

Paper: wes-2016-16

Title: Monitoring offshore wind farm power performance with SCADA data and advanced wake model

Authors: Niko Mittelmeier et al.

Answers to comments of anonymous Referee #1 by

Niko Mittelmeier et al. October 19, 2016

Dear Referee,

Thank you very much for your honest feedback and the very detailed and helpful comments. Your advices and suggestions will certainly help to make the paper clearer and better. In the first part below we have addressed each comment. Your overall message, “be more precise” is understood and we hope to meet your expectations. Our response is marked as follow: *******/ response /*******. In the second part, we have attached the change track version of the word document with all referee comments. We hope this is helpful to find our (RC1) changes in the context. Please use the pdf bookmarks for navigation.

Part 1

General comments

I think that the subject in general is interesting as wind farm underperformance is an important issue that we sometimes do not want to discuss much in wind energy. Therefore, I started to read with interest the manuscript but at about the second page I became really bored of the continuous issues/typos/grammatical problems that the text has. It is not that the English is generally bad; it is more about the way the authors write sentences and connect the ideas. It is generally “very weird” the way they write. In the specific comments, I list a number of issues but as I said I became so bored of these things so I just did it for the first pages; in case the authors have the chance to resubmit, the manuscript has to pass many hands including some English technical experts before resubmitting.

*******/ Introduction will be rewritten. Focus: “be more precise” (see comments below) /*******

More important, the manuscript in its actual form reads more like a technical report describing a method rather than a scientific paper. The authors need to make clear what the contribution to science is (if any) and write the manuscript to establish that the method they suggest is clearly novel (so far I do not see the novelty; the wake model is not new, neither the uncertainty calculation). Also they make things harder to digest by their writing so the text needs some reshuffling to accomplish a good flow.

*******/ For our wind farm monitoring model we have chosen the power matrix approached (look-up tables (LUTs)) which has been used in several studies before. (TC88 WG6, 2005), (Mellinghoff , 2007), (Carvalho and Guedes 2009) , (Westerhellweg et al., 2012) and (Mittelmeier et al. 2013).

We see the advantage of LUTs in the fact, that any wake model can be chosen to provide input for our model. And with further improved wake models, the monitoring method will improve.

The novelty is a new turbine referencing approach. Not the absolute values between model and measurement are compared, but the relation between an observed turbine and all other turbines in the farm. The uncertainty of the resulting performance ratio is much lower than the uncertainties of absolute production or AEPs. Furthermore all the above mentioned publications have proposed to use met mast data and we have demonstrated our method only with measurements which are available on state of the art wind turbines (SCADA data).

Usually measured data from nacelle mounted devices is prone to errors due to disturbed flow behind the rotor. When looking at absolute power values this would lead to high uncertainties. The IEC 61400-12-2 (2013) standard provides an example in Annex J showing uncertainties of approximately 20% on AEP for one turbine. A reduction in AEP uncertainty could be achieved by multiple measurements.

By using reference turbines, uncertainties from air density corrections can be neglected. Furthermore, the uncertainty of the wind speed has a much lower sensitivity factor. Wind direction measurements have a clear contribution to the combined uncertainties in our model, but we could show, that in our example, 7% uncertainty on the performance ratio are an improvement compared to existing methods.

The contribution to science is an explicit investigation on how underperformance can be detected in single wake, double wake and triple wake situations and we provide validation and suggestions how to improve results of the selected wake model in pre and post process. We have used Fuga because it is accessible, fast and easy to handle. But for experienced users of other models, the choice might be different and that's ok for our model.

References:

Carvalho, H. and Guedes, R.: Wind Farm Power Performance Test , in the scope of the 2 . Wind Farm Performance Matrix, , 1–9, 2009.

IEC 61400-12-2: Power performance of electricity-producing wind turbines based on nacelle anemometry., 2013.

Mellinghoff, H.: Wind Farm Power Performance Verification, DEWI., 2007.

Mittelmeier, N., Amelsberg, S., Blodau, T., Brand, A., Drueke, S., Kühn, M., Neumann, K. and Steinfeld, G.: Wind farm performance monitoring with advanced wake models, in Proceedings of the European Wind Energy Association Offshore Conference, Frankfurt., 2013.

TC88 WG6, I.: Wind farm power performance testing working group draft, IEC., 2005.

Westerhellweg, A., Canadillas, B., Kinder, F., Neumann, T. and Windenergie-institut, D. G. D.: Farm Efficiency and Power Matrix based on RANS (CFD) Simulations for the offshore Wind Farm Alpha Ventus and Comparison with Measurements, 2012.

/**

About the subject: There is a clear shift of the direction of the wake even for the single wake case. The authors provide some arguments but in the single wake case the maximum wake deficit should simply be a 0 deg.

*/ We provide you with some recent publications which support the theory, that even in the wake of a single turbine with no yaw error a shift of the wake is observable. These studies have the general aim to investigate active wake control but they also provide examples for 0° yaw error. Fleming (2013) shows in his baseline simulation (no yaw error) a small wake shift to the right when looking downwind. In the LES study of Vollmer et al. (2016) it can be observed, that the wake deflection increases from neutral (Vollmer et al. 2016, Fig. 5) to stable conditions (Vollmer et al. 2016, Fig. 9). These Figures provide simulated results also for a turbine with 0° yaw angle. In both cases the maximum wake deficit is found to be on the right side of the centre line (looking downstream).

Gebraad (2014, p86) gives an explanation for the observations from the simulations by Fleming (2013). The flow reacting on the rotation of the rotor causes the wake to rotate counter clockwise (looking downstream). Higher wind speeds from the upper layer are transported downwards (on the left side) and lower wind speeds from the lower layer are pushed upward on the right side of the wake. As a result the velocity deficit at the right part of the wake increases, so the wake deflects to the right.

Marathe et al. (2015) could show in their field measurement campaign with dual-doppler radar, that in the near wake region, the wake is drifting to the right, as expected by the theory. But in the far wake they registered a contradicting movement. The authors state the hypothesis that this phenomenon may be caused by atmospheric streaks. An offshore field experiment by Beck et al. (2015) provides further evidence that wakes are moving out of the centre line.

References:

Beck, H., Trujillo, J. J., Wolken-möhlmann, G., Gottschall, J., Schmidt, J., Peña, A., Gomes, V., Lange, B., Hasager, C. and Kühn, M.: Comparison of simulations of the far wake of alpha ventus against ship-based LiDAR measurements, in RAVE Conference., 2015.

Fleming, P. A., Gebraad, P. M. O., Lee, S., van Wingerden, J. W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P. and Moriarty, P.: Evaluating techniques for redirecting turbine wakes using SOWFA, in ICOWES2013 Conference., 2013.

Gebraad, P. M. O.: Data-Driven Wind Plant Control, 2014.

Marathe, N., Swift, A., Hirth, B., Walker, R. and Schroeder, J.: Characterizing power performance and wake of a wind turbine under yaw and blade pitch, , doi:10.1002/we, 2015.

Vollmer, L., Steinfeld, G., Heinemann, D. and Kühn, M.: Estimating the wake deflection downstream of a wind turbine in different atmospheric stabilities: An LES study, Wind Energy Sci. Discuss., (September), 1–23, doi:10.5194/wes-1-129-2016, 2016.

/**

The authors use a nacelle-based vane for the wind direction so why not checking if there is a systematic turbine misalignment by looking at the nacelle position signal in the SCADA data?

*/ For our monitoring model we are using the absolute wind direction signal from each turbine which is defined as

$$\vartheta = \text{nacelle position} + \text{wind vane position}$$

The nacelle position is the angle between the rotor axis and a marking for true north. This marking is calibrated as part of the commissioning. But often this signal is not maintained well during operation, because it has no effect on turbine performance. This causes the necessity to apply a bias correction to this signal before using it for reanalysis purposes. The wind vane position indicates the angle of the flow to the rotor axis. It directly provides a value for the yaw error. The turbine controller uses this signal to control the yaw activity. For an infinite averaging the mean value of the wind vane position is 0°. We have used 12127 10-min values for the wake model calibration. A histogram of the vane position signal for the whole data is provided in Figure x below.

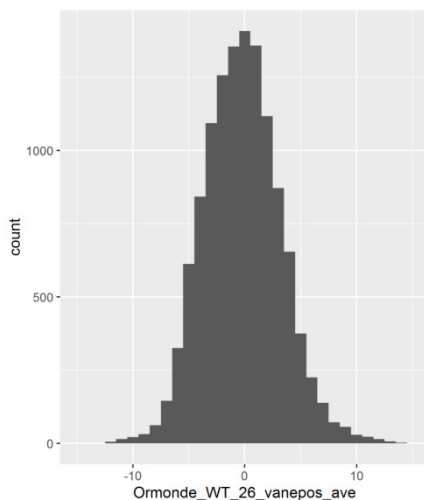


Figure x: Histogram of the wind vane position signal from turbine 26 showing all data that has been used for wake model calibration. Resulting in a mean value of -0.2 and a median of -0.3.

A systematic yaw error resulting from the sensor alignment can be estimated to $\pm 2^\circ$ for a single turbine (IEC 61400-12-2, 2013). A nacelle transfer function for wind direction is used to take the effects of the rotor into account. We do not assume this correction being perfect, so we end up with uncertainties of approximately 3° .

We will include these clarifications in Section 2.1.1. And add further explanations to the data handling, filtering and corrections that are necessary to obtain the right quality signal. (See also Comment 64)

Reference:

IEC 61400-12-2: Power performance of electricity-producing wind turbines based on nacelle anemometry., 2013.

/***

The authors also refer to the study of Vollmer, but in that study, the wake is deflected intentionally by misaligning the turbines. So the most plausible explanation it is simple yaw misalignment unless the authors discard this by showing that the turbines are indeed not misaligned (but they do not do that).

***/ In the study of Vollmer, simulations are showing wake behaviour for 30° , 0° and -30° yaw angle under different atmospheric conditions. Even at 0° yaw angle the maximum wake deficit is not at the centre line (perpendicular to the rotor). This effect increases with increasing atmospheric stability.

Unfortunately we don't have information from the site which would allow a stability classification based on the Monin - Obukhov length. But we obtained the best wake deficit fit between the SCADA data and the Fuga calculations with a $\zeta_0 = 2.72 e - 7$ which is supposed to be used for more stable cases.

We have changed the reference to the following publication:

Vollmer, L., Steinfeld, G., Heinemann, D. and Kühn, M.: Estimating the wake deflection downstream of a wind turbine in different atmospheric stabilities: An LES study, Wind Energy Sci. Discuss., (September), 1–23, doi:10.5194/wes-1-129-2016, 2016.

/***

There is a general problem with the way the authors make references in the text and the reference list itself at the last section. You should write refs. in the text as: "A power curve is given for each turbine (Smith, 2001). However, Jonas (2010) described another method. Such method was also shown in some previous studies (Klinsmann, 2006; Pauli, 2010)". In the specific comments I select some specific cases but most of the references are wrongly made. And the references in the reference list should be made consistently: Names, title (non-capital all refs. or all capital), etc. Such type of reference list makes me wonder about the quality of the whole study. The reference list should be made with consistency.

Also you have a problem with the equations; they are part of the text and should not disrupt it! The dot symbol does not mean multiplication, it means dot product but you don't have such products.

The "same" symbols are sometimes in italics and sometimes in normal text; if they are the symbol of the same thing then they should be written in the same way.

/ Thanks for pointing this out. It will be improved accordingly. /

Specific comments:

1. Page 1 line 16 “: : technical solutions.” This type of statements are very general and not precise and specific. What do you mean by this? Turbines, models, methods?

***/ The intention was to start the paper with a very generic statement cause not only good turbines will make an investment successful. Installation, O&M, grid components, models, monitoring methods and guarantees are also important. But we agree, being more precise here will help the reader.

We will change the wording from “technical solution” to “wind turbine” /***

2. Page 1 line 18 “: : definition (: : :) defines: : :” that the system is ready to operate” this is redundant. Why not “: : definition (: : :) is that related to a system ready to operate”

***/ New wording:

“In wind industry, the common standard IEC TS 61400-26-1 (2011) defines different categories of turbine conditions and describes the calculation of availability”. /***

3. Page 1 line 20 “: : quality and quantity.” Of what? In the next paragraph you kind of explain it but you cannot simply say this here and expect that the reader finds the answer later. If this is the case then that sentence can be removed.

/ You are right. The sentence is moved to the next paragraph. /

4. Page 1 line 21 Replace “: : much SCADA” by “lots of” or “a good amount of”

/ “much” replaced by “lots of” /

5. Page 1 lines 27-28 “Work on: : of 2016”. You don’t need this reference and does not help the paper so remove it

/ Sentence is removed. /

6. Page 1 lines 28- Page 2 line 1 “For most turbines: : . wake effects” You make it sound as it was only a problem for offshore turbines and it is not so replace by e.g. “For most turbines in a typical wind farm, verification of the performance by comparison with the power curve is not suitable: : :” then “: : maintenance of a met mast is very expensive particularly offshore.”

***/ New wording:

“For most turbines in a typical wind farm, verification of the performance by comparison with the power curve is not suitable due to wake effects. And the installation and maintenance of a met mast is very expensive particularly offshore.” /***

7. Page 2 line 3 Replace “accounts” by “account”

/ replaced /

8. Page 2 line 6 “Incorrect parameter settings” you mean “turbine parameter”?

/ New wording: “Incorrect turbine parameter settings...” /

9. Page 2 line 9 “turbine has a limited power output which has been externally applied” You want to refer to the limit but with the use of the “which” you mean the limited power output but surely this is not what is externally applied because one cannot apply a limited power output: : that is a consequence of limiting something else.

***/ New wording:

“A curtailed turbine has a limited power output below its expected power. Possible reasons for curtailments are load reduction or grid requirements. For these incidents, turbine parameters are changed on purpose and therefore documented in the turbines SCADA logs.” /***

10. Page 2 lines 11-16 this is a very weird paragraph. “Upwind turbines influencing the free flow for downwind turbines”. This is a weird sentence because the flow is not free for the downwind turbines. Why not just removing the “free” word. Then it is also weird because you have “: : , wake effects,” so with this construction you say the wake effects are turbines! Then you have these references to Albers (all wrongly made; see my major comment). Then you say “Albers has also looked: : :flow models”: this is a personal communication or is in one of his studies? Then comes “But at that time: : :” what time? Which year or which study in particular? There is also a “to be further development” that should be “to be further developed”

***/ The whole paragraph has been revised to be more precise:

“Albers (2004) has published two methodologies for wind turbine performance evaluation. His integral model uses available wind conditions from the energy production of neighbouring WTs, met masts or a combination of both and transfers the information via flow modelling and wake modelling to the investigated wind farm. The measured yield is corrected for turbine availability and then compared against the modelled yield in absolute values. Due to high uncertainties this method is only proposed as a first general check. To reveal smaller deviations he proposes a relative wind turbine performance evaluation model. For this method, active power of direct neighbours are plotted against each other and by comparing two periods, changes can be evaluated. This method explicitly excludes the sectors where wakes are effecting one of the two turbines.”

References:

Albers, A.: Relative and Integral Wind Turbine Power Performance Evaluation, in EWEC, London., 2004.

/***

11. Page 2 line 18 “: : :which proposed” so the standard stopped at some point proposing this?

***/ The whole paragraph has been revised:

“An international working group (IEC TC88 WG6, 2005) was trying to come up with a standard for wind farm power performance testing. The proposed method uses one or more met masts to establish a measured wind farm power curve matrix. This two dimensional measured power matrix (Wind direction, Wind speed) is compared against a modelled power matrix taking wake effects into account (Mellinghoff, 2007)(Carvalho and Guedes, 2009). The standard could not be established.”

References:

Carvalho, H. and Guedes, R.: Wind Farm Power Performance Test , in the scope of the IEC 61400-12-3, in Wind Power Expo, Chicago., 2009.

IEC TC88 WG6: Wind farm power performance testing working group draft, IEC., 2005.

Mellinghoff, H.: Wind Farm Power Performance Verification, DEWI., 2007.

/***

12. Page 2 line 19-20 “: : :could not be established,” So it is not a standard, it is a working group trying to come up with a standard. Also delete the part “: : :and the support: : : crumbled.” It is not scientific knowledge

/ Paragraph has been revised. Please see comment 11/

13. From line 22 in page 2 onwards you talk about “matrices” but what you mean is “look-up-tables (LUT)” Use that term. There is an unnecessary comma in line 22 after “method”. Also in that line you talk about detection of “curtailment”. Perhaps your method is able to detect curtailment but curtailment is generally artificially imposed or used and so it is/should be recorded in the turbine status of the SCADA.

***/ TC88 WG6 (2005), Mellinghoff (2007), Carvalho and Guedes (2009) and Westerhellweg et al. (2012) have used the terminology of “Power Matrix” in their publications. We will give the proper explanation of power matrices being “Look-Up Tables, LUTs” in the introduction and use from there on the terminology of LUTs.

You are right. “Curtailments” are usually recorded in the turbine status of the SCADA. There is no explicit need for the method to detect these behaviour. But we think that redundancy is valuable in performance monitoring and we think it is helpful to have a second example of underperformance that can be detected by this method.

“or curtailments” has been removed

The comma in line 22 has been deleted. Thank you.

References:

Carvalho, H. and Guedes, R.: Wind Farm Power Performance Test , in the scope of the IEC 61400-12-3, in Wind Power Expo, Chicago., 2009.

IEC TC88 WG6: Wind farm power performance testing working group draft, IEC., 2005.

Mellinghoff, H.: Wind Farm Power Performance Verification, DEWI., 2007.

Westerhellweg, A., Canadillas, B., Kinder, F., Neumann, T. and Windenergie-institut, D. G. D.: Farm Efficiency and Power Matrix based on RANS (CFD) Simulations for the offshore Wind Farm Alpha Ventus and Comparison with Measurements, 2012.

/***

14. Page 2 lines 23-27 “Mittelmeier et al. (2013) presented: : : environmental conditions.” I am not sure this is a new method. In many other studies, authors used wake-model-based LUTs to estimate the efficiency of the wind farm. So the authors need to explicitly say what exactly is new.

***/ This whole paragraph has been revised to address your general comment to establish a better flow and provide more precise statements.

“Mittelmeier et al. (2013) presented a new method where not the absolute values between model and measurement are compared, but the relations between an observed turbine and all other turbines in the farm. In this way, the uncertainty of the measurement chain could be reduced. The model is also based on pre-calculated power matrices which we call from now on “lookup-tables” (LUTs). Different wake models or even combinations of wake model results can be used to provide results for these LUTs. But the model relies on measurements from a met mast which is often not available. Furthermore, with increasing size of wind farms, the assumptions of one measurement position being representative for the whole offshore wind farm is not valid (Dörenkämper, 2015). Further investigations are necessary to obtain a reliable and automated method to detect underperformance at individual turbines in a wind farm.”

