Quantifying Change in Power Performance using SCADA Data

Methods of measuring power performance and a case study to apply side-by-side testing.

Part 3 of 3: How to quantify change in power performance.

Summary

The following document is a summary of the third deliverable in a project to evaluate quantitative methods to measure effects of power performance upgrades to wind turbines. The project is a Master Thesis in collaboration between the Royal Institute of Technology in Stockholm and Breeze.

The project consists of three deliverables.

1. Map upgrades for increased power performance from wind turbines
2. Describe the dynamics between manufactures and owners of wind turbines
3. Evaluate methods for measuring power performance upgrading

The purpose of this work is to incorporate methods of evaluating power performance upgrades into the Breeze Production wind farm management system.

Focus

This final e-book of the 3-part series focuses on measuring change in power performance.

There is a brief review of the Power Curve, Annual Energy Production and common methods of measuring the absolute level of power performance. The alternatives for measuring change in power performance for a specific site are narrowed down.

An in-depth case study is performed, presenting the methodology and results of the Side-by-Side Testing method. Using only SCADA data for the analysis, the effects of a blade add-on upgrade are evaluated. The analysis is based on a relative power relation between a test and reference wind turbine.

The effect of the upgrade is evaluated with uncertainty analysis based on:

- Power Curve change, in the partial power range
- Annual Energy Production change

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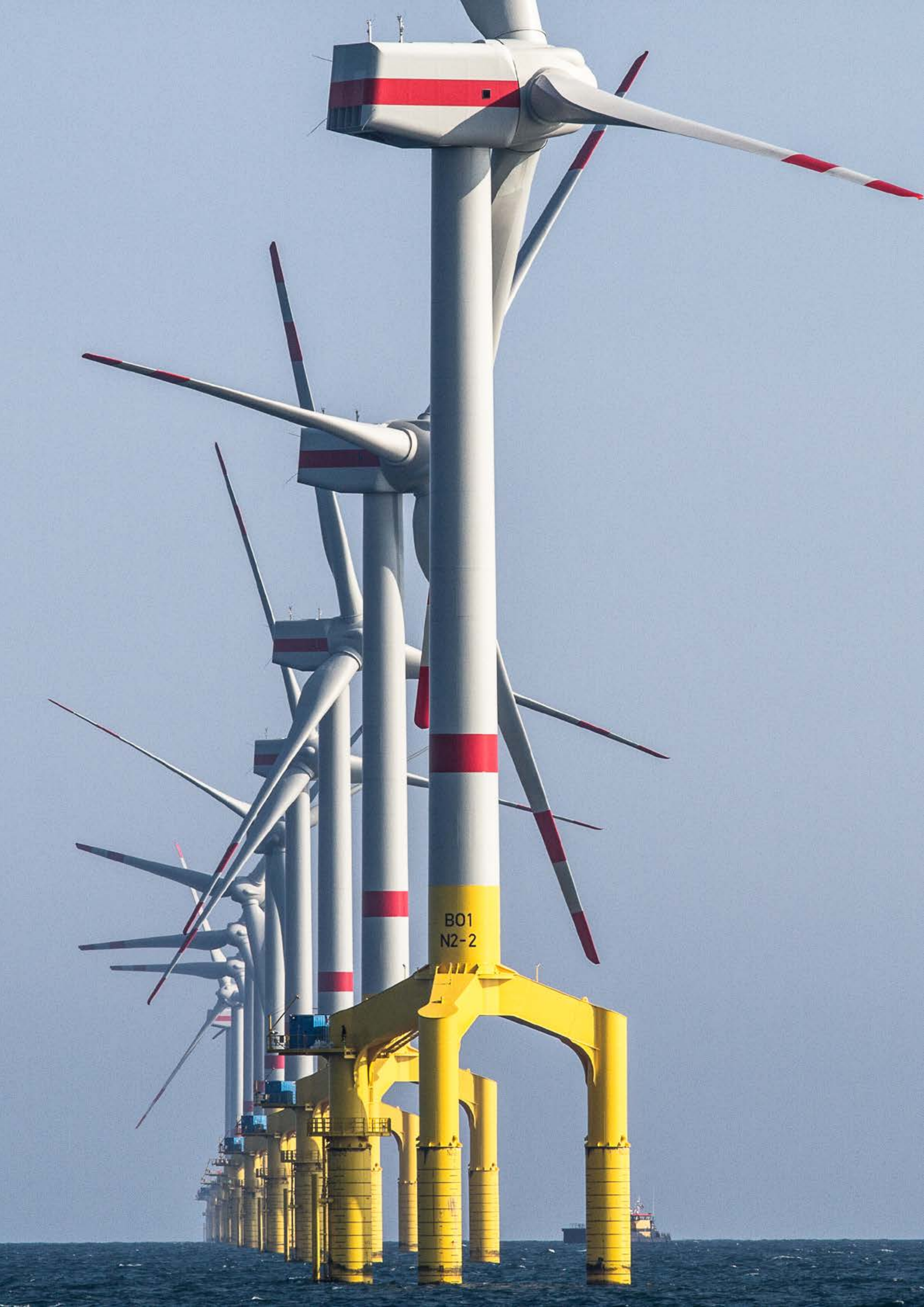
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Nomenclature

PC	Power Curve
AEP	Annual Energy Production
Met Mast	Meteorological Mast / Tower – often equipped for measuring a series of atmospheric properties and weather conditions: wind speed, wind direction, temperature, pressure, rain.
IEC 61400-12-1 (2005)	International standard for measuring power performance of wind turbines, by the International Electrotechnical Commission. This standard is widely used by the industry in power performance assessments and as reference in warranty contracts.
IEC 61400-12-1 (new draft)	The upcoming revision of 61400-12-1 builds upon the previous version. It will introduce the new rotor equivalent wind speed concept and ground-based remote sensing will be accepted for measuring wind.
Remote sensing techniques	LiDAR, SoDAR, RASS (Radar, passive radiowave/microwave)
LiDAR	Light Detection And Ranging. LiDARs send and receive laser light for detecting air flow, capable of wind profiling. These are can be both ground-based or wind turbine nacelle-based. There are two main categories of LiDAR: pulsing and continuous wave.
SoDAR	Sonic Detection And Ranging. SoDARs send sonic waves for measuring air flow, capable of wind profiling. SoDARs vary in size, but are commonly ground-bound by their size. They are often seen with auxiliary RASS systems.
RASS	Radio Acoustic Sounding System, often used as auxiliary system to SoDAR.

Absolute Level of Power Performance

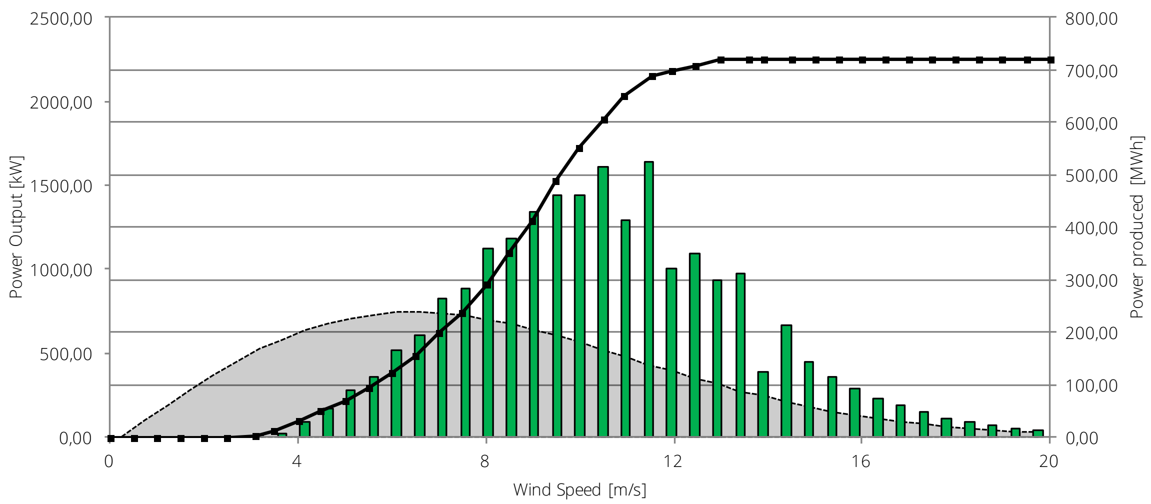
To evaluate the power performance of a wind turbine primarily two attributes are assessed: the power curve and several estimates of the annual energy production at different wind conditions, assuming 100% availability.

The Power Curve (PC) is describing the wind turbine net active electric power as a function of wind speed. Power curves are normalized to a certain air density, and can only be expected to be accurate within its given reference conditions (turbulence levels etc.). Site conditions such as wind characteristics, terrain impact on the wind flow, and wake interaction significantly affect the performance. Determining the power curve accurately without bias from site-specific conditions is therefore complex.

The estimated Annual Energy Production (AEP) is calculated from the power curve, by applying a series of different wind distributions. In the IEC standards, AEP is calculated for 4, 5, 6, ..., 11 m/s average wind speeds using Rayleigh distributions. The resulting estimate of AEP does not reflect the actual expected production, but is used as a frame of reference.

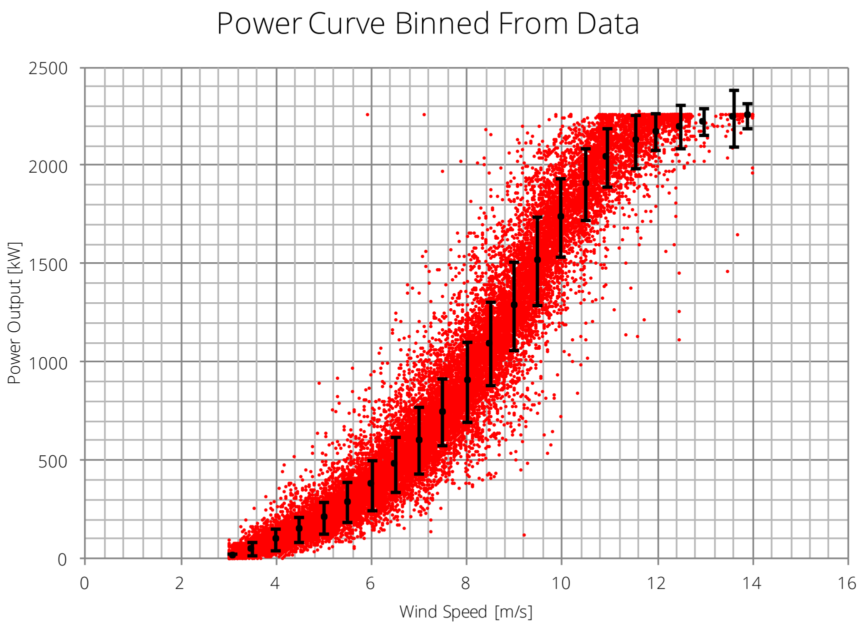
When comparing PCs and estimated AEPs, it is important to keep in mind how the analysed data is filtered, there are often considerable hysteresis effects at cut-in and cut-out which may or may not be included.

Extrapolated Power Curve and resulting AEP



To Determine the Power Curve

The current standard for measuring power performance of wind turbines is 61400-12-1. Here, the power curve consists of primarily two input variables: wind speed and power output. The Method of Bins is used to average the power output in 0.5 m/s wind speed bins. Measuring the electric power is no challenge; however determining the free-stream wind speed is a bit more complex. The uncertainty often lies around 5 %, whereas the wind speed constitutes the largest part by far.



