code by pressing the preview button.

The user can choose to ignore the error code. Alternatively, the error can be treated as normal operation. Both options require loading the data again (see Section 11.1.6).

11.6 Sensor Calibration

Since the methodology behind the post construction analysis assumes consistent nacelle wind speeds, the wind speed signal should be checked for any inconsistencies. Inconsistencies could occur due to anemometer exchange or changes of the scaling factor of the wind speed signal in the turbine controller and should be corrected before undertaking loss evaluations.

In Figure 42, the daily average wind speed signal of a single "Selected WTG" is compared to a daily average reference wind speed signal, obtained from the average of all available signals for each day of the chosen reference turbines and/or other measurement. The reference wind speed signal can come from another single WTG or from a reference wind speed signal (e.g. mesoscale data). The upper graph shows the two wind speed signals to be compared. The lower graph displays the selected time series minus the reference time series with a set averaging time. The averaging time can be annual, monthly, or daily.

Please note, that by default only data is shown where the WTG operates optimally by switching filters on. This ensures that the comparison is not affected by a changing behaviour of the nacelle anemometer when the WTG is switched off, de-rated or similar.

The analysis is supported by a heat map (Figure 43) and the scatter plot of power curve.

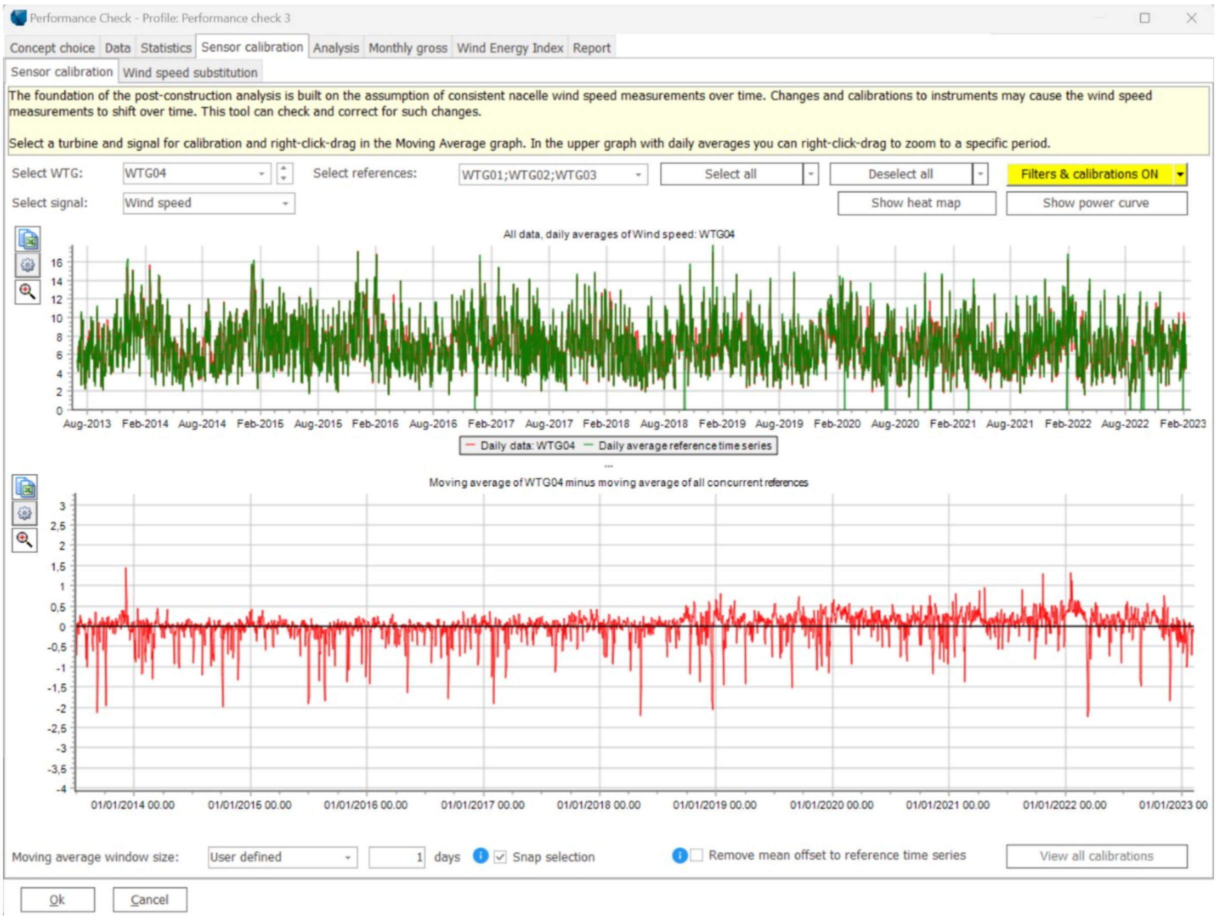


Figure 42: Sensor calibration

The heat map indicates that there is an offset between the average of all chosen reference data sets and the turbine under investigation. It is strongly recommended to also visit the scatter plot of the SCADA power curve for a plausibility check before concluding which signal is trustworthy and which one is not.

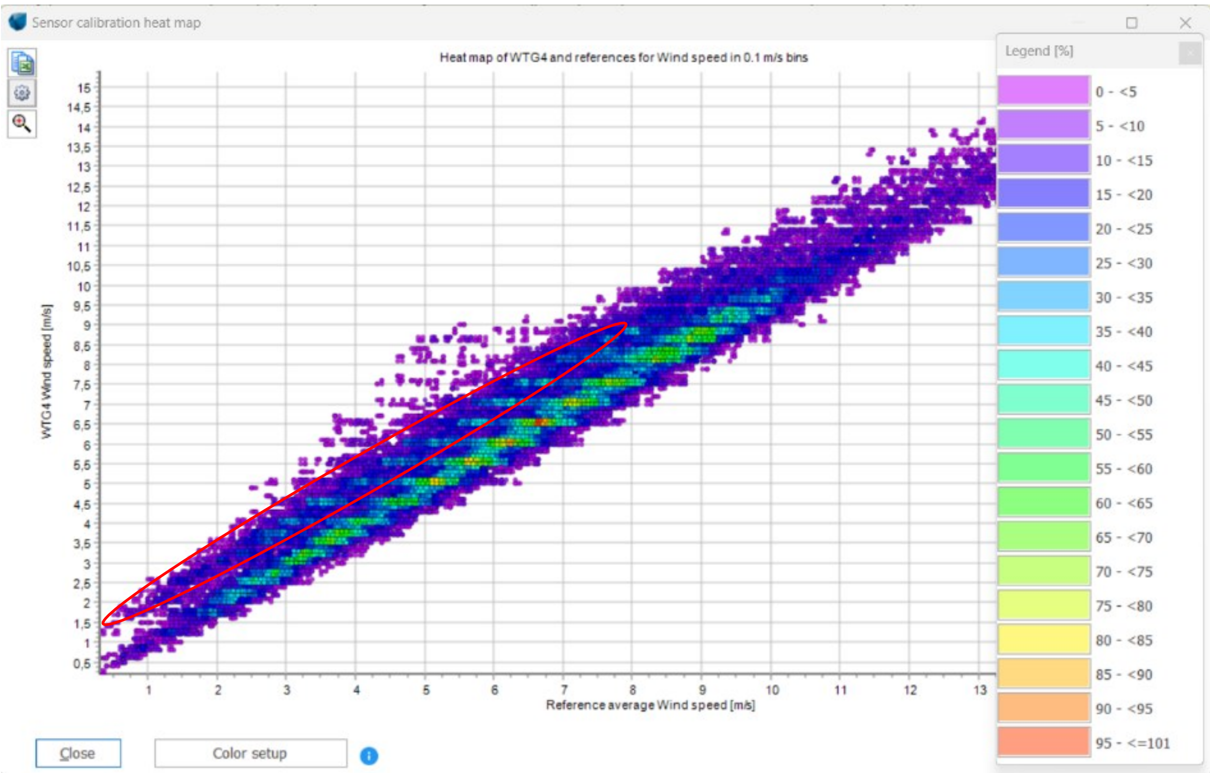


Figure 43: Heat map of reference versus individual wind speed

In this case, a persistent offset is found in the data. The affected time period can be marked by pressing the right mouse button and drag to the end period. Let go of mouse right button and a pop-up window informs about the difference in wind speed between the two signals during the marked period (Figure 44). The user can now decide if the offset should be applied or not.

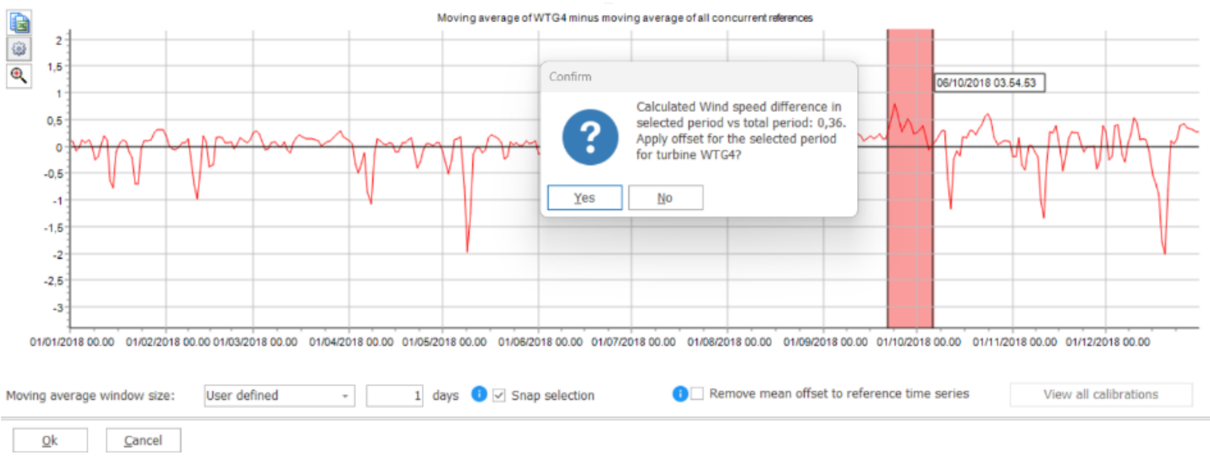


Figure 44: Example of inconsistent nacelle wind speed

Under the condition that the filters are switched on, the graph will update and display the original as well as the resulting corrected signal. It is recommended to plausibility-check the impact on the power curve. E.g. if you chose to compare two individual WTGs rather than using an average as reference, using the heat map and power curve will help in understanding which of the two signals is the correct one.

In the bottom right of the window all applied calibrations can be revisited and deleted again.

11.1.19 Wind speed substitution

Wind speed substitution follows the TR10 standard method 3 for finding the best correlating reference wind speed signal, available in a minimum 3 month running window.

It requires error codes to have been preloaded and a reliable wind direction signal.

The aim is to substitute partly disabled wind speed signals from the imported nacelle/SCADA wind speeds or if there’s gaps in the provided data.

This method establishes a monthly correlation to all other windspeed signals loaded and in 12 x 30° sectors, with a resulting scale and offset between each data signal loaded.

As an example, with 10 turbines and 3 years of Scada data loaded, plus one Mesoscale reference data set; the TR10 method automatically calculates 11 data sets x 36 months x 12 sectors = a TR10 matrix consisting of 4752 correlations along with the Scale and offset between all loaded datasets for these.

Then for any given 10min period where a wind speed signal is disabled or missing, it will select the wind direction for this period, and find the reference which has enabled windspeed data and the highest correlation. It will then use the derived scale and offset on the reference data to substitute over the disabled or missing windspeed signal.

If no wind direction data is available, it can be imported as Mesoscale or possible on-site measured wind data. This is done in the Reference database where loaded METEO objects in the windPRO project are available, and it’s further possible to directly import online reference data sets.

Under “Setup wind direction master,” it’s possible to use one master wind direction dataset for the TR10 evaluation on correlation matrix between all loaded datasets of nacelle wind speeds, reference wind speeds, and direction data are based.

Once reference data and wind direction setup are chosen, pressing calculate will start windPRO’s TR10 calculation, depending on the number of turbines and length of loaded timeseries this can take several minutes.

During the calculation, which is parallelized, thus uses multiple cores if available, the top left window gets updated as each sector and month is completed. When it is done, the top right table is written, listing the combined matrix of all calculated correlations and number of months used to fulfill the TR10 minimum requirements of bins filling per month and sector. See the TR10 manual for further details on the model and its requirements.

The combined TR10 matrix can be exported for documentation purposes.

Once the TR10 method has been completed, pressing “Substitute disabled/missing windspeed signals”, will begin reading all loaded nacelle wind speeds for every sample where it is disabled, or a time stamp is missing a wind speed reading in between first and last known date & time per turbine. It will follow the TR10 method, find the highest correlating reference data which has data in the said period, and apply the scale and offset found. This will overwrite the disabled signal or insert into missing periods.

Note the original wind speed signal will be overwritten if disabled!!!

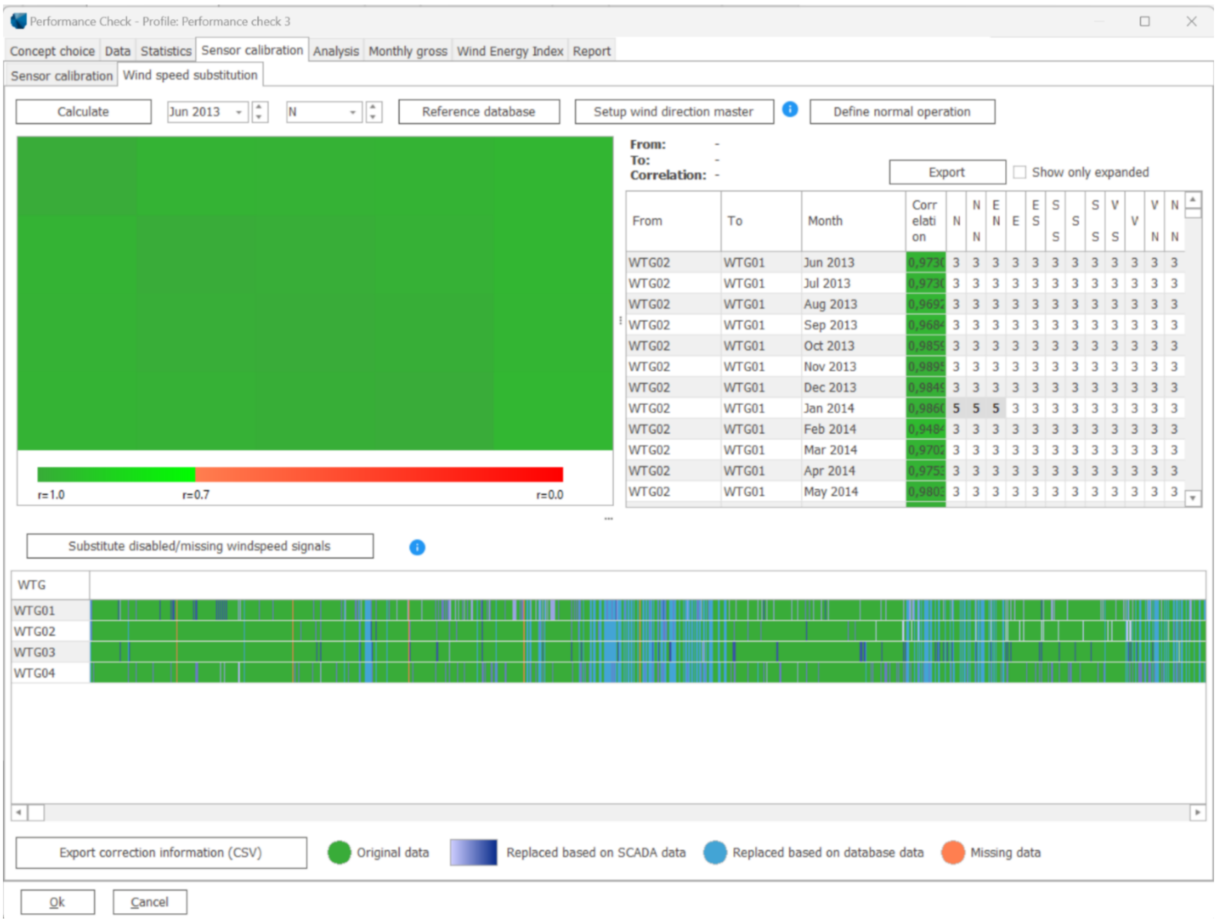


Figure 45: Sensor calibration – Wind speed substitution : TR10 methodology

During the process of substituting the TR10 derived wind speeds, the bottom window gets updated as the software progresses through the loaded timeseries, and graphically indicated with Green original un-touched data. If the data have been substituted by concurrent neighbouring nacelle wind speeds or if no turbines in the park had data, that reference windspeed data has been used instead.

If hourly mesoscale or era-interim data is used as reference, linear fit between hourly windspeed readings are used to find the 10min windspeed substituted result.

Note!! Depending on the number of turbines and length of data set, along with the CPUs of user's computer, this may take several minutes to complete.

Also, if the users regret the choice of substituting the faulty/disabled or missing wind speeds, it's only possible to reload data from the import filters in order to revert to the original import settings. This is done under the main "data" tab, Pair & Load, and re-selecting "Load measured data". Here it's possible recover existing error codes after the fresh reloading of the original SCADA data by selecting "Recover existing error codes after load".

11.7 Create Basic PARK Calculation for losses

To calculate the lost production a *PARK* calculation has to be performed (Figure 46). It calculates the potential production based on the historic power curves of each WTG and the nacelle wind speeds. The nacelle wind speeds of each WTG should have been checked for consistency by comparison with a reference wind speed (see Section 11.6). The basic time-varying *PARK* calculation does not require a detailed flow model set-up. Terrain and roughness information are not required.

Prior to starting the *PARK* calculation, the user has the possibility to perform a more detailed plausibility check of the wind speed signal (Figure 47). While the *Sensor Calibration* addresses consistency in time, the *Wind Speed Correction* allows the user to check consistency for different operational conditions: It is known that the flow around the nacelle of the WTG is different during stand-still than during operation. Consequently, the wind speed measured on top of the nacelle might not be comparable for these two conditions. Since the nacelle wind speed is used for calculating the potential energy, a correction of the wind speed signal during non-optimal performance might be required. It is possible to enter a correction for all WTGs. Alternatively, it is possible to determine a correction factor for each individual WTG.

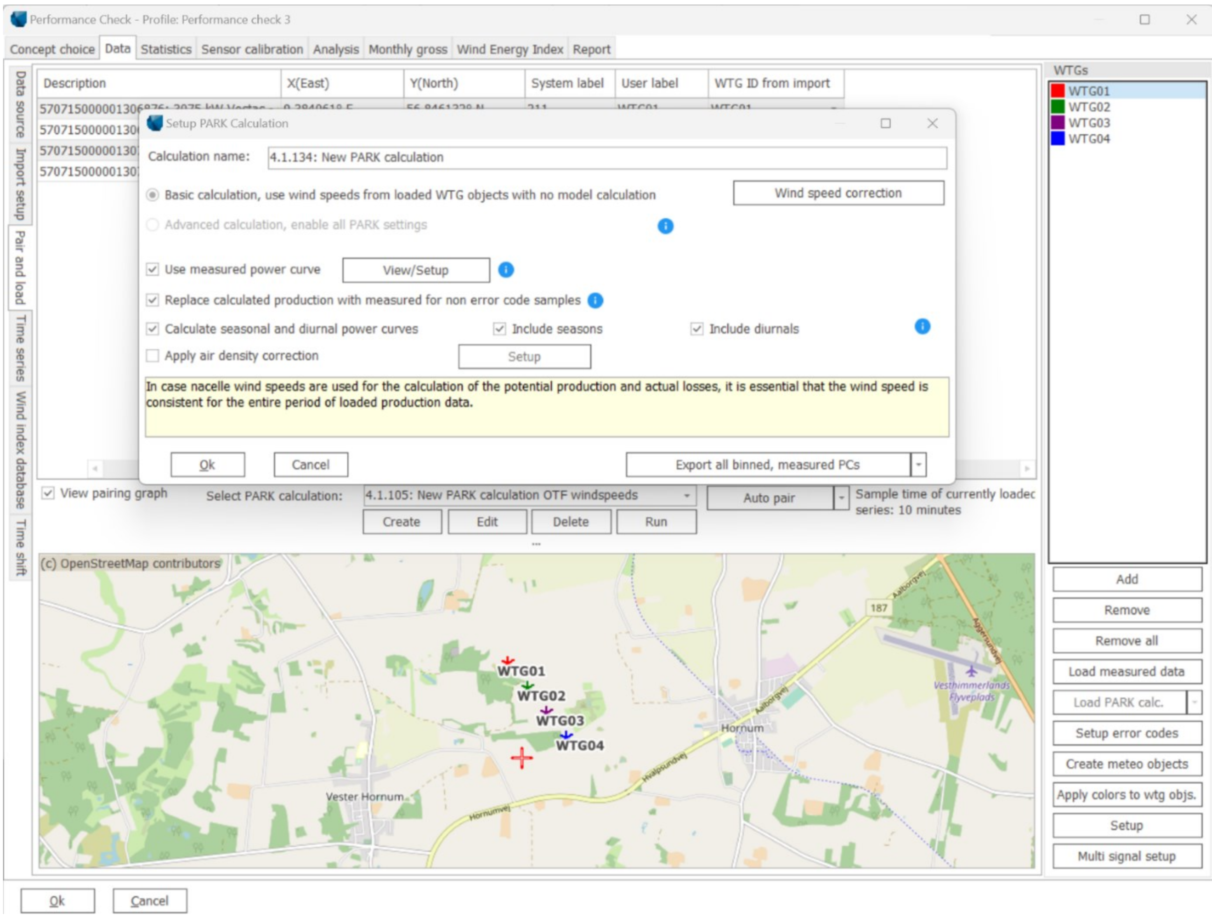


Figure 46: Create time-varying PARK calculation.

For Post Construction path, the PARK calculation is set up under the Data tab, selecting the Pair & load on the left side under the sub-tab window. Here the green button “Create” allows one to initiate the PARK calculation setup.

From windPRO 4.0, it’s possible to include Seasonal and Day & Night power curves. These historic power curves are all binned on “normal operation data” and losses will be calculated relative to time of day and period of year. The individual Power Curve (PC) can now be exported to a file or copied for use in excel. Additionally, Air density correction can be applied to the nacelle wind speed for samples with error codes. This is only recommended if proper concurrent measured temperature and pressure are available.