15. Page 2 lines 27-28 “Especially: : : available.” Already mentioned so remove it

/ Sentence removed/

16. Page 2 lines 31-33 Replace “this” by “the”, add “of” after “method” and use “Mittelmeier et al. (2013)” instead of “(Mittelmeier et al., 2013). Replace “condition” by “conditions”

*** / New wording:

The purpose of this paper is to present the results of extending the wind farm performance monitoring method of Mittelmeier et al. (2013) by using SCADA instead of met mast data. A new combination of methods to obtain representative environmental conditions and further optimisation potential for wake models fine-tuned by SCADA data is presented and an estimation of the uncertainty of these methods is given. / ***

17. Page 3 line 1-2 “Hence the presented: : : LiDAR”. Based on what you have already mentioned one can inferred what is written here so it is not necessary

*** / sentence is deleted / ***

18. Page 3 line 4 it should be change to “: : : of the method by Mittelmeier et al. (2013) is recalled”.

*** / has been changed / ***

19. Page 3 line 11 I know what you mean by “deviation” but you need to be exact so change to “A deviation between $P_{\pi i}$ and P_{μ} ”

*** / Thanks for this advice. It is actually the deviation between π and μ , that indicates underperformance. We have changes the first paragraph and hope this adds clarity:

“To detect underperformance of a wind turbine, we estimate the expected turbine power ratio π (predicted power ratio) between the observed turbine and a reference turbine with a wake model for the actual condition and compare its result with the actual measured power ratio μ . A deviation between π and μ , higher than a certain threshold indicates underperformance.” / ***

20. Page 3 lines 14-15 “The accuracy and calculation : : : real wind farm flow” This is not true. A simple wake model can be as accurate as a complex one.

*** / True! We have revised the whole paragraph:

“The performance monitoring model (Fig. 1) is based on two dimensional LUTs. The user can choose any wake model or even a combination of different model results to provide power output $P_{\pi i,j}$ values for different wind speed bin i and wind direction bin j . The predicted power output P_{π} is derived from the LUTs with linear interpolation knowing the measured wind speed and wind direction.” / ***

21. Page 3 line 16 First “improve the underperformance detection capabilities” This is not always true. And replace “,” by “;” before “on the other hand”

*** / Please see response given to Comment 20 / ***

22. Page 3 line 23 Remove the first “Additional”

*** / is removed / ***

23. Page 3 line 25 “for this purpose” I know what you mean but you have not mention any purpose and you want to refer to the monitoring method, I guess. So be precise

*** / “purpose” replaced by “monitoring method” / ***

24. Page 3 line 28 Replace “: : : averages of 10 minutes” by “: : : averages over 10-min periods”

*** / has been replaced / ***

25. Page 3 line 29 Replace “: : averaging N quantities of 10 minutes time samples” by “averaging a number N of 10-min samples”

/ has been replaced /

26. Page 3 line 30 Remove “the averaging”

/ “the averaging” has been removed /

27. Page 4 line 1 You are talking about “correlation” but this is not a correlation of power it is only a normalization. So as this is wrong the part of “This leads” does not make sense

/ “correlated to “ replaced by “divided by” /

28. Page 4 line 4 “This is described in Eq. (1) and (2)” Well this is not described in the equations; the equations are simply the definition you are using for the normalized powers

***/ “This is described in Eq. (1) and Eq.(2).” Replaced by “We define”
After Eq. (1) “,” replaced by “and”. (from General Comment: Equations should not disrupt the text) /***

29. Page 4 line 12 Replace “can be described with Eq. (3)” by “is defined as”

***/ “can be described with Eq. (3):” replaced by “is defined as”

30. Page 4 lines 16-17 “where $\eta_{ob,ref}$: : (ob) turbine” You already defined everything so there is no need for this

/ sentence deleted /

31. Page 4 lines 26-29 So why do you have to use all the wind vanes (this is what is read from the text)? They could all have a different misalignment and so you will need to analyze each of them (in terms of wake deficits) if you want to use all of them.

***/ In fact, all wind direction signals are corrected for a certain bias, which may results from a combination of systematic yaw error and wrong north marking. We have used only one referencing (based on wake deficits) to conserve effects like the mentioned “wake drift”. We want to use all wind vanes to cover the full variance which we use in our uncertainty calculation.
/***

32. Page 4 line 29 “complex area” what do you mean by complex area?

/ “area” replaced by “plane” /

33. Page 5 line 1 “of the scale” what do you mean by scale?

/ “scale” replaced by “value range” /

34. Page 5 line 2 “+/-1.5IQR” be explicit. If the outliers removed are those outside the range +/-1.5IQR then say so

***/ “defined by the” replaced by “outside”
The dot has been removed in the formula (General comment) /***

35. In Eq. 4 you have constants without units. If alpha is in degrees all these constants have the units of degrees and you need to state that

*** / Decimal separator changed from “,” to “.”

Product symbols removed (general comment), “Equation (4)” removed, so that the equation does not interrupt the text (general comment).

New wording:

$$\alpha = 1.3 \arctan \left(2.5 \frac{D_n}{L_n} + 0.15 \right) + 10 \quad (4)$$

is proposed by IEC 61400-12-1 (2005) and defines the width of the disturbed sector in degrees seen by the downwind turbine (the constants have the dimension of degree). D_n is the rotor diameter of the upwind turbine and L_n the distance between the two turbines defined by Eq. (5).” /***

36. Eq. 6 is not needed

*** / the two sentences before Eq.6 and Eq.6 are deleted.

New wording:

“With β , being the angle between the wake inducing turbine and the northing and the wind direction ϑ the turbine wake indicator γ can be described as:” /***

37. Page 6 line 1 “the north inconsistency need different conditions” Yes obviously

*** / sentence deleted /***

38. Page 7 lines 1-2 “In Mittelmeier et al. (2015): : : wind speeds”. Well that depends on the stability conditions. This will be true if compare unstable conditions with low wind speeds and high sigmas with neutral conditions with lower sigmas and higher wind speeds. But stable conditions will be in the low wind speed range with lower sigmas compared to neutral

*** / You are right. In our demonstration wind farm, we have unfortunately no measurements which would allow us to calculate stability by Monin-Obukhov length. But we definitively do see a strong correlation with the turbulence intensity. We see higher turbulences at low wind speeds and lower turbulences at higher wind speeds. We have changed the wording, to be more precise:

“In Mittelmeier et al. (2015), we could show, that for the prevailing conditions at Ormonde wind farm σ_a is a function of wind speed, decreasing with higher wind speeds.” /***

39. Page 7 line 3 “no impact” you mean “little impact”

*** / “no impact” replaced by “little impact” /***

40. Page 7 lines 7-8. This seems to be quite important and you do not provide any details about the study of Vollmer et al.

*** / Thanks for pointing this out. We have now put more focus on explaining this parameter and a possible theory behind this observed wake drift.

The last paragraph of section 2.2 has been revised as follow:

“The third tuning parameter is applying a simple offset on the wind direction of the LUTs to account for a drift of the wake. We call this phenomena from here on “wake drift”. Fleming (2013) has studied the effects of active wake control and in his baseline simulation (no yaw error) a small wake drift to the right can be observed when looking downwind. In the LES study of Vollmer et al. (2016) the wake drift increases from neutral to stable conditions also for 0° yaw angle. Gebraad (2014, p86) gives an explanation for the observations from the simulations by Fleming (2013). The flow reacting on the rotation of the rotor causes the wake to rotate counter clockwise (looking downstream). Higher wind speeds from the upper layer are transported downwards (on the left side) and lower wind speeds from the lower layer are pushed upward on the right side of the wake. As a result the velocity deficit at the right part of the wake increases, so the wake deflects to the right. Marathe et al. (2015) could show in their field measurement campaign with a dual-doppler radar the wake drifting to the right, as expected by the theory. But in the far wake they registered a movement to the left. The

authors state the hypothesis that this contradicting phenomenon may be caused by atmospheric streaks. In an offshore field experiment by Beck et al. (2015) further evidence is provided that wakes are moving out of the centre line. This wake drift is currently not modelled in Fuga and therefore applied in a further step of the pre-process (Fig. 1).“

References for this paragraph:

Beck, H., Trujillo, J. J., Wolken-möhlmann, G., Gottschall, J., Schmidt, J., Peña, A., Gomes, V., Lange, B., Hasager, C. and Kühn, M.: Comparison of simulations of the far wake of alpha ventus against ship-based LiDAR measurements, in RAVE Conference., 2015.

Fleming, P. A., Gebraad, P. M. O., Lee, S., van Wingerden, J. W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P. and Moriarty, P.: Evaluating techniques for redirecting turbine wakes using SOWFA, in ICOWES2013 Conference., 2013.

Gebraad, P. M. O.: Data-Driven Wind Plant Control, 2014.

Marathe, N., Swift, A., Hirth, B., Walker, R. and Schroeder, J.: Characterizing power performance and wake of a wind turbine under yaw and blade pitch, , doi:10.1002/we, 2015.

Vollmer, L., Steinfeld, G., Heinemann, D. and Kühn, M.: Estimating the wake deflection downstream of a wind turbine in different atmospheric stabilities: An LES study, Wind Energy Sci. Discuss., (September), 1–23, doi:10.5194/wes-1-129-2016, 2016.

/***

41. Page 7 line 31 “usually about 4 to 6%” you need to give a reference here; otherwise show an example

*** / Unfortunately we have no reference for our own experience. Therefore we have changed the sentence and provide the following reference.

New wording:

“Results from the Offshore Wind Accelerator (OWA) (Clerc et al., 2016) provide a range of 2.5% to 5% combined uncertainty for offshore power curve verification based on a measurement chain that include a met mast and all its devices. The usage of LiDAR extends the range up to approximately 7%.”

Reference:

Clerc, A., Stuart, P., Cameron, L., Feeney, S. and Fnc, I. C.: Results from the Offshore Wind Accelerator (OWA) Power Curve Validation using LiDAR Project, in Wind Europe Workshop “Analysis of operating wind farms.”, 2016.

/***

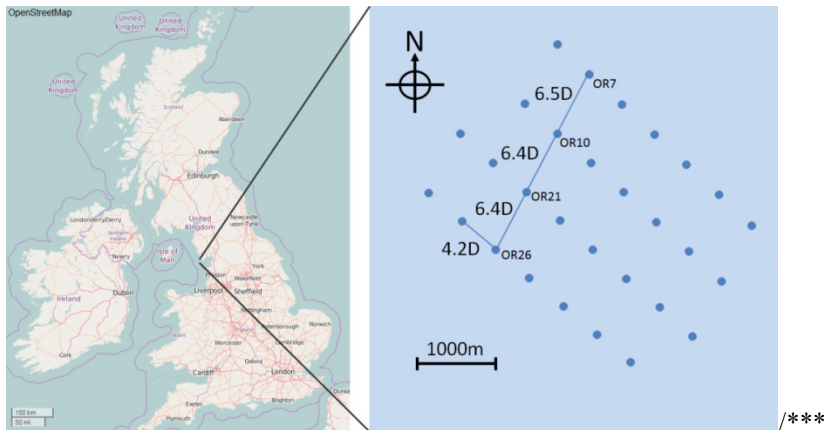
42. Page 8 line 19 “is around 7%” based on what?

*** / New wording:

“The uncertainty derived by Eq. (11) can be displayed as a bandwidth around the underperformance indicator η , visualized in Fig. 4. Its magnitude is dependent on the sample size N . In Fig. 4 we obtain approximately 7 % uncertainty on the performance ratio for $N > 1000$. /***

43. Page 9 line 3 Figure 5: please show a proper layout with north orientation and Scales

*** / New Figure with orientation and scales provided



44. Page 9 line 4 “6.3D” this is between turbines in the same row (does not look like that), between rows? And important what are rows for you: the rows of turbines in a particular direction or all “rows” of turbines?

*** / Not precise! You are right. Following text will add clarity:

“The farm layout displayed in Fig. 5 is structured in a regular array which allows comparison of several wake situations. The closest turbine spacing is in the range of 4.1 D to 4.3 D along the four rows orientated from north west to south east. We have selected a more frequent wind direction from south south west where multiple columns of four turbines are aligned with a distance ranging from 6.3 D to 6.5 D. To simplify the demonstration of underperformance detection we focused on single wake, double wake and triple wake conditions behind turbine OR26 for a south south westerly wind direction and a sector of 30° around the full wake situation.” /***

45. Page 9 line 7 Two years of “10-min” SCADA data?

*** / “for the following demonstration” replaced by “to set up the performance monitoring model” /***

46. Page 9 line 10 “The quality of the derived wind direction” It is not the quality what you show there

*** / Ok, we have revised the wording as follow:

“The wind direction is supposed to be representative for the wind turbines in the monitoring model. In our example, we have averaged up to 30 corrected wind direction signals for each 10-min interval. The variation among the individual signals provides an uncertainty estimate for this artificial wind direction. In Fig. 6, a histogram of the full data set of two years with each count being the difference between a single vane measurement and the corresponding mean wind direction for the averaged period is visualized. This variation can nicely be described by a Gaussian distribution with standard deviation of 3.6°. This value is used for the uncertainty of the wind direction Table 1 is referring to.” /***

47. Page 9 line 16 “from Section: :” Explicitly state which equations

*** / there is not one explicit equation, it’s the methodology we want to refer to.
“equations from” replaced by “methodologies described in” /***

48. Page 9 line 18 “binned into 2 deg” does not look like that but more like 4 deg.

*** / You are right. The 2 deg has been used for the model results and the SCADA results have been displayed with only 4 deg. We have changed the plot. It is now showing 180 instead of 90 points for the SCADA data /***

49. Page 9 line 23 These correlations are very high but the outliers seem to be also quite large so I am very skeptical about these computations

*** / The numbers were related to the correlations between modelled waked wind speed and the wind speed of the virtual met mast. This was in contradiction with the text. We have corrected the sentence:

“A linear regression between the wind speed of the standard model results (red dashed line) and the SCADA measurements equals $R^2 = 0.96$. The improved model (green solid line) gives an $R^2 = 0.97$.” /***

50. Page 9 The wake model seems to have a systematic bias when compared to the measurements (clearly seen at the highest deficits). Why? Is the average wind direction perhaps wrong? Perhaps you should average the wind direction of the turbines in the rows where the flow is not disturbed if you want to compare it with the wake model

***/ The wake model results used in this plot are directly taken from the Fuga Output. No wake model tuning/corrections as proposed in the pre-process step of the monitoring method (Fig. 1) has been applied. The corrected model has an 2.5° offset for all single wake case, 3.5° offset for the double wake cases and a 4.5° offset for the triple wake case for wind directions $207^\circ \pm 15^\circ$. In Fig.7 the offset of the wind direction at 207° (the four demonstration turbines in a column) is approximately 2.2° . At the wind directions 132° and 312° , with the largest wake effects along the four rows of 7 to 8 turbines, the offset is approximately 5° . This fact supports the theory, that with every additional wake added to the flow, the overall “wake drift” increases. We will add this information into the caption of the plot.

“Figure 7: Wind farm averaged wind speed with wake effects normalised with wind farm averaged wind speed without wake effects plotted versus averaged wind farm wind direction. Black dots show the measurements from SCADA and the green solid line represents the results from Fuga with a Gauss averaging for standard deviation of 4° . An offset of the wind direction between model and SCADA can be observed. At 207° the offset is approximately 2.2° and it increases up to 5° for wind directions (132° and 312°) with the largest wake effects. An explanation and correction for this “wake drift” is proposed in section 2.2.” /***

51. Page 10 line 1 The wake model should be presented before the results in 3.1.2!

/ The wake model calibration is based on the “virtual met mast”. This information was missing and will be provided in the revised version. Therefore we think it’s helpful to read first about the wind speed and wind direction handling and then about the wake model calibration./

52. Page 10 line 11 How much data you use for the calibration period?

***/ In our case, we have used two full years of SCADA data to obtain the plots in figure 9. In the current version of the monitoring model, no variation of stability is considered. Therefore the calibrated model should represent the annual average as good as possible. Small improvements could be expected, when extending the dimensions of the LUTs. But this is ongoing work and we think with the presented method we already achieved an underperformance detection level which is acceptable and helpful.

We will add the following clarification:

“The wake model is supposed to provide a two dimensional LUT (wind direction, wind speed) for each turbine. Further dimensions such as stability may improve the accuracy, but research and validation for these models are still ongoing. Therefore our calibrated model has to be representative for the average annual conditions. Two full years of SCADA data have been used for this task.” /***

53. Page 10 starboard and port terms are terms conventionally used in wake studies?

***/ Sorry, being offshore tempt us to use nautical terms.

“Starboard” replaced by “right”

“Port” replaced by “left” /***

54. Page 10 line 17 what do you mean by “global”

/ “global wind direction” replaced by “artificial wind direction from the virtual met mast (Section 2.1.1)” /

55. Page 10 lines 16-22 If this phenomenon occurs in 1 single wake the a very plausible reason is simply yaw misalignment

***/ We will add the following wording:

“We cannot fully rule out the possibility of an unwanted yaw misalignment as the uncertainties within this process of aligning the turbine lies within 3° (IEC 61400-12-2, 2013). But a single wake drift of 2.5° is also within the simulation results for 0° yaw misalignment at stable conditions. (Vollmer et al., 2016)”

Further details to this topic are also given in the answers to the general comments.

References:

IEC 61400-12-2: Power performance of electricity-producing wind turbines based on nacelle anemometry., 2013.

Vollmer, L., Steinfeld, G., Heinemann, D. and Kühn, M.: Estimating the wake deflection downstream of a wind turbine in different atmospheric stabilities: An LES study, Wind Energy Sci. Discuss., (September), 1–23, doi:10.5194/wes-1-129-2016, 2016.

/**

56. Page 10 line 32 “this data has been filtered for a wind direction sector of 5 deg”
Change to “These data have been..”

*/ This data has” replaced by “these data have” /**

57. Page 11 line 2 You mean for prediction of what? AEP? Wind speed? A particular case?

*/ We have referenced all available power data of that specific case with the base model and with the tuned model output.