The net active electric power output is measured between the wind turbine and the electrical connection excluding any self-consumption. In power performance assessments it must be specified whether it is measured before or after the transformer. Measuring the power output of a wind turbine is no concern, as even the standard power transducers of wind turbines often offer high accuracy sufficient for most purposes.

The wind speed of the power curve is the undisturbed free-stream wind speed at hub height, normalized for a certain air density. This is the most common definition, and the one used in the current IEC 61400-12-1 standard (2005).

The wind speed is by far the largest source of uncertainty in power performance assessments. Strictly speaking, there is no free-stream wind to measure at the wind turbine position after the wind turbine is erected. The wind flow is distorted by presence of the wind turbine, that decelerates the flow considerably when operational. This has given rise to several different approaches to measuring the wind speed.

The most common methods of measuring the wind speed for power performance assessments are:

- Meteorological Mast (IEC 61400-12-1 (2005))
- Ground-based LiDAR / SoDAR (IEC 61400-12-1 (new draft))
- Nacelle-mounted LiDAR
- Nacelle-mounted anemometry (EC 61400-12-2 (2013))
- Existing nacelle-mounted anemometry (SCADA)

Added complexity with the new IEC standard

The upcoming revision of the IEC 61400-12-1 standard will add complexity to the calculation of the power curve. In addition to air density normalization, wind shear, veer, and inclination angle will be covered by the rotor equivalent wind speed concept and the resulting power curve will be valid only within a certain turbulence range. This means the power performance according to the new definition is adjusted for the actual wind energy available perpendicular to the rotor swept area. In practice, this introduces a need to measure the full wind profile across the rotor.

Identify Change in Power Performance

To identify a change in power performance of a wind turbine a baseline and a post-upgrade power curve must be determined. The primary attributes evaluated are:

- Change of power curve at each different wind speed bins
- Change of AEP, given the power curve and a specific wind characteristic

In addition to this, the change might be of interest to evaluate in different operating conditions, such as turbulence levels or wind directions.

Testing Uncertainty

Wind turbine performance can degenerate over time and different test procedures will introduce different errors to the testing. Consequently the baseline characteristic should be evaluated with the same testing procedure as the post-upgrade testing, in a rather short time span. Using the same procedure and set-up allows for considerably more accurate testing of the relative change in power performance. If the bias errors affect the two tests the same way, much of it can be cancelled out when comparing the relative change. In contrast to determining the absolute level of power performance, relative testing of the change in power performance can be done quite accurately – with uncertainty levels down at 0.5 %.

Power Performance Assessment

Performing a full power performance test with meteorological mast or remote sensing technologies is expensive. Two full testing periods must be completed to cover the baseline performance, and post-upgrade performance. A meteorological mast or ground based remote sensor usually cover 1-2 wind turbines, but these cover a small valid wind sector generally leading to a 1-3 month testing period test. Nacelle LiDAR might need a shorter testing period, but only cover one wind turbine per installation. Nacelle-mounted anemometers can also be used for testing, but these need basically the same installation effort as nacelle LiDAR and have certain drawbacks compared to measuring the actual free-stream wind.

In essence these on-site testing dedicated installations are needed for validating and establishing a baseline of the true absolute level of power performance of new wind farms. I may also be appropriate to prove the effectiveness of a upgrade. However, looking at the effects of a specific wind farm two full dedicated tests is unreasonable.

Using Existing Nacelle Anemometry

Another approach to determining the relative change in power performance is using the existing nacelle anemometry of the wind turbine. This approach is used by GE in their AEP Validation Methodology used to quantify the site-specific improvements of the PowerUp upgrade platform. The approach allows for testing of each individual wind turbine in a wind farm. Statistical strength can be build by testing many wind turbines in a cheap way. However, there are some inherent flaws using the nacelle anemometer.

Drawbacks of Nacelle-Mounted Anemometry

Nacelle-mounted anemometers are subject to flow distortion by the wind turbine wake and nacelle geometry, and therefore the wind speed measurements needs to be adjusted to reflect the free- stream wind speed. This correlation is in the IEC 61400-12-2 standard called the Nacelle Transfer Function (NTF) and is only valid within rather strict criteria. The NTF is wind turbine model-specific and only valid for a specific anemometer model, terrain type, nacelle geometry, and wind turbine blade aerodynamics for which it was determined.

In essence, this means that testing based on nacelle anemometry must be carried out with a meteorological mast for NTF calibration, unless the turbine-specific NTF is well-known and validated for the site-specific conditions. It also means that the method introduces a significant bias error if it is applied for calculating performance change of any upgrade that affect the wind flow at the nacelle. Special care must be taken to adjust the NTF or other otherwise complement the method for changes affecting the aerodynamic performance such as: vortex generators (especially at the blade root), tweaking of rotor speed, or pitch algorithm.

In other words using the existing nacelle anemometry or installing a dedicated nacelle anemometer may require the same effort as any other method. The IEC 61400-12-2 standard is often viewed as an effective way for testing many wind turbines of exactly the same type, for which the NTF is well known or many turbines can be calibrated with a single meteorological mast.

Comparing Power Output Only

An alternative to performing a full power curve test, is to directly compare the power output of wind turbines. The advantage of this is that the power output measurements are very accurate in comparison to wind speed measurements. The electric power is a directly measured at the source, whilst the wind speed is indirectly measured and adjusted to the free-stream wind at the turbine location. Looking at the power output alone is not meaningful, an some point of reference is needed to determine change. Also, the absolute level of power performance cannot be determined.

Comparing the power output is typically applied to two groups of wind turbines: The relative change is of a modified test group is compared to an unmodified reference group of wind turbines. There are several different ways these relative power comparisons can be applied by looking at the power output or the energy produced, as well as different variations of test turbines and references.

Side-by-Side Testing Method

In the following case study looks at an alternative approach of comparing the power output of two wind turbines. The method is based on establishing a power correlation of a test and reference wind turbine, dependent on wind direction. By introducing an assumed power curve characteristic, wind data is simulated and the change in power output is evaluated on a power curve basis.

The Side-by-side Testing method gives a good indication on the change in power performance in the partial power range, but it cannot determine the absolute level of power performance.

Case Study: Side-by-Side Testing using SCADA Data

Abstract

The side-by-side testing method as explained by Axel Albers was applied to calculate the change in power performance from an upgrade.

The test method incorporates no measured wind data, but simulates wind speed from the reference turbine. This allows power output changes to be tracked in the power curve, relying only on the power measurements. Using only historical SCADA data, the analysis was executed completely off- site.

Two neighbouring identical 2.3 MW wind turbines in were considered. In May 2013, the test turbine installed blade add-ons featuring serrated trailing edges to the blades. The test results indicate an improvement in power performance, in the range of 0.5 % increase in AEP. The analysis needs validation, as the power curve shows signs of artefacts.

Methodology

The method applied here is based upon "Side-by-side Testing to Verify Improvements of Power Curves" presented by Axel Albers at Deutsche Windguard during the Nordic Wind Conference.

The author wishes to express his gratitude to Axel Albers, whose support was essential for carrying out the analysis.

Following the steps of the presentation as close as possible, this analysis aims to test the method and apply it on a specific case. There was no reference for validation, therefore the accuracy of the results is uncertain.

There Were Concerns Using Existing Nacelle Anemometry

In this case study the blade add-on installation was evaluated in hindsight, practically limiting the analysis to using historical SCADA data. There were several concerns using the existing nacelle anemometer wind speed data:

- Upgrade type: Blade add-ons might influence the wind flow at the nacelle.
- Limited knowledge of turbine nacelle anemometer: Positioning, calibration and accuracy. Potential error/bias and change over time.
- Unknown NTF and processing of wind speed: It is unknown how the wind data have been processed before being logged in the SCADA system, and the Nacelle Transfer Function is unknown (correlation between nacelle- measured wind and free-stream wind). As the most significant uncertainty factor, the wind speed and all details of measurement must be known in detail for a proper analysis.
- SCADA data for air density normalization of power curve was incomplete: Additional measurement data of air properties would be needed for complementing the incomplete SCADA data of temperature and pressure.

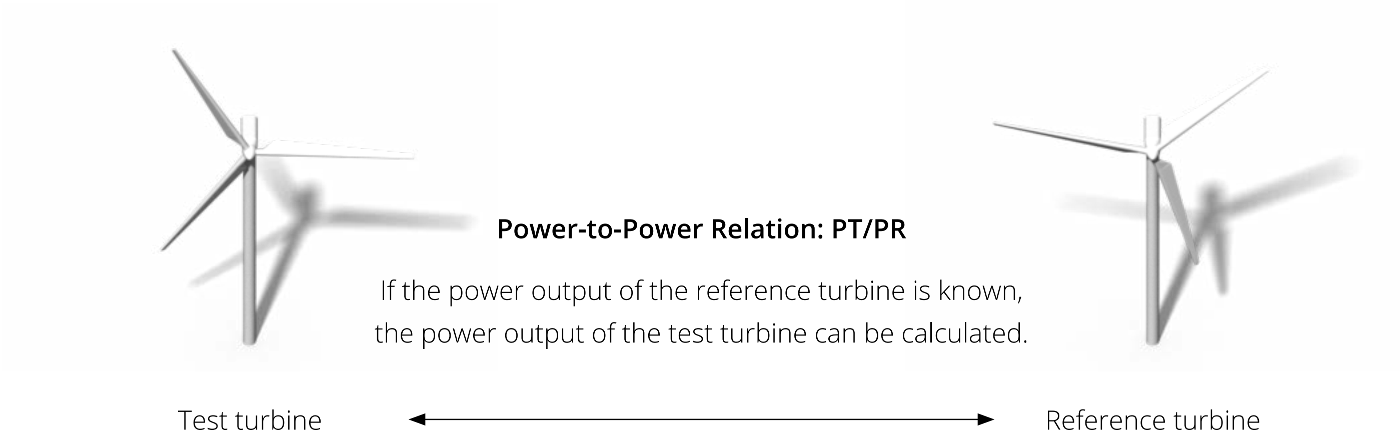
These issues were non-existent using the side-by-side testing method. The analysis was performed independent from wind measurement data, and the method is designed such that an air density normalization is neither needed, nor applicable. For these reasons the side-by-side testing method showed more promise than an analysis based on the existing wind turbine nacelle anemometry.

Side-by-Side Testing in Short

The Side-by-Side Testing method builds upon the idea of measuring relative change in power output of a test and reference wind turbine. By learning a power relation between the two wind turbines, the relative change of the test turbine can be tracked.

This method adds a step to this: in addition to using the power relation to simulate the power output, a power curve is assumed to simulate the wind speed at the test turbine. Thus, the measured turbine power output of the test turbine can be directly binned versus the simulated wind to construct a power curve.

The absolute level of power performance can thus not be detected as it builds upon an assumption; however the relative change can be tracked on basis of the assumed power curve.