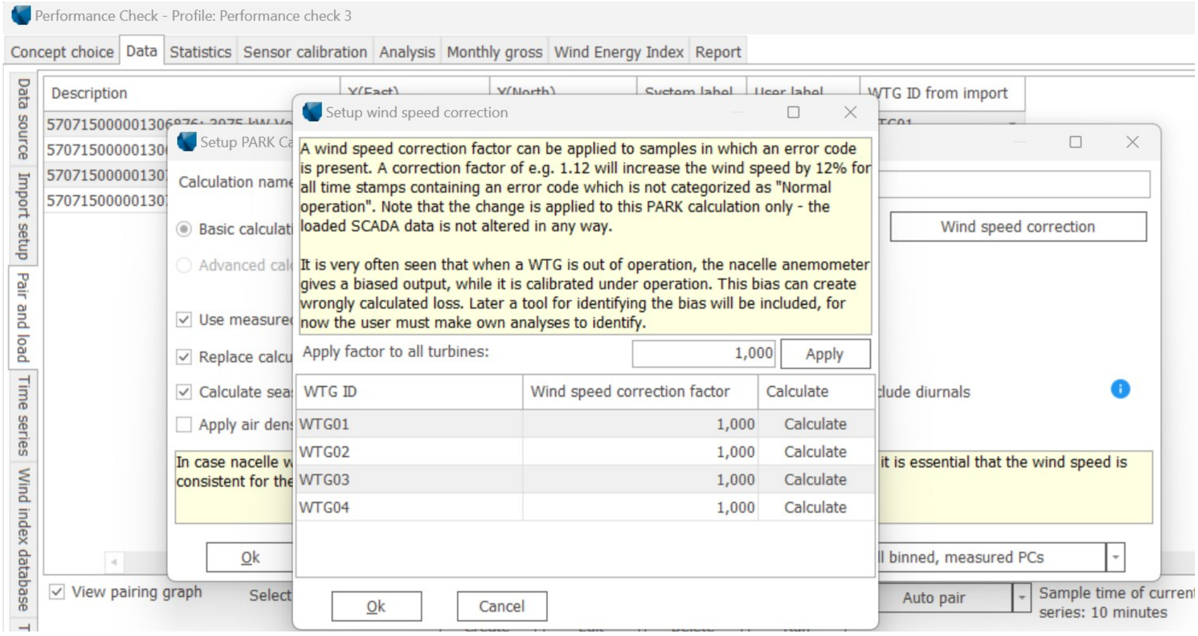


Figure 47: Wind speed correction

The function *Wind Speed Correction* helps the user to make a qualified decision and allows the correction of the wind speed. For each WTG, the nacelle wind speeds are plotted against a reference WTG of the user’s choice as shown in Figure 48 (right plot - after selecting calculate for an individual WTG). Typically, two neighbouring WTGs are compared. The trend line for concurrent time steps with both WTGs operating optimally is shown (red scatter with black trend line). Additionally, another trend line shows the relationship of the nacelle wind speeds for time steps, where the WTG under investigation is operating non-/sub-optimally, but the reference WTG is fully operational (pink scatter with pink trend line). As a plausibility check the scatter plot of the WTG under investigation is shown on the left-hand side. In our example, all pink dots indeed represent non-/sub-optimal operation or stand-still. The difference of the slope between the two trend lines is suggested as a correction factor for the nacelle wind speed and will be applied for each time step with non-optimal performance.

The user can define specific directions to ensure that the two WTGs that are compared are not wake-affected.

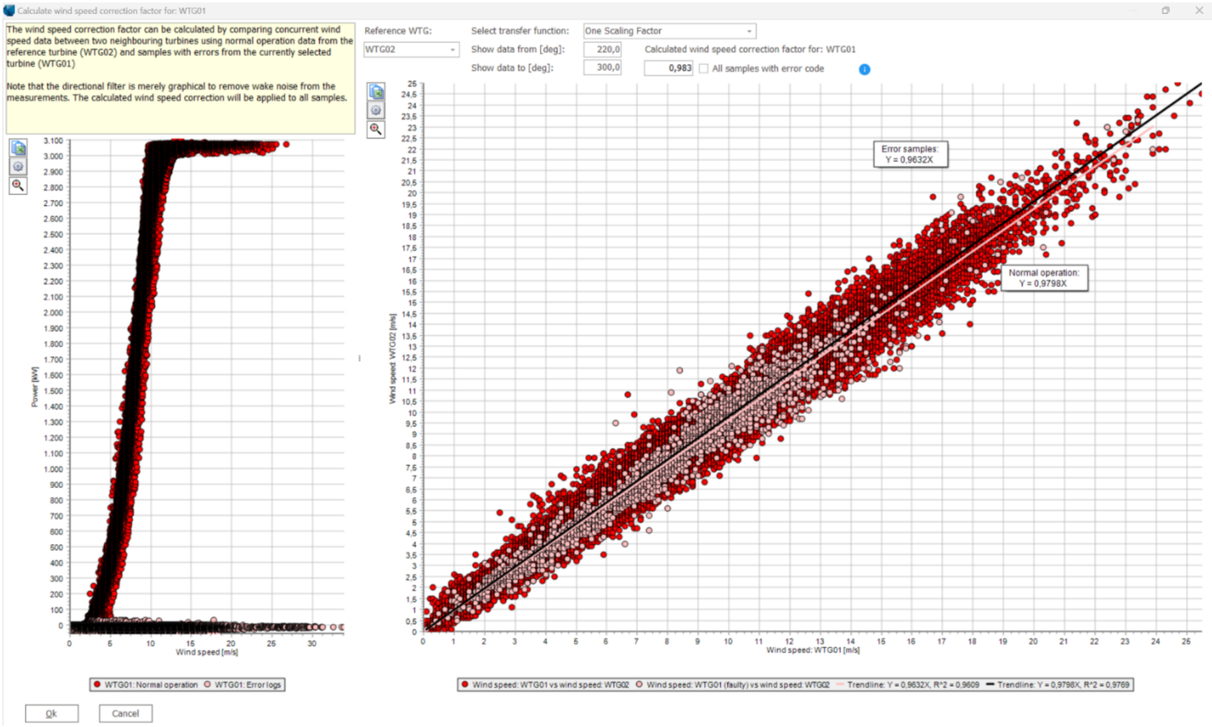
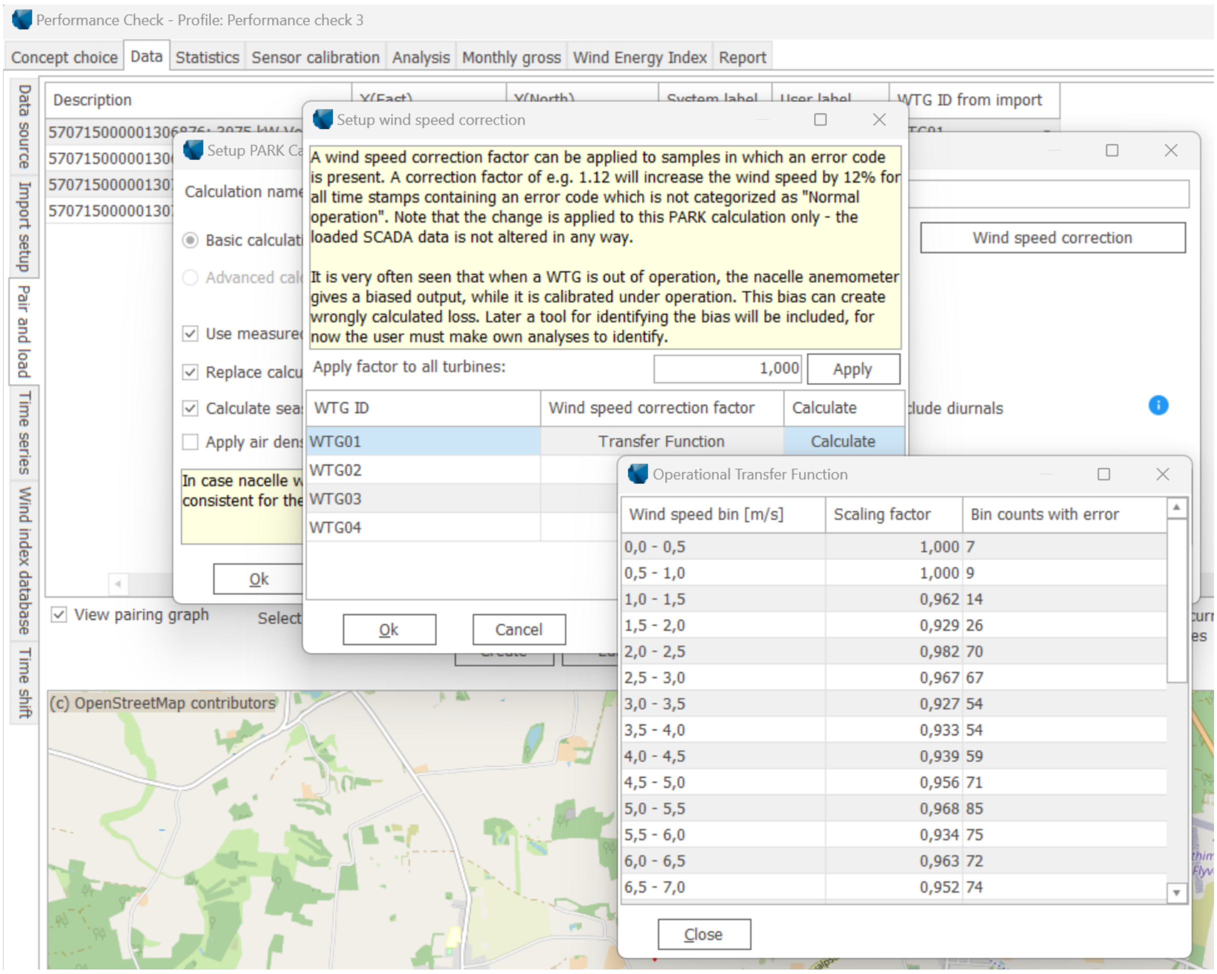


Figure 48: Evaluation of impact of operational condition on the nacelle wind speed

Since windPRO 4.1 two methods for wind speed correction is possible a simple scale factor, or the new OTF “Operational transfer function” this allows for selected windspeed bins an individual scale factor. Should the windspeed ratio to the reference indicate a clear non-linear trend, this would be the preferred method for correcting the windspeed for stopped conditions. If this method is chosen, the resulting OTF can be seen under view, or after accepting the WTG list is updated with the notation “Transfer Function” is selected the individual OTF pops-up and can be copied for documentation if needed.



After correction of the nacelle wind speeds, the user must pay attention that the measured power curve is selected. If the filters are switched on (which they are by default), all time steps with non-optimal performance are disabled. The remaining data forms the historic power curve. The button View/Setup displays the historic power curve (Figure 49). By pressing the right mouse button, it is possible to copy the historic power curve data from the table.

The binned measured power curve as well as the contracted power curve from the *existing WTG* object can be displayed together with the seasonal power curves if chosen. NB the table to left is always the binned normal power curve for all data, the seasonal, and/or time-varying power curves can be exported to file. It is also possible to use alternative set-ups for displaying the data (Figure 50). The user can either display the scatter curve of a different WTG of the wind farm, choose another wind speed signal or limit the period.

Finally, the user has to ensure that the second tick is enabled to “Replace calculated production with measured for non-error code samples”.

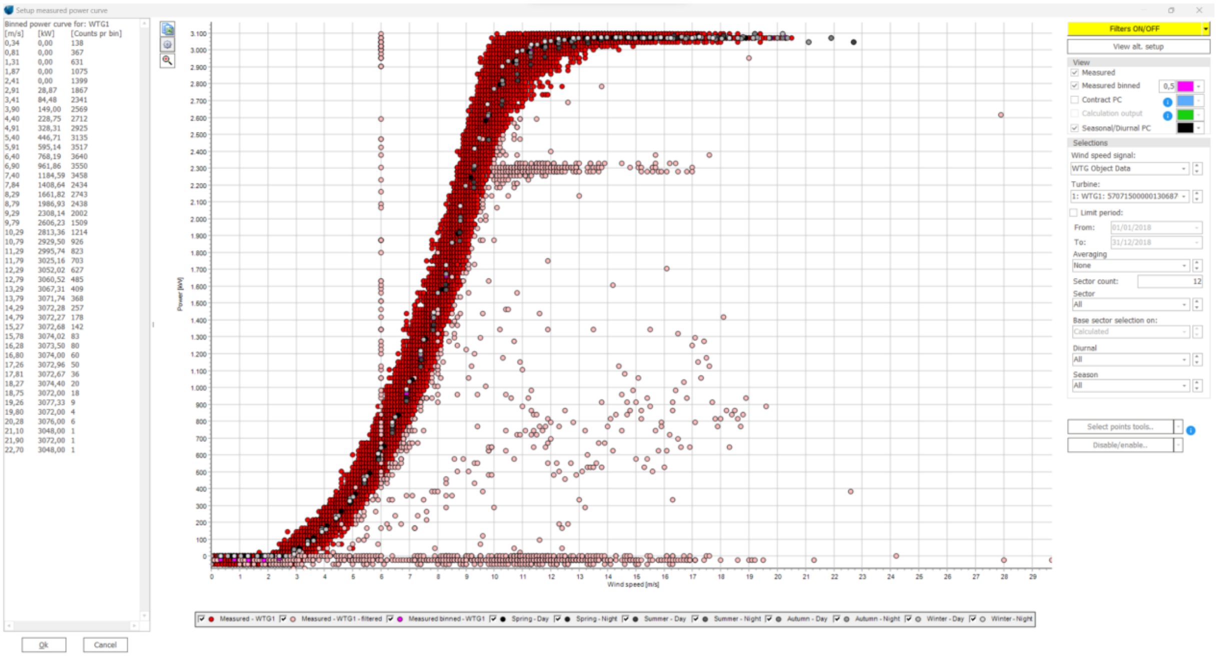


Figure 49: Historic power curve

Figure 50: Alternative set-up for historic power curve display

After the setup of the calculation is done, or if changes are made in filters or periods, a run of the chosen setup needs to be initiated by the Run button.

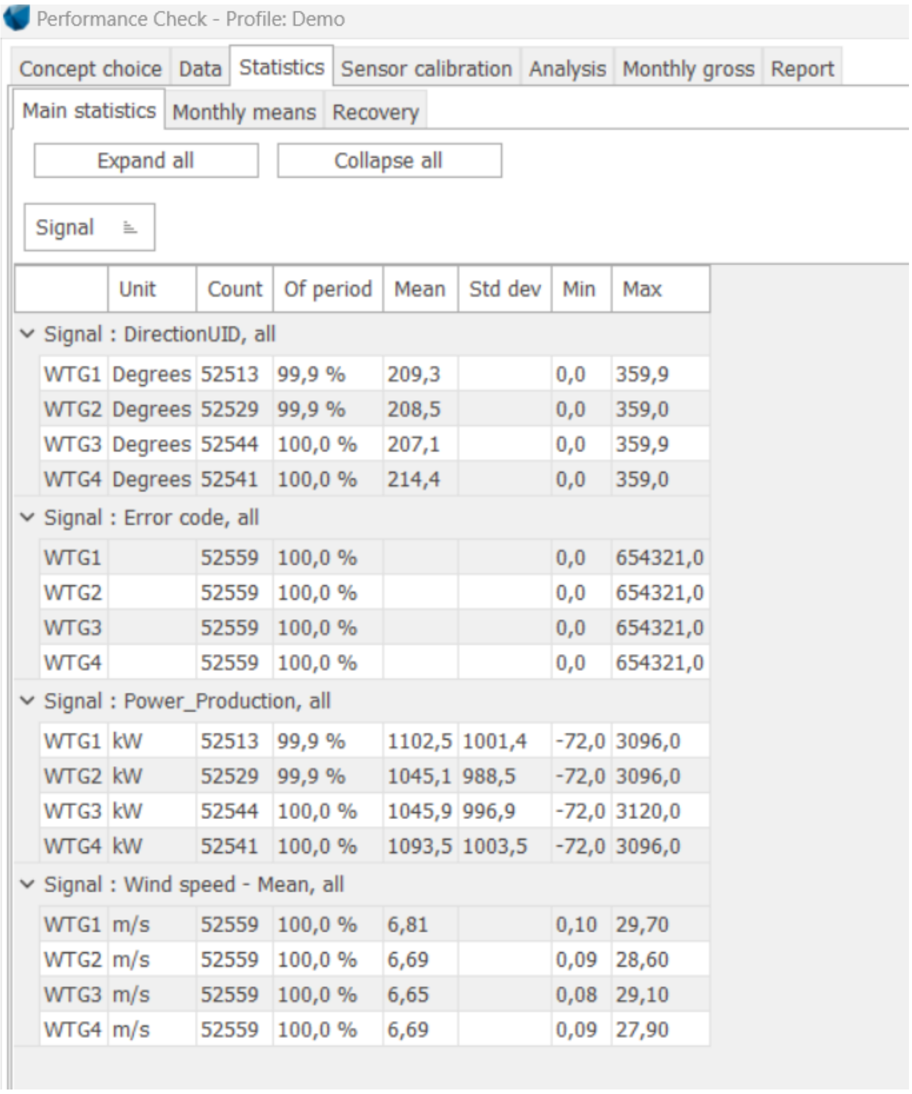
11.8 Statistics

After having loaded the 10-minute time series, having combined it with error codes, description of error codes and their categorisation, the recovery rate and some basic statistics can be found in the *Statistics* tab.

For each signal and for each WTG, the count, recovery rate, mean, standard deviation, minimum, and maximum are shown (Figure 51).

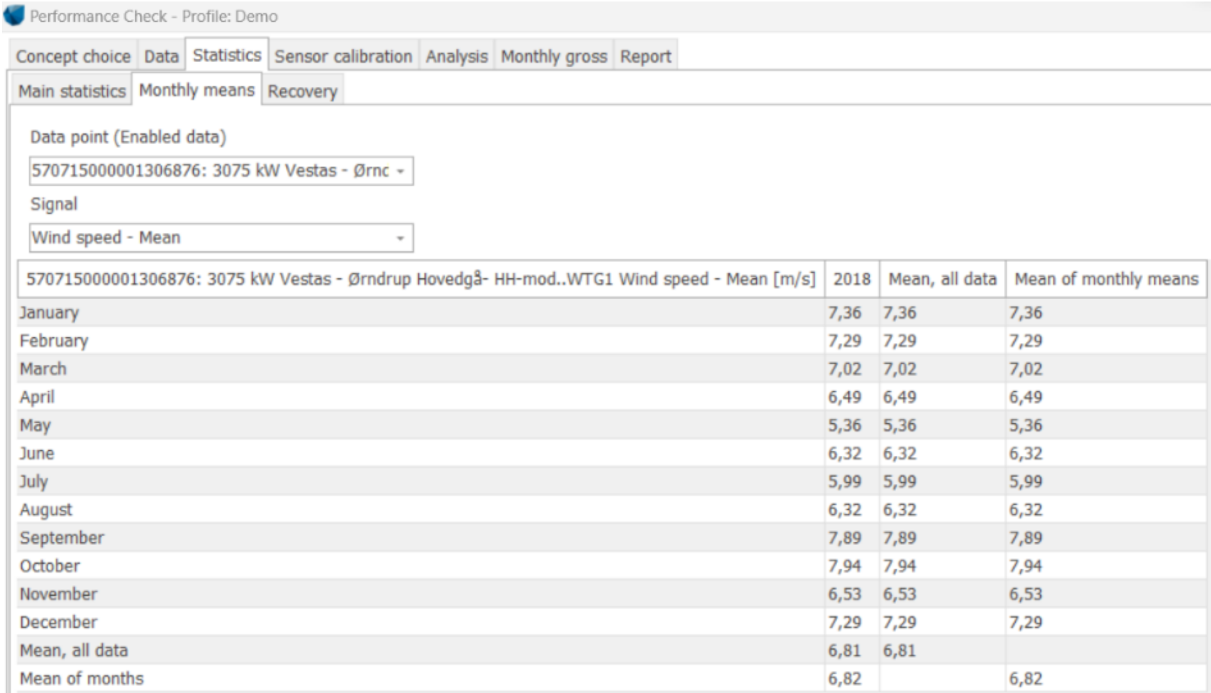
For each signal for each WTG the monthly means can be visited (Figure 52).

Finally, the recovery rate per day can be visited for each WTG (Figure 53). It is possible to mark specific samples in the table and change the status from disabled to enabled or vice versa.



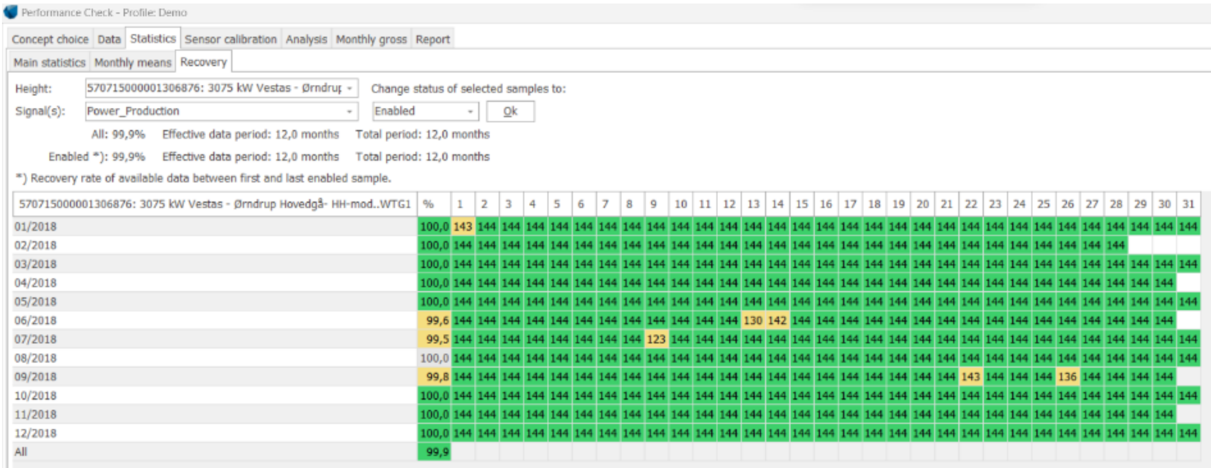
	Unit	Count	Of period	Mean	Std dev	Min	Max
Signal : DirectionUID, all							
WTG1	Degrees	52513	99,9 %	209,3		0,0	359,9
WTG2	Degrees	52529	99,9 %	208,5		0,0	359,0
WTG3	Degrees	52544	100,0 %	207,1		0,0	359,9
WTG4	Degrees	52541	100,0 %	214,4		0,0	359,0
Signal : Error code, all							
WTG1		52559	100,0 %			0,0	654321,0
WTG2		52559	100,0 %			0,0	654321,0
WTG3		52559	100,0 %			0,0	654321,0
WTG4		52559	100,0 %			0,0	654321,0
Signal : Power_Production, all							
WTG1	kW	52513	99,9 %	1102,5	1001,4	-72,0	3096,0
WTG2	kW	52529	99,9 %	1045,1	988,5	-72,0	3096,0
WTG3	kW	52544	100,0 %	1045,9	996,9	-72,0	3120,0
WTG4	kW	52541	100,0 %	1093,5	1003,5	-72,0	3096,0
Signal : Wind speed - Mean, all							
WTG1	m/s	52559	100,0 %	6,81		0,10	29,70
WTG2	m/s	52559	100,0 %	6,69		0,09	28,60
WTG3	m/s	52559	100,0 %	6,65		0,08	29,10
WTG4	m/s	52559	100,0 %	6,69		0,09	27,90

Figure 51: Main statistics



570715000001306876: 3075 kW Vestas - Ørndrup Hovedgå- HH-mod..WTG1 Wind speed - Mean [m/s]	2018	Mean, all data	Mean of monthly means
January	7,36	7,36	7,36
February	7,29	7,29	7,29
March	7,02	7,02	7,02
April	6,49	6,49	6,49
May	5,36	5,36	5,36
June	6,32	6,32	6,32
July	5,99	5,99	5,99
August	6,32	6,32	6,32
September	7,89	7,89	7,89
October	7,94	7,94	7,94
November	6,53	6,53	6,53
December	7,29	7,29	7,29
Mean, all data	6,81	6,81	
Mean of months	6,82		6,82

Figure 52: Monthly mean



570715000001306876: 3075 kW Vestas - Ørndrup Hovedgå- HH-mod..WTG1	%	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
01/2018	100,0	143	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
02/2018	100,0	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144			
03/2018	100,0	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
04/2018	100,0	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
05/2018	100,0	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
06/2018	99,6	144	144	144	144	144	144	144	144	144	144	144	144	130	142	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
07/2018	99,5	144	144	144	144	144	144	144	144	123	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
08/2018	100,0	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
09/2018	99,8	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	143	144	144	144	136	144	144	144	144	
10/2018	100,0	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
11/2018	100,0	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
12/2018	100,0	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
All	99,9																															

Figure 53: Daily recovery rate

Note: if the new TR10 methodology for substitution of faulty or missing wind speeds have been used, the wind speed availability reflects the current availability of the wind speeds with no distinction between original or substituted wind speeds.