We have revised the sentence:

“The three fine-tuning steps decreased the power prediction error in a full wake with $\pm 5^\circ$ sector width from 7% to 1.5%(Mittelmeier et al., 2015) for the presented case.” /**

58. Page 11 line 5 Replace “has been” by “will be”

*/ “has been” replaced by “will be” /**

59. Page 11 line 6 what do you mean by “real data”? so before the data was not real?

*/ “real data and” has been removed /**

60. Page 11 line 9 degradation of 8% in terms of what?

*/ After “: :: 8% “ we have added “of its power production ” “ : ::” /**

61. Page 11 line 13 Replace “in displayed” by “is shown”

*/ “in displayed” replaced by “is shown” /**

62. Page 11 line 18 Why “Therefore”?

*/ “Working with :: wind speeds. Therefore :: 5 m/s.” is replaced by:

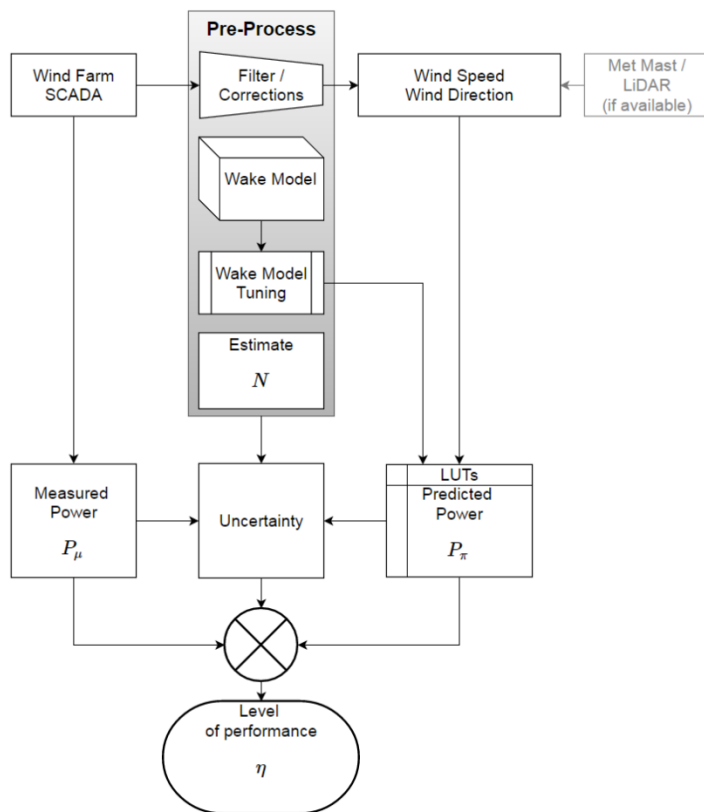
“Below 5m/s we have realized a strong increase in wind direction variation among the turbines compared to the artificial wind direction from the virtual met mast. This variation increases the uncertainty of the model and therefore its filtered out.” /**

63. Page 12 line 10 “horizontal graph” you mean horizontal line?

*/ “graph” replaced by “line”

64. Symbols in Fig. 1 are not the same symbols: : : they are not in italics

*/ Fig. 1 has been improved. It is now also showing the pre-process of cleaning and applying offset corrections to the data, before wind speed and wind direction are derived.



/**

65. Figure 3: The wind direction should not be perpendicular to the rotor? nbeta (which is not the wind direction) is the angle perpendicular to the rotor

/**/ β is perpendicular to the rotor. The wind direction ϑ is in most cases different to β . And for this reason, we decided to display ϑ not perpendicular to the rotor. /**

66. Figure 5: scales, north, coordinates!

/**/ Scales, location, and north have been added. Description and caption adjusted accordingly /**

67. Figure 10: there should be some green points below 0.6, so perhaps it is better to degrade based on the best Cp curve

/**/ The green points below 0.6 are covered by the red points. We have changed the order of colour plotting. Now the points below the curtailment are green. The degradation is visible for all wind speeds /**

In addition to these comments we would like to point out, that by rechecking the filtering procedure a minor filtering bug was revealed (1.5 IQR was static and not dynamic). This has changed the uncertainty of the wind direction from 3.1° to 3.6° which leads to minor changes in the numbers given in Table 3 and Table 4.

Paper: wes-2016-16

Title: Monitoring offshore wind farm power performance with SCADA data and advanced wake model

Authors: Niko Mittelmeier et al.

Answers to comments of anonymous Referee #2 by

Niko Mittelmeier et al. November 1, 2016

Dear Referee,

Thank you very much for reviewing our paper and sharing your experience. It is of great value for us and we hope to have answered your questions and comments sufficiently. Your comments helped us to identify the sections, where certainly more explanations are necessary and it will help to improve the paper.

In Part 1, our responses to your comments are marked as *******/ Response *******. In the second part, we have attached the change track version of the word document with all referee comments. We hope this is helpful to find our (RC2) changes in the context. Please use the pdf bookmarks for navigation.

Part 1

It is an interesting paper, introducing a new validation method for identifying wind farm underproduction. Such methods are highly needed with the large amount of wind turbines are installed in wind farms. The precondition for my review is that the method should also be applicable for implementation and not only be an theoretical exercise. The method, which seems to be a spin-off from an EERA project named ClusterDesign, refers to an ideal determination of the inflow conditions. The proposed method uses wake models estimates as reference, which seems to make a robust estimate of the underproduction. The accumulated uncertainty for the inflow conditions has been estimated to 7% and this number seems realistic when using recent calibrated instruments (cup and vane). This number is not realistic when using derived inflow conditions based on nacelle anemometry, electric power and wind turbine yaw position for periods longer than 1 year according to my experience.

*******/ You are right, this result would not be realistic if it was based on absolute AEP values. But we have obtained 7% combined uncertainty based on normalised reference values compared between model and measurement. We see the advantage of the proposed method in the fact, that a precise wind speed measurement is less important compared to the IEC 61400-12-1 or IEC 61400-12-2. The sensitivity factor for wind speed uncertainty is taken from the slope of the power curve. When we normalize the power curve with the power of the same turbine type, Type B uncertainties become almost 0 in free flow conditions. The second thing we find helpful to reduce the known disadvantages from nacelle wind speed measurements is the fact, that we average all devices from turbines in free flow conditions. The variation among these signals is then represented in the uncertainty estimation.

We can confirm your concern, that yaw positions (nacelle positions) are prone to errors over time if no care is taken. For our monitoring model we are using the absolute wind direction signal from each turbine which is defined as

$$\vartheta = \text{nacelle position} + \text{wind vane position}$$

The nacelle position is the angle between the rotor axis and a marking for true north. This marking is calibrated as part of the commissioning. But often this signal is not maintained well during operation, because it has no effect on turbine performance. This causes the necessity to apply a bias correction to this signal before using it for reanalysis purposes. The wind vane position indicates the angle of the flow to the rotor axis. It directly provides a value for the yaw error. The turbine controller uses this signal to control the yaw activity. We have recalibrated ϑ by looking at the maximum wake deficit behind the turbine 26. This offset has been used to recalibrate all nacelle positions in the farm. *******

Problem: The determination of the wind farm inflow (environmental) conditions (wind speed and wind direction) seems not to be aligned with the state-of-art wind farm signals.

/ One of our main objectives was to establish a method that can be applied with no need for additional hardware installations. Therefore we have used the available SCADA data and a pre-process to derive the wind farm inflow conditions. We agree, with LiDAR techniques improvements may be possible./

In section 2.1.1 the wind direction is derived, but without any reference to how this is done. The wind direction measured on the nacelle is only used for yaw control, where the strategy is to keep the rotor aligned with the wind direction to minimize the yaw-misalignment. This signal can also identify a "forced" yaw misalignment used to determine the "wake drift"? The optimal readings from this instrument is 0, and will not reveal anything about the actual flow direction, which only can be identified from the wind turbine yaw position. The wind turbine yaw position not used by the controller, only when wind farm has sector management (proposed but never seen). The yaw position is usually not calibrated or has a wrong offset, which need to be identified.

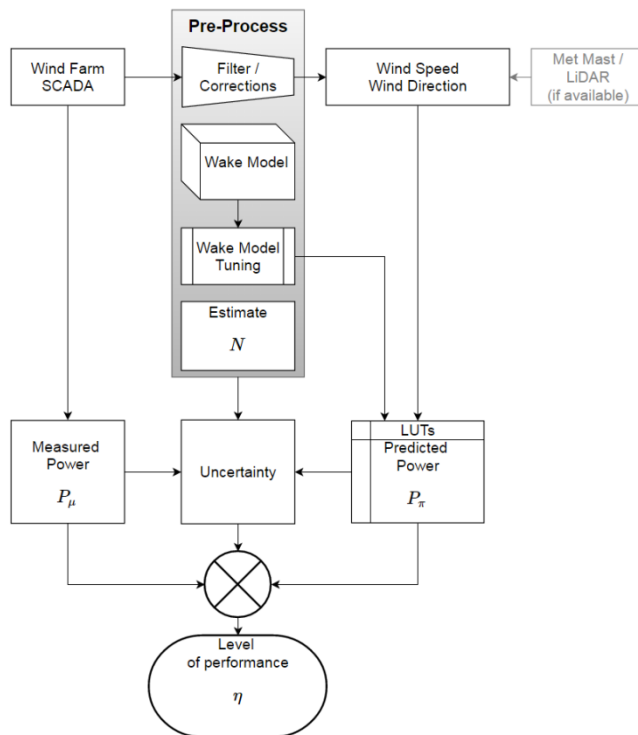
***/ Thanks for pointing this out. We see the need to provide more clarification in this section. We will add the following explanations:

“The first step is to derive a wind direction ϑ for each 10 min interval. For our monitoring model we are using the absolute wind direction signal from each turbine which is defined as

$$\vartheta = \text{nacelle position} + \text{wind vane position} \quad (4)$$

The nacelle position is the angle between the rotor axis and a marking for true north. This marking is calibrated as part of the commissioning. But often this signal is not maintained well during operation, because it has no effect on turbine performance. This causes the necessity to apply an offset correction to this signal before using it for reanalysis purposes. The wind vane position indicates the angle of the flow to the rotor axis. It directly provides a value for the yaw error. The turbine controller uses this signal to control the yaw activity. Within the Pre-Process (Fig.1) of the monitoring model we estimate the north marking offset for one turbine by checking the location of the maximum wake deficit with respect to the true north. Then we compare the average wind direction between corrected turbines and neighbouring turbines to estimate the remaining offset for all turbines. After applying this offset correction, the wind direction from all wind vanes are averaged in the complex plane to account for the wind direction discontinuity at the beginning/end of the value range, after removing outliers outside ± 1.5 IQR (interquartile range).”

Furthermore, we will update Fig. 1 as below, to show the Pre-Process which is necessary to derive the right wind direction signal.



/***/

Section 2.1.2 states to use nacelle anemometry to determine the wind speed; correct this is the only accessible wind speed measured on a wind turbine. This is measured with either a cup anemometer or sonic, located on the nacelle (behind the rotor). The signal is recorded through the controller and stored in SCADA system, but lacks documentation and uncertainty estimation. A correlation check between a number of identical wind turbines reveals a large scatter in the binned power curves. The scatter increases when the turbine operates in a wake compared to free inflow.

Conclusion:

the nacelle wind speed signal is biased. Furthermore the nacelle anemometer changes over years e.g. due to degradation. Even a NTF based wind speed (IEC 61400-12-2) is only applicable for free, undisturbed inflow.

***/ We absolutely agree with you conclusion. But as described in our response above, the monitoring method is less sensitive to wind speed measurements compared to IEC 61400-12-1 and IEC 61400-12-2 cause comparison is based on normalized power curves.

Secondly, the derived wind speed consists of only free and undisturbed nacelle wind speed signals and the variation among the devices is reflected by the uncertainty (one standard deviation) /***/

Conclusion on inflow conditions: the stated uncertainty, for wind speed and wind direction does not meet the requirements given in IEC 61400-12-1 and this need to be addressed both in the method and in the example.

***/ We will add clarification about that in the last paragraph of Section 4 (Discussion):

“The stated uncertainties for wind speed and wind direction may be sufficient for the relative comparison to detect underperformance between turbines but it does not meet the requirements for an absolute performance validation according to IEC 61400-12-1(2005) or IEC 61400-12-2 (2013). One could perform power curve verification test in accordance with the mentioned standards at turbines where its applicable and those turbines being reference turbines in the monitoring method would increase the confidence in underperformance detection. At least for the concurrent period.”

/***/

Comments to the figures: all figures should include proper captions readable out of context. The caption of the figures are not sufficient e.g. while Figure 2b is not addressed in the caption.

***/ Thanks for this advice. Below we provide new captions for each figure so that its understandable out of the context:

Figure 1: Flowchart of the Performance Monitoring Model. Wind speed and wind direction are derived from SCADA data after an offset correction of each wind direction signal and outlier filtering. Wake model calculations and tuning as well as the estimation of the number N of 10-min samples for averaging are pre-processed. N , P_π and P_μ are input values for the uncertainty calculation. An underperformance indicator η lower than the uncertainties indicates underperformance.

Figure 2: Impact of different key tuning aspects on the wake model results step by step. An increasing atmospheric stability increases the wake deficit (from red rhombus to black triangles). Wind direction uncertainty flattens the wake deficit (orange points), and a wind direction bias shifts the deficit horizontally (green squares). The left plot shows the power of the turbine in the wake divided by the power of a turbine in free flow conditions as function of the wind direction. The right plot displays the same power ratio as function of the normalized wind speed. (normalized power curve)

Figure 3: Determination of free flow turbines for wind speed averaging. The turbine at (x_0, y_0) produces a wake on the turbine at (x, y) for the displayed wind direction θ . β is the angle between the orientation of the turbines and the true north. α is the angle of the disturbed sector in accordance with IEC 61400-12-1.

Figure 4: Underperformance indicator η with uncertainty margin as function of the number of measurement values N . Derived with the calibrated model at a turbine in triple wake.

Figure 5: Layout of wind farm Ormonde. The 30 turbines of 5MW class are located in the Irish Sea 10km west of the Isle of Walney. For a wind direction of 207° the single wake, double wake and triple wake behind OR26 has been selected as underperformance demonstration cases.

Figure 6: Estimation of uncertainty of the artificial wind direction. Histogram of the deviation of 30 individual wind vanes from the average wind direction for the full data set filtered for wind speeds $> 5\text{ m/s}$ with a sector of 30° centring the full wake condition. The red curve represents a Gaussian fit with a standard deviation of 3.6° .

Figure 7: Wind farm averaged wind speed with wake effects normalised with wind farm averaged wind speed without wake effects plotted versus averaged wind farm wind direction. Black dots show the measurements from SCADA and the green solid line represents the results from Fuga with a Gauss averaging for standard deviation of 4° . An offset of the wind direction between model and SCADA can be observed. At 207° the offset is approximately 2.2° and it increases up to 5° for wind directions (132° and 312°) with the largest wake effects. An explanation and correction for this “wake drift” is proposed in section 2.2.

Figure 8: Estimation of uncertainty of the artificial wind speed. Histogram of the wind speed difference of a single anemometer to the average wind speed of all free flow anemometers. The displayed Gaussian distribution (red line) has the standard deviation of 0.46 m/s . A sector of 30° centring full wake alignment has been selected.

Figure 9: Tuning of the wake model results. (left column) Power normalized by the power of the free flow turbine as function of the wind direction centred at full wake for $8 \pm 1\text{ m/s}$ wind speed. (right column) Power normalized by the power of the free flow turbine as function of the wind speed normalized by wind speed at rated power for the waked turbine. Black dots represent the measured and binned SCADA data with error bars of one standard deviation. The red triangles show wake model results with Fuga standard settings ($\zeta_0 = 0$, no Gaussian averaging) and the green diamonds provide the tuned results. ($\zeta_0 = 2.72E - 7$, Gaussian averaging as function of the wind speed and applying the wind direction offset to account for the wake drift).

Figure 10: Scatterplot with normalized power as function of the normalized wind speed for four turbines in one row with two error test cases. Green dots are the measured power values and represent optimal operation. 8% degradation of the power output is shown with yellow dots. A curtailment at 58% is shown in red.

Figure 11: Underperformance detection for curtailment (right column) and degradation (left column) at turbines with different levels of wake influence. The displayed values represent the underperformance indicator η as function of the number of values N . We highlight the first time of underperformance detection when the green dotted line is outside of the grey uncertainty bandwidth.

Figure 12: Uncertainties for the underperformance indicator $u(\eta)$ as function of N values for free flow, single wake, double wake and triple wake situation. Uncertainties for free flow conditions (green) are much lower than the uncertainties for the waked turbines.

/**

The description of the method seems to be adequate, but the "wake drift" in section 2.2 is not well defined, I assume this refers to periods with active wake control, which I do not expect has been implemented yet?

*/ The data for our demonstration is without active wake control. We cannot fully rule out the possibility of an unwanted yaw misalignment as the uncertainties within this process of aligning the turbine lies within 3° (IEC 61400-12-2, 2013).

We rather think, that a small wake drift is also possible for a perfectly aligned turbine. Therefore we will add the following explanations and references to provide better explanations of the observed phenomenon.

“The third tuning parameter is applying a simple offset on the wind direction of the LUTs to account for a drift of the wake. We call this phenomena from here on “wake drift”. Fleming (2013) has studied the effects of active wake control and in his baseline simulation (no yaw error) a small wake drift to the right can be observed when looking downwind. In the LES study of Vollmer et al. (2016) the wake drift increases from neutral to stable conditions also for 0° yaw angle. Gebraad (2014, p86) gives an explanation for the observations from the simulations by Fleming (2013). The flow reacting on the rotation of the rotor causes the wake to rotate counter clockwise (looking downstream). Higher wind speeds from the upper layer are transported downwards (on the left side) and lower wind speeds from the lower layer are pushed upward on the right side of the wake. As a result the velocity deficit at the right part of the wake increases, so the wake deflects to the right. Marathe et al. (2015) could show in their field measurement campaign with a dual-doppler radar the wake drifting to the right, as expected by the theory. But in the far wake they registered a movement to the left. The authors state the hypothesis that this contradicting phenomenon may be caused by atmospheric streaks. In an offshore field experiment by Beck et al. (2015) further evidence is provided that wakes are moving out of the centre line. This wake drift is currently not modelled in Fuga and therefore applied in a further step of the pre-process (Fig. 1).“

References for this paragraph:

Beck, H., Trujillo, J. J., Wolken-möhlmann, G., Gottschall, J., Schmidt, J., Peña, A., Gomes, V., Lange, B., Hasager, C. and Kühn, M.: Comparison of simulations of the far wake of alpha ventus against ship-based LiDAR measurements, in RAVE Conference., 2015.

Fleming, P. A., Gebraad, P. M. O., Lee, S., van Wingerden, J. W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P. and Moriarty, P.: Evaluating techniques for redirecting turbine wakes using SOWFA, in ICOWES2013 Conference., 2013.

Gebraad, P. M. O.: Data-Driven Wind Plant Control, 2014.

Marathe, N., Swift, A., Hirth, B., Walker, R. and Schroeder, J.: Characterizing power performance and wake of a wind turbine under yaw and blade pitch, , doi:10.1002/we, 2015.

Vollmer, L., Steinfeld, G., Heinemann, D. and Kühn, M.: Estimating the wake deflection downstream of a wind turbine in different atmospheric stabilities: An LES study, Wind Energy Sci. Discuss., (March), 1–23, doi:10.5194/wes-2016-4, 2016.

/**

Paper: wes-2016-16

Title: Monitoring offshore wind farm power performance with SCADA data and advanced wake model

Authors: Niko Mittelmeier et al.

Answers to comments of anonymous Referee #3 by

Niko Mittelmeier et al. November 1, 2016

Dear Referee,

Thank you very much for your interest and taking the time to review our paper. Your comments and suggestions are very helpful and highly appreciated. In the first part, we have addressed each comment and our responses are marked as *****/ response/*****. In the second part, we have attached the change track version of the word document with all referee comments. We hope this is helpful to find our changes (RC3) in the context. Please use the pdf bookmarks for navigation.