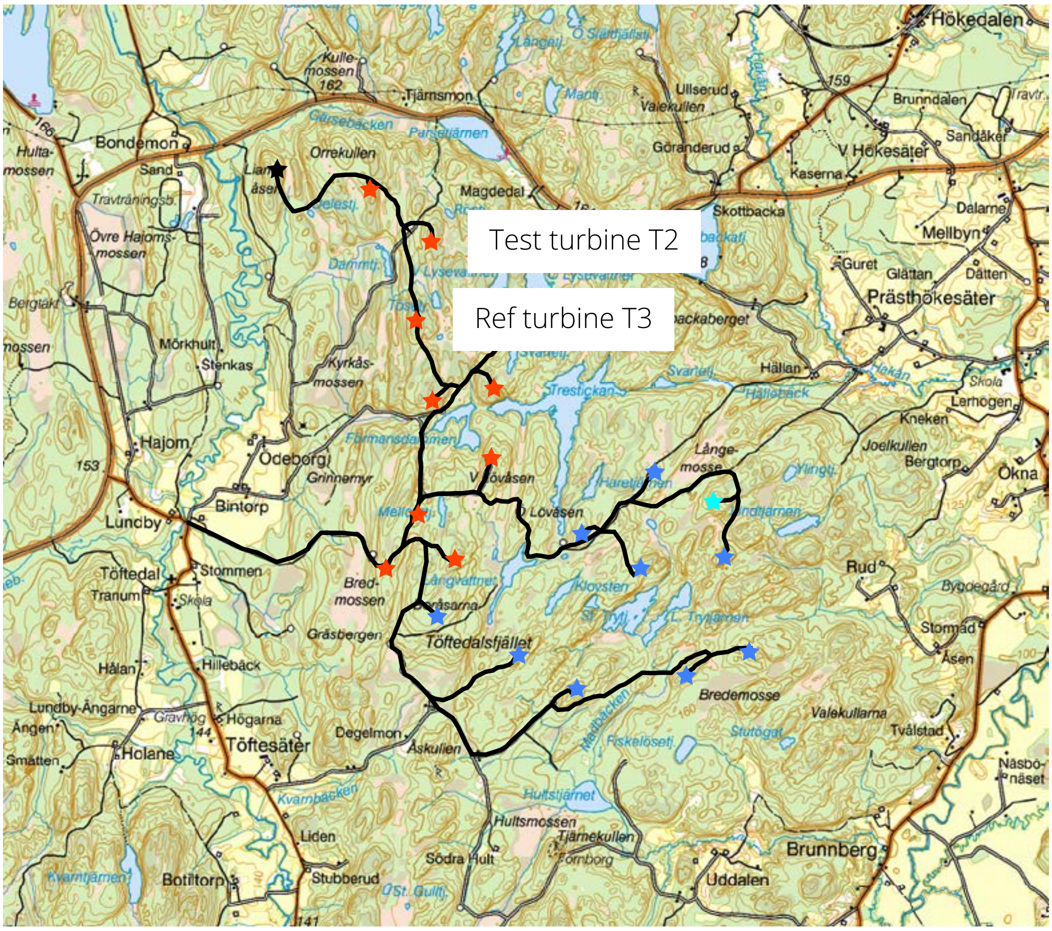


The main line-out of the test method:

- Filter data sets: training period before upgrade, testing period after upgrade
- Establish a power-to-power relation between the turbines in training period
- Simulate test turbine power output and wind speeds in the testing period
- Bin power curve from simulated wind speed and actual power measurement
- Evaluate change in PC and AEP

Tested Wind Turbines

Two identical wind turbines were analysed, sited approximately 500 meter apart in an array-like formation. The wind farm features several 2.3 MW wind turbines with 103m wing span, and have previously installed vortex generators on the mid-sections of the blades. In 2013 four of the wind turbines were additionally upgraded with blade add-ons introducing serrated trialing edges to the blades.



The primary purpose of the serrated trailing edge is to reduce the trailing edge noise, this case study aims to measure its impact on the power performance. The analysed test and reference wind turbine were chosen based on the following criteria:

- Close positioning of test and reference turbine
- Same rated power (both curtailed at 2250 kW)
- Prevailing wind directions: wake free

Input Data

10 minute average SCADA data sets were exported from Breeze Production. Each wind turbine is represented by two primary data sets: A “training period” prior the upgrade, and a “testing period” after the upgrade.

Test turbine Reference turbine	2012-12-19	→	2013-05-10
Blade add-ons installed on test turbine			
Test turbine Reference turbine	2013-05-19	→	2013-12-31

A longer training period would probably benefit the accuracy of the learned power relation, but it

was not be further extended back in time due to different curtailment of the wind turbine. The following data was used in the analysis:

- Net Electric Power Output
- Nacelle Direction
- Rotational speed, generator and rotor
- Blade pitch angle
- Turbine status logs

Correcting Nacelle Direction

The nacelle direction may need adjustment prior to filtering the data, due to drifting. In case of the signal have drifted considerably, the true north should be identified and adjusted for both wind turbines.

In this case the drifting was considered minor, and the nacelle direction of the test turbine was simply off-set by 3.4 degrees to match the reference wind turbine.

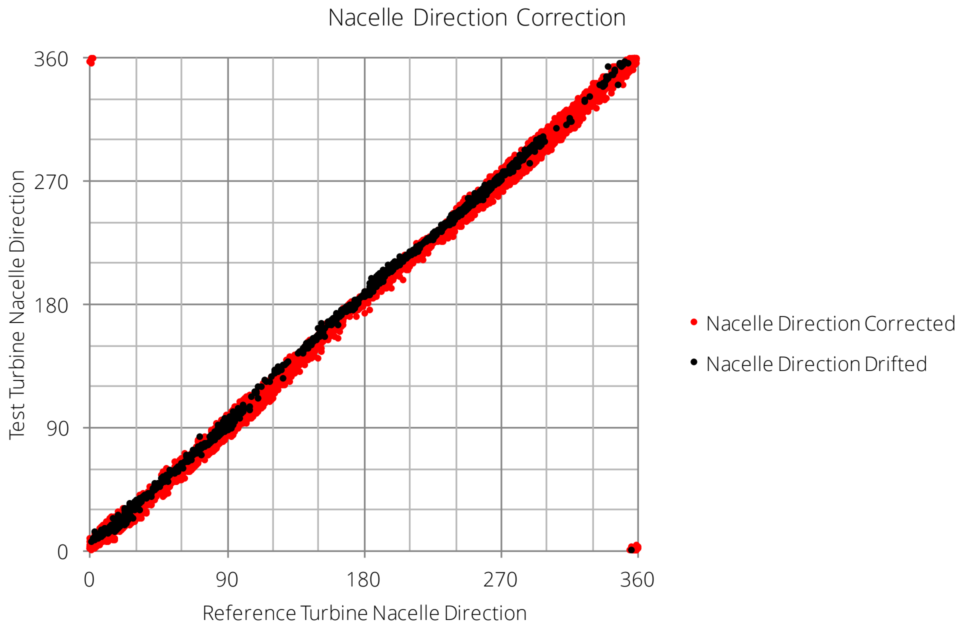


Figure 1. Plot of nacelle direction, visualizing how the two wind turbines agree on yawing. The test turbine data was offset by 3.4 degrees to match the ref. turbine.

Data Filtering

The input data was filtered to include only data in which both wind turbines were online and operating at full performance at the same time. It is important that the data of the two turbines are correlated with identical time stamps; if one wind turbine underperforms the data of both turbines must be rejected.

Filtering used:

- Wind turbine operational (filtered on both rotor and generator, due to incomplete data)
  - Rotational speed of rotor > 6 RPM
  - Rotational speed of generator > 600 RPM
- Nacelle alignment
  - Max 10 degree difference between test and reference nacelle direction
- Wind turbine status logs
  - Minor curtailment period removed from data
  - No events indicating otherwise reduced performance

80% of the data passed filtering.

Due to partially incomplete temperature SCADA data, potential icing could not be filtered. It is assumed to have little impact on the testing, since the site climate is temperate and both the test and reference turbines are assumed to be affected similarly.

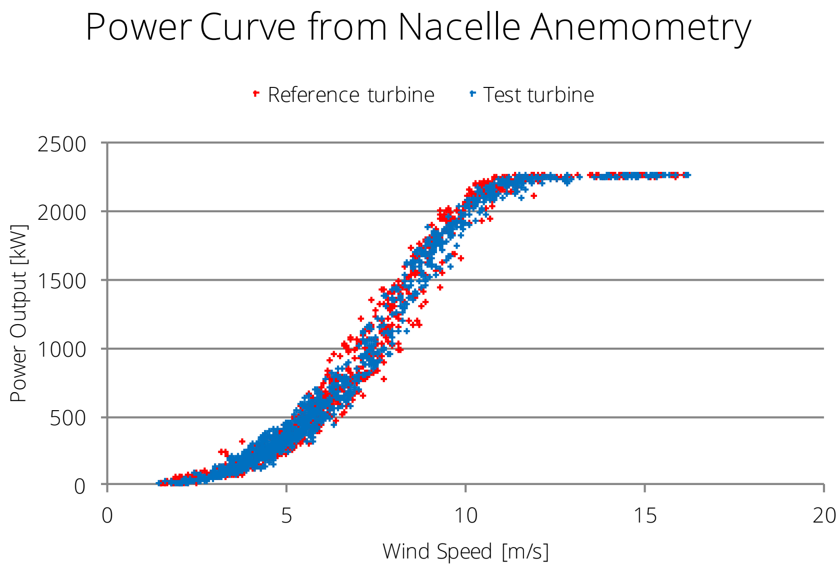
Visual Inspection of Filtered Data

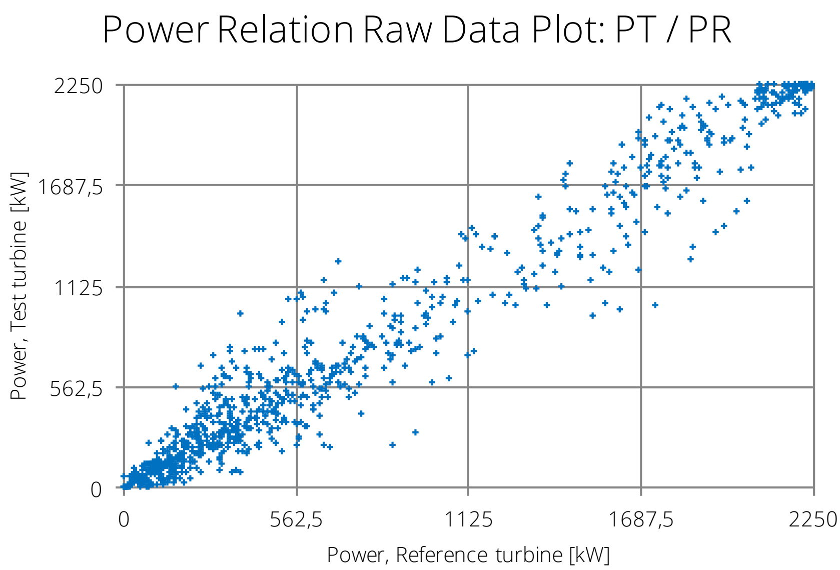
The data passing the filtering conditions was carefully reviewed. Several attributes not otherwise used for calculations were inspected to spot deviations from normal wind turbine operation.