11.9 Analysis

In the *Analysis* tab it is now possible to visualise the data.

11.1.20 Analysis – Time series

All loaded signals from each WTG can be displayed in various ways, either as time series in the temporal resolution they have been loaded in, as monthly values, as a diurnal plot or as radar plot. The functionality is very similar to the tools in the *Meteo* object.

In Figure 54 the time series of wind direction and wind speeds are shown together with the production from two WTGs. The user can adjust how many days are displayed in the window. By clicking and holding the left mouse button it is possible to zoom in a specific area. It is also possible to display an averaged timeline.

Further it is possible to manually enable/disable data. Specifically, the wind speed should be checked as the potential production is later determined using the nacelle anemometer. For example, the nacelle anemometer could be suffering from icing and shows zero or a constant small value, this data should be corrected or disabled. The methodology assumes consistent nacelle wind speeds, thus jumps occurring from anemometer exchange or changes of the scaling factor of the wind speed signal in the turbine controller should be corrected before undertaking loss evaluations (see Section 11.7).

A number of extra functions become accessible when the user has prepared a time-varying *PARK* calculation. It is possible to compare the measured production data with modelled production data. As preparation, the user must run a time-varying *PARK* calculation. There are two concepts available:

In case of post construction, the nacelle wind speed and historic power curve of the individual turbines will be used to calculate for each time step what the WTG should have produced. The time-varying PARK calculation does not require any flow modelling in this case. It can be started from within the Performance Check module, see Section 11.7.

In case of *Performance Check*, a full flow model has to be set-up. As wind speeds, it is possible to use local masts as well as mesoscale data, see page 76.

If a time-varying *PARK* calculation has been performed, the thin line series represents the modelled signal for periods where there has been an error code. If the filters (top right corner) are switched off, also the corresponding measured values are visible as thick line.

Figure 54: Display time series

By default, the filters are switched on and all error codes other than zero are filtered out (Figure 55). This is necessary to calculate the potential production later in the process. It is possible to define additional filters. For example, the user might want to investigate a specific direction and/or a specific wind direction range. “*Inside Range*” means that the data inside the range will be filtered out. If a PARK calculation has been loaded it is also possible to add filters to the modelled signals.

Please note, that if you use the “Excel” button on the left-hand side of the graph all data including the filtered data will be copied.

If sensors have extra calibration, they can be applied here (Figure 55). Please note that *sensor calibrations* are explained in Section 11.6.

It is possible to define the minimum number of WTGs that must be operating simultaneously.

It is also possible to filter events out depending on how much the measured production deviates from the modelled production.

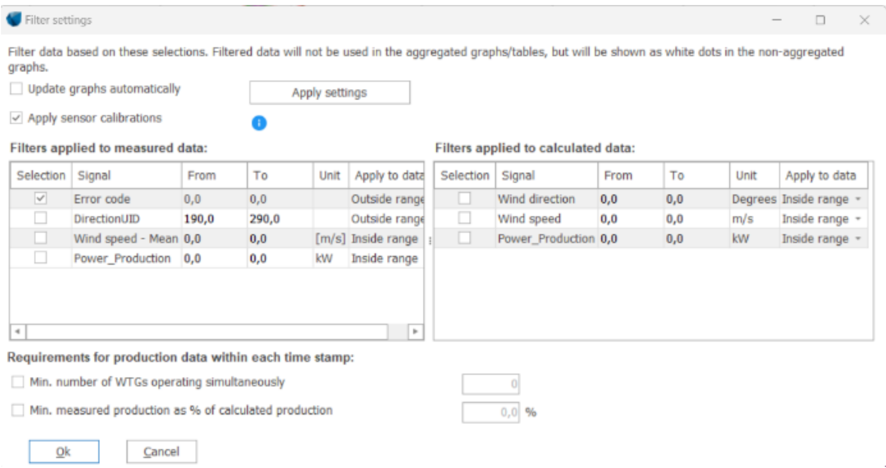


Figure 55: Application of filters

11.1.21 Analysis – Error Loss Statistics

As explained in Section 11.5 the user can either combine the 10-minute SCADA time series with error codes and their description or as a fall-back plan set up user-defined errors in case error codes are not available. Depending on which one of these two options is selected, the tab *Error Loss Statistics* contains different levels of details.

Measured negative production is not accounted as a loss, but the amount is informed in the top right corner of the window. In addition, the following are shown:

MTBF (mean time between failures): the average time between the error code's appearance and disappearance.

MTTR (mean time to repair): the average length of a specific error code.

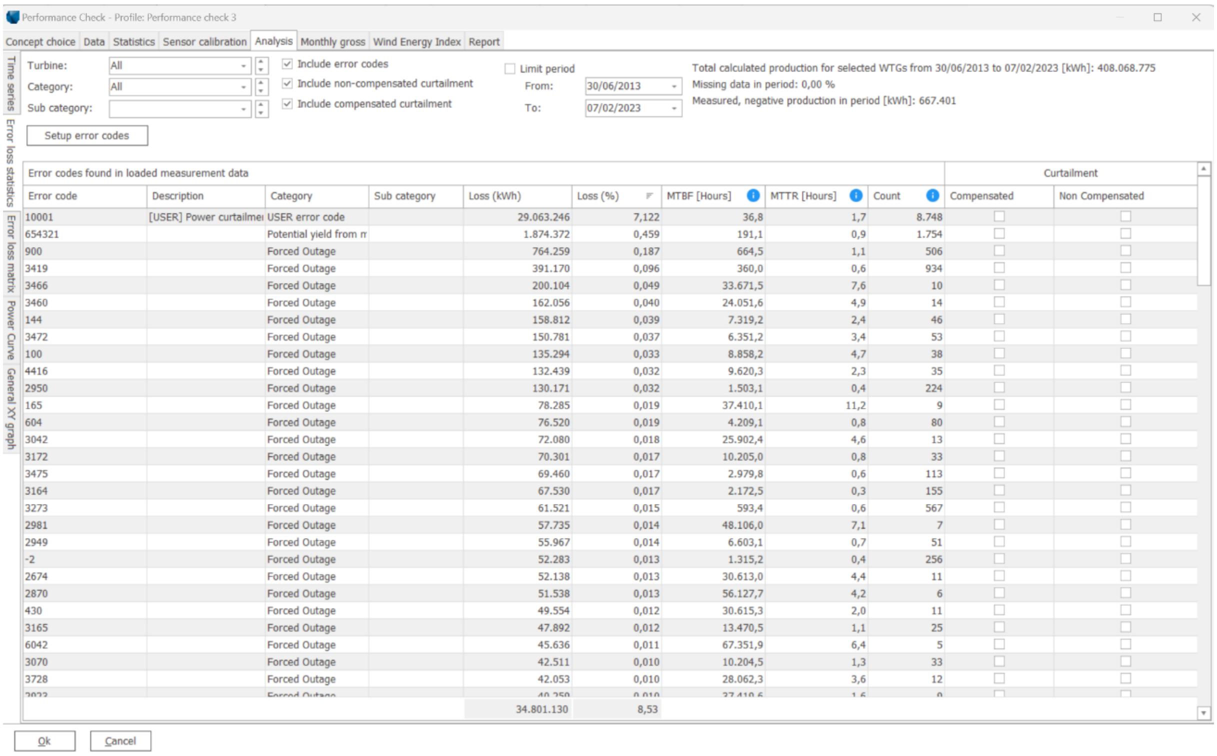
Count: the number of periods with a specific error code (the count is independent of the length of the individual event; the count is 1 no matter if the event is one second or one weeklong)

If the user wants to change the categorisation if losses are compensated or not, it is possible to re-visit *Setup Error Codes*. It can be decided to exclude each of these in the sum.

It is possible to limit the period to see the losses within e.g. a specific month or year. Note: it's recommended to set the time to cover complete years for later use in long-term correction, to avoid potential seasonal bias.

It is also possible just to look a specific turbine or a specific category or sub-category.

With detailed error codes loaded, the above-described information becomes available for each individual error code (Figure 56).



Error code	Description	Category	Sub category	Loss (kWh)	Loss (%)	MTBF [Hours]	MTTR [Hours]	Count	Compensated	Non Compensated
10001	[USER] Power curtailme	USER error code		29.063.246	7,122	36,8	1,7	8.748		
654321		Potential yield from m		1.874.372	0,459	191,1	0,9	1.754		
900		Forced Outage		764.259	0,187	664,5	1,1	506		
3419		Forced Outage		391.170	0,096	360,0	0,6	934		
3466		Forced Outage		200.104	0,049	33.671,5	7,6	10		
3460		Forced Outage		162.056	0,040	24.051,6	4,9	14		
144		Forced Outage		158.812	0,039	7.319,2	2,4	46		
3472		Forced Outage		150.781	0,037	6.351,2	3,4	53		
100		Forced Outage		135.294	0,033	8.858,2	4,7	38		
4416		Forced Outage		132.439	0,032	9.620,3	2,3	35		
2950		Forced Outage		130.171	0,032	1.503,1	0,4	224		
165		Forced Outage		78.285	0,019	37.410,1	11,2	9		
604		Forced Outage		76.520	0,019	4.209,1	0,8	80		
3042		Forced Outage		72.080	0,018	25.902,4	4,6	13		
3172		Forced Outage		70.301	0,017	10.205,0	0,8	33		
3475		Forced Outage		69.460	0,017	2.979,8	0,6	113		
3164		Forced Outage		67.530	0,017	2.172,5	0,3	155		
3273		Forced Outage		61.521	0,015	593,4	0,6	567		
2981		Forced Outage		57.735	0,014	48.106,0	7,1	7		
2949		Forced Outage		55.967	0,014	6.603,1	0,7	51		
-2		Forced Outage		52.283	0,013	1.315,2	0,4	256		
2674		Forced Outage		52.138	0,013	30.613,0	4,4	11		
2870		Forced Outage		51.538	0,013	56.127,7	4,2	6		
430		Forced Outage		49.554	0,012	30.615,3	2,0	11		
3165		Forced Outage		47.892	0,012	13.470,5	1,1	25		
6042		Forced Outage		45.636	0,011	67.351,9	6,4	5		
3070		Forced Outage		42.511	0,010	10.204,5	1,3	33		
3728		Forced Outage		42.053	0,010	28.062,3	3,6	12		
				34.801.130	8,53					

Figure 56: Error loss statistics – detailed error codes

11.1.22 Analysis - Error Loss Matrix

In this tab (Figure 57) functionalities similar to a Pivot table can be found. Different data fields have been defined, which can be dragged and dropped freely in the table section to aggregate losses. The losses can be presented as absolute numbers or percentage (radio button selection on top). Following data fields are available:

- Year
- Month
- WTG
- Category

With the two last listed data fields (WTG and Category), it is possible to deselect specific WTGs or categories and thereby only show a subset of the data by clicking on the arrow at the data field (Figure 58).

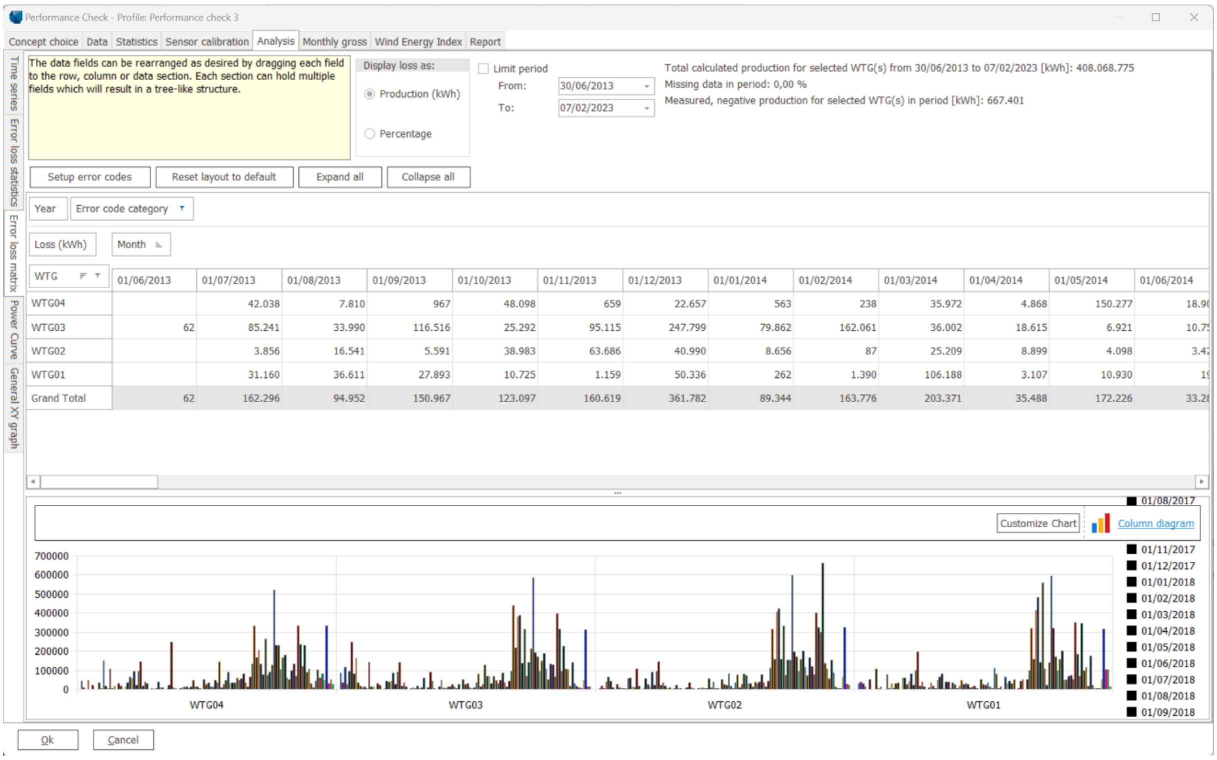


Figure 57: Error loss matrix

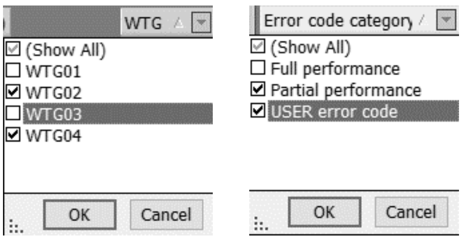


Figure 58: Selecting WTGs and categories.

Further, when for example dragging additionally *Month* into table set-up, the *Expand All* and *Collapse All* button facilitate to reveal analysis such as monthly production per WTG quickly and easily.

The *Reset Layout to Default* button brings the default pivot set-up back.

The graphical display is fully customisable. The user can change from bar charts to pie charts, etc.

11.1.23 Analysis – Power Curve

Before explaining the functionalities on this tab, it must be stressed that visualised power curve is not necessarily identical with the contracted power curve provided by the manufacturer. The contracted power curve refers to the free wind speed, while the power curve displayed here is based on the nacelle wind speed and does consequently not follow the IEC 61400-12-1. The IEC 61400-12-1 allows the validation of the power curve through use of the nacelle anemometer. However, this standard requires a very strict and precise measurement setup which is very rare for a commercial operating wind farm.

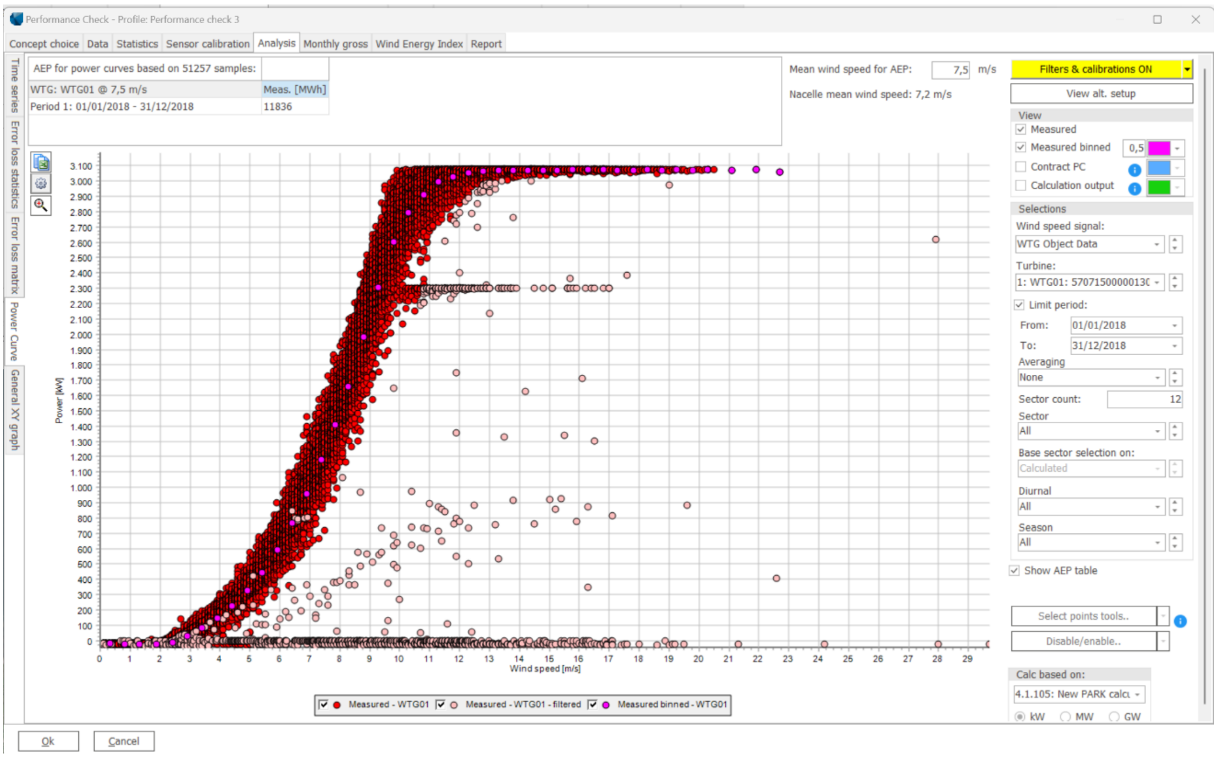


Figure 59: Power Curve tab

In the top left corner (Figure 59), the AEP table gives a quick overview of the expected production for a Rayleigh distribution for a user-defined wind speed. The measured power curve (normally based on the nacelle wind speed) can be compared with the contracted power curve. Of course, this only makes sense if the used wind speed signal is identical with free wind speed, which is not the case if the nacelle wind speed is used. Please note, that not all high wind speed bins might contain enough data to derive the full measured power curve. In such a case the power curve is extrapolated to the cut-out wind speed as specified at the power curve in the WTG object.

Following display options are available (starting from the top):

It is possible to use *alternative set-ups* for displaying the data (Figure 50). The user can either display additionally the scatter curve of a different WTG of the wind farm, choose another wind speed signal or limit the period. This can be useful for example for comparing two binned power curves from two different WTGs. If two WTGs are chosen here, the AEP table will update accordingly and display both AEPs for the defined Rayleigh distribution. The user can also compare two periods with each other.

The *measured binned* power curve as well as the *contracted* power curve from the *existing WTG* object can be displayed. Please note, that the contracted power curve is valid for one, fixed air-density. Also, the *calculated* production can be displayed. If the user has run the time-varying *PARK* calculation as part of the post construction process, the calculated production corresponds to the potential production. If the user has run a full flow model-based time-varying PARK calculation (see Section 11.4), the calculated production can optionally include site-specific correction for turbulence, shear, air-density etc.

The wind speed signal which is used for the scatter plot can be altered. By default, it is using the calculated wind speed. The difference between calculated wind speed and the wind speed in the WTG object consists of any correction the user might have applied to the nacelle wind speed, like described in Section 11.6 or *wind speed correction* as described in Section 11.7. If the user has run a full flow model-based time-varying *PARK* calculation (see Section 11.4), the calculated wind speed comes from the flow model. Additionally, the user can load data from any *Meteo* object. Of course, all data can be exported to Excel for further analysis e.g. advanced comparison for different temperatures or turbulence intensities.

11.1.24 Analysis – XY Graph

With this tool, any measured signal can be plotted against each other, either as scatter plot or binned. The x- and y-values can be from the same or different turbines, and any signal imported can be chosen.

The period can be reduced to see if a specific phenomenon belongs to a specific period.

Averaging in time can give a better overview than having a large "cloud of points".

Finally, a trend line can be shown (limited to linear) – the formula will appear in the legend.

Figure 60 shows an example how the direction measurements from the one WTG differ from the other WTG.

An example of operational strategy visualization based on the XY graph tool is given in Figure 61, where RPM is plotted against pitch angle with wind speed as colour scale.