Part 1

Dear Authors,

thank you for a interesting and novel idea for the detection of underperforming wind turbines. While I agree with the overall tenet of the paper, there are a few issues I would like to have clarified. Particularly, the SCADA system delivers data at a much higher rate than the 10-min averages. What would happen if you'd make use of the 1-sec resolution available from the data? 130 values would suddenly be 2 minutes instead of 21 hours, if every assumption stays unchanged - which it probably doesn't.

*******/That is a very good question. And you are right, SCADA data can be recorded with 1-sec resolution. For our particular case, we have used two years of measurements to obtain a fairly good average result for the tuned wake model. And for this period only 10-min data was available. We see the problem with the higher resolution in the increasing scatter of the measurement. Particularly for 1-sec data wind direction and wind speed measured behind the rotor has a very large variation. As we are using this variation to determine the uncertainty of the measurement we would obtain a much higher uncertainty for the detection of underperformance. Type A uncertainties will decrease faster but Type B uncertainties will increase. *******

How do you deal with intra-10-min variability? Do you require a relatively stable weather situation or at least wind direction to be able to do it?

*******/ We are working with 10-min averages and we need N values of 10-min to be averaged, before we can highlight underperformance. Therefore we think that intra-10-min variability is averaged out in most cases. The intra-10-min variability of the wind direction is supposed to be covered by the Gaussian averaging method proposed by Gaumond et al. (2014).

The model is tuned for the annual average weather conditions. In weather conditions, where the model systematically under-, or over-predicts the wake effects the underperformance indicator η will be biased. This has not been explicitly tested, but we think that $n(n-1)$ calculations would reveal turbines which deviate compared to the fleet.

A degradation of the whole wind farm will probably be a slow process and would therefore be much closer at annual averaged conditions for which the wake model is tuned.

References:

Gaumond, M., Réthoré, P., Ott, S., Pena, A., Bechmann, A. and Hansen, K. S.: Evaluation of the wind direction uncertainty and its impact on wake modeling at the Horns Rev offshore wind farm, Wind Energy, 17, 1169–1178, doi:10.1002/we.1625, 2014.

More detailed comments:

Page 2 Line 1: Offshore met masts are very expensive. Are people really putting up met masts offshore to verify the turbine performance? Or onshore?

/ The installation of an offshore met mast purely for power curve verification has probably not happened yet. But there are already quite a number of offshore met masts installed which are used for performance and research investigations. Just mentioning a few: Fino1-3, Nordsee Ost, Amrumbank, Horns Rev. /

P3L17: I think this is debatable. Since you need quite a number of values / quite some time to detect the deviations, the method is not really real time anyway, so it could also be analysed retroactively every now and then. It also could be run on a larger highperformance computer based on downloaded SCADA data. Besides, the connection between higher computational cost and accuracy of the wake models is sketchy at best, see e.g. the results presented in WindBench.

***/You are right, this whole paragraph has been revised as follow:

“The performance monitoring model (Fig. 1) is based on two dimensional LUTs. The user can choose any wake model or even a combination of different model results to provide power output $P_{\pi_{i,j}}$ values for different wind speed bin i and wind direction bin j . The predicted power output P_{π} is derived from the LUTs with linear interpolation knowing the measured wind speed and wind direction. “

With real time calculation speed, we meant the fact, that in our performance monitoring model each and every single 10-min SCADA measurement is recalculated by the wake model and therefore the wake model must be at least be able to calculate one single conditions in 10-min. The detection of underperformance is due to the averaging of many 10-min samples not “real time” anymore.

/***

2.1.1: I wonder why you do not use the same correction method on all the wind farms wind vanes? It just requires SCADA data and some computer power, so it would not be too difficult. Also, when you’re calculating a mean wind direction for the whole farm, aren’t you relying on a smaller size farm far away from the coast? For example, if you have a location like Anholt, then you have wind and direction gradients due to the proximity of the land across the wind farm. How would that influence your method and its accuracy?

***/This is a very valid point. In our model, the wind direction should be representative for the selected turbines. The variation among the individual wind vanes is used to come up with an uncertainty estimate. With larger wind farms, we expect this variation to increase which will lead to an increase of the uncertainties. We would recommend to divide very large wind farms in smaller groups. One way of defining a quality criteria could be to ensure, that the standard deviation of the single wind directions compared to the average wind direction is smaller or equal to 3.6° (values we have obtained).

We will add the following wording in the paper, to better describe the wind direction correction and estimation:

“The first step is to derive a wind direction ϑ for each 10 min interval. For our monitoring model we are using the absolute wind direction signal from each turbine which is defined as

$$\vartheta = \text{nacelle position} + \text{wind vane position} \quad (4)$$

The nacelle position is the angle between the rotor axis and a marking for true north. This marking is calibrated as part of the commissioning. But often this signal is not maintained well during operation, because it has no effect on turbine performance. This causes the necessity to apply an offset correction to this signal before using it for reanalysis purposes. The wind vane position indicates the angle of the flow to the rotor axis. It directly provides a value for the yaw error. The turbine controller uses this signal to control the yaw activity. Within the Pre-Process (Fig.1) of the monitoring model we estimate the north marking offset for one turbine by checking the location of the maximum wake deficit with respect to the true north. Then we compare the average wind direction between corrected turbines and neighbouring turbines to estimate the remaining offset for all turbines. After applying this offset correction, the wind direction from all wind vanes are averaged in the

complex plane to account for the wind direction discontinuity at the beginning/end of the value range, after removing outliers outside ± 1.5 IQR (interquartile range).”

We are using the wake “centre check” only at one turbine because of the observed “wake drift” (We will give more explanation to this term three comments later) /***

P4L1: Is that one reference turbine for the whole farm, or one particular one for each of the other turbines? If it is one for the farm, how is it defined?

/ we take one turbine (turbine under observation) and use every single turbine in the farm as reference. (One after each other) Then we take the next turbine to observe. In this way, we obtain $n(n-1)$ results. In this way we increase the confidence in underperformance detection cause a real underperforming turbine will be highlighted multiple times. /

P7L23: So the Type A uncertainties do not multiply in a multiple wake situation?

***/ It certainly makes a difference in the Type A uncertainties in which wake situation you are and this is reflected by the prediction accuracy of this wake itself. We use the standard deviation of N differences between the modelled power and the measured power and divide it with the square root of N .

We have changed the wording to be more precise:

“For the predicted power P_{π} , we are using a combined uncertainty with statistical type A uncertainties, being the experimental standard deviation of the mean from the difference between wake model predictions and measurements and type B uncertainties which conclude from the instrument devices to estimate wind speed and wind direction. “/***

P10L15-22: This is quite interesting. Has this behaviour been observed anywhere else? Another explanation could be that the overall wind flow is skewed at the Ormonde location, which judging by the map is not impossible, seeing that the wind farm is wedged between land and a larger offshore wind farm. Or do I understand this wrong, and it is an effect from Fuga which is described here? Did you switch on the meandering mechanism in Fuga?

***/ The effect we are describing here is not modelled in Fuga. During our wake model results validation, we have also looked into the meandering option, but we obtained better results with the Gaussian averaging method. It might also be possible, that the neighbouring wind farms have an effect and play a role on the observed behaviour. But we can also provide some publications below which have observed and tried to explain a similar wake behaviour.

These studies have the general aim to investigate active wake control but they also provide examples for 0° yaw error. Fleming (2013) shows in his baseline simulation (no yaw error) a small wake shift to the right when looking downwind. In the LES study of Vollmer et al. (2016) it can be observed, that the wake deflection increases from neutral (Vollmer et al. 2016, Fig. 5) to stable conditions (Vollmer et al. 2016, Fig. 9). These Figures provide simulated results also for a turbine with 0° yaw angle. In both cases the maximum wake deficit is found to be on the right side of the centre line (looking downstream).

Gebraad (2014, p86) gives an explanation for the observations from the simulations by Fleming (2013). The flow reacting on the rotation of the rotor causes the wake to rotate counter clockwise (looking downstream). Higher wind speeds from the upper layer are transported downwards (on the left side) and lower wind speeds from the lower layer are pushed upward on the right side of the wake. As a result the velocity deficit at the right part of the wake increases, so the wake deflects to the right.

Marathe et al. (2015) could show in their field measurement campaign with dual-doppler radar, that in the near wake region, the wake is drifting to the right, as expected by the theory. But in the far wake they registered a contradicting movement. The authors state the hypothesis that this phenomenon may be caused by atmospheric streaks. An offshore field experiment by Beck et al. (2015) provides further evidence that wakes are moving out of the centre line.

References:

Beck, H., Trujillo, J. J., Wolken-möhlmann, G., Gottschall, J., Schmidt, J., Peña, A., Gomes, V., Lange, B., Hasager, C. and Kühn, M.: Comparison of simulations of the far wake of alpha ventus against ship-based LiDAR measurements, in RAVE Conference., 2015.

Fleming, P. A., Gebraad, P. M. O., Lee, S., van Wingerden, J. W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P. and Moriarty, P.: Evaluating techniques for redirecting turbine wakes using SOWFA, in ICOWES2013 Conference., 2013.

Gebraad, P. M. O.: Data-Driven Wind Plant Control, 2014.

Marathe, N., Swift, A., Hirth, B., Walker, R. and Schroeder, J.: Characterizing power performance and wake of a wind turbine under yaw and blade pitch, , doi:10.1002/we, 2015.

Vollmer, L., Steinfeld, G., Heinemann, D. and Kühn, M.: Estimating the wake deflection downstream of a wind turbine in different atmospheric stabilities: An LES study, Wind Energy Sci. Discuss., (March), 1–23, doi:10.5194/wes-2016-4, 2016.

/**

Figure 5: A map of the location would be good here (see above).

*/ New Figure with orientation and scales provided

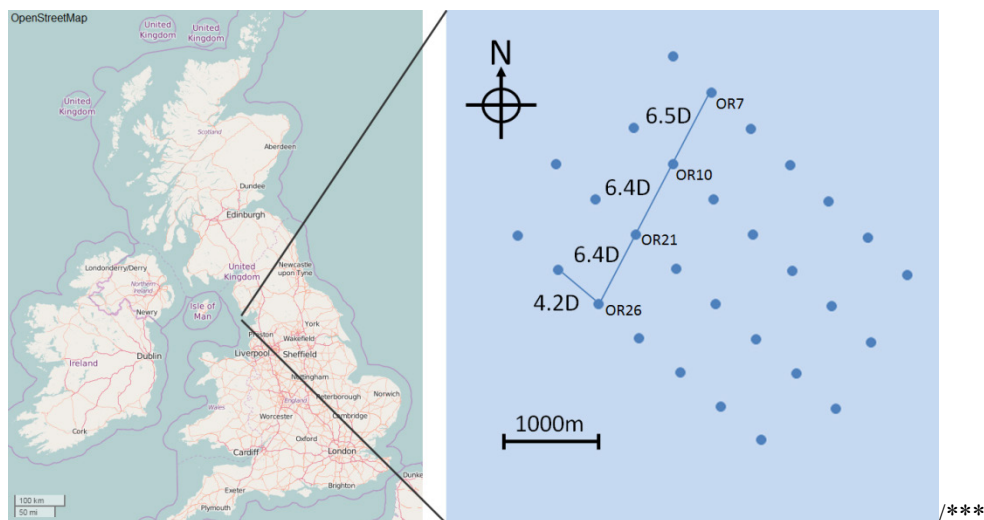


Figure 7: There seems to be a shift in wind direction between the SCADA system and the calculations - any idea where that is coming from?

*/ The wake model results used in this plot are directly taken from the Fuga Output. No wake model tuning/corrections as proposed in the pre-process step of the monitoring method (Fig. 1) has been applied. The corrected model has an 2.5° offset for all single wake case, 3.5° offset for the double wake cases and a 4.5° offset for the triple wake case for wind directions $207^\circ \pm 15^\circ$. In Fig.7 the offset of the wind direction at 207° (the four demonstration turbines in a column) is approximately 2.2° . At the wind directions 132° and 312° , with the largest wake effects along the four rows of 7 to 8 turbines, the offset is approximately 5° . This fact supports the theory, that with every additional wake added to the flow, the overall “wake drift” increases. We will add this information into the caption of the plot.

“Figure 7: Wind farm averaged wind speed with wake effects normalised with wind farm averaged wind speed without wake effects plotted versus averaged wind farm wind direction. Black dots show the measurements from SCADA and the green solid line represents the results from Fuga with a Gauss averaging for standard deviation of 4° . An offset of the wind direction between model and SCADA can be observed. At 207° the offset is

approximately 2.2° and it increases up to 5° for wind directions (132° and 312°) with the largest wake effects. An explanation and correction for this “wake drift” is proposed in section 2.2.” /***

Table 2: Is the source of that the IEC Annex D uncertainty estimation, or own values?

/The values are based on the example given in IEC 61400-12-1 (2005) Annex E. We will add this information in the caption of Table 2./

Textual issues:

P1L9: The presented method or the present method?

/We will change the sentence to: ” The method, presented in this paper, estimates.../

P1L18: "The common [...] definition defines that the system is ready to operate" might not be exactly what is in the availability standard. Please rephrase.

***/Thanks for the advice, here is our new sentence:

“In wind industry, the common standard IEC TS 61400-26-1 (2011) defines different categories of turbine conditions and describes the calculation of availability”/***

P1L23: What’s the difference between IEC 61400 and IEC TS 61400?

***/ TS stands for “Technical Specification”.

Both Documents (IEC TS 61400-26-1 and IEC TS 61400-26-2) are technical specifications. An “International Standard” has a higher degree than a “technical specification”. Work is ongoing to bring these TS to the level of an “International Standard”

We have revised the references accordingly./***

P2L25: To lower uncertainties, ... ??

***/We have rephrase the whole paragraph:

“Mittelman et al. (2013) presented a new method where not the absolute values between model and measurement are compared, but the relations between an observed turbine and all other turbines in the farm. In this way, the uncertainty of the measurement chain could be reduced. The model is also based on pre-calculated power matrices which we call from now on “lookup-tables” (LUTs). Different wake models or even combinations of wake model results can be used to provide results for these LUTs. But the model relies on measurements from a met mast which is often not available. Furthermore, with increasing size of wind farms, the assumptions of one measurement position being representative for the whole offshore wind farm is not valid (Dörenkämper, 2015). Further investigations are necessary to obtain a reliable and automated method to detect underperformance at individual turbines in a wind farm.”/***

P6L15: You might want to explain what you mean by "wake drift".

***/Sure. We understand the need to provide more explanation and references on this topic. The last paragraph of section 2.2 has been revised as follow:

“The third tuning parameter is applying a simple offset on the wind direction of the LUTs to account for a drift of the wake. We call this phenomena from here on “wake drift”. Fleming (2013) has studied the effects of active wake control and in his baseline simulation (no yaw error) a small wake drift to the right can be observed when looking downwind. In the LES study of Vollmer et al. (2016) the wake drift increases from neutral to stable conditions also for 0° yaw angle. Gebraad (2014, p86) gives an explanation for the observations from the simulations by Fleming (2013). The flow reacting on the rotation of the rotor causes the wake to rotate counter clockwise (looking downstream). Higher wind speeds from the upper layer are transported downwards (on the left side) and lower wind speeds from the lower layer are pushed upward on the right side of the wake. As a result the velocity deficit at the right part of the wake increases, so the wake deflects to the right.

Marathe et al. (2015) could show in their field measurement campaign with a dual-doppler radar the wake drifting to the right, as expected by the theory. But in the far wake they registered a movement to the left. The authors state the hypothesis that this contradicting phenomenon may be caused by atmospheric streaks. In an offshore field experiment by Beck et al. (2015) further evidence is provided that wakes are moving out of the

centre line. This wake drift is currently not modelled in Fuga and therefore applied in a further step of the pre-process (Fig. 1).“

References for this paragraph:

Beck, H., Trujillo, J. J., Wolken-möhlmann, G., Gottschall, J., Schmidt, J., Peña, A., Gomes, V., Lange, B., Hasager, C. and Kühn, M.: Comparison of simulations of the far wake of alpha ventus against ship-based LiDAR measurements, in RAVE Conference., 2015.

Fleming, P. A., Gebraad, P. M. O., Lee, S., van Wingerden, J. W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P. and Moriarty, P.: Evaluating techniques for redirecting turbine wakes using SOWFA, in ICOWES2013 Conference., 2013.

Gebraad, P. M. O.: Data-Driven Wind Plant Control, 2014.

Marathe, N., Swift, A., Hirth, B., Walker, R. and Schroeder, J.: Characterizing power performance and wake of a wind turbine under yaw and blade pitch, , doi:10.1002/we, 2015.

Vollmer, L., Steinfeld, G., Heinemann, D. and Kühn, M.: Estimating the wake deflection downstream of a wind turbine in different atmospheric stabilities: An LES study, Wind Energy Sci. Discuss., (March), 1–23, doi:10.5194/wes-2016-4, 2016.

/***

P9L9/L15: "of demonstration wind farm" could be deleted without detriment.

/ Thanks for pointing this out. We will delete that part. /

P9L13: This value is used_for the uncertainty...

/ Thanks. It is corrected./

P10L5: I would drop the brackets around the version number of Fuga.

/ Agreed./

P10L14: I don't think I've seen zeta_naught introduced before?

***/ This value is directly used as an input parameter in Fuga. The theory behind it is described in Ott and Nielsen (2014). We will add “Secondly, the **Fuga** parameter to model the effect of atmospheric stability $\zeta_0 \dots$ ”

References:

Ott, S. and Nielsen, M.: Developments of the offshore wind turbine wake model Fuga, Report E-0046, DTU Wind Energy., 2014. /***

P10L15: While wind and nautical terms can easily be construed to have a connection, not everyone is familiar with "starboard".

***/ Sorry, being offshore tempt us to use nautical terms.

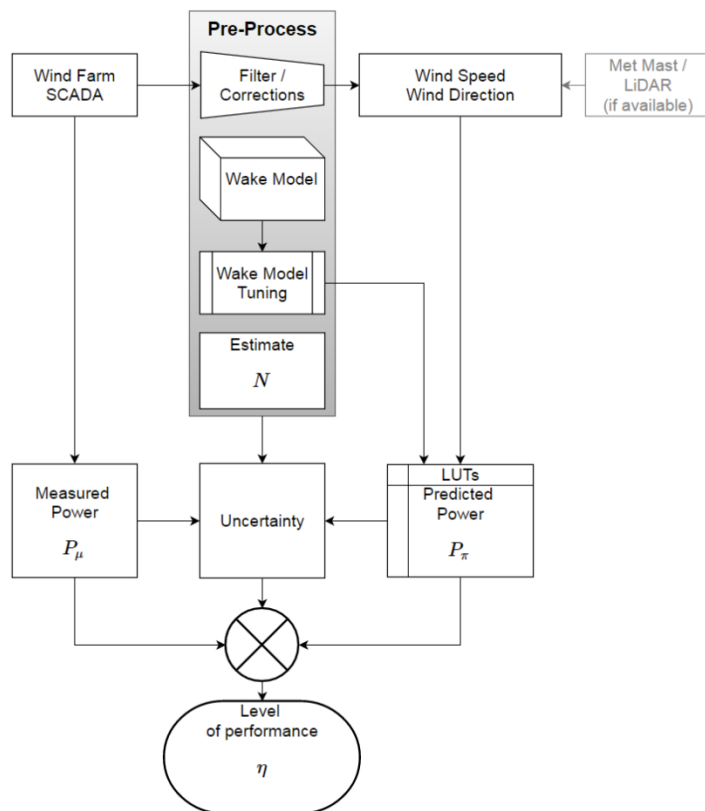
“Starboard” replaced by “right”

“Port” replaced by “left” /***

Figure 1 center: Should that really be called Uncertainty, or rather something like Deviation?