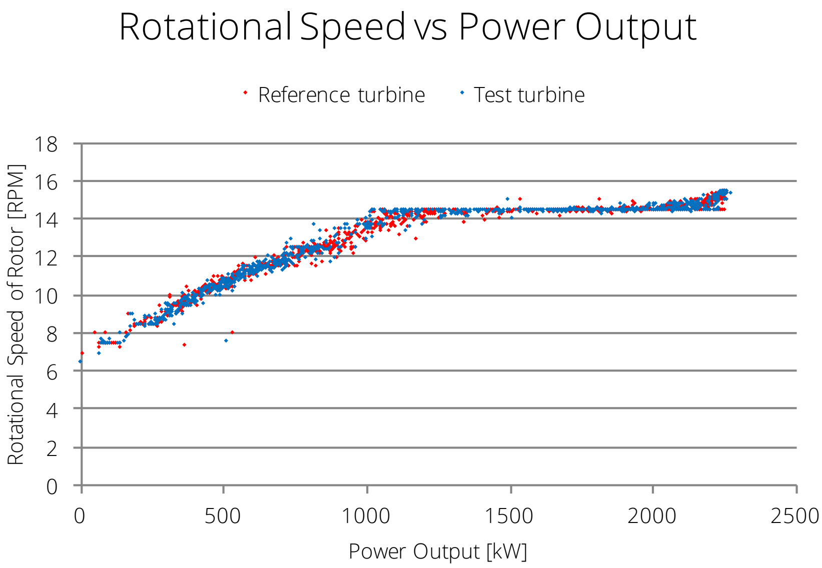
In particular, the following graphs were plotted and evaluated:

- Power Curve from nacelle anemometry: raw data, test vs reference turbine.
  - Consistent, no deviations.
  - Test and reference turbine power curve appear to match well.

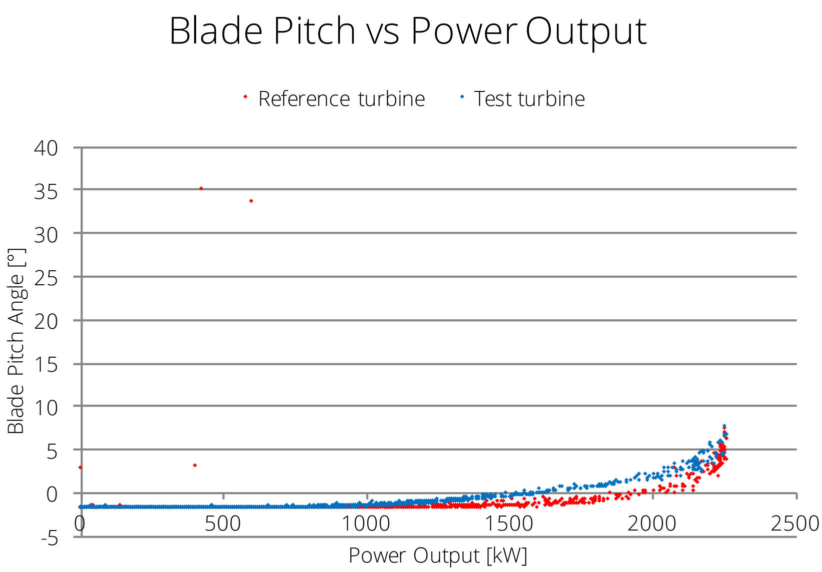
- Power output comparison, reference turbine on X-axis, test turbine no Y-axis.
    - No partial performance curtailment or other deviations visible.
    - Rather broad spectrum of power output scatter.
- Nacelle direction alignment, reference turbine on X-axis, test turbine no Y-axis.
    - Well aligned yawing in all wind directions.
    - Scattered data rejected in filtering.
- Rotational speed vs Power output, test vs reference turbine.
    - Consistent power to rotational speed relation.
    - Test and reference characteristic match well.
- Pitch angle vs Power output, test vs reference turbine.
    - Individually consistent behavior.
    - Test turbine pitching behavior differs slightly from Reference turbine.


Power Curve from Nacelle Anemometry
Reference turbine
Test turbine
2500
2000
1500
1000
500
0
Power Output [kW]
0
5
10
15
20
Wind Speed [m/s]


Power Relation Raw Data Plot: PT / PR
2250
1687,5
1125
562,5
0
Power, Test turbine [kW]
0
562,5
1125
1687,5
2250
Power, Reference turbine [kW]



Rotational Speed vs Power Output
Reference turbine
Test turbine
Rotational Speed of Rotor [RPM]
18
16
14
12
10
8
6
4
2
0
0
500
1000
1500
2000
2500
Power Output [kW]



Blade Pitch vs Power Output
Reference turbine
Test turbine
Blade Pitch Angle [°]
40
35
30
25
20
15
10
5
0
-5
0
500
1000
1500
2000
2500
Power Output [kW]

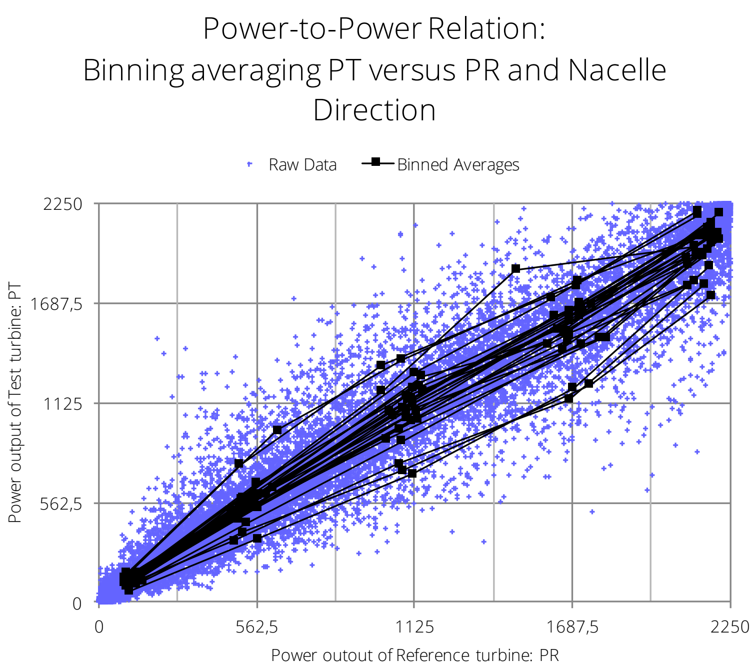
Establish Power-to-Power Relation

The primary purpose of the training period data set is to establish a relation between the test and reference wind turbine. The purpose of the power relation is to predict the power output at the test turbine from only reference turbine data.

In complex terrain, the power relation is wind direction dependent. The power output of the test turbine is thus a function of both power output and nacelle direction of the reference turbine. 5 ranges of power output and 10 degree wide nacelle direction bins were used, as in Axel Albers' presentation:

- 0, 25, 50, 75, and 100% of rated power
- 0, 10, 20, 30, ..., 350 degrees nacelle direction

The filtered data of the training period was bin averaged accordingly. The resulting Power-to-Power Relation is seen in the figures below.



Dir. ± 5 [˚]	Power bin ± 281 [kW]	PT, average [kW]	PR, average [kW]	Samples
40	0	103	96	149
	563	612	595	229
	1125	1134	1118	148
	1688	1612	1624	110
	2250	1964	2128	29
50	0	109	103	232
	563	548	569	398
	1125	979	1070	235
	1688	1531	1667	75
	2250	1941	2093	23
60	0	145	142	309
	563	533	535	434
	1125	1071	1094	233
	1688	1583	1676	104
	2250	1904	2101	36
70	0	128	123	305
	563	537	542	455
	1125	1025	1114	308
	1688	1511	1676	224
	2250	1809	2123	89
80	0	105	108	242
	563	472	493	254
	1125	1045	1096	171
	1688	1475	1674	127
	2250	1783	2102	74

Improvement of Power Curve

All calculation steps for establishing a Measured Power Curve were done independently for both the training and testing period data sets. The procedure is the same for both data sets, as explained below.

The testing period data set is is used to determine the improvement of the power curve.

The training period data set are essentially "dummy calculations", used for the uncertainty analysis. These should result in zero change of the power curve.

Procedure Overview

The established power-to-power relation is used to simulate the power output of the test turbine (Step 1). In turn, this simulated power output is used to simulate the wind speeds at the test turbine by assuming a power curve (Step 2). Lastly, the power curve of the test turbine can be binned from the actual measured power output and the simulated wind speeds (Step 3). The improvement of the power curve is then calculated as the change from the assumed power curve and the Measured Power Curve (Step 4).

The methodology and associated abbreviations are visualized in the following figure:

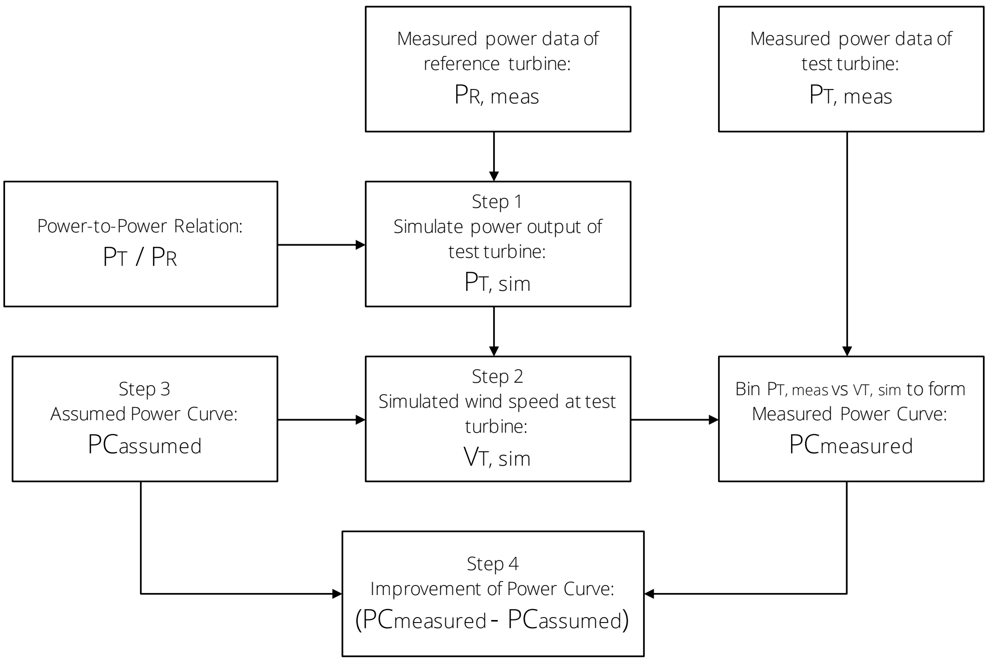


Figure 2. The calculation procedure for determining the change in power curve of the test turbine.

Step 1: Simulate the Power Output of the Test Turbine: $P_{T,\,sim}$

Knowing the power output of the reference turbine and the power-to-power relation, the power output of the test turbine can be predicted. For each measured power output of the reference turbine $P_{R,\,meas}$ the power output at the test turbine is simulated: $P_{T,\,sim}$.