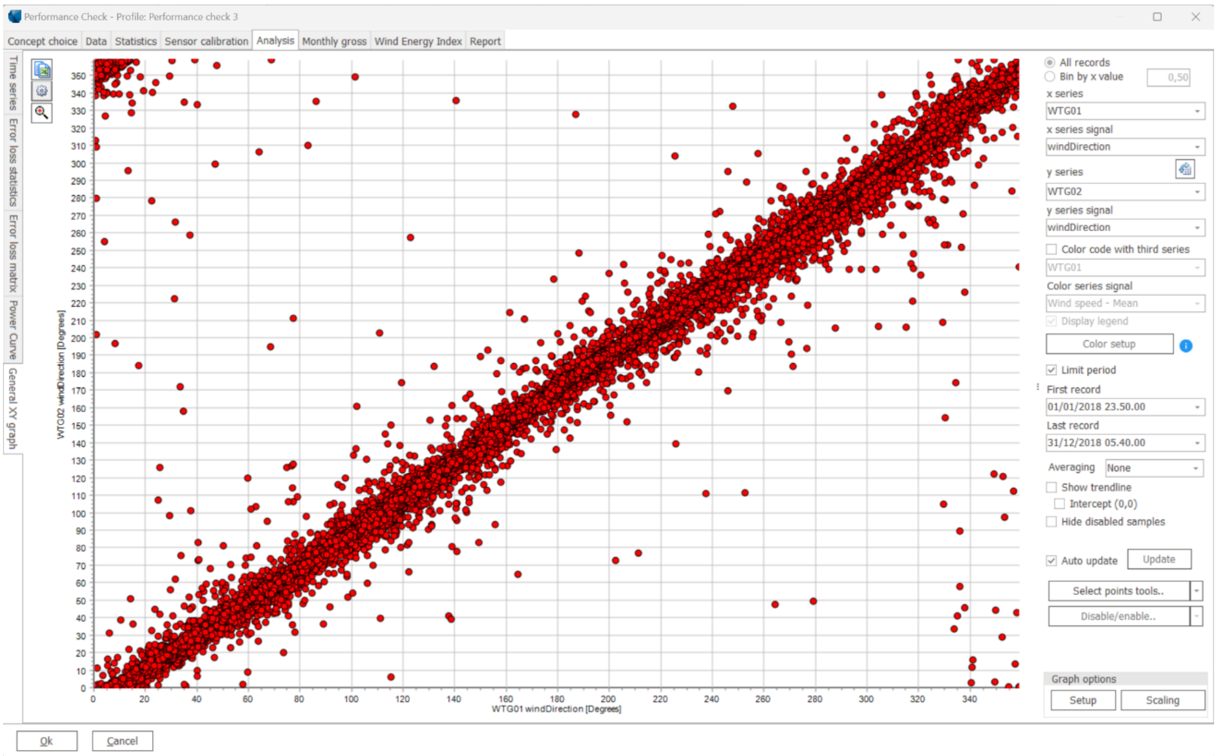


Figure 60: Example XY graph - nacelle directions

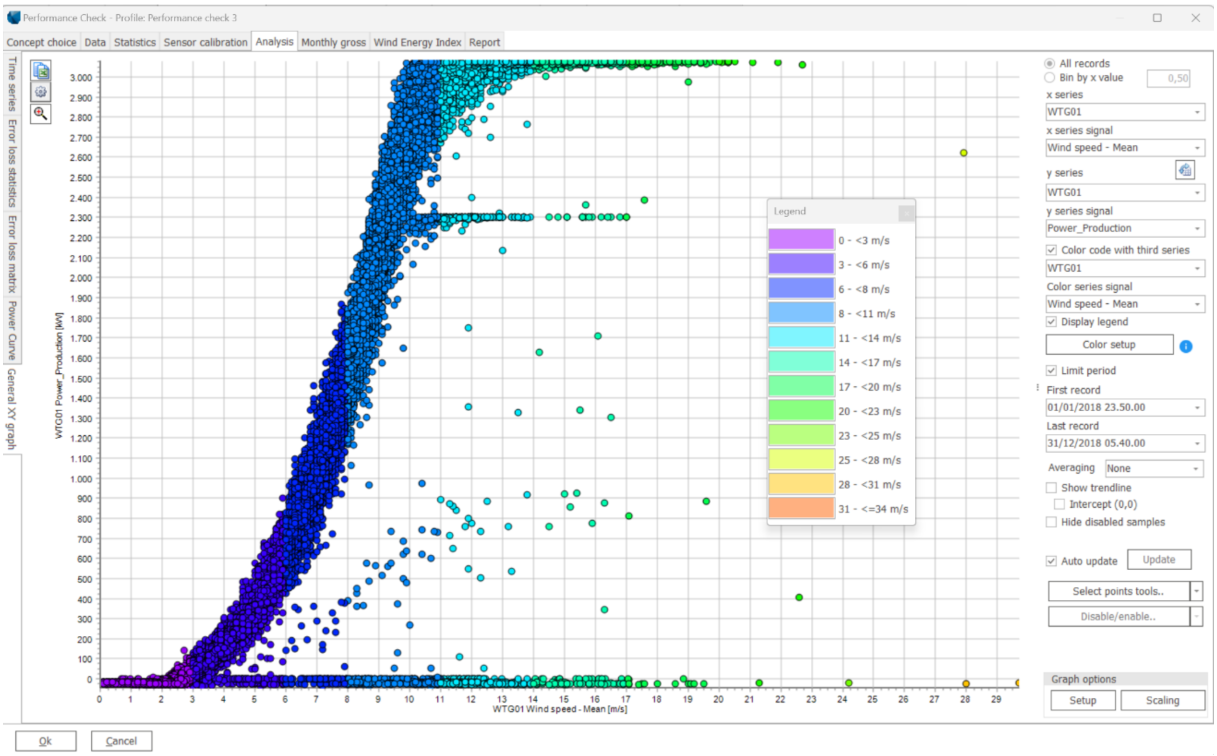


Figure 61: Example XY graph

11.10 Monthly Gross

The tab *Monthly Gross* aggregates the production data to a monthly time series, which is the basis for long-term correcting the production data. Depending on the available input data, different methods can be chosen to compensate for incomplete time series e.g. missing periods or unreliable nacelle wind speed. The output of this process is the GROSS production “Monthly Potential production”, which is fed into the WCP tool (wind corrected production = long-term corrected production) for long-term energy index correction, see Section 11.1.25. The resulting time series of monthly production will be saved in the *Existing WTG* object with the label Month Gross.

The user has to choose a time-varying PARK calculation, which is based on the nacelle wind speed (see Section 11.7).

Four different methods can be chosen to compensate for missing data. Note the recovery rate is based on the enabled pairs of nacelle wind speed and production.

Divide with recovery rate: Recommended for data recovery rate > 95%. The missing data is assumed to be caused by data loss. During the period of data loss, the WTG is assumed to produce as observed on average for the available data in each month.

Ignore recovery rate: Recommended for data recovery rate > 99% and when TR10 data substitution have been used. The missing data is assumed to represent periods with lost production, which is also representative for the future.

Skip month if recovery rate is too low: If this option is chosen a field is activated where the user can define the minimum recovery rate, which only affects the long-term correction.

Take from alternative calculation: This is not to be used for post construction methodology.

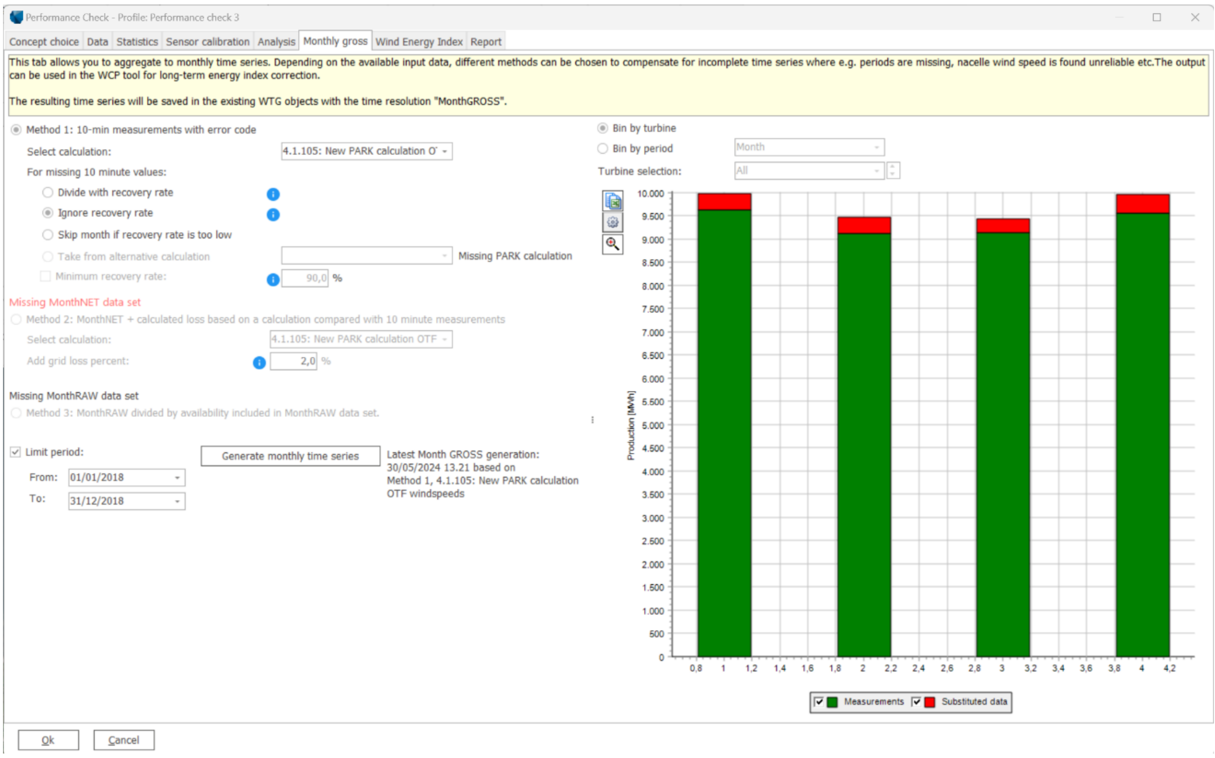


Figure 62: Monthly gross tab

Further, two methods become available if monthly data has been read directly into the *Existing WTG* object. These options are greyed out in the post construction process if none of the required monthly data has been loaded into the *Existing WTG* object.

Method 2: Month NET + calculated loss: If the monthly NET (sold production) is loaded into the *Existing WTG* object, it is possible to evaluate the grid losses. Please note that 100% availability in the other methods does not include the grid loss.

Method 3: Monthly RAW divided with month availability: If the monthly RAW is loaded into the *Existing WTG* object and includes monthly availability figures, the production can be availability-corrected by division with the availability. This very simple method assumes there is a column with availability information in the RAW data. The RAW data can both be with or without grid loss, this must be handled in the later loss settings when creating a report.

Pressing [Generate monthly time series] aggregates the 10-minute data to monthly Gross and saves the monthly data to the *Existing WTG* objects. A graph appears on the right-hand side showing the actual production (called "measurement") and the actual loss (called "substituted").

The user can jump directly to the *Wind Energy Index* tab.

11.1.25 Analysis – Wind Energy Index

Note: For a new project setup, the user must first aggregate Monthly Gross production, before this tab is available(see Section 11.10).

This tab allows the user to analyse the long-term correction of the potential production for each WTG. There are many different options available, but the basic concept is simple: Based on monthly production and monthly wind energy indexes, the Wind Index Corrected Production (WCP) is calculated.

There are two basic concepts for performing this calculation:

The sum method: The sum of production is divided with the sum of index for the enabled months.

The regression method: A linear regression line is established for the monthly potential production versus monthly wind energy index, and the production for an index value of 100% is found.

The two methods deliver very similar results. Only for shorter periods and/or poor correlation with the index, will the results from the two methods differ.

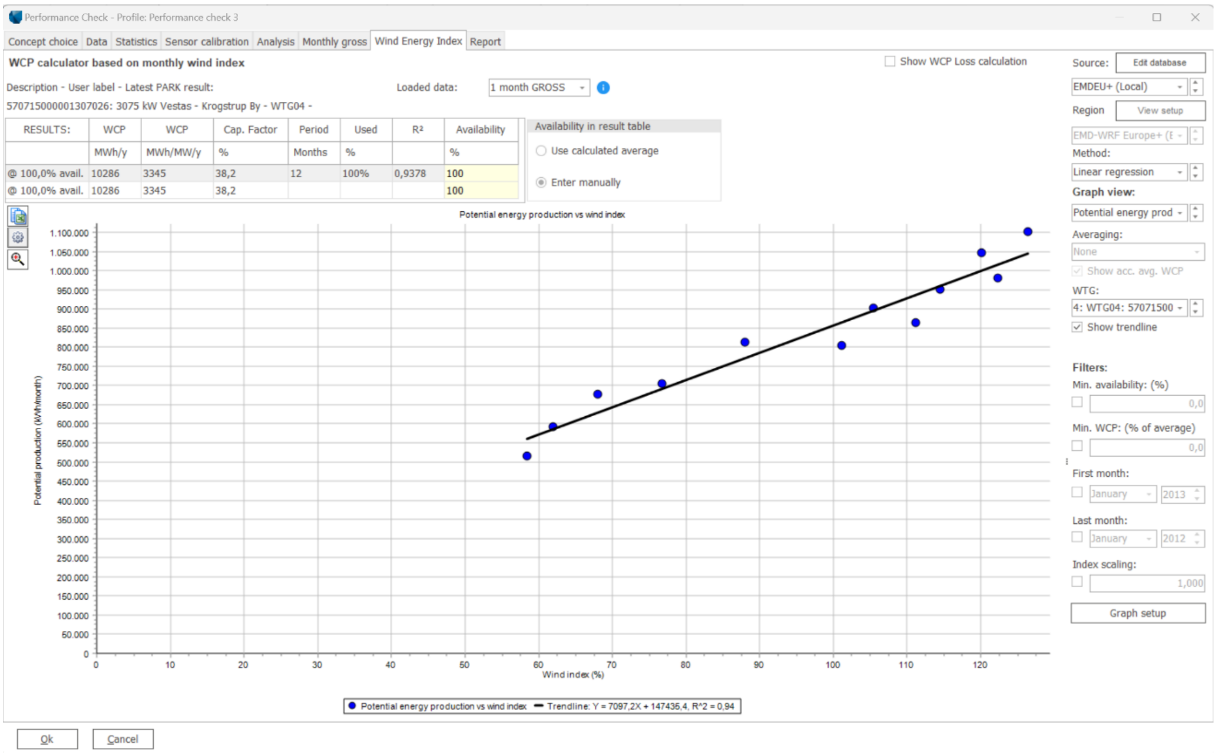


Figure 63: Wind Energy Index tab

The user can choose and edit the data base of wind indices (see Section 11.1.8). The indices which are part of the chosen database can be selected individually. This could be e.g. several re-analysis and mesoscale indices. The correlation (R^2) of the different indices with the monthly potential gross production can be seen in the AEP table in the top left corner. Next to the correlation, the WCP (Wind Index Corrected Production), the annual production per MW installed, the capacity factor, the length of the available data, and the usage of that data are shown. Please note, that all production at this point reflect 100% availability as all times steps with any form of non-optimal performance have been identified and corrected for.

Following graphical displays can be chosen from.

Energy Production vs wind index plots the monthly potential gross production against a chosen index (see).

Time series RAW plots the monthly potential gross production per month. Additionally, the monthly index is shown referring to the secondary y-axis. Ideally the two curves should follow each other.

Time series WCP shows the index-corrected production per month. The index-corrected production resembles a combination of the previous graph showing the monthly production and the index. This line should be ideally horizontal. Any deviations from the horizontal could point towards inconsistencies during time. Any slope could point towards degradation in performance or other issues. A step change could indicate that a neighbouring wind farm has been commissioned.

Time series WCP/MW shows the index-corrected production per MW per month.

WCP vs wind index shows the index-corrected production against the wind energy index. Ideally the values should all exhibit the same production. Any slope indicates that the correlation for low and high wind speeds differs. This is typically the case when the index has been developed based on the wrong wind speed assumption (see Section 11.1.8 and Figure 18). The precise set-up of the wind energy index is more important when the production data only covers a short period.

The following option show results for all WTGs:

All WTGs, AEP Avg + WCP shows the measured AEP, and the wind energy index corrected production for each WTG. If the production data spans a different period than an integer number of years, the measured production is corrected by dividing the production with the number of months and multiplying with 12 months.

All WTGs, AEP Avg + WCP/MW shows the measured AEP per MW and the wind energy index corrected production per MW for each WTG.

All WTGs, Cap. Factor shows the measured capacity factor, and the wind energy index corrected capacity factor for each WTG.

All WTGs, Correlation shows the correlation (R^2) between monthly gross production per WTG and wind energy index. Ideally this should be 1.

WF GEO shows the map of the WTGs under investigation. This graph is most meaningful if a full flow-model-based time-varying PARK calculation has been performed (see Section 11.4)

For some of the graphical displays further options are available like increasing the averaging from 1 month to several or showing the accumulated average WCP.

For the regression plot, a simple tool can help to identify outliers by defining a maximum deviation from the WCP in %. For example, 90% means that the actual monthly production should not be more than 90% different than the WCP of that very month.

Further, it is possible to limit the period, e.g. to filter out the first months of operation, because they could have some poorer performance.

A scaling option for the data is available.

The *WCP loss form* is not relevant in the context of post construction analysis.

11.11 Report

The post construction report highlights the actual production with actual losses as covered by the 10-minute SCADA data. The potential production represents 100% availability. The actual losses are ranked, the lost kWh, MTBF (mean time between failure) and MTTR (mean time to repair) are given. Long-term correction of the potential power results in the normalised production. Including future losses leads to the future expected Net production. The process follows the IEC 61400-26-1 structure using the historic power curve and nacelle wind speed.

The report consists of following sections:

- Main
- Historic Power Curve
- Actual Losses
- Normalized Production
- NET Production
- Comments

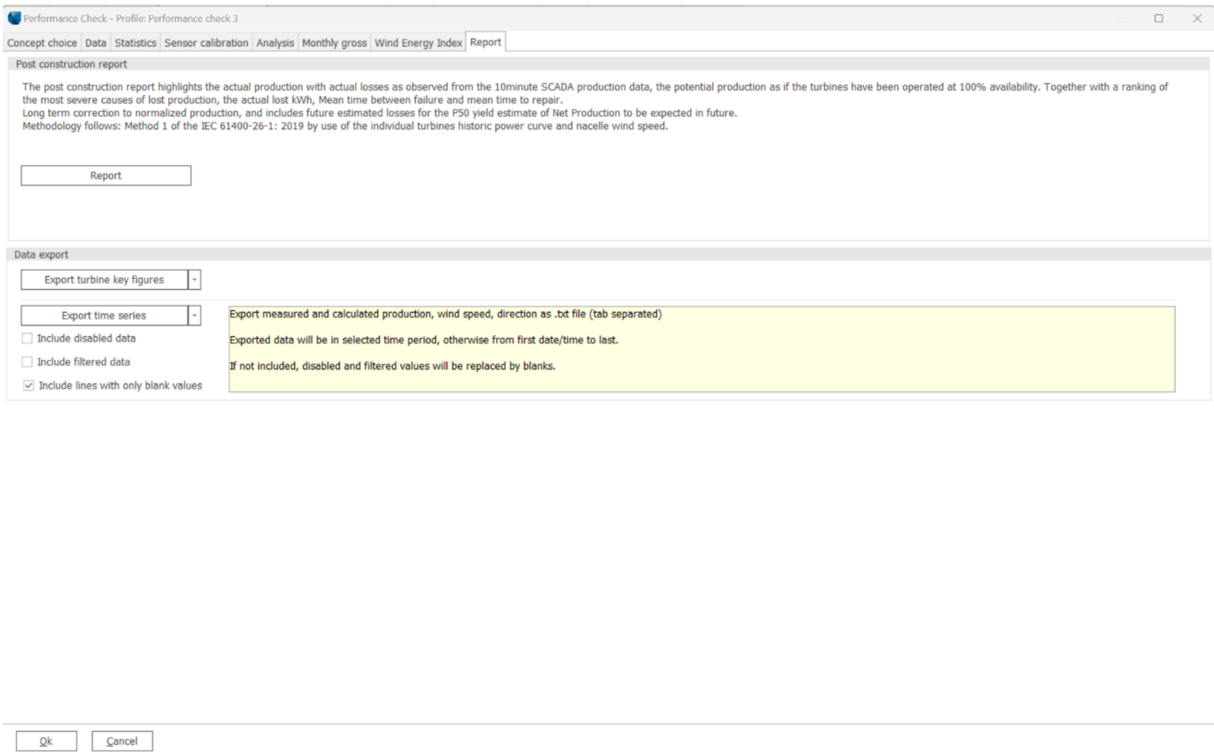


Figure 64: Post construction report

11.1.26 Main section

The Main section starts with an explanation of calculation method with the glossary. A table with the main results follows (Figure 65). The table includes the potential production of the analysed period (which could be different from one year) as well as an annual basis simply by correcting for the number of months. Please note, that having, for example 1½ years of data with two summers and one winter can make the annual production look out of proportion due to seasonal bias. It is recommended to use complete years to avoid any misleading seasonal bias.

Results

	Actual production [MWh]	Actual losses [%]	Potential production [MWh] / [MWh/y]	LT correction* [%]	Normalized production AEP [MWh/y]	Expected total losses [%]	Net production AEP [MWh/y]
Park	232110	3,11	239562 / 43013	0,86	43385	4,61	41385
WTG01	59632	2,72	61299 / 11028	0,86	11123	4,22	10653
WTG02	56978	2,62	58513 / 10507	0,88	10599	4,12	10162
WTG03	56156	4,13	58576 / 10510	0,87	10601	5,63	10004
WTG04	59343	2,99	61174 / 10969	0,85	11062	4,49	10565

* Based on ratio between Potential productions AEP & Normalized production AEP, see Normalized Production section for details.

Figure 65: Main results

11.1.27 Historic Power Curve

The table with the results is followed by the scatter plot and the historic power curve (Figure 66). The filtered events are marked in a lighter colour.

The user can choose in the tab Turbine selection – historic power curve which WTG to display (Figure 67).

Performance Check - Historic power curve for WTG: WTG01

Binned power curve

[m/s]	[kW]
1,98	15,00
2,69	25,87
3,08	47,35
3,53	87,29
4,02	145,97
4,53	219,29
5,04	313,39
5,55	428,32
6,05	564,42
6,53	712,69
7,01	887,89
7,52	1097,29
8,02	1332,71
8,53	1600,75
9,04	1906,04
9,52	2210,12
9,99	2485,98
10,50	2718,70
11,01	2870,09
11,53	2960,90
12,03	3016,71
12,53	3041,26
13,02	3055,33
13,49	3062,46
14,01	3066,81
14,51	3069,41
15,02	3070,78
15,53	3071,20
16,04	3071,37
16,51	3069,80
16,99	3069,54
17,51	3070,90
18,01	3069,53
18,53	3070,26
19,02	3070,00
19,56	3068,45
20,01	3065,76
20,50	3069,34

Actual measured SCADA power curve, with applied filters indicating stopped or suboptimal performance. The self-consumption has been excluded for the individual turbines historic power curves. Measured binned power curve is the result of the presumed normal operational data and used for calculation of losses for time stamps which have been filtered as a stopped or suboptimal operation period.

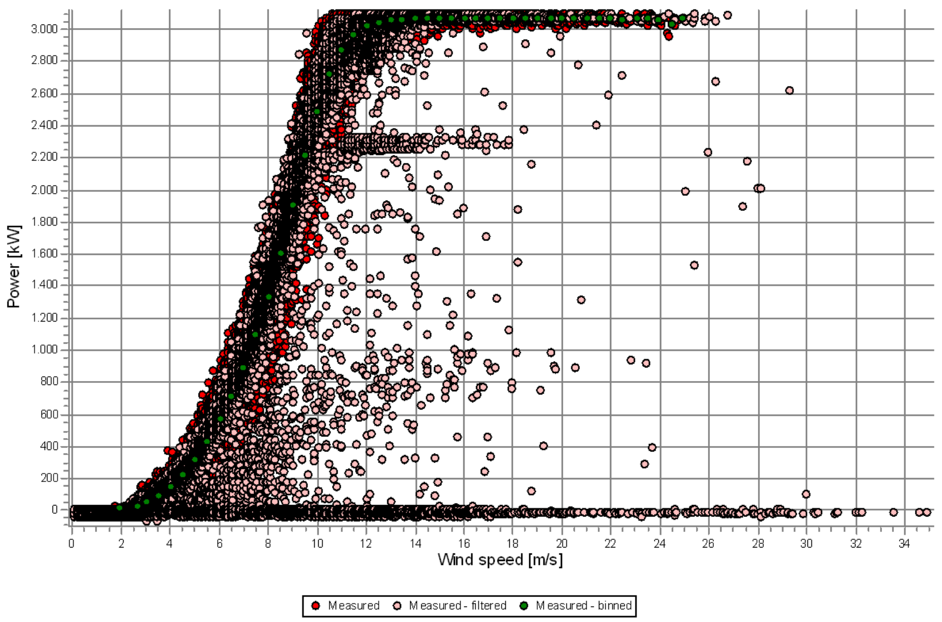


Figure 66: Example historic power curve based on the nacelle wind speed.