***/ We have updated Fig. 1. (see below). We are calculating an uncertainty value for each 10-min SCADA measurement. And the input for this calculation comes from the SCADA power, the N and the LUTs. This uncertainty is a variable threshold for the model. Only if the deviation between the ratio π and the ratio μ is

higher than the uncertainty, then underperformance is highlighted. For this reason we will keep the wording “uncertainty” in Fig.1. /***



/***

Part 2

Monitoring offshore wind farm power performance with SCADA data and advanced wake model

Niko Mittelmeier¹,Tomas Blodau¹, Martin Kühn²

¹Senvion GmbH, Überseering 10, 22297 Hamburg, Germany

²ForWind – Carl von Ossietzky University of Oldenburg, Ammerländer Heerstraße 136, 26129 Oldenburg Germany

Correspondence to: Niko Mittelmeier (niko.mittelmeier@senvion.com)

Abstract. Wind farm underperformance can lead to significant losses in revenues. Efficient detection of wind turbines operating below their expected power output and immediate corrections help maximise asset value. The presented method, presented in this paper, estimates the environmental conditions from turbine states and uses pre-calculated power matrices/look-up tables (LUTs) from a numeric wake model to predict the expected power output. Deviations between the expected and the measured power output ratio between two turbines are an indication of underperformance. The confidence of detected underperformance is estimated by detailed analysis of uncertainties of the method. Power normalisation with reference turbines and averaging several measurement devices can reduce uncertainties for estimating the expected power. A demonstration of the method’s ability to detect underperformance in the form of degradation and curtailment is given. Underperformance of 8% could be detected in a triple wake condition.

1. Introduction

To increase confidence in offshore wind energy investments, investors need reliable technical solutions wind turbines. The two pillars of system reliability are operational availability and the ability to achieve predicted power performance. In the wind industry, the common standard availability definition (IEC TS 61400-26-1, (2011)) defines different that categories of turbine conditions and describes the calculation of availability~~the system is ready to operate~~. However within this standard the “Full Performance” category requires only the status of not being restricted in power production but there is no indication verification of about the quality of the power performance ~~of the whole wind farm under given conditions~~. The key to an economic investment is a function of quality and quantity.

The key to an economic investment is a function of quality and quantity and quality. Quantity is linked to availability and wind turbines can provide lots of much SCADA (supervisory control and data acquisition) information which enables analysis of ~~the~~ time based (IEC TS 61400-26-1, 2011) and production based availability (IEC TS 61400-26-2, 2014). The A power curve verification test according to the international standard (IEC 61400-12-1, 2005) proves the quality of the power performance of a single turbine in specific conditions using a hub height met mast typically for a very limited period

Kommentar [NM1]: RC3: P1L9: The presented method or the present method?

Kommentar [MN2]: RC1: 1. Page 1 line 16 “: : technical solutions.” This type of statements are very general and not precise and specific. What do you mean by this? Turbines, models, methods?

Kommentar [NM3]: RC3: P1L18: "The common [...] definition defines that the system is ready to operate" might not be exactly what is in the availability standard. Please rephrase.

Kommentar [NM4]: RC3: P1L23: What's the difference between IEC 61400 and IEC TS 61400?

Kommentar [MN5]: RC1: 2. Page 1 line 18 “: : definition (: :) defines: : :” that the system is ready to operate” this is redundant. Why not “: : : definition (: :) is that related to a system ready to operate”

Feldfunktion geändert

Kommentar [MN6]: RC1: 3. Page 1 line 20 “: : : quality and quantity.” Of what? In the next paragraph you kind of explain it but you cannot simply say this here and expect that the reader finds the answer later. If this is the case then that sentence can be removed.

Kommentar [MN7]: RC1: 4. Page 1 line 21 Replace “: : : much SCADA” by “lots of” or “a good amount of”

of time can be tested in accordance with the international standard (IEC 61400-12-1; (2005)). ~~Work on a second edition of the IEC is ongoing which would allow smaller masts in combination with a remote sensing device (e.g. LiDAR or SODAR) and is expected for release by the end of 2016.~~ For most turbines in a typical offshore wind farm, this verification of the performance by comparison with the power curve is not suitable due to wake effects. And the installation and maintenance for an offshore of a met mast is very expensive particularly offshore. Quantifying changes in power production based on wind speed measurements from nacelle anemometry relies on the quality of the device itself and its transfer function which should account for the flow distortion behind the rotor. Using this approach still requires a wake free sector and leads to an increase in uncertainties. (Albers et al., 1999). (IEC 61400-12-2, 2013).

Efficient detection of underperformance of wind turbines increases asset value (Albers, 2004a). Incorrect turbine parameter settings, degradation of the blades, pitch or yaw errors all lead to less production than expected. We differentiate between degradation and curtailments. ~~A turbine that is degraded reaches rated power, but does not fulfil its expected power curve.~~ A curtailed turbine has a limited power output which has been externally applied and is below its expected power. Possible reasons for curtailments are load or sound reductions or grid requirements. For these incidents, turbine parameters are changed on purpose and therefore documented in the turbines SCADA logs. ~~A turbine that is degraded reaches rated power, but does not fulfil its expected power curve.~~ These kind of underperformance are more difficult to detect, especially when operating in the wake of neighbouring wind turbines.

~~Several approaches to evaluate the performance of a whole wind farm have been published before. Upwind turbines influencing the free flow for downwind turbines, called wake effects, add complexity to the task. Much work has been done by Axel Albers (Albers and Gerdes, 1999), (Albers et al., 2003) and (Albers, 2004) who has investigated performance verification and underperformance detection methods based on correlations between the individual turbines and the wind farm as a whole. Albers has also looked into the possibility of verifying wind farm performance by comparison with wake flow models. But at that time he concluded that the models have to be further development especially for complex terrain.~~ (Albers, 2004b) has published two methodologies for wind turbine performance evaluation. His integral model uses available wind conditions from the energy production of neighbouring WTs, met masts or a combination of both and transfers the information via flow modelling and wake modelling to the investigated wind farm. The measured yield is corrected for turbine availability and then compared against the modelled yield in absolute values. Due to high uncertainties this method is only proposed as a first general check. To reveal smaller deviations he proposes a relative wind turbine performance evaluation model. For this method, active power of direct neighbours are plotted against each other and by comparing two periods, changes can be evaluated. This method explicitly excludes the sectors where wakes are effecting one or both turbines.

Kommentar [MN8]: RC1: 5. Page 1 lines 27-28 "Work on: : of 2016". You don't need this reference and does not help the paper so remove it

Kommentar [MN9]: RC1: 6. Page 1 lines 28- Page 2 line 1 "For most turbines: : : wake effects" You make it sound as it was only a problem for offshore turbines and it is not so replace by e.g. "For most turbines in a typical wind farm, verification of the performance by comparison with the power curve is not suitable: : : " then " : : maintenance of a met mast is very expensive particularly offshore."

Kommentar [NM10]: RC3: Page 2 Line 1: Offshore met masts are very expensive. Are people really putting up met masts offshore to verify the turbine performance? Or onshore?

Kommentar [MN11]: RC1: 7. Page 2 line 3 Replace "accounts" by "account"

Kommentar [MN12]: RC1: 8. Page 2 line 6 "Incorrect parameter settings" you mean "turbine parameter"?

Kommentar [MN13]: RC1: 9. Page 2 line 9 "turbine has a limited power output which has been externally applied" You want to refer to the limit but with the use of the "which" you mean the limited power output but surely this is not what is externally applied because one cannot apply a limited power output: : : that is a consequence of limiting something else.

Kommentar [MN14]: RC1: 10. Page 2 lines 11-16 this is a very weird paragraph. "Upwind turbines influencing the free flow for downwind turbines". This is a weird sentence because the flow is not free for the downwind turbines. Why not just removing the "free" word. Then it is also weird because you have " : : : wake effects," so with this construction you say the wake

An international ~~standard-working group~~ (IEC TC88 WG6, 2005) ~~was trying to come up with a standard for wind farm power performance testing, which The proposed method~~ ~~uses one or more~~ met masts to establish a measured wind farm power curve matrix. This two dimensional measured power matrix (Wind direction, Wind speed) ~~and is compared against a wake model modelled for performance verification of the wind farm as a whole~~ power matrix taking wake effects into account (Mellinghoff, 2007)(Carvalho and Guedes, 2009). ~~The standard could not be established due to high uncertainties and inaccurate results and the support from the Technical Committee members crumbled.~~

Further investigations are necessary to obtain a reliable and automated method, to detect underperformance or curtailment at individual turbines in a wind farm. (Mittelmeier et al., (2013) presented a new method ~~where not the absolute values between model and measurement are compared, but the relations between an observed turbine and all other turbines in the farm. In this way, the uncertainty of the measurement chain could be reduced. The model is also based on pre-calculated power matrices which we call from now on "lookup-tables" (LUTs). Different wake models or even combinations of wake model results can be used to provide results for these LUTs. But the model relies on measurements from a met mast which is often not available, to compare expected power results generated from complex wake models (pre-calculated and stored in matrices) with the actual wind turbine power output to detect underperformance in multiple wake situations. To lower uncertainties the method is based on ratios between the observed turbine and all reference turbines in the wind farm. This method relies on measurements from a met mast to determine the environmental conditions. Especially for offshore sites, a met mast is very expensive and therefore often not available.~~ Furthermore, with increasing size of wind farms, the assumptions of one measurement position being representative for the whole offshore wind farm is not valid (Dörenkämper, 2015). ~~Further investigations are necessary to obtain a reliable and automated method to detect underperformance at individual turbines in a wind farm.~~

The purpose of this paper is to present the results of extending ~~this~~ wind farm performance monitoring method of Mittelmeier et al. (Mittelmeier et al., 2013) by using SCADA instead of met mast data. A new combination of methods to obtain representative environmental conditions and further optimisation potential for wake models fine-tuned by SCADA data is presented and an estimation of the uncertainty of these methods is given. ~~Hence the presented method in (Mittelmeier et al., 2013) will be available with no requirement for installation of measurement equipment such as met masts or LiDAR.~~

In Section 2 the general approach of the method ~~by Mittelmeier at al. (Mittelmeier et al., 2013)~~ is recalled. A new approach to generate a virtual met mast from SCADA data is explained in detail in Section 2.1. The wake model optimisations are described in Section 2.2. A closer look at the uncertainties of the method especially in relation to the establishment of a virtual met mast is discussed in Section 2.3. In Sections 3, 4 and 5 results for a demonstration case are presented, followed by a detailed discussion and the final conclusions.

Kommentar [MN15]: RC1: 11. Page 2 line 18 " : : : which proposed" so the standard stopped at some point proposing this?

Kommentar [MN16]: RC1: 12. Page 2 line 19-20 " : : : ,could not be established," So it is not a standard, it is a working group trying to come up with a standard. Also delete the part " : : : and the support : : : crumbled." It is not scientific knowledge

Kommentar [MN17]: RC1: 14. Page 2 lines 23-27 "Mittelmeier et al. (2013) presented : : : environmental conditions." I am not sure this is a new method. In many other studies, authors used wake-model-based LUTs to estimate the efficiency of the wind farm. So the authors need to explicitly say what exactly is new.

Kommentar [MN18]: RC1: 13. From line 22 in page 2 onwards you talk about "matrices" but what you mean is "look-up-tables (LUT)" Use that term. There is an unnecessary comma in line 22 after "method". Also in that line you talk about detection of "curtailment". Perhaps your ...

Kommentar [NM19]: RC3: P2L25: To lower uncertainties, ... ??

Kommentar [MN20]: RC1: 15. Page 2 lines 27-28 "Especially : : : available." Already mentioned so remove it

Kommentar [MN21]: RC1: 16. Page 2 lines 31-33 Replace "this" by "the", add "of" after "method" and use "Mittelmeier et al. (2013)" instead of "(Mittelmeier et al., 2013)". Replace "condition" by ...

Kommentar [MN22]: RC1: 17. Page 3 line 1-2 "Hence the presented : : : LiDAR". Based on what you have already mentioned one can infer what is written here so it is not necessary

Kommentar [MN23]: RC1: 18. Page 3 line 4 it should be change to " : : : of the method by Mittelmeier et al. (2013) is recalled".

2. Methods

To detect underperformance of a wind turbine, we estimate the expected turbine power $\text{ratio } \pi P_{\pi}$ (predicted power ratio) between the observed turbine and a reference turbine with a wake model for the actual condition and compare its result with the actual measured power $\text{ratio } \mu P_{\mu}$. A deviation between π and μ ; higher than a certain threshold indicates underperformance.

The accuracy and calculation speed of a wake model are dependent on the degree of simplifications that are made to describe the real wind farm flow. Fewer simplifications will increase computation time and accuracy to a certain degree and therefore improve the underperformance detection capabilities, on the other hand, a performance monitoring method needs to predict the power P_{π} in real time or faster.

To be able to use a more sophisticated and more computational expensive wake model on a common personal computer, the power output $P_{\pi,i,j}$ can be pre-calculated for each wind turbine for each wind speed bin i and wind direction bin j and saved in a two dimensional matrix. The performance monitoring model (Fig. 1) is based on two dimensional LUTs. The user can choose any wake model or even a combination of different model results to provide power output $P_{\pi,i,j}$ values for different wind speed bin i and wind direction bin j . The predicted power output P_{π} is derived from the matrix-LUTs with linear interpolation knowing the measured wind speed and wind direction.

Additional information about the turbulence intensity, pressure, temperature and humidity from additional devices could be used to increase the dimensions of the power matrix and may add accuracy. As we are focusing on a monitoring method that uses only SCADA data, we will discuss and demonstrate one way to extract an useful wind speed and wind direction for this purpose monitoring method in Section 2.1.

Commonly used power measurements are averages of over 10-min periods minutes. Due to the fact that there is a high scatter on power measurements for the same wind speed and wind direction bin, averaging a number N quantities of 10-min minutes time samples is necessary until the power value converges to a satisfactory degree. The power matrix and the averaging N are derived in a pre-process as shown in Figure 1, which gives an overview on the whole performance monitoring process.

The power of the wind turbine under observation P_{ob} is correlated to divided by the power of a reference wind turbine P_{ref} . This leads to a normalized power curve with much lower slope in a wide range of partial load (See Figure 2 Fig. 2) and therefore decreases sensitivity on wind speed measurement uncertainty. We define This is described in Eq. (1) and Eq. (2).

Kommentar [MN24]: RC1: 19. Page 3 line 11 I know what you mean by "deviation" but you need to be exact so change to "A deviation between P_{π} and P_{μ} "

Kommentar [MN25]: RC1: 20. Page 3 lines 14-15 "The accuracy and calculation : : : real wind farm flow" This is not true. A simple wake model can be as accurate as a complex one.

Kommentar [MN26]: RC1: 21. Page 3 line 16 First "improve the underperformance detection capabilities" This is not always true. And replace ", " by "; " before "on the other hand"

Kommentar [NM27]: RC3: P3L17: I think this is debatable. Since you need quite a number of values / quite some time to detect the deviations, the method is not really real time anyway, so it could also be analysed retroactively every now and then. It also could be run on a larger highperformance computer based on downloaded SCADA data. Besides, the connection between higher computational cost and accuracy of the wake models is sketchy at

Kommentar [MN28]: RC1: 22. Page 3 line 23 Remove the first "Additional"

Kommentar [MN29]: RC1: 23. Page 3 line 25 "for this purpose" I know what you mean but you have not mention

Kommentar [MN30]: RC1: 24. Page 3 line 28 Replace ": : : averages of 10 minutes" by ": : : averages over 10-min periods"

Kommentar [MN31]: RC1: 25. Page 3 line 29 Replace ": : : averaging N quantities of 10 minutes time samples" by

Kommentar [MN32]: RC1: 26. Page 3 line 30 Remove "the averaging"

Kommentar [NM33]: RC3: P4L1: Is that one reference turbine for the whole farm, or one particular one for each

Kommentar [MN34]: RC1: 27. Page 4 line 1 You are talking about "correlation" but this is not a correlation of

Kommentar [MN35]: RC1: 28. Page 4 line 4 "This is described in Eq. (1) and (2)" Well this is not described in

$$\mu = \frac{1}{N} \sum_{n=1}^N \frac{P_{\mu ob n}}{P_{\mu ref n}} \text{ and} \quad (1)$$

$$\pi = \frac{1}{N} \sum_{n=1}^N \frac{P_{\pi ob n}}{P_{\pi ref n}}, \quad (2)$$

5 where $P_{\mu ob}$ and $P_{\pi ob}$ are the measured and predicted power of the observed turbine. $P_{\mu ref}$ and $P_{\pi ref}$ are the measured and predicted power of the reference turbine.

The underperformance indicator ~~can be described with Eq. (3)~~ is defined as:

$$\eta_{ob,ref} = 100 \% - \left(1 - \frac{\pi}{\mu}\right) \cdot \omega \quad (3)$$

10 where $\eta_{ob,ref}$ describes the deviation of the measured correlation and the model predicted correlation in percent valid for the selected turbine pair of one reference (*ref*) and one observed (*ob*) turbine. Having the measured power correlation in the nominator increases the sensitivity. The underperformance interval range of the indicator is in this way between $[0, -\infty[$. Non-operating turbine values have to be filtered out.

15 If $\eta_{ob,ref}$ is larger than the uncertainty (Section 2.3), underperformance has been detected. This correlation is repeated for each combination of turbines which leads to $n - (n - 1)$ results (n = number of turbines in the farm). This adds further confidence to the detection, because an underperforming turbine will meet the criteria several times.

2.1 Determination of environmental conditions

20 2.1.1 Wind direction

The first step is to derive a wind direction ϑ for each 10-min interval. ~~For our monitoring model we are using the absolute wind direction signal from each turbine which is defined as~~

$$\vartheta = \text{nacelle position} + \text{wind vane position} \quad (4)$$

25 The nacelle position is the angle between the rotor axis and a marking for true north. This marking is calibrated as part of the commissioning. But often this signal is not maintained well during operation, because it has no effect on turbine performance. This causes the necessity to apply an offset correction to this signal before using it for reanalysis purposes. The wind vane position indicates the angle of the flow to the rotor axis. It directly provides a value for the yaw error. The turbine controller uses this signal to control the yaw activity.