Linear interpolation was used between the two closest power relation power bins, in the appropriate wind direction bin. For values outside the binned range, $P_{T,\,sim}$ was instead linearly extrapolated from the two closest bins.

$$P_{T,sim} = \frac{P_{T,j,i} - P_{T,j,i-1}}{P_{R,j,i} - P_{R,j,i-1}}\left(P_{R,meas} - P_{R,j,i-1}\right) + P_{T,j,i-1}$$

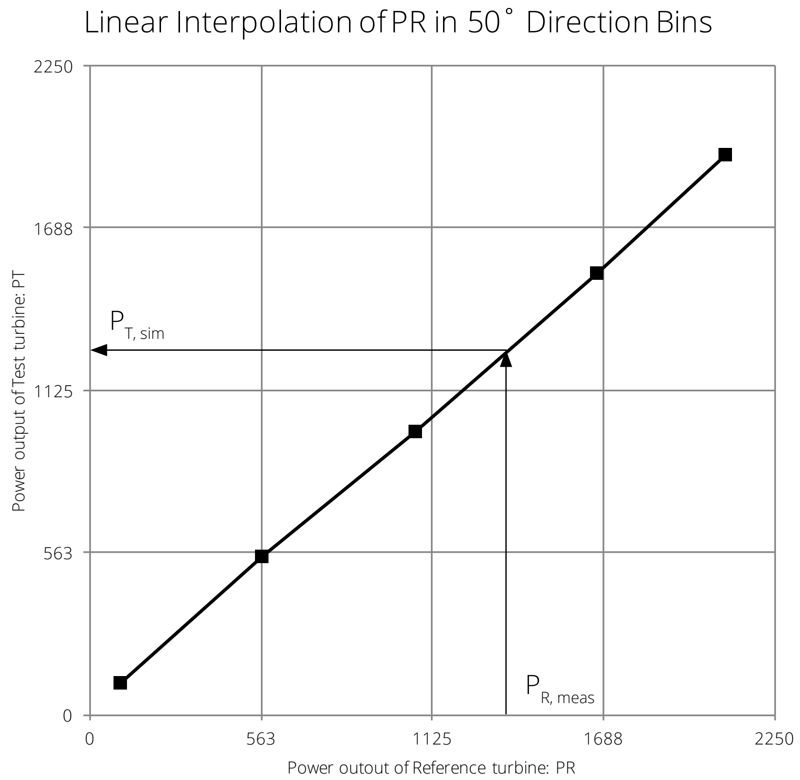


Figure 3. The bin-wise linear PT / PR relation is used to simulate the test turbine power output, from the measured data of the reference.

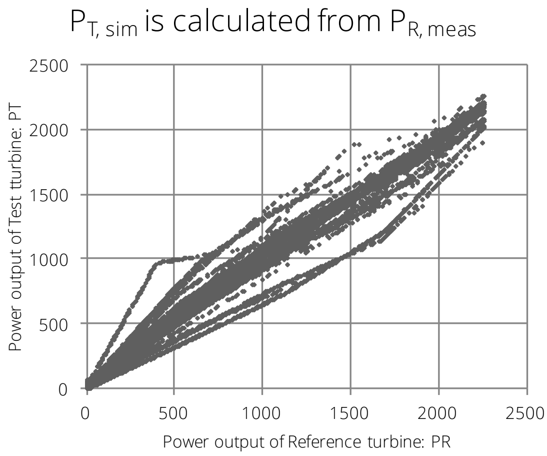


Figure 4. The resulting data set of power output of at the test turbine is simulated from the reference turbine power output. The linear PT / PR relation of each wind direction can be distinguished.

Step 2: Simulate the Wind Speed at the Test Turbine: $V_{T, sim}$

The power output that is simulated for the test turbine is in turn used to simulate the wind speed at the same. This is done by assuming a power-to-wind relation, in other words a power curve is used in reverse.

$V_{T, sim}$ is calculated by a power-to-wind relation according to an Assumed Power Curve (manufacturer- stated, or other). In this case both the test and reference wind turbines were curtailed at 2250 kW instead of stock 2300 kW rated power, therefore the Assumed Power Curve was derated accordingly. It is on the basis of the Assumed Power Curve the results are evaluated, and the changes in power output are seen.

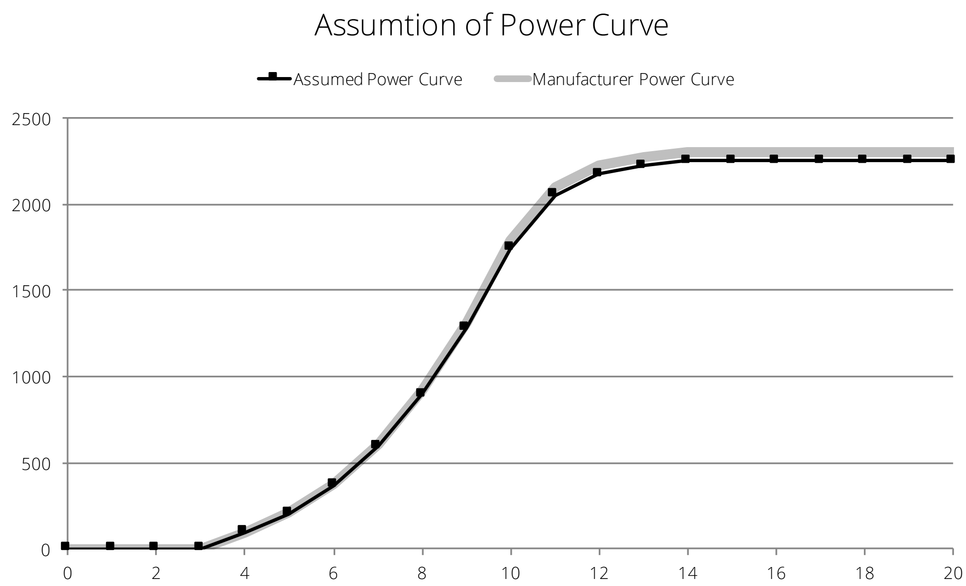


Figure 5. The manufacturer-supplied power curve was adjusted from 2300 kW to 2250 kW, by reducing the power output at each bin by a factor of 0,978.

The $V_{T,\,sim}$ is calculated from the Assumed Power Curve, by tracking each simulated power output to the correlating wind speed in the power curve. In this case, $P_{T,\,sim}$ data points below rated power were set to cut-in wind speed, and data points above rated power were set to rated wind speed.

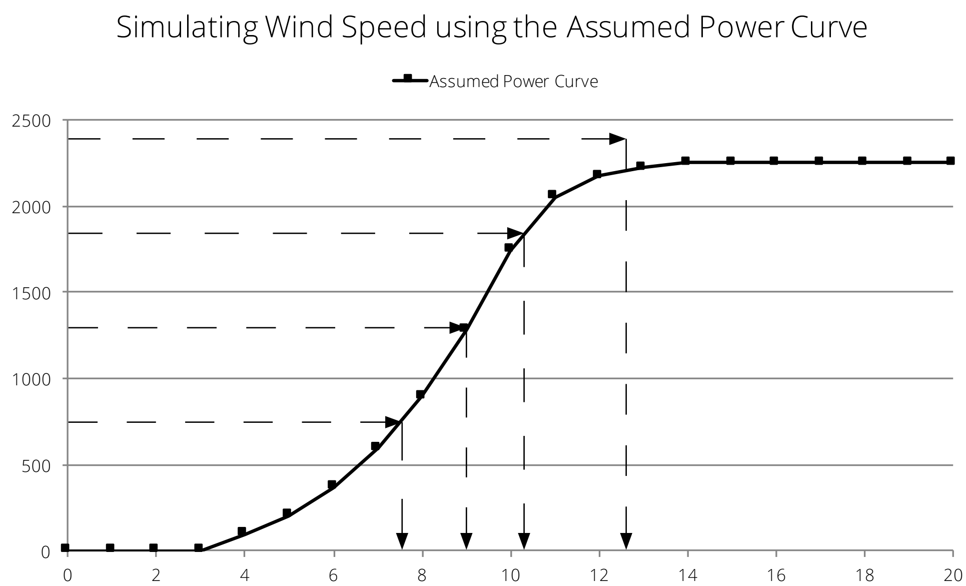


Figure 6. Each $P_{T,\,sim}$ data point is used to simulate a 10-minute average wind speed data point for the test turbine, forming the $V_{T,\,sim}$ data set.

Note: the wind speed data cannot be accurately simulated above rated power, thus limiting the evaluation of the power output to the partial-load range of the power curve.

As a result, there will also often be stacking of data points at cut-in and cut-out wind speed.

Step 3: Bin-Average Power Curve from $P_{T,\,meas}$ and $V_{T,\,sim}$

The actual power out measured by the test turbine is plotted versus the simulated wind speed, this is the date basis for the Measured Power Curve, i.e. binning the $P_{T,\,meas}$ versus the $V_{T,\,sim}$ yields the $PC_{measured}$.

The resulting power curve scatter data can be seen in the figure below.

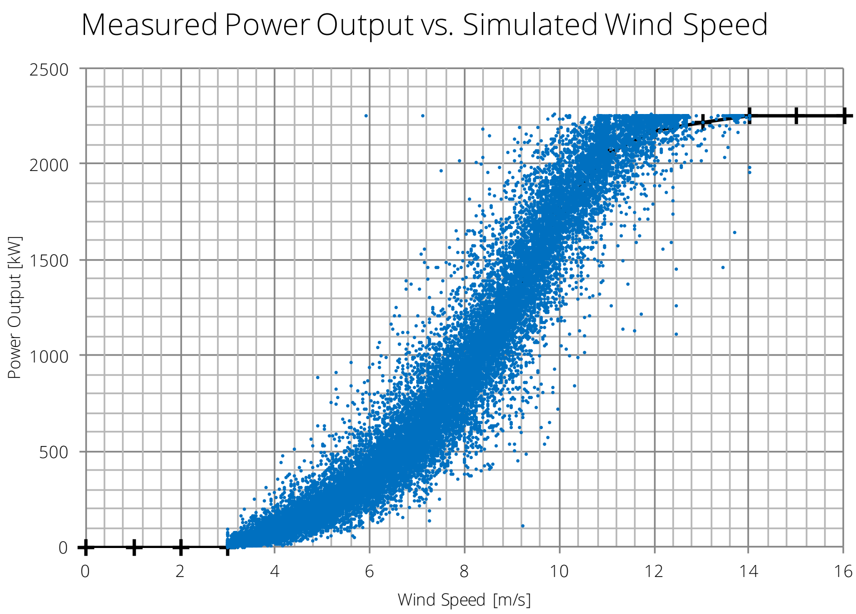


Figure 7. The measured power of the test turbine is plotted versus the simulated wind speed. At wind speeds above 12 m/s, the data is scarce. The black crosses indicate the assumed power curve.

The wind speeds are simulated through the unmodified reference wind turbine, meaning that an upgrade of the test turbine will not affect the simulated wind speeds. However, an upgrade will change the actual measured power output of the test turbine.

Both the simulated power and measured power can be plotted versus the simulated wind speed data. $P_{T,\,sim}$ lie exactly on $PC_{assumed}$, and $P_{T,\,meas}$ lie scattered in Y-axis direction.

The Y-scatter is in other words the deviation of measured versus the simulated power output. A very accurate power-to- power relation will result in low Y-axis power scatter.

The Method of Bins is applied directly to the power/wind scatter, using 0.5 m/s wide bins. No air density normalization is used, as the two turbines are assumed to experience the same air properties. Each bin of the Measured Power Curve is thus characterized by an average value, maximum value, minimum value, standard deviation, and number of samples.