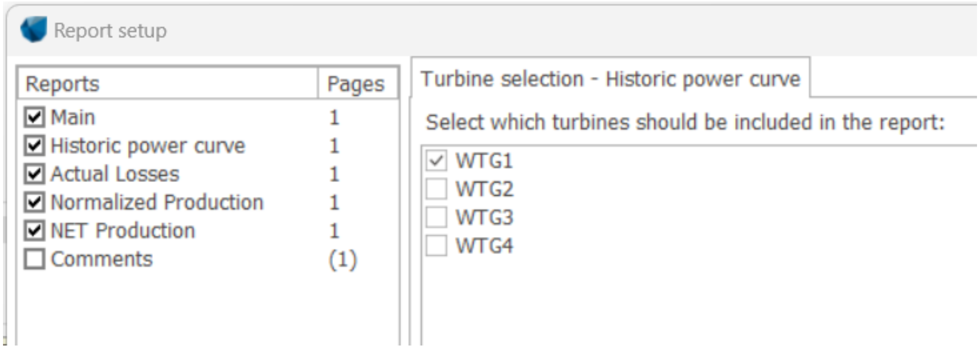


Figure 67: WTG selection historic power curve

11.1.28 Actual Losses

The next pages show the actual losses aggregated in different ways: by WTG, by category, by error code, and by month (Figure 68 and Figure 69). Combination of actual production and actual losses leads to the potential production which is summarized in a table (Figure 70).

Performance Check - Actual Losses

The actual losses are derived for each time step concurrent with an error event as the difference between the measured power and the potential power based on the historic power curve and the (corrected) nacelle wind speed.

Actual losses in kWh

WTG ID	Others	Manufacturer	Normal	Utility	Environment	Remote shut down	USER error code	Grand Total
Grand Total [kWh]	4095	2165070	27564	24233	93635	2089973	3047604	7452175
WTG01 [kWh]	331	625773	0	1930	36562	466446	535814	1666857
WTG02 [kWh]	-50	320237	0	7778	7573	493544	705545	1534627
WTG03 [kWh]	3813	679373	27564	12577	26619	535720	1134407	2420072
WTG04 [kWh]	0	539688	0	1948	22881	594264	671838	1830619

Actual losses in %

WTG ID	Others	Manufacturer	Normal	Utility	Environment	Remote shut down	USER error code	Grand Total
Grand Total [%]	0,00	0,90	0,01	0,01	0,04	0,87	1,28	3,12
WTG01 [%]	0,00	1,02	0,00	0,00	0,06	0,76	0,87	2,72
WTG02 [%]	0,00	0,55	0,00	0,01	0,01	0,84	1,21	2,62
WTG03 [%]	0,01	1,16	0,05	0,02	0,05	0,91	1,94	4,13
WTG04 [%]	0,00	0,88	0,00	0,00	0,04	0,97	1,10	2,99

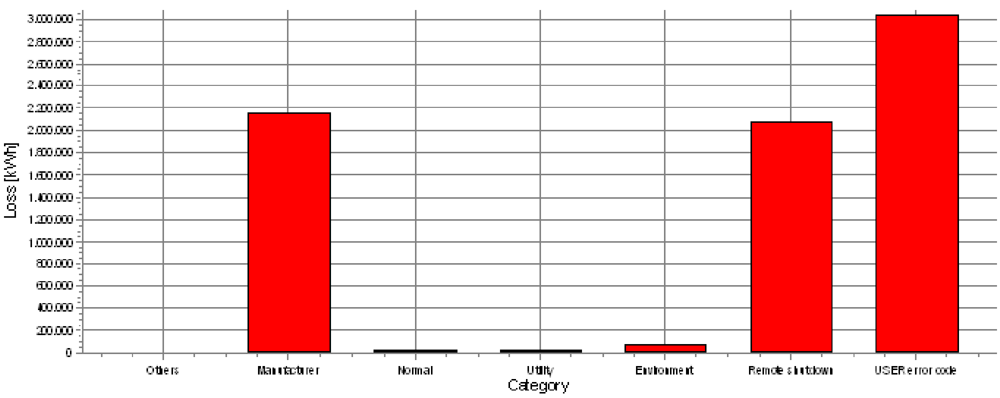
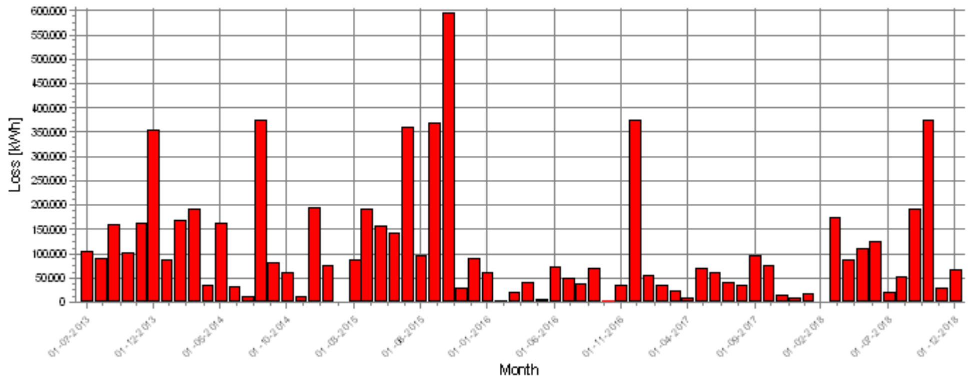


Figure 68: Actual losses by category and WTG

Performance Check - Actual Losses



Error loss statistics

Error code	Description	Category	Loss [kWh]	Loss [%]	MTBF [Hours]	MTTR [Hours]	Count
10000	[USER] Stop without error code	USER error code	2359936	0,99	123,18	0,83	1565
309	Pause over RCS	Remote shut down	2089973	0,87	254,51	1,87	757
10001	[USER] Power curtailment / outlier	USER error code	711064	0,30	58,85	0,31	3281
900	Pause pressed on keyboard	Manufacturer	565168	0,24	495,47	3,46	389
3164	PwrStopActive,Par1____Par2____	Manufacturer	298481	0,12	1107,00	2,05	175
3178	ModeSelectorInStop:Tow__Nac__	Manufacturer	202107	0,08	2850,59	3,58	68
3139	LSCHWErr, ConvModule_,Par2____	Manufacturer	192264	0,08	9698,43	5,73	20
3070	EmergStopButtonActivated__	Manufacturer	151578	0,06	3344,12	2,15	58
3472	SafetySystem Reset Required	Manufacturer	95912	0,04	7458,24	6,51	26
2950	GenHighPhaseTemp: Min__Max__Ã‚Â°	Manufacturer	57678	0,02	902,19	0,52	215
3466	LineSideBreakerTripped. Mod:__	Manufacturer	56168	0,02	21556,22	8,59	9
3222	HighTempMSC.IGBT:Mod__	Manufacturer	52907	0,02	6064,32	0,79	32
144	High windspeed: __._ m/s	Environment	52749	0,02	7462,11	2,63	26
2863	ConvWaterCoolPressLow____bar	Manufacturer	46193	0,02	6689,58	2,95	29
2969	Supply CommonCB Nacelle Opened	Manufacturer	45132	0,02	64679,22	15,22	3
3172	PowerStopHighTemp	Manufacturer	43730	0,02	6260,23	0,52	31
3419	Shadow Detected	Environment	37201	0,02	311,96	0,57	621

Figure 69: Actual losses by month and by error code

Results: Potential Production

The potential production refers to what could have been realised if the turbine had been operating as per the full performance using the historic power curve.The potentia production is consequently the sum of the actual production and the actual losses.

Performance Check data export, version:1
Data from: 2018-04-13
Data to: 2019-01-18
PARK calculation: 3.4.311: New PARK calculation - Measured power curve used - Calculated production replaced with OK measured values
Coordinate system: UTM (north)-ED50 (Europe) Zone: 32

WTG ID	Actual production	Potential production	Actual loss	Own consumption	Turbine type	Easting coordinate	Northing coordinate	Hub height	Recovery rate of wind speed*	Wind speed correction factor
	[kWh]	[kWh]	[%]	[kWh]				[m]	[%]	
WTG01	7,350,020	7,617,407	3.5	11,604	VESTAS V112 3075 112.0 !O	523,510	6,300,530	84.0	99.9	1.000
WTG02	6,824,904	7,167,630	4.8	12,844	VESTAS V112 3075 112.0 !O	523,717	6,300,270	94.0	99.9	1.000
WTG03	6,838,024	7,149,404	4.4	13,344	VESTAS V112 3075 112.0 !O	523,923	6,300,011	94.0	99.9	1.000
WTG04	7,215,716	7,566,548	4.6	13,568	VESTAS V112 3075 112.0 !O	524,130	6,299,752	94.0	99.9	1.000

* Potential AEP has been adjusted to 100% availability per month based on the recovery rate ratio difference to 100%. I.e. recovery loss of SCADA data assumes that the turbine was in "average monthly" performance for the duration of missing information.

Figure 70: Potential Production

11.1.29 Normalized Production

This section of the report shows the normalized production. At the top of the page the normalized production per year and per MW/y is given. The normalized production is assumed to have 100% availability.

The monthly potential production versus the wind energy index, the time series of the production, and the chosen wind energy index as well as the timeline are displayed (Figure 71).

Results:

	MWh/y	MWh/MW/y	Cap. factor
Calculated normalized production at 100,0 % avail *)	11123	3617	41,3 %
Correlation (R^2)	0,94		

*) Losses are substituted so that the production represents 100% availability

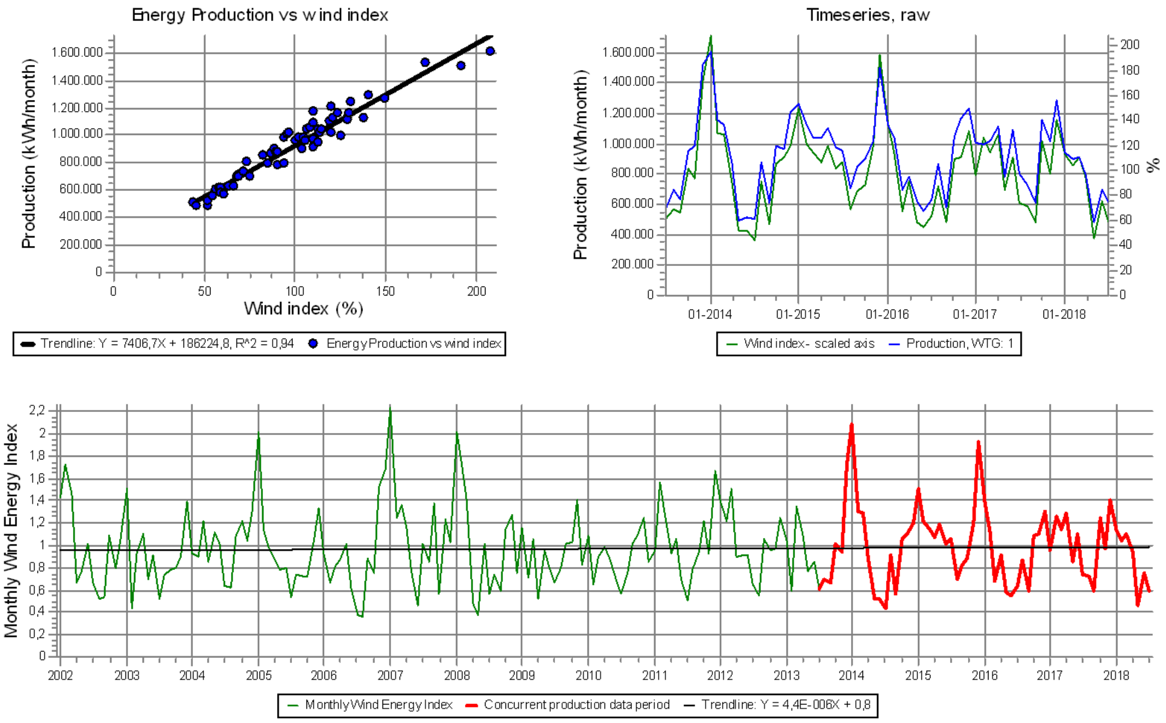
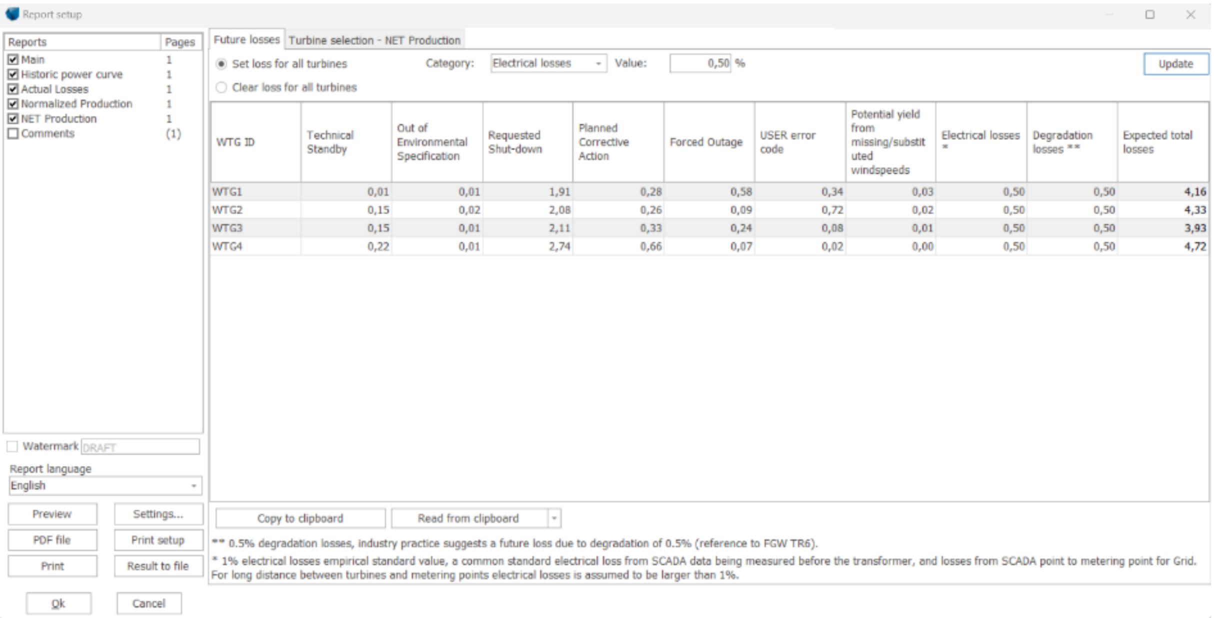


Figure 71: Normalized production - wind energy index correction

11.1.30 NET Production

The NET production requires the quantification of future losses (Figure 72). The actual losses are by default transferred as future losses; however, the user can modify these values, either manually one-by-one or through definition of the loss of a category. For the second option the Apply button has to be pressed to actively change the settings. An electrical loss default of 1% is assumed, with degradation 0.5% which leans towards the FGW TR6.

The final table (Figure 73) summarises the NET production and lists all assumptions.



WTG ID	Technical Standby	Out of Environmental Specification	Requested Shut-down	Planned Corrective Action	Forced Outage	USER error code	Potential yield from missing/substituted windspeeds	Electrical losses *	Degradation losses **	Expected total losses
WTG1	0,01	0,01	1,91	0,28	0,58	0,34	0,03	0,50	0,50	**4,16**
WTG2	0,15	0,02	2,08	0,26	0,09	0,72	0,02	0,50	0,50	**4,33**
WTG3	0,15	0,01	2,11	0,33	0,24	0,08	0,01	0,50	0,50	**3,93**
WTG4	0,22	0,01	2,74	0,66	0,07	0,02	0,00	0,50	0,50	**4,72**

** 0.5% degradation losses, industry practice suggests a future loss due to degradation of 0.5% (reference to FGW TR6).
* 1% electrical losses empirical standard value, a common standard electrical loss from SCADA data being measured before the transformer, and losses from SCADA point to metering point for Grid. For long distance between turbines and metering points electrical losses is assumed to be larger than 1%.

Figure 72: Quantification of future losses

Performance Check - NET Production

The Normalized production represents the future optimal yield of the wind farm with 100% availability and 100% windiness (wind energy index). The Net production is the normalized minus expected future losses presented below.

The losses are accumulated depending on their statistical dependencies.

WTG ID	Normalized production	Others	Manufacturer	Normal	Utility	Environment	Remote shut down	USER error code	Electrical losses *	Degradation losses **	Expected total losses	Net production
	[MWh/y]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[MWh/y]
Park	43385	0,00	0,90	0,01	0,01	0,04	0,87	1,28	1,00	0,50	4,62	41385
WTG01	11123	0,00	1,02	0,00	0,00	0,06	0,76	0,87	1,00	0,50	4,22	10653
WTG02	10599	0,00	0,55	0,00	0,01	0,01	0,84	1,21	1,00	0,50	4,12	10162
WTG03	10601	0,01	1,16	0,05	0,02	0,05	0,91	1,94	1,00	0,50	5,63	10004
WTG04	11062	0,00	0,88	0,00	0,00	0,04	0,97	1,10	1,00	0,50	4,49	10565

* 1% electrical losses empirical standard value, a common standard electrical loss from SCADA data being measured before the transformer, and losses from SCADA point to metering point for Grid. For long distance between turbines and metering points electrical losses is assumed to be larger than 1%.

** 0.5% degradation losses, industry practice suggests a future loss due to degradation of 0.5% (reference to FGW TR6).

Figure 73: NET Production

11.1.31 Export

The user can export either the key figures or the time series to the clipboard or to a file (Figure 74). Data that have been disabled or filtered can be included upon request.

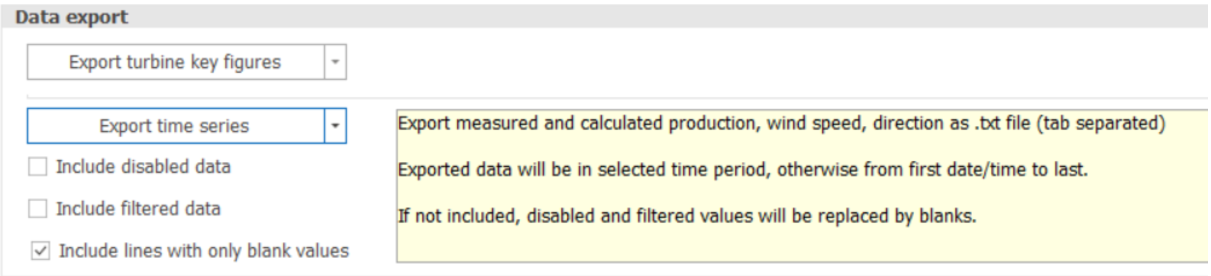


Figure 74: Export options

11.12 Chapter 2: Monthly production to long-term yield

The simplest and very robust approach within Performance check module is to wind index correct measured monthly production data. It is although important to notice that a wind energy index can be biased and thereby could lead to wrong results!

11.1.32 Wind Energy Index Correction

Data setups see: 11.3
Load PERFORMANCE CHECK module from the main Tab, Loads & Operation, and Performance Check.
Set up import filter for measured production data if data are not already loaded in existing WTG objects. See Section 11.1.5
Decide which existing WTG objects to include in analysis (assumed created in project).
Pair WTG ID's from the import setup to existing turbine objects and load (import) the data.
Go to "Analysis" > choose "Wind index WCP"
Select a wind index (see section: 11.1.8)
Check the correlation; utilize the filters, availability settings etc. to establish a trustworthy Wind Index Corrected Production (WCP) = long term production expectation for each turbine in analysis.
Use the different graph views to extract results to Excel or print the reports for documentation, includes the long-term expectations and also a coarse loss evaluation and prognoses with P50, P90 etc. (WCP report)

11.1.33 Analysis – Monthly time resolution

Very often the data basis which the evaluation of the performance of operating wind farms is done is just on monthly basis. This is also quite good, if the data period is reasonable in length and there are well established methods for performing performance check on monthly basis, like the wind energy index method. Higher time resolution data can also be loaded as described in previous chapters.

Monthly data can be with or without grid losses. This is important to know when the calculation model is fine-tuned.

With monthly data it is possible to "just" calculate expected long term production (wind energy index corrected). But it is also possible to compare with model calculations based on time-varying PARK calculations where results are aggregated on monthly level.

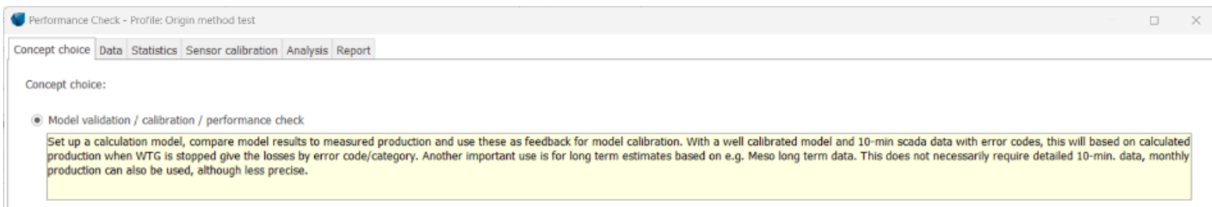


Figure 75 Monthly data work path

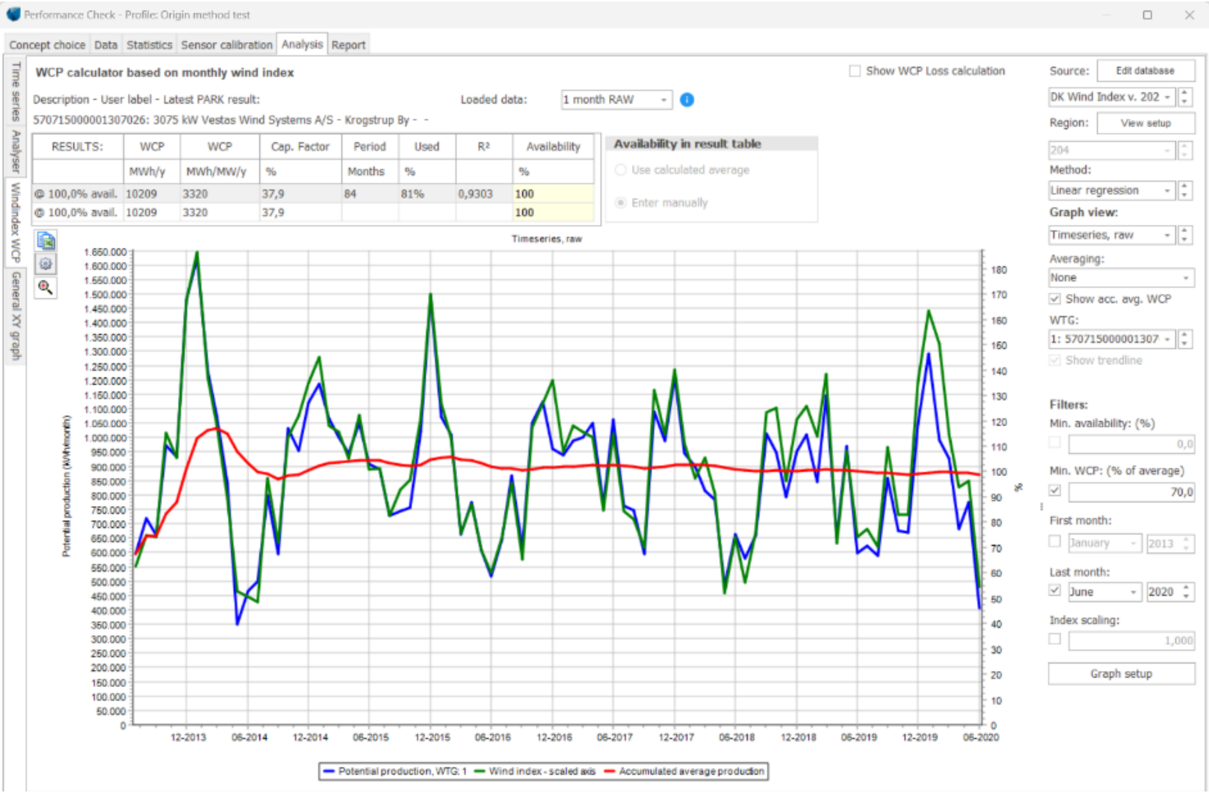


Figure 76 Normalized monthly production data.