Kommentar [MN36]: RC1: 29. Page 4 line 12 Replace "can be described with Eq. (3)" by "is defined as"

Kommentar [MN37]: RC1: 30. Page 4 lines 16-17 "where neta_ob.ref: : : (ob) turbine" You already defined everything so there is no need for this

Kommentar [NM38]: RC2: In section 2.1.1 the wind direction is derived, but without any reference to how this is done. The wind direction measured on the nacelle is only used for yaw control, where the strategy is the keep the rotor aligned with the wind direction to minimize the yaw-misalignment. This signal can also identify a "forced" yaw misalignment used to determine the "wake drift"? The optimal readings from this instrument is 0, and will not reveal anything about the actual flow direction, which only can be identified from the wind turbine yaw position. The wind turbine yaw position not used by the controller, only when wind farm has sector management (proposed but never seen). The yaw position is usually not calibrated or has a wrong offset, which need to be identified.

Kommentar [NM39]: RC3: 2.1.1: I wonder why you do not use the same correction method on all the wind farms wind vanes? It just requires SCADA data and some computer power, so it would not be too difficult. Also, when you're calculating a mean wind direction for the whole farm, aren't you relying on a smaller size farm far away from the coast? For example, if you have a location like Anholt, then you have wind and direction gradients due to the proximity of the land across the wind farm. How would that influence your method and its accuracy?

Within the Pre-Process (Fig.1) of the monitoring model we estimate the north marking offset for one turbine by checking the location of the maximum wake deficit with respect to the true north. Then we compare the average wind direction between corrected turbines and neighbouring turbines to estimate the remaining offset for all turbines. Before doing so, the wind vane alignment must be checked by comparing one turbine's vane to the direction of the wake deficit on a downstream turbine. All other wind vanes in the farm are then referenced to this vane and any bias is corrected with the mean difference between the reference vane and the corrected vane. After applying this offset correction, the wind direction from all wind vanes are averaged in the complex area-plane to account for the wind direction discontinuity at the beginning/end of the scale value range, after removing outliers, defined by the outside $\pm 1.5 \cdot \text{IQR}$ (interquartile range).

Kommentar [MN40]: RC1: 31. Page 4 lines 26-29 So why do you have to use all the wind vanes (this is what is read from the text)? They could all have a different misalignment and so you will need to analyze each of them (in terms of wake deficits) if you want to use all of them.

Kommentar [MN41]: RC1: 32. Page 4 line 29 "complex area" what do you mean by complex area?

Kommentar [MN42]: RC1: 33. Page 5 line 1 "of the scale" what do you mean by scale?

Kommentar [MN43]: RC1: 34. Page 5 line 2 "+1.5IQR" be explicit. If the outliers removed are those outside the range $\pm 1.5\text{IQR}$ then say so

2.1.2 Wind speed

Having determined an averaged wind direction we are now able to derive the averaged free flow wind speed. For this task we use the nacelle anemometry but only from wind turbines that are not affected by upwind turbines. To determine whether a turbine is affected by an upwind turbine or not we use the specification for power curve measurements from the international standard (IEC 61400-12-1, 2005). Each turbine location is checked against all other turbine locations according to the averaged wind direction. This is done within a Cartesian coordinate system where x represents the easting and y being the northing (See Figure 3). The wind turbine of interest WT_i is located at the position (x, y) and the turbine wake is from the turbine WT_0 at location (x_0, y_0) .

$$\alpha = 1.73 - \arctan\left(2.75 \cdot \frac{D_n}{L_n} + 0.715\right) + 10 \quad (5)$$

Kommentar [MN44]: RC1: 35. In Eq. 4 you have constants without units. If alpha is in degrees all these constants have the units of degrees and you need to state that

Feldfunktion geändert

Equation (4) is proposed by IEC 61400-12-1 (2005) and describes the width of the disturbed sector of the wake angle in degrees seen by the downwind turbine (the constants have the dimension of degree), where D_n is the rotor diameter of the upwind turbine and L_n the distance between the two turbines described by Eq. (5):

$$\begin{aligned} d_x &= |x - x_0|, \\ d_y &= |y - y_0|, \\ L_n &= \sqrt{d_x^2 + d_y^2}, \end{aligned} \quad (6)$$

With Eq. (6) the orientation β can be derived (See Figure 3). β describes the angle between the wake inducing turbine and the northing.

$$\beta = \begin{cases} \frac{\pi}{2} - \arctan\left(\frac{d_y}{d_x}\right) & x_0 > x \text{ and } y_0 > y \\ \frac{\pi}{2} + \arctan\left(\frac{d_y}{d_x}\right) & x_0 > x \text{ and } y_0 \leq y \\ 0 & x_0 = x \text{ and } y_0 > y \\ \pi & x_0 = x \text{ and } y_0 \leq y \\ \frac{3}{2}\pi - \arctan\left(\frac{d_y}{d_x}\right) & x_0 < x \text{ and } y_0 \leq y \\ \frac{3}{2}\pi + \arctan\left(\frac{d_y}{d_x}\right) & x_0 < x \text{ and } y_0 > y \end{cases}, \quad (6)$$

Kommentar [MN45]: RC1: 36. Eq. 6 is not needed

~~Each quadrant and the north inconsistency need different conditions~~ With β_* being the angle between the wake inducing turbine and the northing and the wind direction ϑ the turbine wake indicator γ can be described as:

Kommentar [MN46]: RC1: 37. Page 6 line 1 "the north inconsistency need different conditions" Yes obviously

Formatiert: Englisch (Großbritannien)

$$\gamma = \begin{cases} |\beta + 360 - \vartheta| - \frac{\alpha}{2} & 0 < \beta < 90 \text{ and } 270 < \vartheta < 360 \\ |\beta - 360 - \vartheta| - \frac{\alpha}{2} & 270 < \beta < 360 \text{ and } 0 \leq \vartheta < 90, \\ |\beta - \vartheta| - \frac{\alpha}{2} & \text{else} \end{cases} \quad (7)$$

The wind turbine of interest WT_i is categorized as waked turbine for $\gamma < 0$. The wind speed for the virtual met mast is therefore the average of the subset of the nacelle anemometer signals from all wind turbines with $\gamma > 0$.

2.2 The wake model

The wake model is a key factor in our performance monitoring method. Several benchmark tests have been published with a large variety of different models (Gaumont et al., 2012), (Réthoré et al., 2013) and (Steinfeld et al., 2015). And research is still ongoing to further improve prediction accuracy of such models.

In Figure 1 we highlight that the wake model and its tuning is part of the pre-process. The performance monitoring method itself is based on linear interpolation from the ~~result matrices~~ LUTs only. In (Mittelmeier et al., 2015), we have identified three key parameters for the tuning of the wake model (stability, wind direction uncertainty and wake drift). Figure 2_ gives an example of how the different key parameters change the wake model results. The left plot visualises the active power of a turbine in wake normalised with a free flow condition in 6.3 D distance. The 0° on the x-axis locates the full wake situation according to the simulation. The right plot is a representation of the same data as normalised power curve with wind speed on the x-axis normalised with the wind speed, when wake effects fade away due to pitching activities of the upwind turbine.

In the first step, the wake model needs to be set up with the right atmospheric stability parameters. An increasing stability will cause higher wake losses and therefore shift the wake plot vertically down (from red rhombus to black triangles).

The next two steps are applied on the wake model results which need to be calculated for a directional resolution of 0.5° and for each wind speed bin of 1 m/s. This resolution was proposed by Gaumond et al. (Gaumond et al., 2014) for his method to account for measurement uncertainties related to the wind direction which is the second key parameter in our tuning process. In his paper, three main sources of uncertainty are mentioned: The yaw misalignment of the reference turbine, the spatial variability of the wind direction within the wind farm and the variability of wind direction within the averaging of a 10 min interval. This causes a higher scatter in the data and leads to averaging effects that are not modelled in the simulation. In a post process each wind direction is averaged with weighted neighbouring results. A Gaussian distribution with a standard deviation σ_a has been proposed as a weighting function. The effect of this step is visualised in Figure 2 (red rhombus are without and orange points are with σ_a weighted averaging). In (Mittelmeier et al., (2015), we could show, that for the prevailing conditions at Ormonde wind farm σ_a is a function of the wind speed, decreasing with higher wind speeds. Looking at the full wind rose for an AEP estimation, the Gaussian averaging has little impact on the result (Gaumond et al., 2014). But the smaller the wind direction bin size, the larger the prediction error made by the wake model. Hence it is crucial for our monitoring method to increase accuracy for smaller wind direction bin sizes which will decrease the uncertainty of the method.

The third tuning parameter is applying a simple offset on the wind direction of the LUTs to account for a drift of the wake. We call this phenomena from here on "wake drift". (Fleming et al., (2013) has studied the effects of active wake control and in his baseline simulation (no yaw error) a small wake drift to the right can be observed when looking downwind. In the LES study of (Vollmer et al., (2016) the wake drift increases from neutral to stable conditions also for 0° yaw angle. (Gebraad, (2014, p86) gives an explanation for the observations from the simulations by Fleming et al. (2013). The flow reacting on the rotation of the rotor causes the wake to rotate counter clockwise (looking downstream). Higher wind speeds from the upper layer are transported downwards (on the left side) and lower wind speeds from the lower layer are pushed upward on the right side of the wake. As a result the velocity deficit at the right part of the wake increases, so the wake deflects to the right. (Marathe et al., (2015) could show in their field measurement campaign with a dual-doppler radar the wake drifting to the right, as expected by the theory. But in the far wake they registered a movement to the left. The authors state the hypothesis that this contradicting phenomenon may be caused by atmospheric streaks. In an offshore field experiment by (Beck et al., (2015) further evidence is provided that wakes are moving out of the centre line. This wake drift is currently not modelled in Fuga and therefore applied in a further step of the pre-process (Fig. 1).

Kommentar [MN47]: RC1: 38. Page 7 lines 1-2 "In Mittelmeier et al. (2015): : wind speeds". Well that depends on the stability conditions. This will be true if compare unstable conditions with low wind speeds and high sigmas with neutral conditions with lower sigmas and higher wind speeds. But stable conditions will be in the low wind speed range with lower sigmas compared to neutral

Kommentar [MN48]: RC1: 39. Page 7 line 3 "no impact" you mean "little impact"

Kommentar [NM49]: RC3: P6L15: You might want to explain what you mean by "wake drift".

Kommentar [NM50]: RC2: The description of the method seems to be adequate, but the "wake drift" in section 2.2 is not well defined, I assume this refers to periods with active wake control, which I do not expect has been implemented yet?

Formatiert: Standard

~~The third tuning parameter is correcting the bias of the wind direction in the wake model results (Wake drift). Large Eddy simulations made by Vollmer et al. [22] confirm this behaviour. In the following section, we will have a closer look at the uncertainties of the proposed method.~~

Kommentar [MN51]: RC1: 40. Page 7 lines 7-8. This seems to be quite important and you do not provide any details about the study of Vollmer et al.

2.3 Uncertainties and underperformance criteria

It is essential to understand the uncertainties of the method to judge the confidence in underperformance detection. Any false alarm can cause unnecessary trouble shooting.

For this evaluation, we follow the “Guide to the expression of Uncertainties in Measurements” ~~(GUM)~~ (JCGM, 2008), which distinguishes between statistical Type A and instrumental Type B uncertainties. The important measurands of the method are the measured power and the predicted power for each wind turbine under observation and for reference ($P_{\mu ob}, P_{\mu ref}, P_{\pi ob}, P_{\pi ref}$). For the measured power P_{μ} we only use Type B, because each measurand is obtained from different environmental conditions and therefore statistical Type A uncertainties are not applicable. The combined uncertainty can be derived with Eq. (8).

Kommentar [MN52]: RC3: P7L23: So the Type A uncertainties do not multiply in a multiple wake situation?

$$u_c(P) = \sum_{k=1}^K (c(P)_k \cdot u_k)^2, \quad (8)$$

where c_k is the sensitivity factor and u_k the uncertainty of the k-th component of the measurement chain. For the predicted power P_{π} , we are using a combined uncertainty with statistical type A uncertainties, being the experimental standard deviation of the mean from the difference between wake model predictions and measurements and type B uncertainties which conclude from the instrument devices to estimate wind speed and wind direction. Table 1 shows the uncertainty components of the predicted power P_{π} and provides the sensitivity factors, with $P_{\pi i,j}$ being the power value in the matrix referring to the wind speed bin i and the wind direction bin j . $V_{i,j}$ being the wind speed and $\theta_{i,j}$ being the wind direction of the element. In Table 2, the corresponding components for the uncertainty of the measured power P_{μ} are listed.

Results from the Offshore Wind Accelerator (Clerc et al., 2016) provide a range of 2.5% to 5% combined uncertainty for power curve verification based on a measurement chain that include a met mast and all its devices. The usage of LiDAR extends the range up to approximately 7%. The authors experience in power curve verifications has shown that the combined uncertainty of the measurement chain that includes a met mast and all its devices is usually about 4% to 6%. In our case, the wake model will add further uncertainties which would lead to even higher values and therefore yields an unacceptable rate for underperformance detection. To lower this impact, the monitoring method is based on normalised measurements and normalised predictions. An error at the estimated wind speed has a much lower impact on the ratio of the power of two turbines than on their absolute power performance. The uncertainty for Eq. (1) can be described as:

Kommentar [MN53]: RC1: 41. Page 7 line 31 "usually about 4 to 6%" you need to give a reference here; otherwise show an example

$$u(\mu) = u\left(\frac{P_{\mu ob}}{P_{\mu ref}}\right) = \frac{P_{\mu ref}}{P_{\mu ob}} \cdot \sqrt{\left(\frac{u_c(P_{\mu ob})}{P_{\mu ob}}\right)^2 + \left(\frac{u_c(P_{\mu ref})}{P_{\mu ref}}\right)^2} \quad (9)$$

Equation (9) explains how to calculate the uncertainty of a summation in quadrature for division (Bell, 2001). The equation is equivalent for $u(\pi)$ and is applied on each 10-min sample.

With the two uncertainties $u(\mu)$ and $u(\pi)$ being independent the standard propagation of errors for η can be simplified according to (Ku, 1966) to the following equation:

$$u^2(\eta) = \left(\frac{\partial \eta}{\partial \mu}\right)^2 u^2(\mu) + \left(\frac{\partial \eta}{\partial \pi}\right)^2 u^2(\pi), \quad (10)$$

which leads to an uncertainty in η of:

$$u(\eta) = \frac{100}{\mu} \sqrt{u^2(\pi) + \left(\frac{\pi}{\mu}\right)^2 u^2(\mu)} \quad (11)$$

The uncertainty derived by Eq. (11) is around 7% and can be displayed as a bandwidth around the underperformance indicator η , visualized in Fig. 4. Its magnitude is dependent on the sample size N . In Fig. 4 we obtain approximately 7 % uncertainty on the performance ratio for $N > 1000$. The confidence level is one standard deviation, which is considered to be acceptable for underperformance detection.

In the next step we need to estimate the required number of power samples N for averaging (see Eq. (1) and Eq. (2)). This is directly linked with the earliest point in time when underperformance can be detected. We define this point as having a lower prediction error (with the optimal turbine operation model) than the prediction error derived by the model with the erroneous data taking the uncertainty into account.

3 Results and Demonstration

The objective of this paper was to present a developed method, using only SCADA data and pre-calculated numerical wake model results to detect underperformance at wind turbines in waked conditions within the wind farm. We have chosen the Ormonde wind farm to demonstrate the new method. The 30 turbines have a rated power of 5 MW and are owned by Vattenfall. The wind farm is located in the Irish Sea 10 km west of the Isle of Walney.

The farm layout displayed in Fig. 5 is structured in a regular array which allows comparison of several single wake, double wake and triple wake situations. The closest turbine spacing is in the range of 4.1 D to 4.3 D along the four rows

Kommentar [MN54]: RC1: 42. Page 8 line 19 "is around 7%" based on what?

Kommentar [MN55]: RC1: 43. Page 9 line 3 Figure 5: please show a proper layout with north orientation and scales

orientated from north west to south east. We have selected a more frequent wind direction from south-south west where multiple columns of four turbines are aligned with a distance ranging from 6.3 D to 6.5 D. ~~The turbine distance for the investigated wake situation is 6.3 D. The neighbouring rows are at 4.3 D.~~ To simplify the demonstration of underperformance detection, ~~we selected four turbines in one row. With south westerly wind direction,~~ we focused on single wake, double wake and triple wake conditions behind turbine ~~number~~ OR26 for a south-south westerly wind direction and a sector of 30° around the full wake situation. Two years of 10-min SCADA data were used to set up the performance monitoring model for the following demonstration.

Kommentar [MN56]: RC1: 44. Page 9 line 4 "6.3D" this is between turbines in the same row (does not look like that), between rows? And important what are rows for you: the rows of turbines in a particular direction or all "rows" of turbines?

Kommentar [MN57]: RC1: 45. Page 9 line 7 Two years of "10-min" SCADA data?

3.1 Environmental condition of demonstration wind farm

3.1.1 Wind direction of demonstration wind farm

The wind direction is supposed to be representative for the wind turbines in the monitoring model. In our example, we have averaged up to 30 corrected wind direction signals for each 10-min interval. The variation among the individual signals provides an uncertainty estimate for this artificial wind direction. In Fig. 6, a histogram of the full data set of two years with each count being the difference between a single vane measurement and the corresponding mean wind direction for the averaged period is visualized. This variation can nicely be described by a Gaussian distribution with standard deviation of 3.6°. This value is used for the uncertainty of the wind direction Table 1 is referring to.

Kommentar [MN58]: RC3: P9L9/L15: "of demonstration wind farm" could be deleted without detriment.

Formatiert: Standard

The quality of the derived wind direction is visualized by plotting a histogram (Figure 6) for the full data set of two years with each count being the differences between a single wind vane measurement and the corresponding mean wind direction for the averaged period. The deviation of the single wind vanes from the averaged wind direction is nicely described by a Gaussian distribution with standard deviation of 3.1°. This value is used for the uncertainty of the wind direction Table 1 is referring to.

Kommentar [MN59]: RC3: P9L13: This value is used for the uncertainty...

Kommentar [MN60]: RC1: 46. Page 9 line 10 "The quality of the derived wind direction" It is not the quality what you show there

3.1.2 Wind speed of demonstration wind farm

Figure 7 demonstrates the quality of the virtual met mast derived with the equations from methodologies described in Section 2.1.1 and Section 2.1.2. The average wind speed of all nacelle anemometers has been normalised by the averaged nacelle anemometer wind speed of the wake free subset. The full data is binned into 2° and plotted against the averaged wind direction. The errors bars indicate the experimental standard deviation of the mean (JCGM, 2008). We obtain a quite good agreement with the Fuga model which has been used with a Gaussian averaging of standard deviation- $\sigma_a = 4^\circ$ equal to 4°. So far there is no instruction available on how to determine this standard deviation which should take wind direction uncertainty into account (Gaumond et al., 2014). We have chosen this value, because of a quite nice fit with the SCADA data. A linear regression between the wind speed of the standard model results (red dashed line) and the SCADA measurements equals $R^2 = 0.9675$. The improved model (green solid line) gives an $R^2 = 0.9857$.

Kommentar [MN61]: RC1: 47. Page 9 line 16 "from Section: : " Explicitly state which equations

Kommentar [MN62]: RC1: 48. Page 9 line 18 "binned into 2 deg" does not look like that but more like 4 deg.