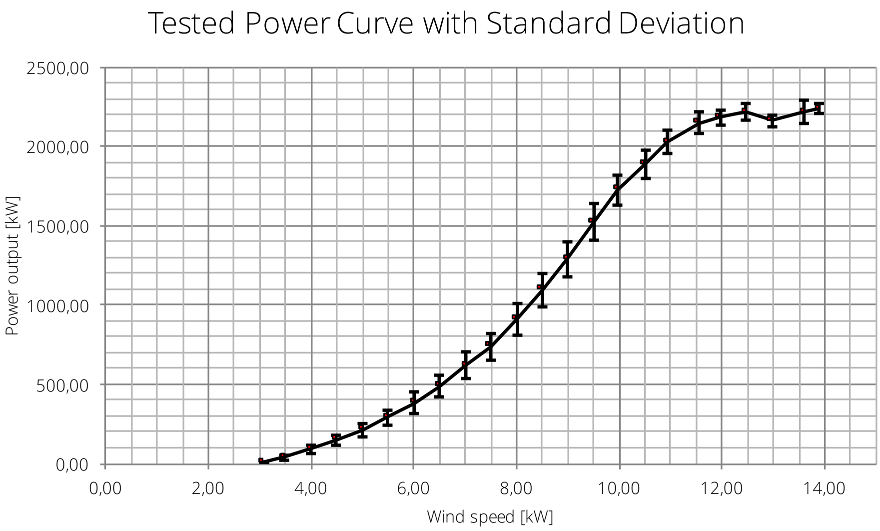


Figure 8. The bin-averaged power curve is plotted with standard deviation of the scatter. The standard deviation should in this case not be confused with the actual uncertainty of the Measured Power Curve. The lack of data at higher wind speeds appears as irregularities at 12-14 m/s.

Step 4: Improvement of Power Curve: $PC_{measured} - PC_{assumed}$

The change in the power curve from upgrading the test turbine can be read as the deviation of the Measured Power Curve from the Assumed Power Curve. Before calculating the deviation, the Assumed Power Curve is adjusted to have the same bin centers as the Measured Power Curve.

The relative difference is calculated by deviding the absolute difference by the Assumed Power Curve current bin power output. Therefore, the deviations at the initial wind speeds might appear to be deviating more.

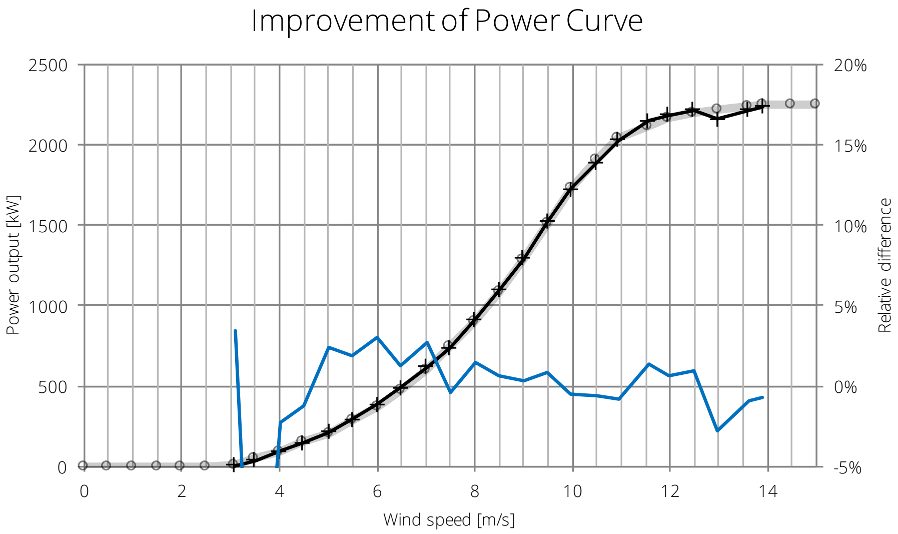


Figure 9. The Measured Power Curve was compared to the assumed power curve. The improvement of the power curve is the relative difference between the two, plotted as a blue line.

Improvement of Annual Energy Production

It's important to note that the Measured Power Curve calculated here is not the same as in the IEC standards. It only covers the partial power range. Therefore it cannot be checked versus the Extrapolated Power Curve whether it is complete. Instead, the power curve is checked for artifacts and number of samples, to find invalid bins that may render the results erroneous.

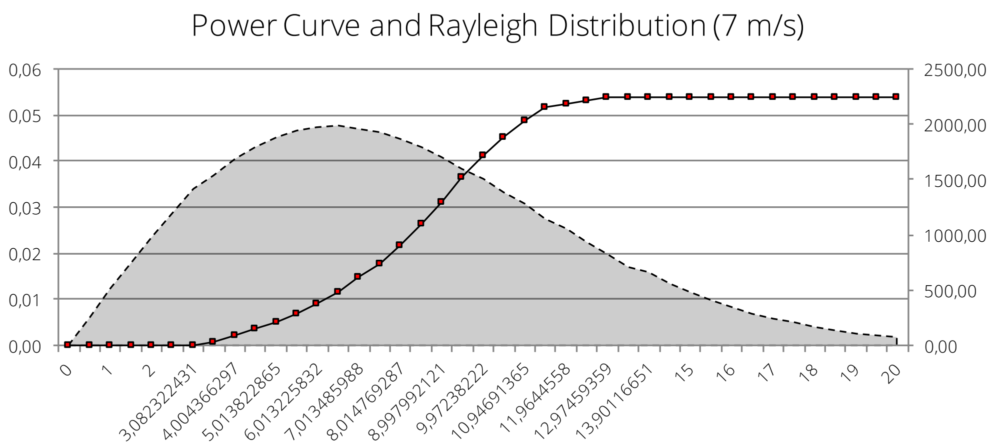
This calculation aims to indicate the change in AEP rather than an estimate level of AEP. Furthermore, the method only applies for change in the partial power range. Therefore, the Extrapolated Power Curve was defined slightly different than in IEC 61400-12-1 to exclude impact from outside the applicable testing range: invalid bins and bins outside partial power range was set identical to those of the assumed power curve.

- Measured Power Curve – the valid bins from testing only
- Extrapolated Power Curve – the valid bins from testing plus artificial bins filling in invalids and the full power range as identical to the assumed power curve
- Assumed Power Curve – as defined for calculating the VT, sim

AEP Calculating Procedure

The AEP associated with each power curve was otherwise calculated as described in the IEC 16400- 12-1 standard. In short, the AEP is calculated by summarizing the partial AEP contribution of each power curve bin. Each bin-wise AEP can be visualized by using the current and previous bin to calculate and multiply Power, Wind speed probability, and 8760 hours. [1]

[1] In the IEC standard, the 8760 hours are multiplied to a summation of partial bin contributions instead of each individual bin, yielding the same end result.



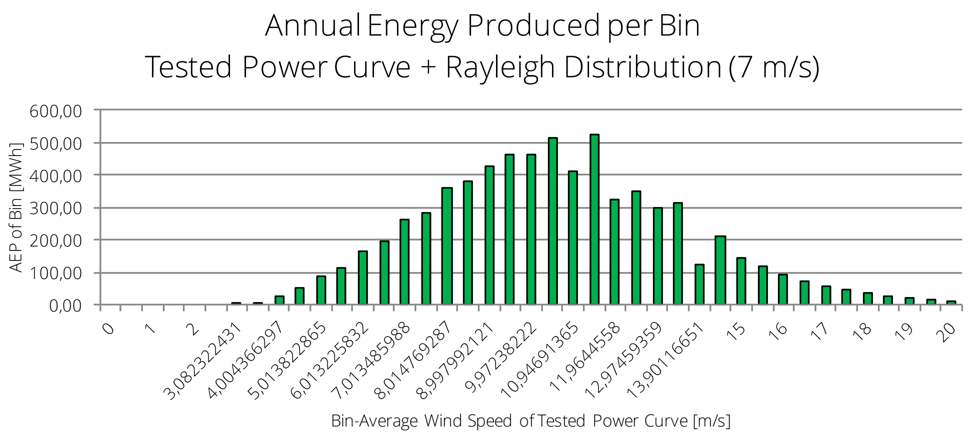


Figure 10. $AEP_{measured}$ calculated using an average wind speed of 7 m/s. The different bin widths is causing irregularities in the bin-wise AEP, which is expected.

Eight different average wind speeds were considered for each power curve: 4, 5, 6, 7, 8, 9, 10, and 11 m/s. The improvement in AEP was calculated as the difference between AEP extrapolated and assumed.

Wind dist. v-average [m/S]	AEP measured [MWh]	AEP extrapolated [MWh]	AEP assumed [MWh]	AEP improvement [%]
4,00	1750	1752	1740	0,64%
5,00	3299	3347	3324	0,68%
6,00	4895	5191	5160	0,60%
7,00	6134	7008	6971	0,53%
8,00	6868	8586	8546	0,47%
9,00	7154	9802	9761	0,42%
10,00	7117	10618	10577	0,39%
11,00	6877	11064	11025	0,36%

Figure 11. Each average wind speed wind distribution is associated with a different improvement in AEP.

Sector Self-Consistency Check

After establishing a Measured Power Curve, a sector-wise control method is applied. It's used to validate and filter out invalid wind direction sectors from the test. This control method is similar but not identical to the sector self-consistency check used for validating the NTF in nacelle anemometry- based power performance testing according to IEC standard 61400-12-2.

The procedure is applied the same manner in both training and testing period data and associated power curves. Wind sectors that are deviating and determined invalid are excluded in the final test results. It's only applied in the training period for uncertainty calculation purposes.

General Procedure

Essentially, the wind speed at the test turbine is calculated in two different ways, using the test and reference power data respectively. If the ratio of these wind speeds on average match well for a wind sector, the data and power-to-power relation is considered valid in this wind sector.

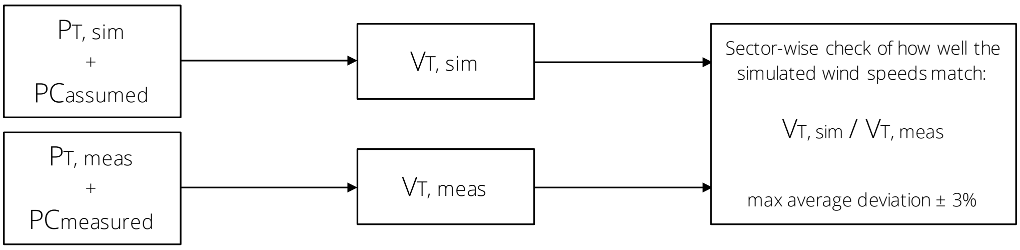


Figure 12. Procedure overview of the Sector Self-Consistency Check.

A power curve is used to track the power output data to corresponding wind speeds. This procedure is identical to Step 2 when determining the Measured Power Curve, i.e. VT, sim is already calculated.