With monthly production data imported with or without availability, the monthly production is paired to the wind energy index, and the WCP is calculated. This gives the expected long-term yield based on correlation between wind energy index and the observed production. In Figure 76, in blue is measured monthly production, green is the wind energy index from the Danish index model, and in red is the accumulated average wind corrected production, showing that this turbine has a very stable yield over the 8 years production period.

The WCP (Wind index Calculated Production = Long term expected production based on wind index correction method) calculator has many refinements. But the basic concept is simple: Based on monthly production and monthly wind energy indexes, the Wind Index Corrected production is calculated. There are two basic concepts for performing this calculation:

The sum method: The sum of productions is divided with the sum of index's (for non-filtered months).

The regression method: A linear regression line is established for production vs index, and the production for index 100% is found.

We have performed numerous analyses with the two different methods, and we cannot in general say which is the best – they both have advantages. If data quality is good and a long period of data is available, the results will be almost identical. It is when having shorter data periods and/or poor correlation, the two methods can differ.

NB the WCP is the expected P50 long term yield of the evaluated turbine. It's important to know if it's the raw power from SCADA or from the Grid metering point; if it's including availability or not to assess possible losses imposed on the WCP value that is calculated.

It's also possible to load a time-varying PARK calculation based on monthly aggregated results), This PARK calculation shall include the existing turbines under investigation. Then it's possible to evaluate if the wind model is over- or under-estimating the actual yield. In the Scaler it's then possible to make changes to the mean wind speed, and/or the seasonal, possible wake settings, and iterate the comparison of the wind model to the actual production observed.

11.1.34 WCP – loss form

The loss form is a small tool for making assessments of losses for a specific period. This can be used e.g. to assess if the availability information from the control system is in the right size/order; or to assess how large the loss was in a period with specific problems, e.g. power curtailment. To base loss assessments on wind index is a coarse method. Much more refined methods are described using the analyser (require more detailed production data).

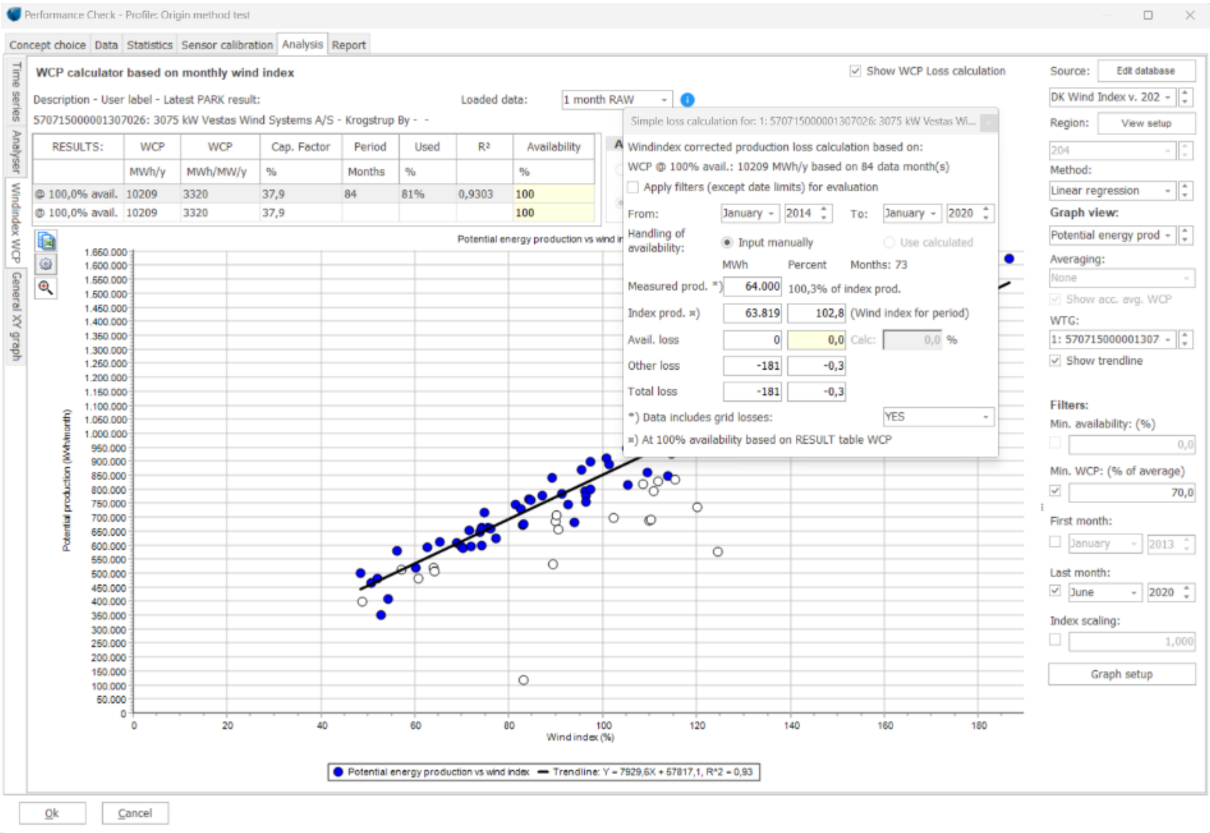


Figure 77: WCP Loss calculation

Three different “basic settings” that can be used:

1. **NO filter on WCP calculation**. All months are used, but with full availability correction (if availability data are imported or an availability figure for all periods is entered in result table)
2. **With filter on WCP calculation**. Months not meeting the filter criteria are filtered out in the WCP calculation. For the remaining months, availability-based correction is performed as described above.
3. **With filter on WCP calculation AND filters are used within the period in investigation**. Here only months not disabled by filter criteria are included in the loss evaluation form.

Based on the calculated WCP from all non-filtered data, and the wind index for the months with available production data, the expected production for the months in investigation are calculated. This gives measured production and the expected loss as the difference WCP – measured for the same months.

Due to the wind index is describing the production expectation relatively coarse, the calculated loss will also be somewhat coarse. Due to this, it can be negative for some periods. The longer the period, the more reliable.

With availability information for each month, the calculated availability-related loss for the months in investigation is shown separately. If this reflects the found loss precisely, the field "other loss" then becomes 0. Therefore, it will be 0 if all data used for calculating the WCP is used. This is "self-fulfilment", while the calculation method assumes losses equal to the informed availability loss taking all data.

Whether the data does or does not include grid losses, it can be set in the drop-down box. This is just an info field. If grid losses are included (data from sales metering used), the WCP is the expected annual sale. If data from turbine controller is used, the WCP will typically be higher and assumed grid losses must be subtracted from WCP to get expected annual energy sale.

11.1.35 WCP - reports

When having established the settings giving "comfortable results", reports can be printed.

There are 3 report pages from the WCP tool:

1. Main – assumptions and results including graphics.
2. Losses – Loss tables and graphics giving "rough" loss estimates.
3. Prognosis – Expected monthly productions incl. probability of exceedance based on user specifications.

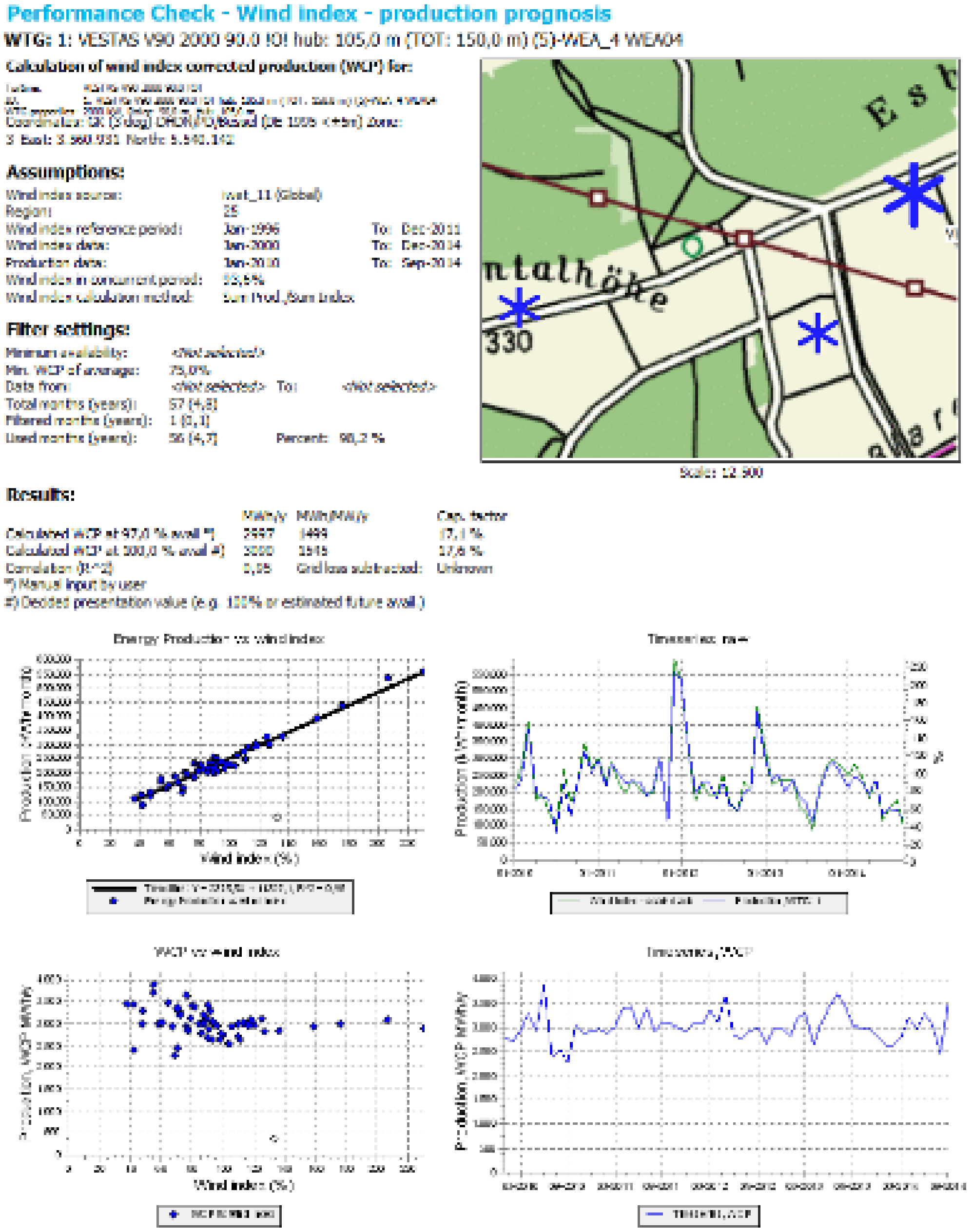


Figure 78 WCP report page 1

The main page is where the results from the WCP tool are presented. Note that even though there is a very good correlation, this is no guarantee the result really represents the long-term production. This requires that the wind energy index is correctly calibrated.

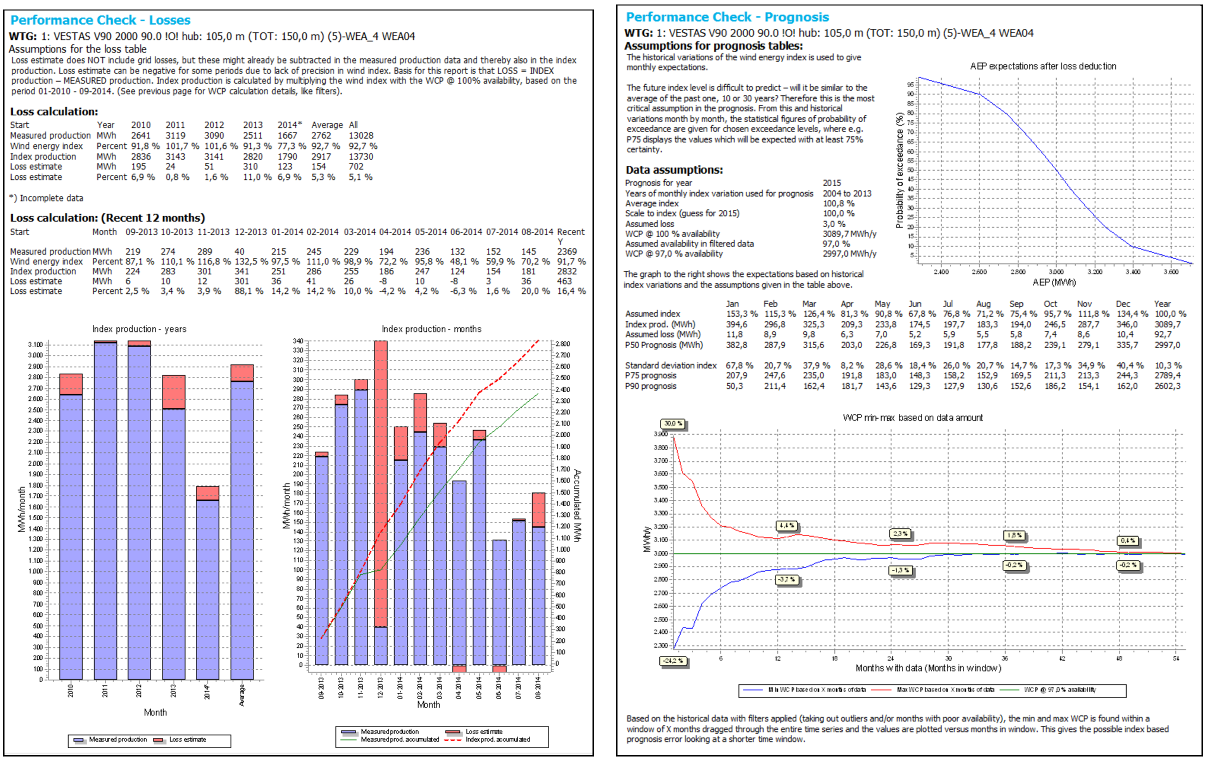


Figure 79 WCP report losses & prognosis

The loss page gives a year-by-year table, where the measured production subtracted from the (wind index x WCP) based production gives the loss. For recent 12 months, a similar table is visible. As seen in the table of recent 12 months loss calculation, negative losses appear which illustrates the limitation of the wind index accuracy. But it shows how approximately 300 MWh were lost December-2013. Especially 2010 and 2013 were years with loss above what should be; and 2014 does not look too good either. 2011-2012 were seen better with low losses and good wind. It can also be seen that low winds were worse than the losses during 2010 and 2013.

The prognosis page show what to expect for a future year – based on a guess on the wind, where a 100% wind index normally is the most reasonable guess. Also, the loss is a guess, with a value of 3 % here.

With these two guesses, the presentation shows like P90, which is based on wind index variation calculations. There is 90% probability that at least 2602 MWh will be the outcome in 2015. But most likely (P50) 2997 MWh will be the outcome after loss deduction. The expectations are shown month by month, again based on historical wind index variations.

The “trumpet graph” shows how well the wind index correction works at this specific turbine. Having only 6 months of data, up to +/-10% error could be seen when having the worst period seen during the almost 5 year of operation. With a full year of data, the maximum error that could be seen is round +/-4%. This illustrates how well an index corrected production can be trusted.

11.13 Chapter 3 Model calibration & Performance Check

The basic concept behind the Model validation / Calibration / Performance check path is:

Evaluate/calibrate PARK calculation against measured production based on time step PARK calculation.

Input can be external mast(s) or nacelle wind speed + direction loaded in Meteo object. The wind speed can be wake cleaned in Meteo object OR data from more masts/WTGs can be merged, so only wake free wind is used.

Based on the comprehensive analyser in Performance Check, it can be found which adjustments to the PARK model setup that will be needed to get a good match, e.g. adjust the Wake Decay Constant.

The gains by this method:

- Wake losses can be quantified quite precisely.
- Model calibration experience can be used for calculation of EYA on new wind farms.
- Loss evaluation does not require all WTGs to have good wind speed signals and the problem with biased wind speeds when turbines are stopped can be handled.

The calibrated model can be reused with mesoscale modelled winds (or initially based on); then the modelled winds can be calibrated using the Scaler for the period with production data. With such a setup, long term expectation can be calculated very precisely using long term mesoscale data (10-20y), where e.g. direction distribution is long term representative.

All variants can be run for the same park, but in separate “sessions”. When starting the tool, the session name must be entered by giving it a name e.g. Southern windfarm. More sessions of each type can be setup for e.g. When different data filtering is allocated to each session or different periods with different number of turbines operating. It should although be mentioned that a PARK calculation can utilize Start/Stop dates within each WTG object and thereby a performance check can be performed as ONE session on wind farms where different turbines are in operation during the period with data. PARK calculation also handles like day/night operation modes (noise reduction) or other curtailments like sector management.

The wind energy index database must be mentioned as an important part of the basic concept. A comprehensive wind energy index database concept is developed. This handles as well “official” wind energy index is as it has its own index calculator based on wind data. The wind data can be downloaded in METEO objects from the ONLINE data service, where datasets such as MERRA2 data or the ERA5 data can be used for creating site- and turbine-specific wind energy indices.

11.1.36 Model Calibration, loss estimate and long-term expectation.

The more refined use of Performance Check is to use it in combination with a PARK calculation. The measured performance is compared to the calculated-on time step basis, and thereby comparisons can be performed by different aggregations, like by direction. Problems in the calculation model or model setup or scaling of mesoscale wind data can be identified and corrected.

Set up and run a time-varying PARK calculation (must be based on “existing WTG objects.”). Note that the aggregation level in the PARK setup should match the available production data (like monthly or hourly or 10 min.). The wind data for the PARK calculation can be from one or more measurement masts at site or from nacelle measurements or from Meso/Model data. BUT note the wind data must be “wake free,” which might require some preprocessing, like merging data from more sources by direction or utilizing the wake cleaning option in Meteo object.

Arrange the measured production data etc. in ASCII text files ready for import.
Load PERFORMANCE CHECK module from main Tab, Loads & Operation.
Setup import filter for measured production data if data are not already loaded in existing WTG objects.
Decide which existing WTG objects to include in analysis.
PAIR WTG ID's from the import setup to existing turbine objects and load (import) the measured data.
Load PARK calculation – now concurrent calculated and measured data are available by time step.
Load error codes if available, either as part of the production data files or separate from error log, or if no error code data available, use the "user error code" to assign error codes to events with stop at wind > x m/s or production below shifted power curve (sub-optimal performance/power curtailment).
Utilize the analyzer and other tools to get an idea if some model setup must be revised or data cleaned further. E.g., modify the PARK calculation setup and run this again. Use analyzer to see if modifications worked. Continue this process until results are satisfying.
Extract results from graphs, like loss, to Excel, to build up the documentation (no reporting yet available within this part of Performance Check)
If e.g. a Meso data-based calibration is performed, now run a new PARK calculation with found calibrations, based on for e.g. 20 years of mesoscale data to calculate the expected long-term AEP, wake losses etc.

11.1.37 Time Varying PARK Calculation for Performance Check

The time-varying PARK calculation is essential for the performance check analysis. There are two ways to go:

- A traditional PARK time step calculation, where the models calculate free and wake reduced wind speeds at each WTG position from which the power is calculated with optional corrections (air density, Turbulence, shear etc.).
- Nacelle wind-based calculation (no models involved, see Post construction path manual).

Setting up a traditional time-varying calculation model where it is included to offer the user the possibility to check if the model calculation performs well aggregated e.g. by wind direction, wind speed, season, etc.

The basic concept is to scale the wind data for each time stamp to each turbine position. The transfer function (by direction) between the wind data source (measurement(s) or Meso scale data) and turbine position is calculated and used for each time stamp in the used wind data source.

The transfer function is calculated by performing a WAsP or WAsP-CFD or FLOWRES based calculation on a generic wind distribution at each turbine position in hub height. The ratios between the calculated mean wind speeds (or Weibull A parameters) are the scaling factors.

Refined options like RIX correction or displacement heights can be part of the calculation. Also, turbulence intensity (TI) data are transferred to WTG positions by assuming a constant st.dev. by height, the change in wind speed thereby leads to change in turbulence intensity at each WTG, or by using a model calculated TI. The turbulence can be used for each time step for the power curve correction or as an input for advanced wake loss calculation. Similarly, the air density can be calculated at each time stamp based on temperature and/or pressure data for correction of the power curve. Finally, also shear and veer correction of power curves are optional.

Using mesoscale data gives access to a refined downscaling (taking out meso terrain, applying micro terrain)., Another advantage of mesoscale data is that the shear variations in time are included in the calculation. See more details on calculation method in Chapter 3 ENERGY.

11.1.38 Wind data.

As input for the time-varying PARK calculation, wind speed and direction for one or more specific positions in METEO object(s) can be used. This can be data from measurement masts, LIDAR/SODAR, nacelle measurements, or modelled data. **It must although be data that are concurrent to the turbine operation in time.**

If wind data is from a local mast within the vicinity of another wind farm or is from WTG nacelles, wake reductions are included, whereas the calculation model assumes the free wind speed. This can be handled by a quite comprehensive data cleaning where the wake reductions are “removed”.

An alternative is to combine data from more sources by direction, where only wake free measurements are used. Finally, the scaling by direction can be a simple way to compensate for the wake influence if the data are waked, and similarly this could also be used for removing issues such as mast shadow. For air density correction, it is often convenient to take temperature and turbulence from mesoscale data. Even though these are at hourly resolution, they can be used with 10 min. data, while an interpolation is automatically performed.

Although, turbulence data from modelled datasets can be tricky to rely on. Having local measured data is of course the best, but there is no simple way to correct for wake influence of TI. Only merging data from free measurements will give reliable data.

They can be taken from mesoscale data, but there a quality check that should be performed. They could be very wrong, while the mesoscale data do not capture the mechanical turbulence reasonably - due to the coarse resolution of the terrain data.