Kommentar [MN63]: RC1: 49. Page 9 line 23 These correlations are very high but the outliers seem to be also quite large so I am very skeptical about these computations

When considering the demonstration sector of 30° around the full wake alignment behind wind turbine 26, the free flow wind speed can also be described by a Gaussian distribution (Figure 8) with a standard deviation of 0.46 m/s.

This information is important for the investigation of the uncertainties Table 1 is referring to

3.2 Wake model for demonstration wind farm

For the demonstration of the described method, we used the Fuga wake model which uses linearized Reynolds Averaged Navier Stokes equations developed by (Ott et al., 2011). With the second version of the S software new features were added (Ott and Nielsen, 2014) to account for different atmospheric stabilities and for wind direction uncertainties. The results for this paper have been produced with Fuga (version 2.8.4.1). We have chosen this wake model for two reasons: Firstly, there is already a confident number of validations with measurements published (Gaumond et al., 2012), (Mortensen et al., 2013) and (Steinfeld et al., 2015) and secondly, the Gaussian averaging feature described by Gaumond et al. (Gaumond et al., 2014) is already implemented.

To get a more reliable monitoring model we need to calibrate the wake model settings and compare several different calculation results with measured SCADA data based on the established virtual met mast. The wake model is supposed to provide a two dimensional LUT (wind direction, wind speed) for each turbine. Further dimensions such as stability may improve the accuracy, but research and validation for these models are still ongoing. Therefore our calibrated model has to be representative for the average annual conditions. Two full years of SCADA data have been used for this task.

We identified three steps to obtain a better match between the power modelled by the wake model Fuga and the measurements. Firstly, the standard deviation σ_a to account for the wind direction uncertainty was found to be decreasing with increasing wind speed. Secondly, the Fuga parameter to model the effect of atmospheric stability $\zeta_0 = 2.72E - 7$ was set to more stable conditions and thirdly, the centre of the wake was found to be shifting drifting towards starboard the right side when traveling downwind. Approximately 2.5° in the single wake and an additional 1° is added with every turbine adding an additional wake to the flow. This results in a total offset of 4.5° for the triple wake referenced to the artificial wind direction from the virtual met mast (Section 2.1.1) global wind direction. One possible explanation for this behaviour is the fact, that the upwards moving blade diverts the flow with higher wind speeds downwards to regions with lower wind speeds and the downwards moving blade causes the opposite. This results in a higher wind speed on the left port side than on the starboard right side of the wake and leads to a drift of the wake centre. A second explanation can be derived from the Coriolis force, which leads to an increased force to starboard right (northern hemisphere) on accelerating air particles. We cannot fully rule out the possibility of an unwanted yaw misalignment as the uncertainties within this process of aligning the turbine lies within 3° (IEC 61400-12-2, 2013). But a single wake drift of 2.5° is also within the simulation results for 0° yaw misalignment at stable conditions (Vollmer et al., 2016). Large Eddy simulations made by Vollmer et al. confirm this behaviour (Vollmer et al., 2014).

Kommentar [MN64]: RC1: 50. Page 9 The wake model seems to have a systematic bias when compared to the measurements (clearly seen at the highest deficits). Why? Is the average wind direction perhaps wrong? Perhaps you should average the wind direction of the turbines in the rows where the flow is not disturbed if you want to compare it with the wake model

Kommentar [MN65]: RC1: 51. Page 10 line 1 The wake model should be presented before the results in 3.1.2!

Kommentar [NM66]: RC3: P10L5: I would drop the brackets around the version number of Fuga.

Kommentar [MN67]: RC1: 52. Page 10 line 11 How much data you use for the calibration period?

Kommentar [NM68]: RC3: P10L14: I don't think I've seen zeta_naught introduced before?

Kommentar [MN69]: RC1: 53. Page 10 starboard and port terms are terms conventionally used in wake studies?

Formatiert: Nicht Hervorheben

Kommentar [NM70]: RC3: P10L15-22: This is quite interesting. Has this behaviour been observed anywhere else? Another explanation could be that the overall wind flow is skewed at the Ormonde location, which judging by the map is not impossible, seeing that the wind farm is wedged between land and a larger offshore wind farm. Or do I understand this

Kommentar [MN71]: RC1: 54. Page 10 line 17 what do you mean by "global"

Kommentar [NM72]: RC3: P10L15: While wind and nautical terms can easily be construed to have a connection,

Formatiert: Nicht Hervorheben

Formatiert: Hervorheben

Kommentar [MN73]: RC1: 55. Page 10 lines 16-22 If this phenomenon occurs in 1 single wake the a very plausible

Figure 5 shows the location and layout of the demonstration wind farm. ~~The plot indicates the estimated wakes with heat colours.~~ The row-column of turbines behind turbine OR26 has been selected for the validation of the wake model settings. The benchmark are simulations for neutral conditions with none of the post processing's mentioned in section 2.2 to take wind direction uncertainty, atmospheric stability and wake shifts-drifts into account. Figure 9 demonstrates the improvement of model prediction and its capabilities for single wake, double wake and triple wake situation. The left column visualises wake deficit plots where the power has been normalized with the free flow turbine, as function of the wind direction, centred to the full wake. The data is filtered for wind speed of 8 ± 1 m/s. The right column are normalized wake power curves. The power, normalized with free flow power, is shown as function of the wind speed, normalized with wind speed at rated power for the ~~waked-turbine in the wake.~~ These data have been filtered for a wind direction sector of 5° . The optimised simulation results with the green diamonds follows the SCADA data with the black dots much closer than the benchmark case marked as red triangles. The error bars indicate one standard deviation of the measured SCADA data at each bin. The three fine-tuning steps decreased the power prediction error in a full wake with $\pm 5^\circ$ sector width from 7% to 1.5% (Mittelmeier et al., 2015) for the presented case.

Having now an optimised wake model, the first two steps of the pre-process (Figure 1) are accomplished and the matrices for the "predicted power" can be established. In the next Section, the detection of underperformance ~~has been~~ will be demonstrated with real data and two test cases.

3.3 Demonstration Case

Two years of SCADA data have been contaminated with two different error types. The first manipulation simulates a degradation of 8 % of its power production for which the original data set that has been used to calibrate the model, is multiplied by 0.92. According to the findings in Section 2.3 a degradation of 8 % is just high enough to distinguish from the uncertainties of a turbine in triple wake. The second test case is a simple power curve curtailment at 60 % rated power.

In Figure 10 the normalized power as function of the normalized wind speed ~~in displayed is shown~~ in a scatterplot. The coloured points in green represent correct turbine performance (P_{optimal}). The yellow dots (P_{degraded}) describe the degradation and the red dots ($P_{\text{curtailed}}$) are the data with the curtailment. Measurements from above rated wind speed are removed to concentrate on the part of the power curve where underperformance is more difficult to detect.

~~Working with relative predictions the prediction error in percent rises with lower power production at low wind speeds. Therefore the model is supposed to treat only measurements above 5 m/s. Below 5m/s we have realized a strong increase in wind direction variation among the turbines compared to the artificial wind direction from the virtual met mast. This variation increases the uncertainty of the model and therefore it is filtered out.~~

Kommentar [MN74]: RC1: 56. Page 10 line 32 "this data has been filtered for a wind direction sector of 5 deg" Change to "These data have been.."

Kommentar [MN75]: RC1: 57. Page 11 line 2 You mean for prediction of what? AEP? Wind speed? A particular case?

Kommentar [MN76]: RC1: 58. Page 11 line 5 Replace "has been" by "will be"

Kommentar [MN77]: RC1: 59. Page 11 line 6 what do you mean by "real data"? so before the data was not real?

Kommentar [MN78]: RC1: 60. Page 11 line 9 degradation of 8% in terms of what?

Kommentar [MN79]: RC1: 61. Page 11 line 13 Replace "in displayed" by "is shown"

Kommentar [MN80]: RC1: 62. Page 11 line 18 Why "Therefore"?

To further increase the certainty of the result, we calculate the underperformance indicator for each turbine with any other possible combination of reference turbine. For the whole wind farm of 30 turbines this ~~would lead~~s to 870 combinations. For simplification in this demonstration, we are only focussing on the four turbines in the row behind turbine OR26.

- 5 At first, we need to estimate the required number of power samples N for averaging. This is directly linked with the earliest point in time when underperformance can be detected. We define this point by having a lower prediction error with the optimal turbine operation model than the prediction error derived by the model with the erroneous data taking the uncertainty into account. This can be visualized in Figure 11. The graphs present the accumulated level of underperformance η as function of the number of samples (N values). The data with the error appears in a solid line and grey uncertainty margin.
- 10 The dashed green line represents the data with the turbine in optimal operation. The lowest quantity N , where the “optimal” (green dashed) line confirms a lower η than the border of the grey area, is the point where we highlight underperformance with sufficient certainty. Figure 11 demonstrates the two test cases with a turbine under curtailment at different wake situations and the corresponding situation for a degraded turbine. A wake model bias has been corrected in such a way, that the results for the optimal turbine prediction with the full two years data equals to zero.
- 15 In Table 3 we have listed the N values which are necessary to measure for each case until underperformance can be detected with sufficient certainty. They can be translated into hours by $N/6$ as we are using 10~~-~~min averages.

Figure 12 is a graphical representation of the development of uncertainty with increasing number of averaging data. The free flow has a comparatively low uncertainty in comparison with the three wake situations. All four graphs have higher
20 uncertainty in the beginning and quickly decrease with increasing N . At approximately $N = 150$ the uncertainty of all three wake states has dropped at least once below 8 %. With $150 < N < 500$, $u(\eta)$ is still very unstable and stretches between 8 % and 10 %.

A clear additional drop, even below 7 %, can be seen from $500 < N < 1000$. Beyond $N > 1000$, $u(\eta)$ stabilizes towards a more and more horizontal graphline. In Table 4 the corresponding uncertainty for the estimated first time of
25 detection is listed.

The power curve scatter plot of all four wake conditions with the number of quantities, necessary for detection are visualized in Figure 13.

4. Discussion

The model was able to detect the selected demonstration error cases after a certain averaging time. With the proposed
30 sources of uncertainty and the described method to obtain a combined level a very clear increase of uncertainty can be seen from free flow to wake condition cases. The reason for this behaviour can be led back to the normalization procedure. The largest source of uncertainty is usually the wind speed measurement, followed by the wind direction measurement (category

Kommentar [MN81]: RC1: 63. Page 12 line 10 “horizontal graph” you mean horizontal line?

B uncertainties). Looking at the sensitivity factor for both readings, which are based on the slope of the quotient between neighbouring normalized ~~matrix~~-LUTs cells, they approximately equal to zero for the free flow case. Therefore only category A uncertainties are left, which quickly decrease with increasing number of measured values ~~NN~~.

5 | In our example, the curtailment took less than ~~130-170~~ values to be detected (see Table 3). This of course is very dependent on the wind distribution. The wind has to be high enough to force the turbine into the underperformance. At rated wind, detection is much faster than at wind varying around the power limitation. The right column in Table 3 is showing the total values N and in brackets the values considering only wind speeds high enough to force the turbine into the curtailment. The N values ~~to the first detection~~ in Table 3 increase with each additional wake added to the flow. Furthermore, the figures show that curtailments (values in brackets) can be detected earlier than degradation.

15 | The tuning of the wake model is an essential part of the method. The key tuning parameters have been estimated by trying to obtain the best fit with the SCADA data. This is a clear weak point of the method and further investigations are necessary to find ways to predict the right settings without measured data. Without such tuning, each of these parameters will contribute as an additional source of uncertainty and therefore reduce the accuracy. A further improvement could be to extend the dimensions of the ~~look-up tables (matrices)~~LUTs with atmospheric stability. (Dörenkämper et al., (2012) could show that the influence on the development of wind turbine wakes is measurable. A link from SCADA data to atmospheric stability would be needed. An investigation is planned for future work.

20 | The sensitivity of the underperformance indicator η states the measured power correlation in the nominator of Eq. (3). In this way the interval range increases from $[0, -100]$ to $[0, -\infty[$. Division with 0 is prevented by filtering non-operating conditions. The increased interval leads to a higher sensitivity and therefore further reduces the N values for the first underperformance detection.

25 | Using wind speed and wind direction measurements derived from a large number of devices can lead to acceptable levels of uncertainties although each single device for itself has comparably high uncertainties as described in more detail in the power verification standard using nacelle anemometry (IEC 61400-12-2, 2013). The stated uncertainties for wind speed and wind direction may be sufficient for the relative comparison to detect underperformance between turbines but it does not meet the requirements for an absolute performance validation according to IEC 61400-12-1, (2005) or IEC 61400-12-2, (2013). One could perform power curve verification test in accordance with the mentioned standards at turbines where they are applicable and those turbines being reference turbines in the monitoring method would increase the confidence in underperformance detection. At least for the concurrent period.

Kommentar [NM82]: RC2:
Conclusion on inflow conditions: the stated uncertainty, for wind speed and wind direction does not meet the requirements given in IEC 61400-12-1 and this need to be addressed both in the method and in the example.

5. Conclusion

A method for offshore wind farm power performance monitoring with SCADA data and advanced wake models was introduced. Wind speed and wind direction have been extracted from all devices in the wind farm to obtain a global measurement for the whole wind farm. In this way, the level of uncertainty could be lowered compared to a single nacelle measurement. Furthermore the uncertainties in performance level prediction could be reduced by normalization and referencing correlations. A suitable wake model was chosen, calibrated with SCADA data and used in a demonstration case.

A procedure to determine the optimal number N of 10-min samples to detect underperformance with sufficient certainty has been presented. Here the method was capable of detecting a degradation of 8 % in a triple wake situation with the confidence of one standard deviation. The described method can be used after a wake model recalibration with approximately two years of wind farm SCADA data. This ~~would~~can enable a real time monitoring from then on for the rest of the operational lifetime.

Acknowledgement

The presented work is partly funded by the Commission of the European Communities, Research Directorate-General within the scope of the project “ClusterDesign” (Project No. 283145 (FP7 Energy)).

We would like to thank Vattenfall Wind Power and Senvion SE for making this investigation possible.

Furthermore we would like to thank the R Core Team for developing the open source language R (R_Core_Team, 2015).

References

Albers, A.: Efficient wind farm performance analysis, in DEWEK, Deutsche WindGuard Consulting GmbH., 2004a.

Albers, A.: Relative and Integral Wind Turbine Power Performance Evaluation, in EWEC, London., 2004b.

Albers, A., Klug, H. and Westermann, D.: Power performance verification, in EWEC, Nice. [online] Available from: http://www.dewi.de/dewi/fileadmin/pdf/publications/Publikationen/albers_powerperformance_ewec99.pdf, 1999.

Beck, H., Trujillo, J. J., Wolken-möhlmann, G., Gottschall, J., Schmidt, J., Peña, A., Gomes, V., Lange, B., Hasager, C. and Kühn, M.: Comparison of simulations of the far wake of alpha ventus against ship-based LiDAR measurements, in RAVE Conference., 2015.

Bell, S.: A Beginner’ s Guide to Uncertainty of Measurements, Meas. Good Pract. Guid., 11(2), 41, 2001.

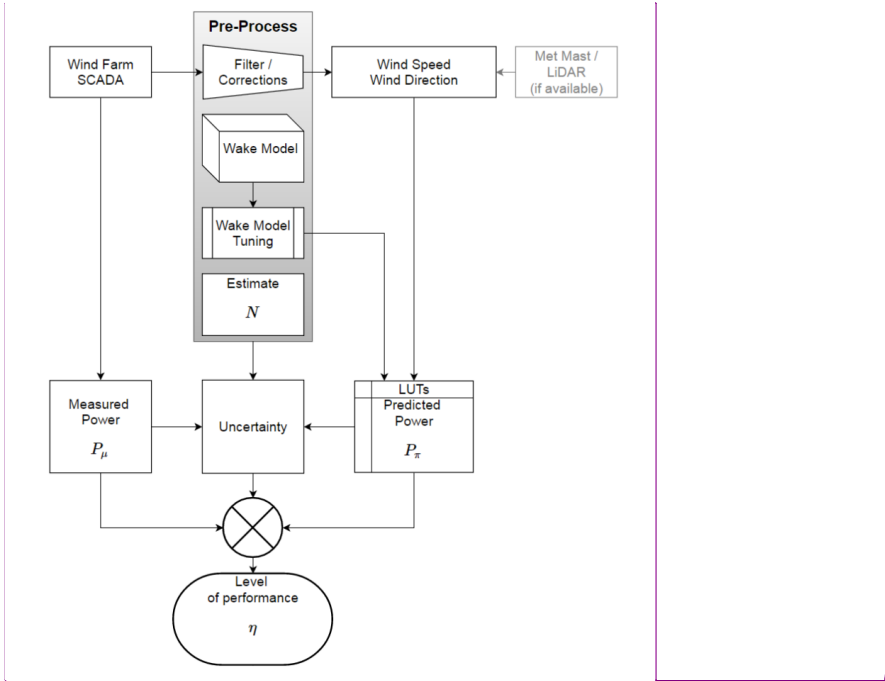
Carvalho, H. and Guedes, R.: Wind Farm Power Performance Test , in the scope of the IEC 61400-12-3, in Wind Power Expo, Chicago., 2009.

Clerc, A., Stuart, P., Cameron, L., Feeney, S. and Fnc, I. C.: Results from the Offshore Wind Accelerator (OWA) Power Curve Validation using LiDAR Project, in Wind Europe Workshop “Analysis of operating wind farms.”, 2016.

Dörenkämper, M.: An investigation of the atmospheric influence on spatial and temporal power fluctuations in offshore wind farms, PhD Thesis., University of Oldenburg., 2015.