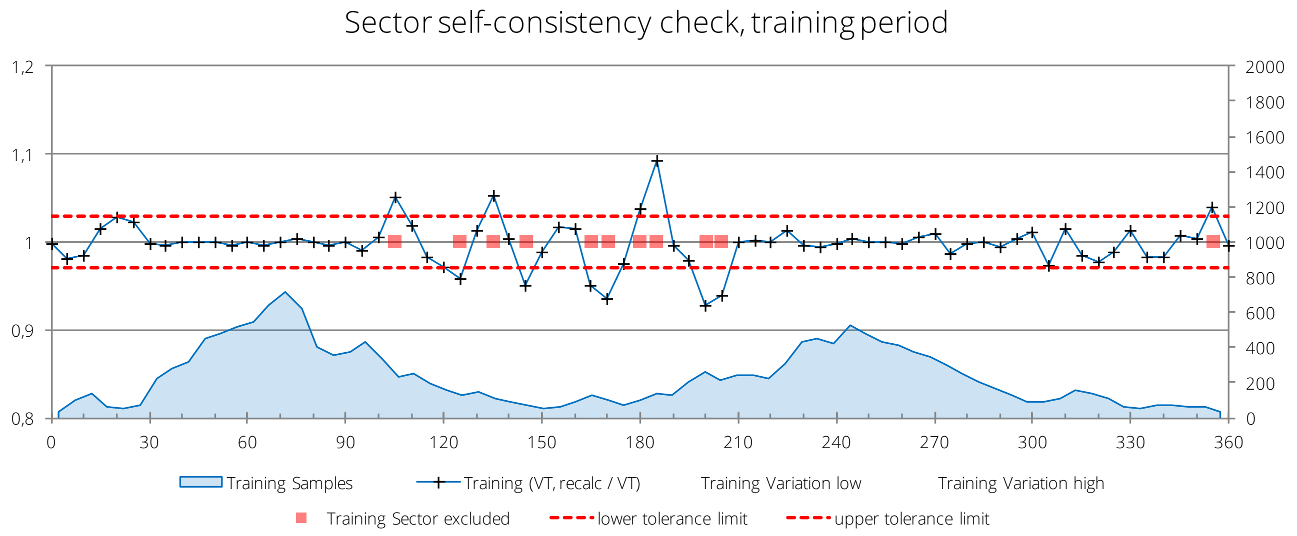
- The first wind speed $V_{T, sim}$ is based on the power data of the reference turbine. Through the Power-to-Power Relation the power output of the test turbine is simulated, and matched with the assumed power curve.

- The second wind speed $V_{T, meas}$ is based on the actual power data of the test turbine. The measured power output is matched with the measured power curve.

Steps Taken in Case Study

The exact same steps were used to perform the sector self-consistency check in the training and testing period:

- Only $P_{T, sim}$ and $P_{T, meas}$ data between 50 and 2200 kW was used, to avoid influence from the artifacts in the Measured Power Curve at cut-in and rated wind speed.
- The $V_{T, sim}$ / $V_{T, meas}$ ratio was calculated for each valid power output data point
- The $V_{T, sim}$ / $V_{T, meas}$ data was binned for each 5 degree wind direction sector, determining bin average, standard deviation, number of samples, and variance.
- Each bin-average $V_{T, sim}$ / $V_{T, meas}$ passing criteria was set to max 3% deviation from 1:1.



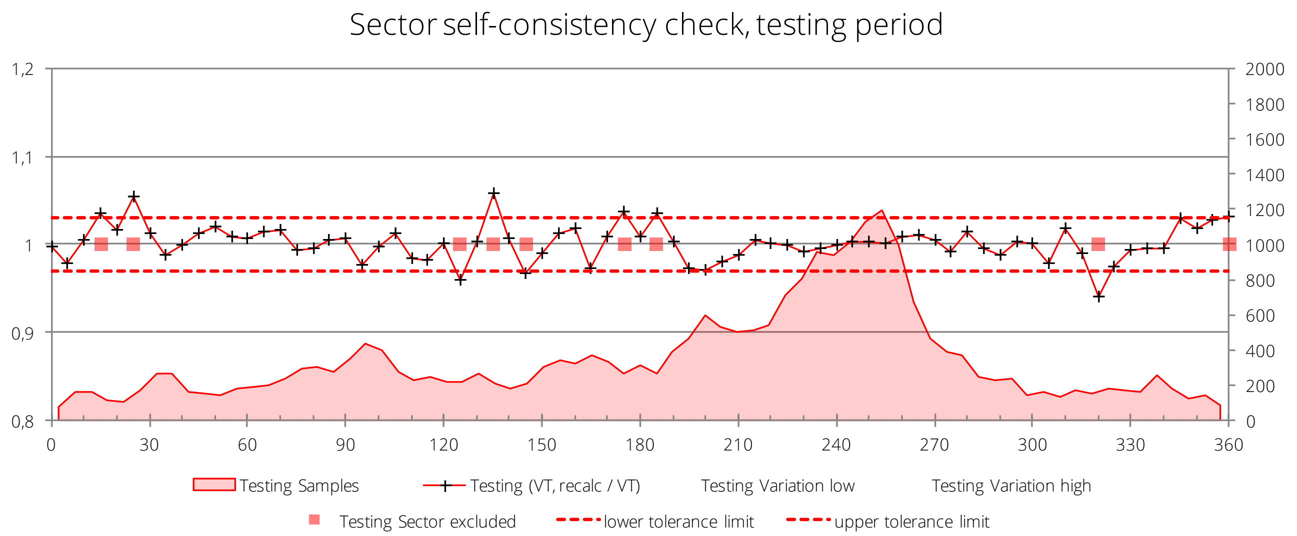


Figure 13. For each wind direction the average $V_{T,\,sim}$ / $V_{T,\,meas}$ ratio is evaluated for the training and testing period, respectively. Sectors exceeding the set tolarance limit are considered invalid and are excluded from the analysis (see red markings).

The final results were calculated using two criteria in addition to the Sector Self-Consistency Check. In addition to the conditions set forth by Axel Albers in the method presentation, the following criteria were added to the Power-to-Power Relation sectors to exclude wakes and weak sector bins:

- Each power bin of a power relation sector must be based on at least 5 samples. Being a low wind speed site, generally the 2250 kW power bins failed this condition. The prevailing wind directions were not affected.

- The average P_T/P_R ratio of each sector must not exceed a 1 ± 0,25 deviation. These sectors were considered to be in wake conditions.

The valid sectors used in the final analysis are presented in the table. All prevailing wind directions of the training period generally pass all criteria.

Sector	Training	Testing
0	Valid	Valid
10	Valid	Valid
20	-	-
30-100	Valid	Valid
110	-	-
120	Valid	Valid

Sector	Training	Testing
130-200	-	-
210-310	Valid	Valid
320	-	-
330-340	Valid	Valid
350-360	-	-

Uncertainty Analysis

The following uncertainty analysis covers the uncertainty of Power Output and resulting AEP. The analysis is based on the four power output uncertainty components described in Axel Albers presentation: A1, A2, B1, and B2. Lacking in-depth explanation of the uncertainty calculations, these were treated like type A and type B uncertainties, performing the uncertainty analysis according to the IEC 61400-12-1 standard.

- Type A uncertainties are evaluated by statistical methods. These are characterized by estimated variances s_i^2 or standard deviation si and are typically drawn from the variance of the data scatter.

- Type B uncertainties are evaluated by other means, characterized by quantities, which may be treated like variances u_j^2 or standard deviations u_j.

- Equipment calibration or manufacturer specifications
- Previous measurement data and experience
- Reference handbooks or standards.

Uncertainty in Power Output

The power output uncertainty components were determined for each wind speed bin of the Measured Power Curve, from 3 to 14 m/s.

- A1: Statistical uncertainty of the Measured Power Curve. Calculated as variation of power output scatter, Measured Power Curve in testing period
- A2: Statistical uncertainty of the power-to-power relation. Calculated as variation of power output scatter, Measured Power Curve in training period
- B1: Power curve reproduction capability. Calculated as deviation of Measured Power Curve from Assumed Power Curve in training period
- B2: Possible shift of power-to-power relation with time. Drawn from the Sector Self-Consistency Test. For each wind speed bin, the power output corresponding to the change in $V_{T, meas}$ / $V_{T, sim}$ from training to testing period was calculated.

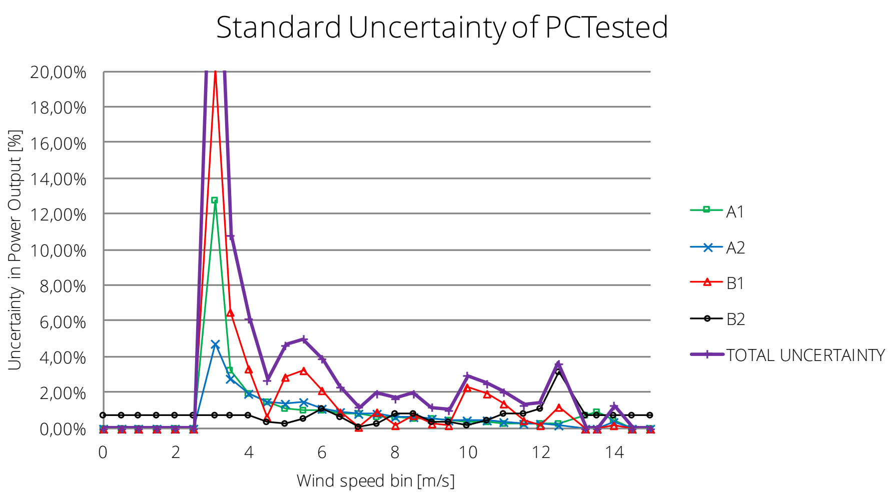


Figure 14. Each individual Type A and B uncertainty was plotted, as well as the combined total standard uncertainty.

Uncertainties in Annual Energy Production (AEP)

The uncertainty in AEP is based on the power output uncertainty components, but the calculations are far more complex. The uncertainty in AEP is dependent on both the power output uncertainty and the probability of occurrence of that wind speed, for each wind speed bin.

The uncertainty in AEP was calculated using the approximation expression for combined uncertainties of type A and type B in the IEC 61400-12-1 standard (Annex E, ekv 5). This approximation may slightly overestimate the uncertainty. The high uncertainty in power output of the first two wind speed bins increase the total AEP uncertainty for wind distributions with low average wind speed.

Wind distribution v-average [m/s]	AEP measured [MWh]	Uncertainty AEP [MWh / %]	
4,00	1750	32	1,85%
5,00	3299	50	1,52%
6,00	4895	69	1,40%
7,00	6134	83	1,35%
8,00	6868	90	1,31%
9,00	7154	92	1,28%
10,00	7117	90	1,27%
11,00	6877	86	1,25%

Figure 15. Uncertainty in AEP, for the evaluated wind distributions.

Final Results

The final results were calculated using the filtered data of the valid wind directions rendered from the Sector Self-Consistency Check and additional conditions.

The 6 month training period was used to establish the Power-to-Power Relation. The training period data was also used for dummy calculations, used for uncertainty analysis purposes.

The 6 month testing period was used to establish the Measured Power Curve. The Improvement in Power Performance was derived by comparing the Measured Power Curve with the input assumption.

The uncertainty is drawn from the four uncertainty components A1, A2, B1, and B2, in combination with the methodology set forth in the IEC 61400-12-1.

Improvement in Power Output

It is important to keep in mind that the Measured Power Curve doesn't represent the absolute level of power performance, but the relative change from the assumed baseline behaviour. The actual measure of improvement is therefore the relative difference between the Measured Power Curve and the Assumed Power Curve, plotted as the blue in Figur 16. This is the effect of the upgrade on the Power Curve.