11.1.39 Calculation setup traditional PARK calculation

The time-varying calculation is selected in the PARK module using the following highlighted option as shown below:

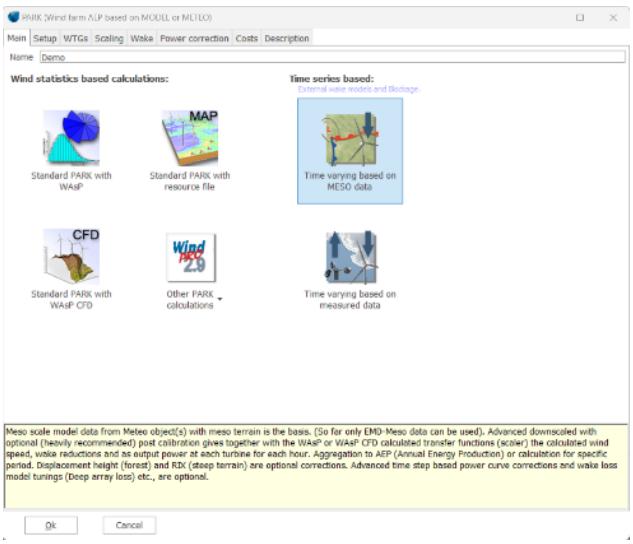


Figure 80 Park module start time varying calculation.

The two right most icons allow to run a time-varying calculation.

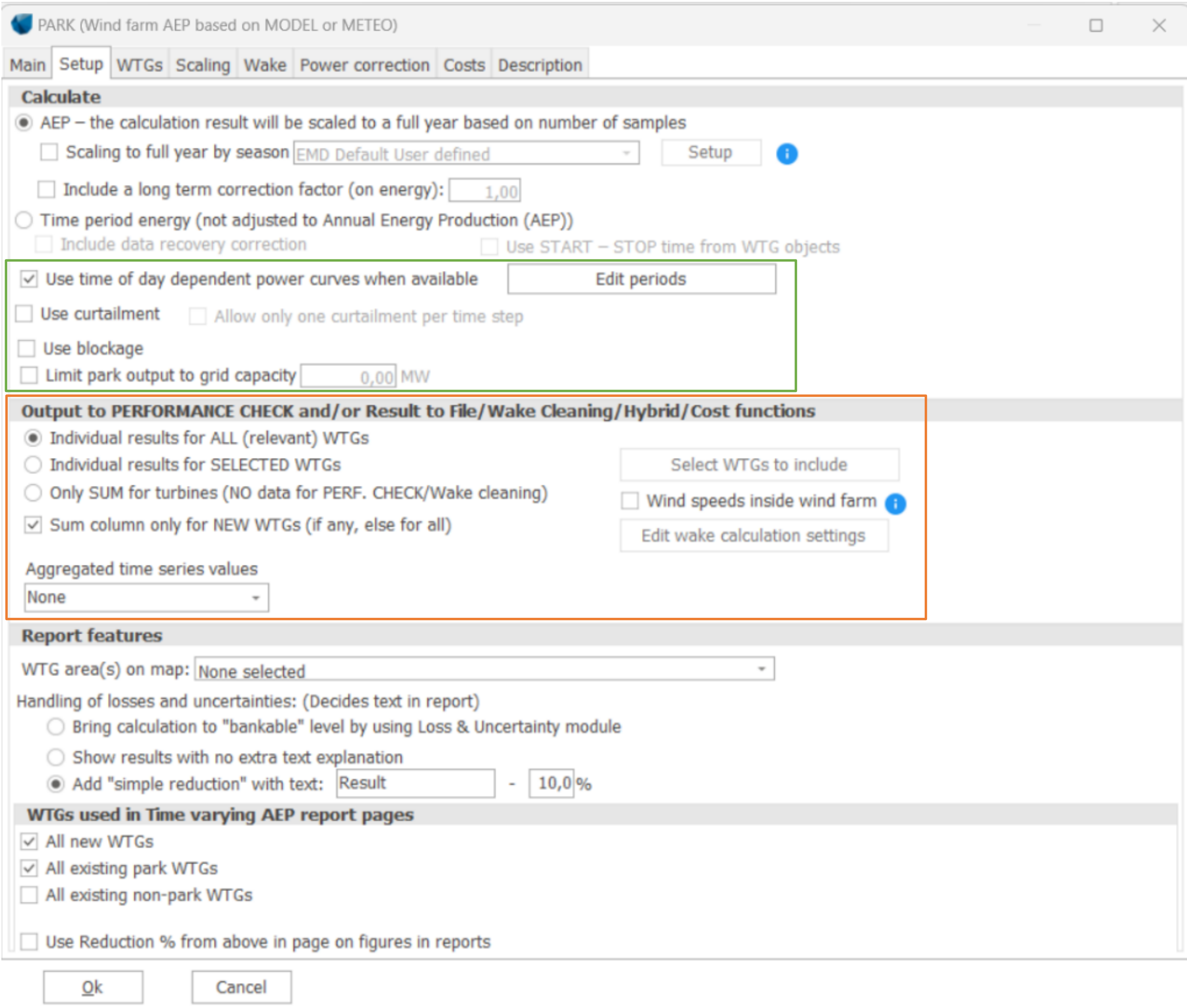


Figure 81 Time varying park calculation setup

At the SETUP tab (Figure 81), the output for Performance check is defined within the shown red square.

Within the green square is seen a number of more advanced options, like:

- Use time dependent power curves, like night noise-reduced power curve
- Use curtailments based on settings within the WTG objects (can be edited from PARK calculaiton setup too)

By default all turbines (existing) in the calculation are included in the output, and the data are aggregated to monthly values. By monthly aggregation, the result file (and thereby the project file size) is heavily reduced. But if 10-min or hourly production data are available for doing Performance check, the resolution shall be set to match the measurements, normally by setting aggregation to “none”.

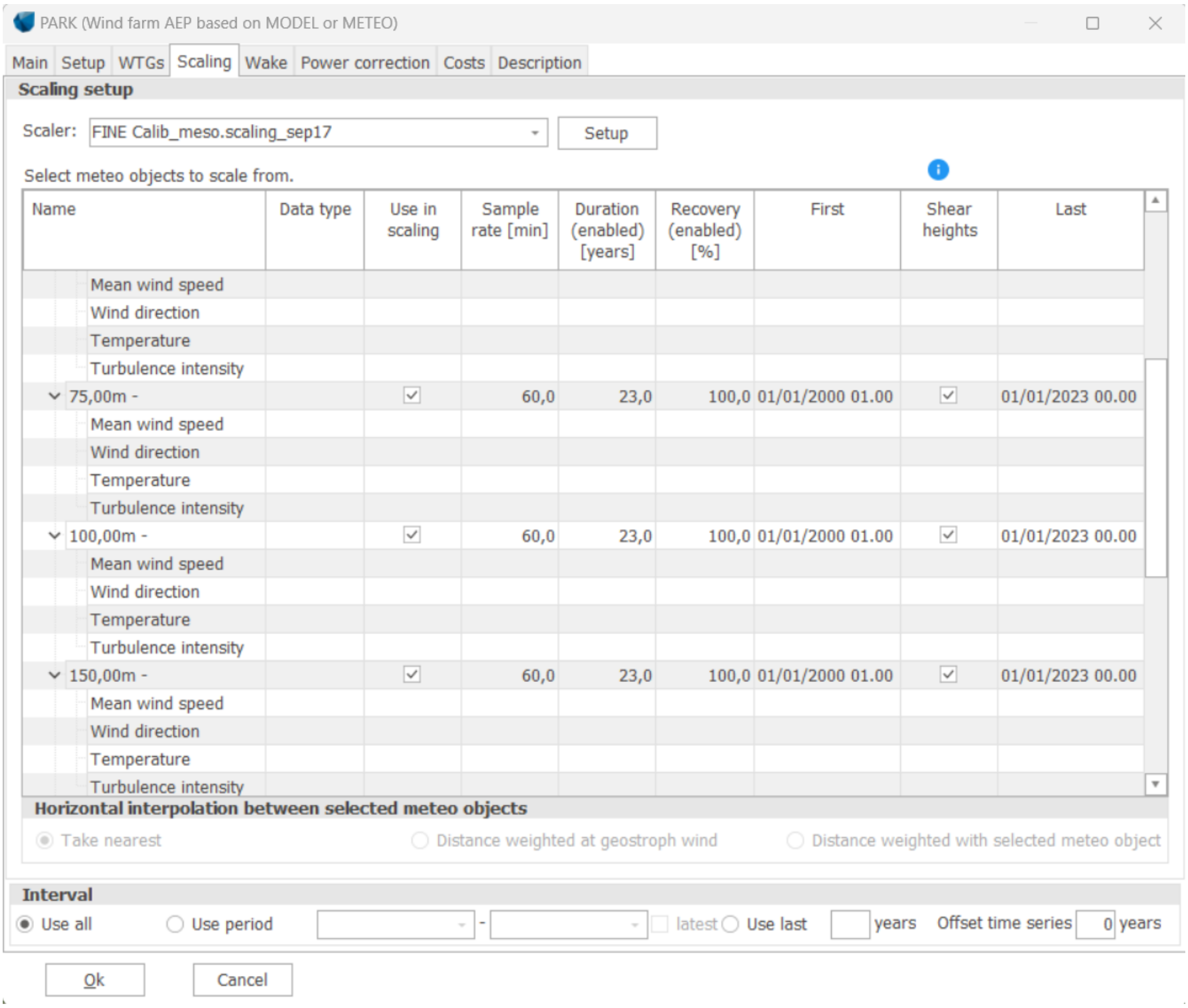


Figure 82 Scaling of time varying park setup

At the SCALING tab it is decided which wind data source(s) is to be used for time varying calculation.

A very important component is the SCALER.

The SCALER decides how the transfer function between wind data position and turbine positions are established. This can be based on the WAsP model or the WAsP-CFD model or other CFD modelled results.

It holds advanced features like mesoscale data downscaling, RIX correction, displacement height calculation, and the post-calibration scaling option, which makes it possible to adjust the transfer function by direction, month, hour, and/or wind speed. But most importantly the “main scaling”, which is the place where the general level of the wind speeds is adjusted to make the calculation match measurements. The reason for this need is mainly when using mesoscale data, which typically will be biased some relative value to the real wind. For more information on the scaler, see Chapter 3 ENERGY.

11.1.40 Data preparation

See section: 11.3

11.1.41 Performance Check – Model calibration start

Activate the Performance Check module from the main Tab “Loads and Operation”.

Start with creating a new “session” or open a previously created.

Choose the desired work path, (TR10 requires separate license to be activated)

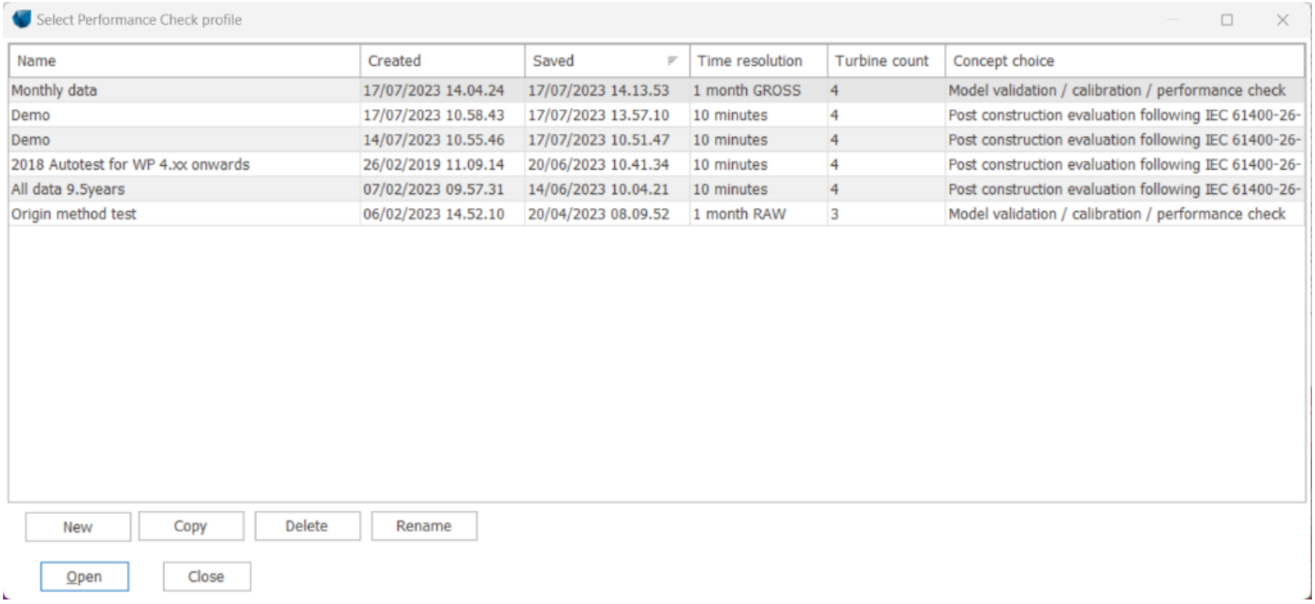


Figure 83 Create new Performance Check session.

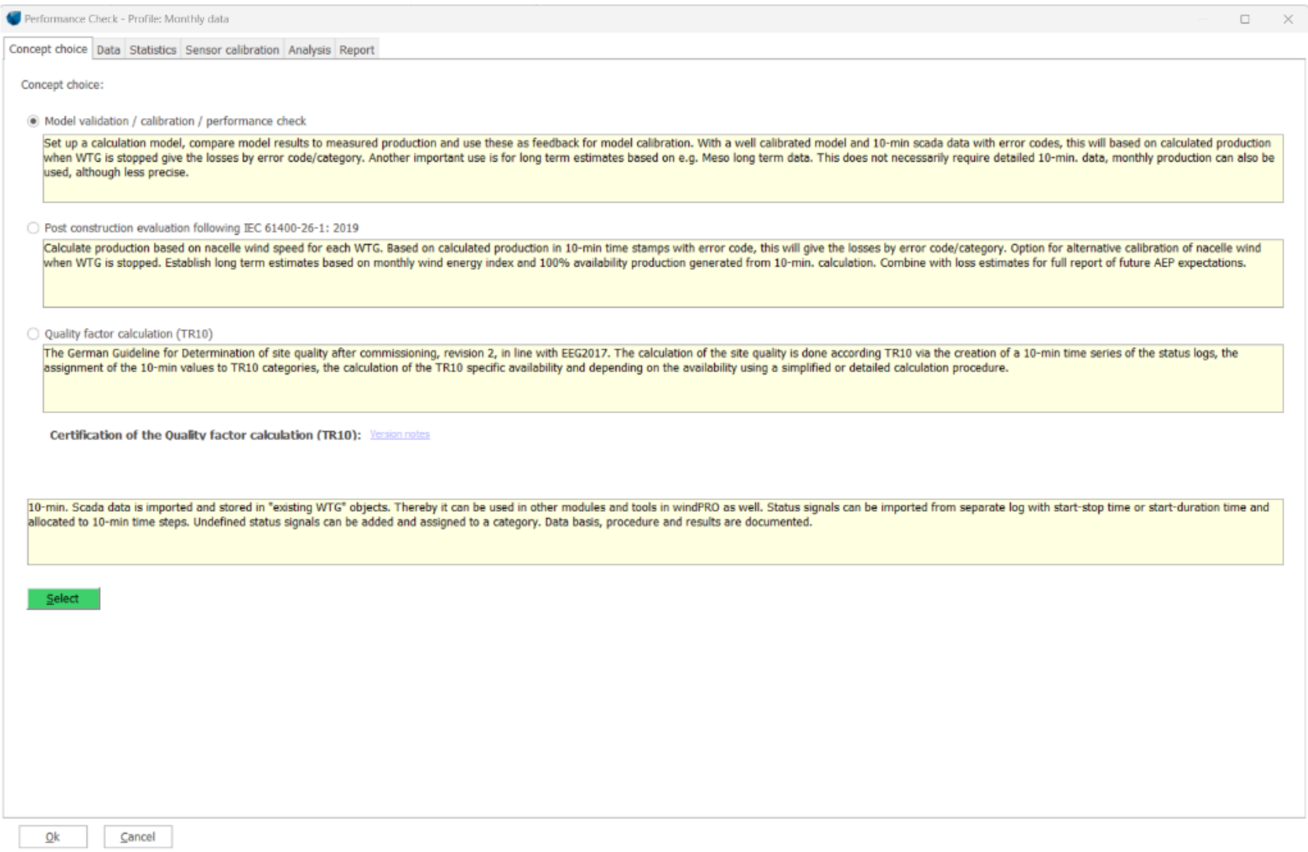


Figure 84 Model validation & calibration

Starting a new session requires for the user to decide if new data are to be imported into the existing WTG objects, or already imported shall be used. Note: for hourly data or other time resolution, select the 10 min Scada data option.

11.1.42 Detailed 10-min / hourly data vs model

A performance check session based on detailed data gives access to the power curve tool and the analyser tool, where a time-varying PARK calculation must be performed with non-aggregated data – or aggregated to the level where measured data are available.

For most of the settings and work flow it's identical to the Post Construction methodology.

Data Import See section: 11.1.5

11.1.43 Data – Pair and load

Load PARK calc. – load the results from the PARK calculation shown next to the "auto pair" button into the Performance check session. Later on while doing the analyses, an alternative PARK calculation can be selected and can be loaded and replace currently loaded PARK calculation. (Note that PARK calculation can also be created within Performance check tool, edited, and rerun).

- Setup Error codes see: 11.5
- Sensor Calibration see: 11.6
- Data Time series: See 11.1.7
- Data time shift see: 0
- Wind Energy Index database see: 11.1.8
- Statistic Tab see: 11.8

11.1.44 Analysis of detailed time resolution

Detailed time resolution is referred to as being more detailed than 1 month. It would typically be daily, hourly, or 10-min data. These data typically will come from Scada systems or turbine controllers. This normally means that grid loss is not included in data. These data are especially well-suited for checking details in the model calculations, partly while data can be aggregated by wind direction, and for power curve validation, where data should have a preferable resolution of 10 minutes. They can also be used for detailed Post-Construction analysis to quantify losses from the error event logs, and to derive Potential production (100% availability), and based on historic performance estimate future NET Production.

11.1.45 Time series

Inspecting time series gives the possibility to screen the data quality on a very detailed level. It is especially interesting if a time-varying PARK calculation is included. It is also interesting for Post-construction, through the use of the historic power curve derived for each turbine's SCADA data, when the turbine is only in normal operation mode.

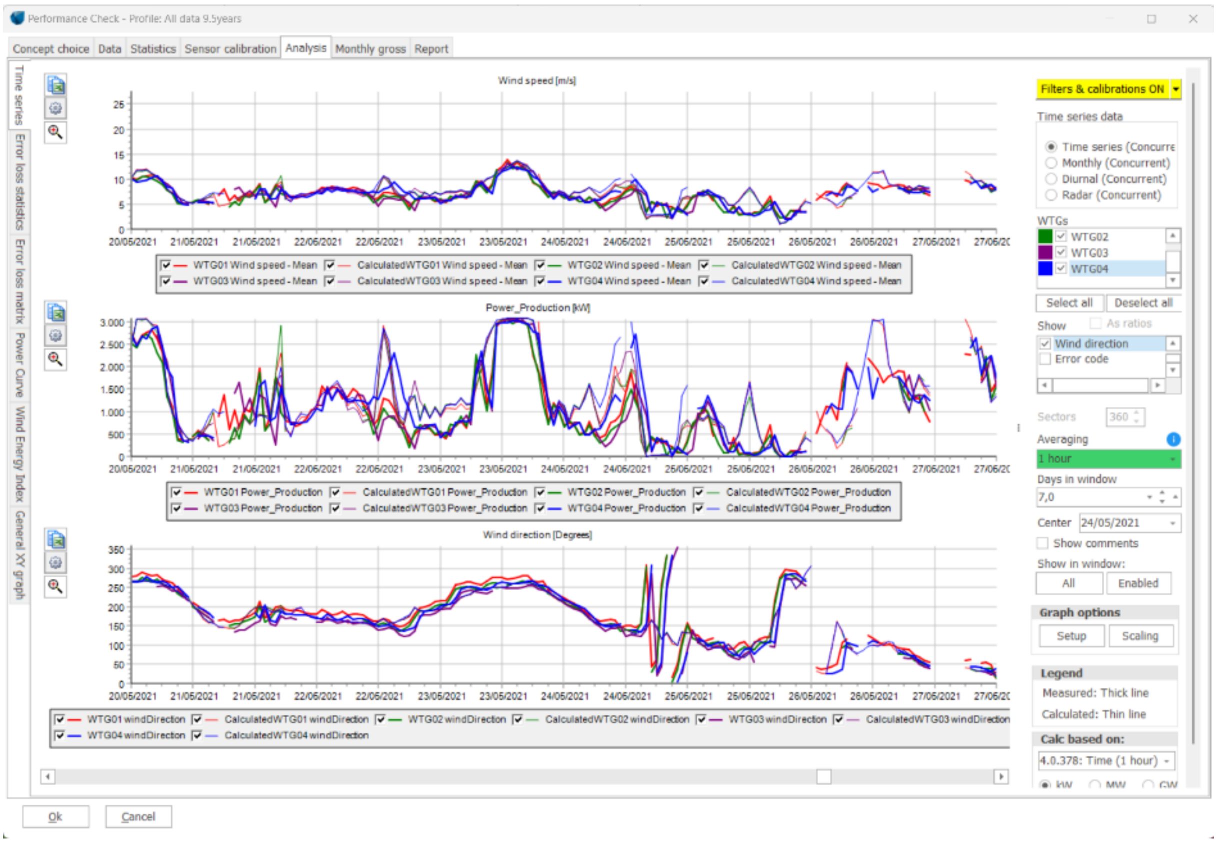


Figure 85 Time Varying Park vs Measurements

Figure 85 shows an example of time variation graphics. Both measured and calculated data are shown. Thick line for measured, thin for calculated. A checkbox can be used to only use calculated direction as well. This is normally recommended, especially to make the radar graph make sense. Just a small turn between measured and calculated makes the radar graph non-comparable. By checking “use only calculated”, concurrent time stamps are compared.

Data evaluation based on different aggregations can be performed like in Meteo object.

ONE difference from using Meteo object is that we Do NOT disable “poor performance” data here. An important part of the analysis is to identify losses due to poor performance. How to handle this by the FILTERS is explained later.

Only erroneous data should be disabled. Erroneous data are data that do not represent how the turbine did produce. An example is when the Scada data show exact same production from many time stamps in a row. This is also called “frozen signal” – the computer does not get new input but just continue to store the most recent value it got for the new time stamps.

11.1.46 Power curve

It is of high importance to notice that validation of the power curve and whether it is within the specifications as provided by manufacturer cannot be expected, unless a very precise measurement setup is arranged (see IEC 61400-12-1 standard). This is very rare to find within a commercial operating wind farm.

The power curve evaluation tool is more for finding changes in time, e.g. before and after a modification of the turbine and more such analyses.

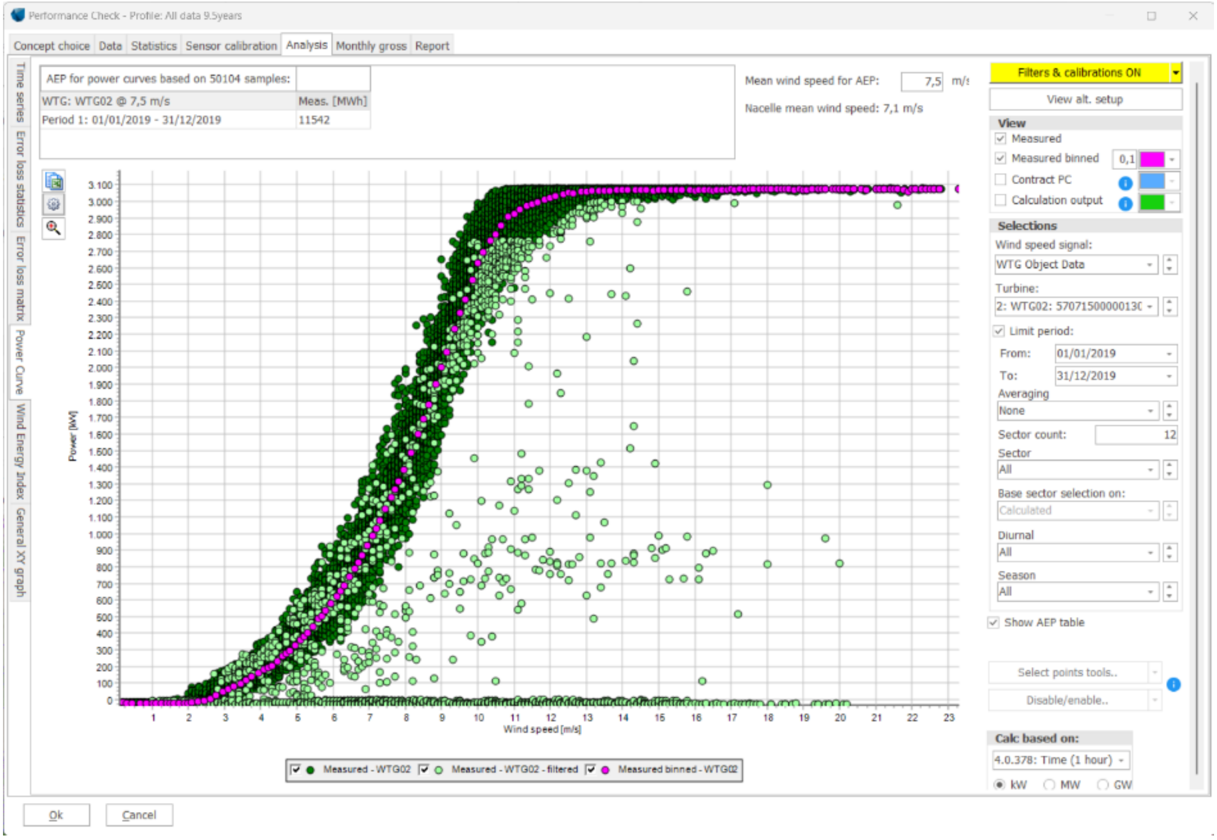


Figure 86 Power curve

The basis selections are: **Wind speed signal**: choosing the WTG object data, the wind speeds loaded into the turbine object is used. This will typically be the nacelle anemometer data, which are influenced by the nacelle and rotor blades quite a bit. But it is also possible to choose calculated wind speed (if a time-varying PARK calculation model is loaded), or data from any Meteo object. So, there is freedom in selection and the user must assess what can be used for which specific analysis.

Turbine: power output from any of the turbines in the Performance check session can be selected.

[ ] Measured – show the power vs selected wind speed signal – filtered data will be shown with light colour.

[ ] Measured binned – as above but binned by choice of bin size.

[ ] Contract PC – show the power curve selected at the WTG object “as is”, meaning the values in the table without any corrections. If the site differs from standard air density corrections, the site-specific power curve at site air density should be selected to make it comparable to measured.

[ ] Calculation output – show the power curve from the calculated time series, which includes power corrections as air density, turbulence, shear, and veer corrections, if chosen in calculation.

A special feature is the AEP window, where the power curves seen is converted to an annual energy production at a given mean wind speed (Rayleigh distributed). This tells very exact how much the measured power curve deviates from e.g. the contract power curve or another time period’s power curve. The ratio will also be shown. The calculation is based on a binned power curve with 0.5 m/s bin size, and the use of windPRO’s “normal” power curve extrapolation features. This means that the power curve is extrapolated to the Cut-out wind speed specified within the power curve in the WTG object. If there are too few data points for creating this part, then an extrapolation to cut-out wind speed and the corresponding power value is performed.

View alt. setup - this button opens the window below (Figure 87):

Here, comparisons to other turbines can be made, with an alternative wind speed signal or an alternative period can be chosen.

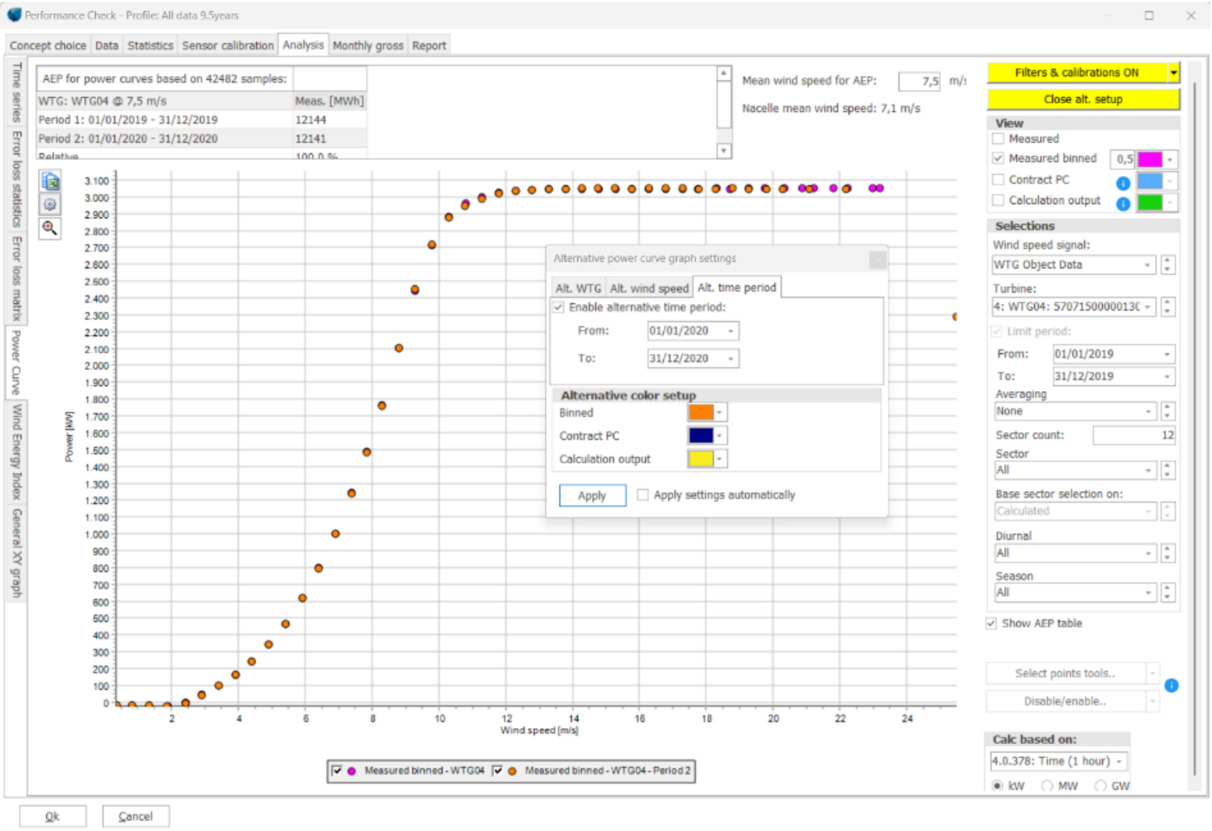


Figure 87 Two periods binned power curves plot.

An example where two periods are compared is shown in Figure 87, along with the calculated output. For the two calculation periods, exact same power curve performance is seen (as expected).

For power curve evaluations, the filtering shall be handled carefully. If e.g. all power <=0 is filtered out, the curve at the low wind speeds are “lifted”. Best option is therefore to add USER error codes and filter those. Filters and selections as described previously are also available in the power curve analysis.

For power curve evaluations based on measurement mast in front of a turbine, use the filter by direction to filter out data in disturbed wind directions. Use the IEC 61400-12-1 tool in windPRO to find the disturbed directions, which also can find the directions disturbed by terrain complexity.

11.1.47 Analyzer, detailed data

The analyser is the place where the most comprehensive comparisons between measured and calculated data can be performed, and wherever needed, inputs to the calculation revisions can be identified.

Notice: For Post-Construction work path, the analyser tab is removed as this simple calculation is based on turbine SCADA data and not a wind model, which is analysed here to identify potential changes in performance, investigate wake model settings, etc.

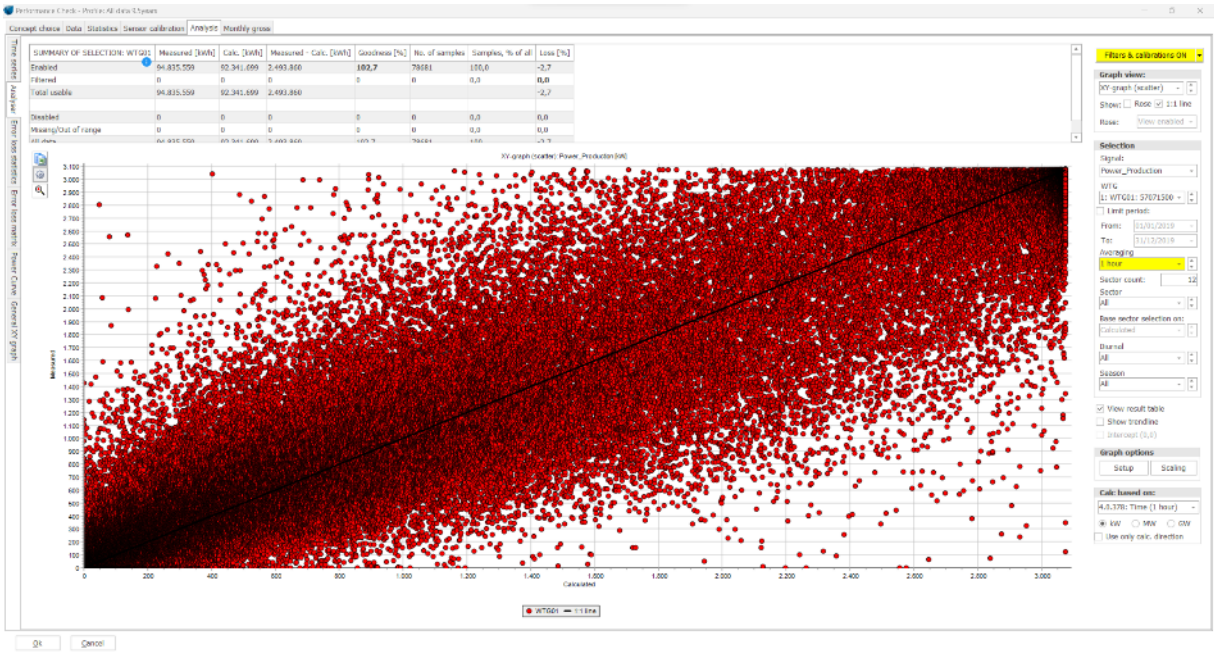


Figure 88 XY plot Calculated power vs Measured power.

Here, hourly measured versus calculated data are seen. When using mesoscale data, quite a huge scatter will often be seen because these data can often be shifted in time. But by aggregating the data to a different resolution, quite good correlations can be seen.

Another important thing is that applying filters will take out the availability events of the analysis and the comparison is then made only on the good data, where turbines are in normal operation. With filters applied, reasonably precise production losses due to availability problems can be identified.

Filters can be applied to measured and calculated data.

Most common is to filter data with error codes, assuming these are established. Even if no error codes are available, it is possible to establish USER error codes and thereby utilize error code filtering. See section 11.1.15

A very simple filter is measured must be a certain percent of calculated. Here it is important to be aware of the time resolution.

Having monthly data, 75% seems like a reasonable value to filter out months with larger availability problems.

Having daily data, 25% seems like a reasonable to filter out days with larger availability problems.

Having hourly data, 1% seems like a reasonable value; thereby just the “non-performance” hours typically are taken out.

But having a large spread in the data, it is important not just to filter out the low performing and keep the high performing, which would introduce a skewness in the filtering.

While using performance Check on a larger wind farm, it can be an issue that several turbines are not running for some periods. This can lead to wrong conclusions regarding wake losses. Therefore, it is possible to set that a certain minimum number of turbines to be in operation to include the time stamp.

For the measured or calculated, the lists are automatically build based on signals available.

It is possible to apply filter inside or outside an interval.

Taking negative plus 0 values out, set start to -9999 and end to 0, apply to “inside interval”

Taking just negative, set start to 0 and end to 9999 and apply to “outside interval”.

With the filter settings, also special analyses can be made. Filter e.g. on temperature or rpm.

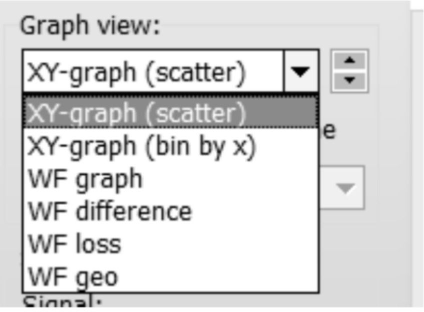


Figure 89 Setup of different graph views for x/y plots.

Several different graph views are available. These have the purpose to analyse how the model calculation works compared to the measurements.

The XY-graph (scatter) has been presented. In the following the other views are presented.

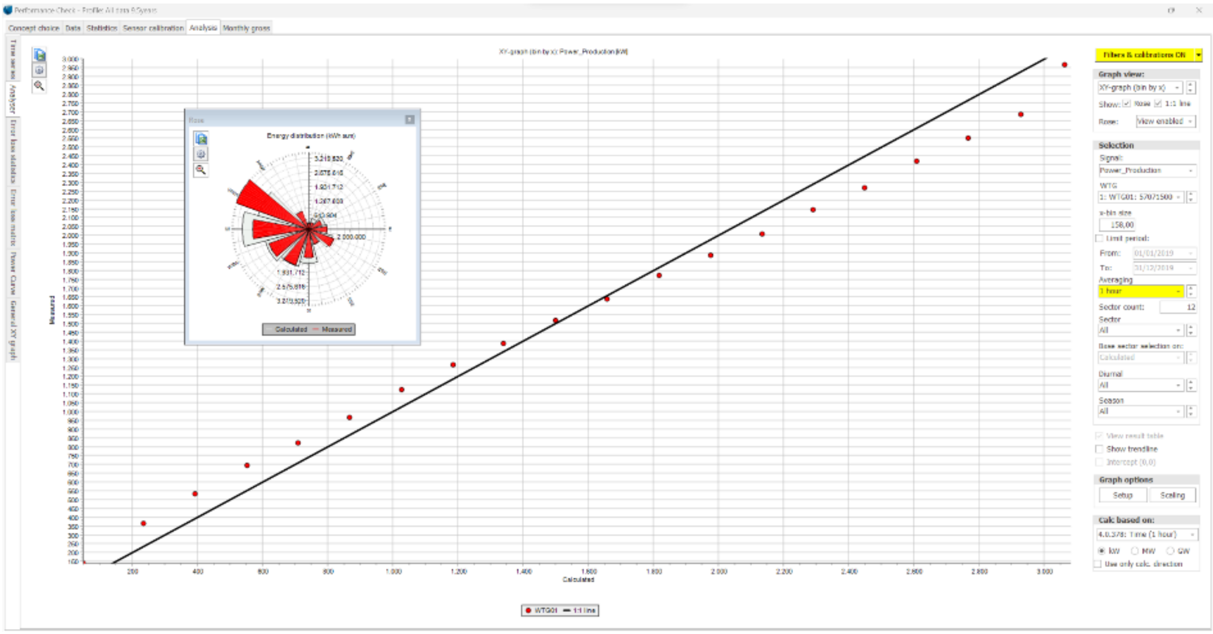


Figure 90 Binned calculated power vs measured for model validation.

XY Graph (binned by x) Figure 90**.** The binned version of the measured vs. calculated show good correlation. When using mesoscale model data, this is often not the case. It will typically be seen that at lower production, the calculation underestimates and at higher production it overestimates. This typically will require an offset at the wind speed post-calibration level to solve the issue.

We also see the wind rose here, showing a good match between measured and calculated by direction.

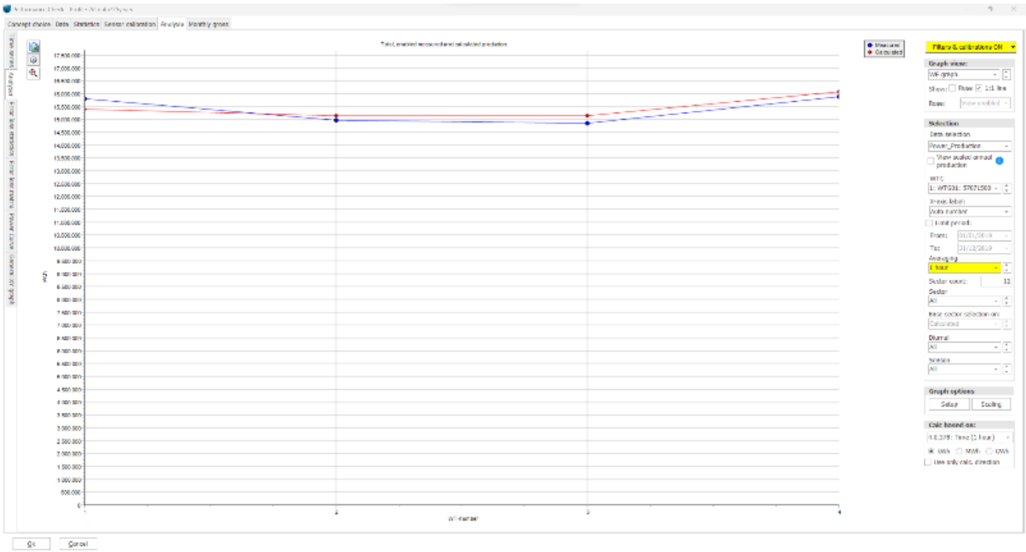


Figure 91 WF graph view.

The WF graph (Wind Farm graph) shows results for all turbines in the same graph. This is where it can be observed if some turbines are over- or under-predicted. If so, the hunt for identifying model problems starts. There are many possible issues to consider, like wake model parameters, terrain, etc.

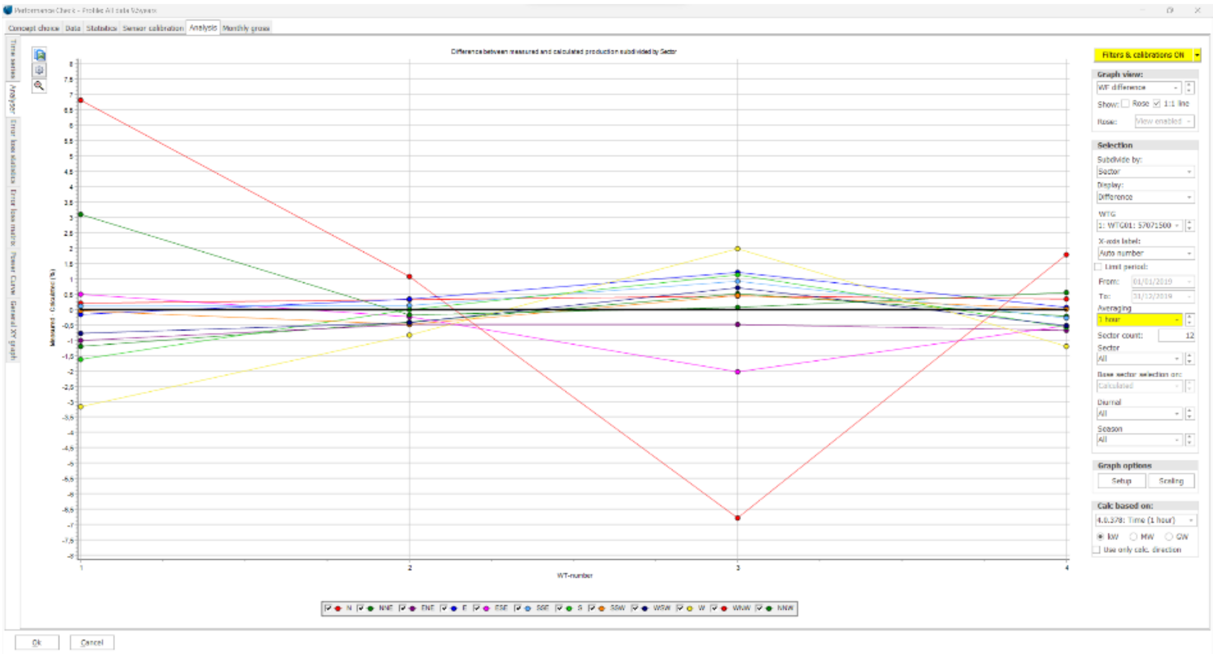


Figure 92 Difference between measured and calculated, by sector using calculated windspeed.

The WF difference graph showing the difference OR ratios between measured and calculated for all individual turbines aggregated by sector, season etc. is a very strong tool for evaluation of model problems. If all turbines perform poor from one direction sector, the problem is how the model handles this direction sector. It could be a bias in mesoscale wind, or a mast speed up (due to sensor mounting details), a roughness issue, forest issue, or hill speedup problem. Below are a few explanations:

Showing the **difference**, the over- or under-performance in total are shown. The deviation in one sector is divided with the total calculated production.

Showing the **ratios**, each e.g. direction sector is evaluated not depending on how large part of the production that comes from this sector.

It is thereby possible with the use of the difference graph to focus on what really matters, while the ratio graph makes an equal evaluation of each sector, season, etc.

The WF difference graph allows to evaluate by sector, by season, diurnal and by wind speed interval.

The next **WF loss** can be seen as a "historical" feature, while in the versions of windPRO (from 3.2 onwards) there are more comprehensive tools for loss evaluation, see the following paragraph.

The WF loss graph show the calculated "loss" by turbine. With loss what is meant is calculated – measured for a specific selection of the data. The "loss" calculation selection can be based on:

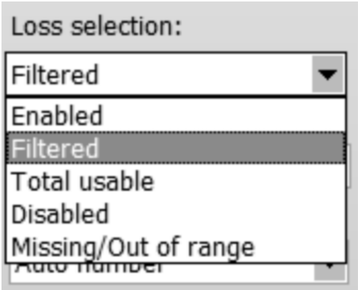


Figure 93 Filter settings for loss selection.

The filtered will typically represent the values where turbines have been out of operation and thereby account for the availability loss. But also, poor performance data can be included. It is the filter settings that decide what is included, and it shall also be mentioned (again) that the concept is: Calibrate model to reproduce "normal operation" as best as possible. It is a reasonable assumption that the difference calculated – measured for the "non-normal" operation will reflect losses, i.e. potential production, that has not been captured.

Figure 94 WF Geo view.

WF geo gives the result geographically. The NE turbine is calculated to perform 4% better than the two other relativ.

NB its an enginnering analysis to investigate the directional and wake models output VS the actual performance of individual turbines in a park, and evaluate if the wake model needs adjustment, or its possibly related to forrest model, or a seasonal bias in the wind data and re-adjust the Park calculatoin and re-validate the model output vs the real yield of the existing turbines.

With iterations it possible to calibrate the windmodel to quite accurately be able to predict the real yield of existing wind turbines, thereby have confidence that the moddel can be used to predict expansion, or nearby new project or repowering of the existing site with low uncertainty.