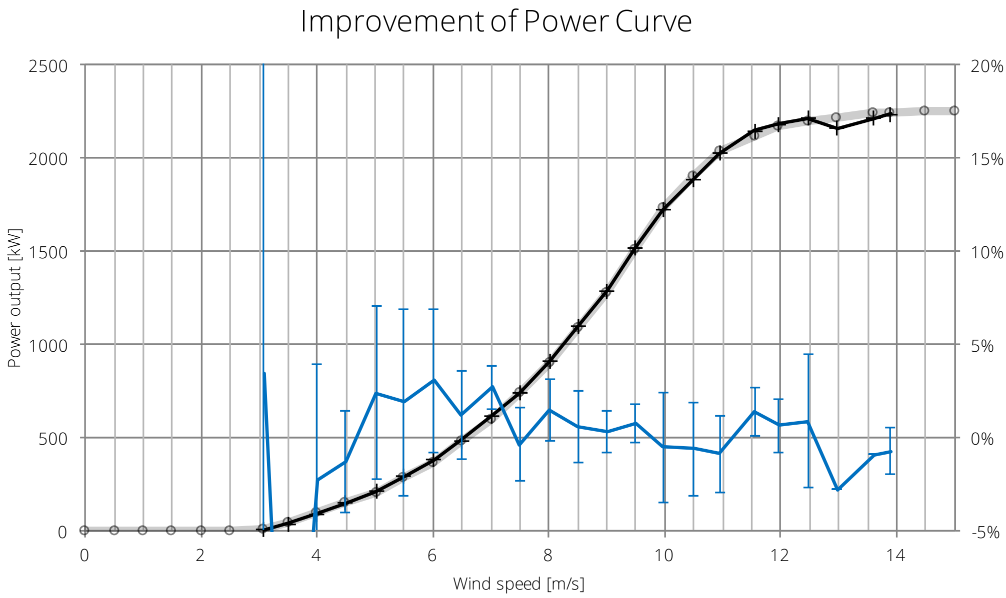


Figure 16. The Measured Power Curve is plotted in black. The grey line indicates the baseline Assumed Power Curve. The blue line indicates the improvement in power and uncertainty levels, relative to the assumption.

The test results show an overall improvement in power performance from the upgrade of serrated trailing edge add-ons.

The most reliable results were conceived at mid-range of the Measured Power Curve, between 4.5 and 12 m/s. This range of the power curve indicates an overall improvement of power performance, and is of most significance given the site-average wind speed of about 7 m/s. The details of the improvement in power curve are listed on the following page.

Bin no.	Hub height ws [M/S]	Power output [kW]	Data sets (10 min. avg.)	Uncerta-inty Cat. A [kW]	Uncerta-inty Cat. B [kW]	Combined uncertainty [kW / %]		Change in power output [kW / %]	
1	0,00								
2	0,50								
3	1,00								
4	1,50								
5	2,00								
6	2,50								
7	3,08	6	555	1	1	2	34%	0	3%
8	3,49	38	836	2	3	5	11%	-11	-22%
9	4,00	93	906	3	3	6	6%	-2	-2%
10	4,49	149	895	3	1	4	3%	-2	-1%
11	5,01	213	1101	4	6	10	5%	5	2%
12	5,49	291	1139	5	9	14	5%	5	2%
13	6,01	383	1132	5	9	14	4%	11	3%
14	6,49	486	1155	6	5	11	2%	6	1%
15	7,01	618	1274	7	1	7	1%	16	3%
16	7,49	739	1213	7	7	15	2%	-3	0%
17	8,01	911	1269	8	7	15	2%	13	1%
18	8,50	1097	1234	9	12	21	2%	6	1%
19	9,00	1290	1246	9	6	15	1%	4	0%
20	9,50	1522	1213	10	6	15	1%	12	1%
21	9,97	1724	942	10	41	51	3%	-9	-1%
22	10,51	1888	772	11	37	48	3%	-11	-1%
23	10,95	2027	677	9	33	42	2%	-18	-1%
24	11,55	2147	622	8	19	28	1%	30	1%
25	11,96	2182	344	7	24	31	1%	14	1%
26	12,47	2215	375	6	73	79	4%	20	1%
27	12,97	2159	16					-62	-3%
28	13,60	2215	49					-21	-1%

29	13,90	2234	41	12	16	28	1%	-16	-1%
30	14,50								
31	15,00								
32	15,50								
33	16,00								
34	16,50								
35	17,00								
36	17,50								
37	18,00								
38	18,50								
39	19,00								
40	19,50								
41	20,00								

Artefacts in the Measured Power Curve

The apparent power dips at cut-in wind speed and close to rated power are thought to be artefacts of the testing method. The very highest wind speeds simulated were underestimated, leaving few simulated wind speeds at the three highest bins (13, 13.5, and 14 m/s). The uncertainty analysis could not be completed at 13 and 13.5 m/s.

Testing different turbines and data combinations within the same wind farm indicated erroneous results at the outskirts of the Measured Power Curve. The complex terrain of the test site means the test and reference wind turbine are highly directional dependent, and the Power-to-Power Relation gets relatively spread out.

Applying the power relation at the end bins close to cut-in and rated power, this cause some significant binning effects when extrapolating end bins with spread P_T/P_R ratio. This is apparent at 13 m/s in the Measured Power Curve. The scarce number of data samples close to rated power stems from the $P_{T, sim}$ being underestimated at rated power. Similarly, the power is a bit overestimated at 12 and 12.5 m/s.

These results suggest that the Power-to-Power Relation could be applied more accurately at the end bins using a different approach of extrapolation, for more accurate results.

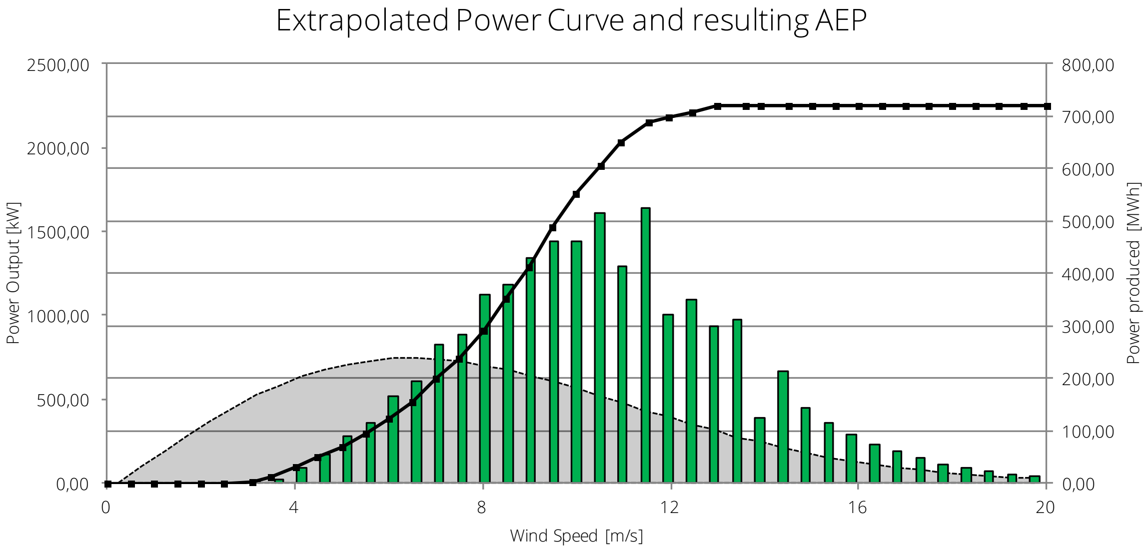
Improvement in Annual Energy Production

The presented results are representing the blade add-on effect on Annual Energy Production (AEP) in the partial power range, 3 → 12.5 m/s.

The upgrade is estimated to have improved the AEP by +0.53%, with an uncertainty of ±1,35% $AEP_{measured}$.

This was calculated on an average wind speed of 7 m/s, which is representative for the site. The calculation excluded the the last three measured bins (13, 13.5, and 14 m/s), due to the flaws in this range and inability to complete the uncertainty analysis for these incomplete bins.

The results based on 7 m/s average wind speed is graphed and highlighted in the table results.



Wind dist. v-average [m/s]	AEP measured [MWh]	AEP uncertainty [MWh / %]		AEP extrapolated [MWh]	AEP assumed [MWh]	AEP improvement [%]
4,00	1750	32	1,85%	1752	1740	0,64%
5,00	3299	50	1,52%	3347	3324	0,68%
6,00	4895	69	1,40%	5191	5160	0,60%
7,00	6134	83	1,35%	7008	6971	0,53%
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10,00	7117	90	1,27%	10618	10577	0,39%
11,00	6877	86	1,25%	11064	11025	0,36%

Breeze - A Modern System for Data Collection and Wind Farm Optimization

With more turbines comes more data and a universal need to capture and understand this data. Collecting, managing and analyzing data are challenges for owners and operators with expanding, diverse portfolios. For many years, software solutions for the wind energy industry were lacking or immature.

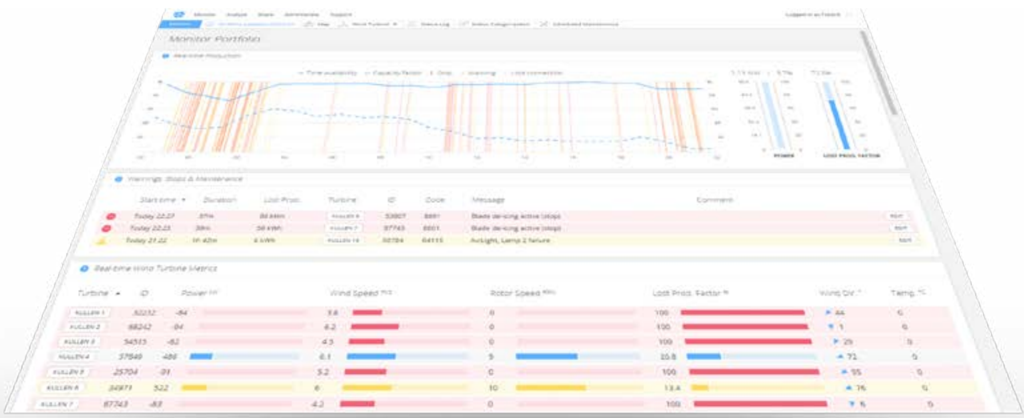
Created specifically for the wind energy industry, Breeze is a modern scalable wind farm management system used by active owners and operators to increase energy production.

A key task in increasing power performance is to identify under performing wind turbines and to discuss what actions can be taken to increase power performance of individual wind turbines or the wind farm as a whole.

Breeze has the capabilities to measure and verify the effects of actions and expenditures intended to improve performance. By quantification of the ROI, the owner will know if actions make financial sense to implement on other wind turbines.

This is an exciting field that will become more and more important and widespread as turbines are managed under production based availability contracts and as turbines come out of warranty. Breeze intends to maintain a leadership role in this field.

To learn more about Breeze, visit www.breezesystem.com.



breeze

Greenbyte AB
Kristinelundsgatan 16
411 37 Gothenburg, Sweden

Phone: +46 (0) 31 788 03 00
sales@breezesystem.com
www.breezesystem.com