- Dörenkämper, M., Tambke, J., Steinfeld, G., Heinemann, D. and Kühn, M.: Influence of marine boundary layer characteristics on power curves of multi megawatt offshore wind turbines, in DEWEK, pp. 1–4, DEWEK., 2012.
- Fleming, P. A., Gebraad, P. M. O., Lee, S., van Wingerden, J. W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P. and Moriarty, P.: Evaluating techniques for redirecting turbine wakes using SOWFA, in ICOWES2013 Conference., 2013.
- 5 Gaumont, M., Réthoré, P. and Bechmann, A.: Benchmarking of wind turbine wake models in large offshore wind farms, in the Science of Making Torque from Wind Conference, Oldenburg., 2012.
- Gaumont, M., Réthoré, P., Ott, S., Pena, A., Bechmann, A. and Hansen, K. S.: Evaluation of the wind direction uncertainty and its impact on wake modeling at the Horns Rev offshore wind farm, *Wind Energy*, 17, 1169–1178, doi:10.1002/we.1625, 2014.
- 10 Gebraad, P. M. O.: Data-Driven Wind Plant Control, 2014.
- IEC 61400-12-1: Power performance measurements of electricity producing wind turbines., 2005.
- IEC 61400-12-2: Power performance of electricity-producing wind turbines based on nacelle anemometry., 2013.
- IEC TC88 WG6: Wind farm power performance testing working group draft, IEC TC88 WG6 DRAFT, IEC., 2005.
- IEC TS 61400-26-1: Time-based availability for wind turbine generating systems., 2011.
- 15 IEC TS 61400-26-2: Wind turbines – Part 26-2: Production-based availability for wind turbines., 2014.
- JCGM: Evaluation of measurement data — Guide to the expression of uncertainty in measurement, First Ed. Sept. 2008, 2008.
- Ku, H.: Notes on the use of propagation of error formulas, *J. Res. Natl. Bur. Stand.* (1934)., 70C(4), 263–273, 1966.
- Marathe, N., Swift, A., Hirth, B., Walker, R. and Schroeder, J.: Characterizing power performance and wake of a wind turbine under yaw and blade pitch, , doi:10.1002/we, 2015.
- 20 Mellinghoff, H.: Wind Farm Power Performance Verification, DEWI., 2007.
- Mittelmeier, N., Amelsberg, S., Blodau, T., Brand, A., Drueke, S., Kühn, M., Neumann, K. and Steinfeld, G.: Wind farm performance monitoring with advanced wake models, in Proceedings of the EuropeanWind Energy Association Offshore Conference, Frankfurt., 2013.
- 25 Mittelmeier, N., Blodau, T. and Kühn, M.: Offshore wake model validation – Methodology for linking model results and operational data, in DEWEK., 2015.
- Mortensen, N. G., Nielsen, M. and Jørgensen, H. E.: First Offshore Comparative Resource and Energy Yield Assessment Procedures (CREYAP), 2013.
- Ott, S. and Nielsen, M.: Developments of the offshore wind turbine wake model Fuga, Report E-0046, DTU Wind Energy., 30 2014.
- Ott, S., Berg, J. and Nielsen, M.: Linearised CFD Models for Wakes, Risø National Laboratory, Roskilde, Denmark., 2011.
- R_Core_Team: R: A Language and Environment for Statistical Computing, [online] Available from: <https://www.r-project.org/>, 2015.
- Réthoré, P., Hansen, K. and Barthelmie, R.: Benchmarking of wind farm scale wake models in the EERA-DTOC project, 35 Int. Conf. Aerodyn. Offshore Wind Energy Syst. wakes, (June), 2013.
- Steinfeld, G., Mittelmeier, N., Drüke, S., Brand, A., Hait, T. and Amelsberg, S.: Report on the results of benchmarks for wake models. [online] Available from: www.cluster-design.eu, 2015.

Vollmer, L., Steinfeld, G., Heinemann, D. and Kühn, M.: Estimating the wake deflection downstream of a wind turbine in different atmospheric stabilities: An LES study, Wind Energy Sci. Discuss., (September), 1–23, doi:10.5194/wes-1-129-2016, 2016.



Kommentar [NM83]: RC2: Comments to the figures: all figures should include proper captions readable out of context. The caption of the figures are not sufficient e.g. while Figure 2b is not addressed in the caption.

Figure 1: Flowchart of the Performance Monitoring Model. Wind speed and wind direction are derived from SCADA data after an offset correction of each wind direction signal and outlier filtering. Wake model calculations and tuning as well as the estimation of the number N of 10-min samples for averaging are pre-processed. N , P_{π} , P_{μ} and P_{μ} are input values for the uncertainty calculation. An underperformance indicator η lower than the uncertainties indicates underperformance. Flowchart of the Performance Monitoring Model.

Kommentar [NM84]: RC3: Figure 1 center: Should that really be called Uncertainty, or rather something like Deviation?

Formatiert: Schriftart: Kursiv

Formatiert: Schriftart: Kursiv

Formatiert: Schriftart: Kursiv

Kommentar [MN85]: RC1: 64. Symbols in Fig. 1 are not the same symbols: : : they are not in italics

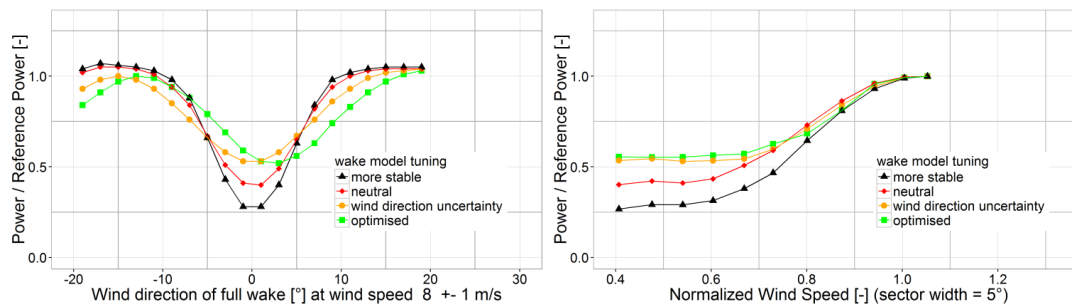


Figure 2: Impact of different key tuning aspects on the wake model results step by step. An increasing atmospheric stability increases the wake deficit (from red rhombus to black triangles). Wind direction uncertainty flattens the wake deficit (orange points), and a wind direction bias shifts the deficit horizontally (green squares). The left plot shows the power of the turbine in the wake divided by the power of a turbine in free flow conditions as function of the wind direction. The right plot displays the same power ratio as function of the normalized wind speed. (normalized power curve)

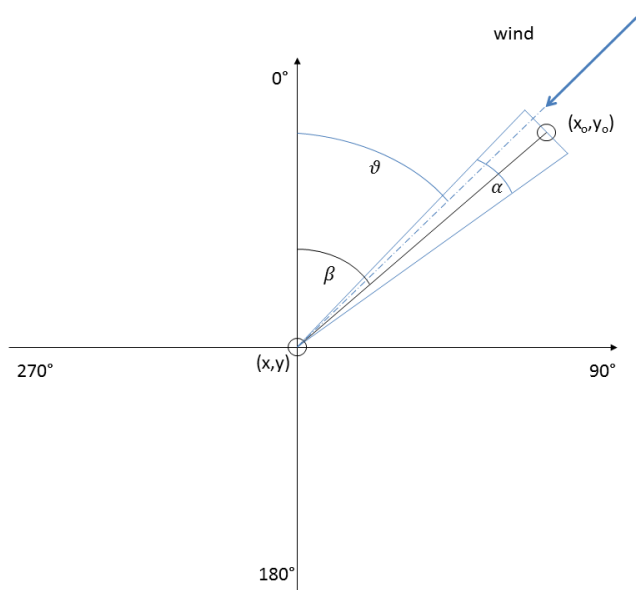
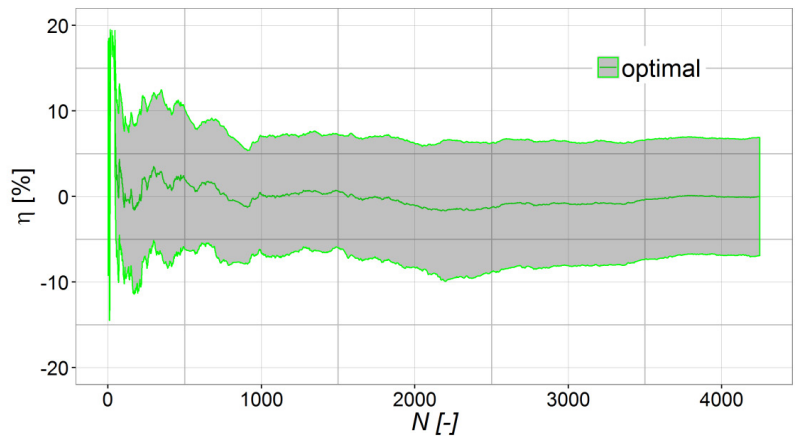


Figure 3: Determination of free flow turbines for wind speed averaging. The turbine at (x_0, y_0) produces a wake on the turbine at (x, y) for the displayed wind direction ϑ . β is the angle between the orientation of the turbines and the true north. α is the angle of

the disturbed sector in accordance with IEC 61400-12-1. Determination of the waked sector. The turbine at (x_0, y_0) produces a wake on the turbine at (x, y) for the displayed wind direction θ .



Kommentar [MN86]: RC1: 65.
Figure 3: The wind direction should not be perpendicular to the rotor? η_{β} (which is not the wind direction) is the angle perpendicular to the rotor

Figure 4: Underperformance indicator η with uncertainty margin as function of the number of measurement values N . Derived with the calibrated model at a turbine in triple wake. Underperformance indicator η with uncertainty margin as function of the number of measurement values N . Derived with the calibrated model at a turbine in triple wake.

Formatiert: Schriftart: Kursiv

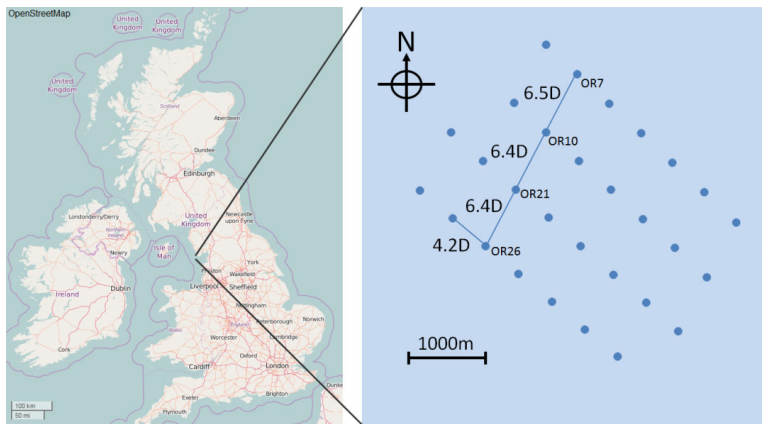


Figure 5: Layout of wind farm Ormonde. The 30 turbines of 5 MW class are located in the Irish Sea 10km west of the Isle of Walney. For a wind direction of 207° the single wake, double wake and triple wake behind OR26 has been selected as underperformance demonstration cases. Wind farm Ormonde layout with simulated wakes for a full wake situation from a south-westerly wind direction.

Kommentar [NM87]: RC3: Figure 5:
A map of the location would be good here (see above).

Kommentar [MN88]: RC1: 66.
Figure 5: scales, north, coordinates!

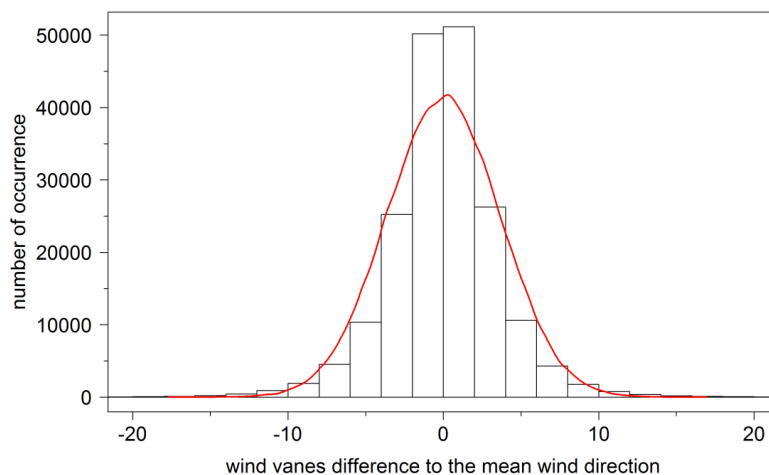


Figure 6: Estimation of uncertainty of the artificial wind direction. Histogram of the deviation of 30 individual wind vanes from the average wind direction for the full data set filtered for wind speeds $> 5\text{ m/s}$ with a sector of 30° centring the full wake condition. The red curve represents a Gaussian fit with a standard deviation of 3.6° . Histogram of the deviation of 30 individual wind vanes from the average wind direction for the full data set with a sector of 30° centering the full wake condition.

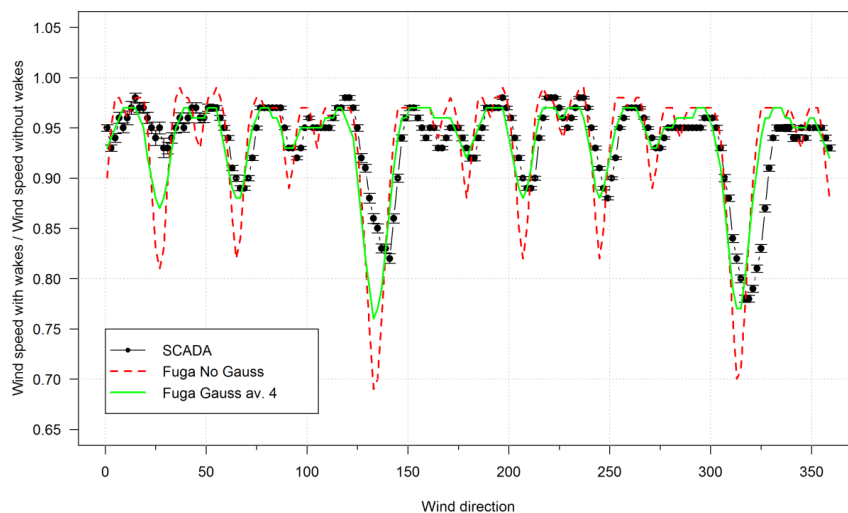
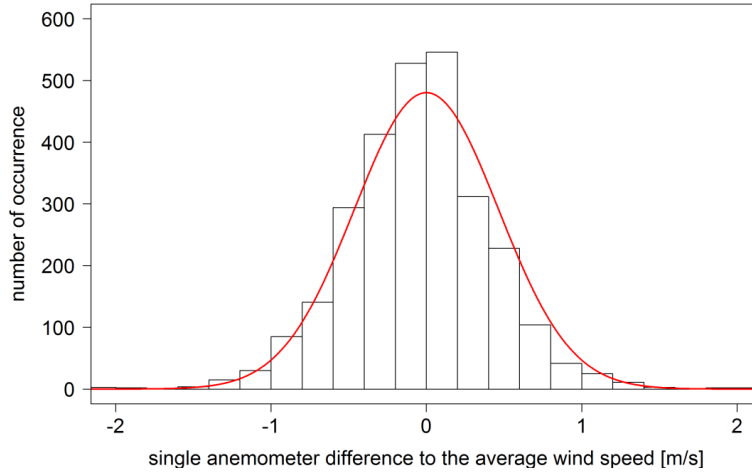


Figure 7: Wind farm averaged wind speed with wake effects normalised with wind farm averaged wind speed without wake effects plotted versus averaged wind farm wind direction. Black dots show the measurements from SCADA and the green solid line represents the results from Fuga with a Gauss averaging for standard deviation of 4° . An offset of the wind direction between model and SCADA can be observed. At 207° the offset is approximately 2.2° and it increases up to 5° for wind directions (132° and 312°) with the largest wake effects. An explanation and correction for this “wake drift” is proposed in section 2.2. Wind farm

Kommentar [NM89]: RC3: Figure 7: There seems to be a shift in wind direction between the SCADA system and the calculations - any idea where that is coming from?

averaged wind speed with wake effects normalised with wind farm averaged wind speed without wake effects plotted versus averaged wind farm wind direction. Black dots show the measurements from SCADA and the green solid line represents the results from Fuga with a Gauss averaging for standard deviation of 4° .



5 | **Figure 8: Estimation of uncertainty of the artificial wind speed. Histogram of the wind speed difference of a single anemometer to the average wind speed of all free flow anemometers. The displayed Gaussian distribution (red line) has the standard deviation of 0.46 m/s. A sector of 30° centring full wake alignment has been selected.**

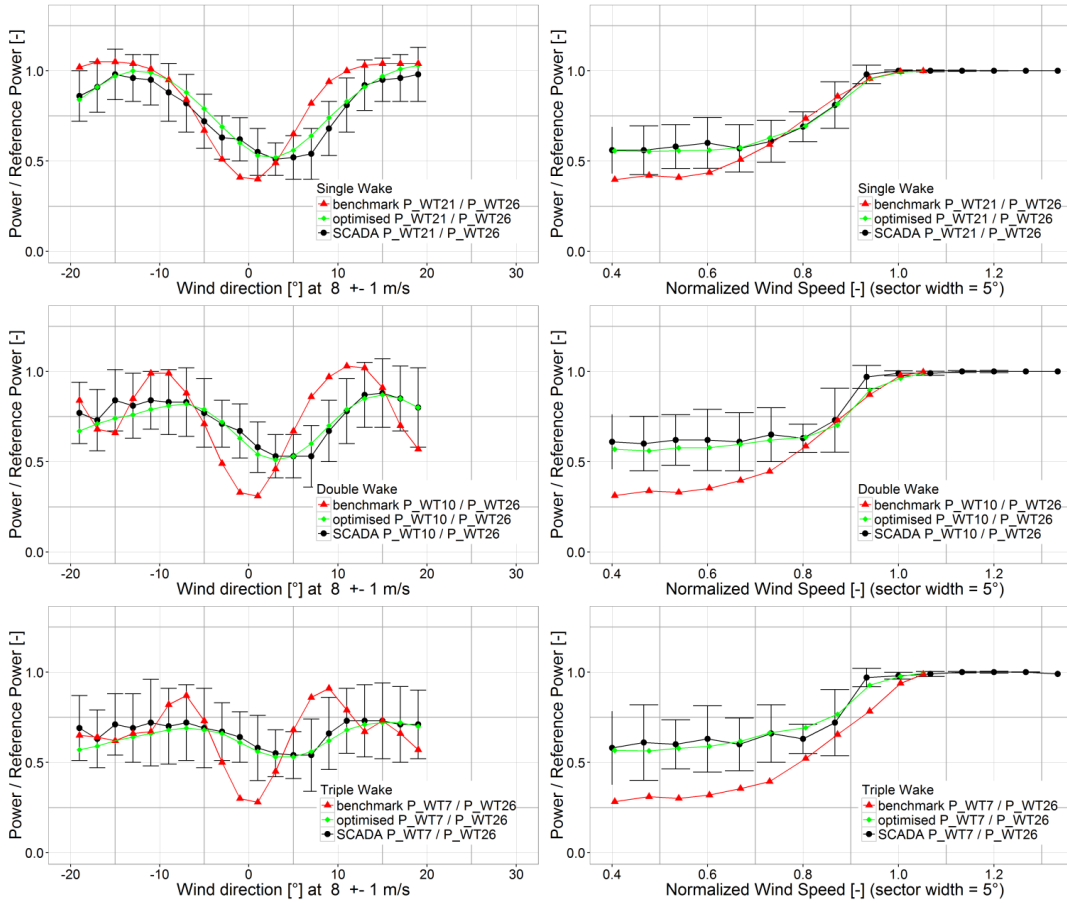


Figure 9: Tuning of the wake model results.(left column) Power normalized by the power of the free flow turbine as function of the wind direction centred at full wake for 8 ± 1 m/s wind speed. (right column) Power normalized by the power of the free flow turbine as function of the wind speed normalized by wind speed at rated power for the waked turbine. Black dots represent the measured and binned SCADA data with error bars of one standard deviation. The red triangles show wake model results with Fuga standard settings ($\zeta_0 = 0$, $\xi = 0$, no Gaussian averaging) and the green diamonds provide the tuned results. ($\zeta_0 = 2.72E-7$, $\xi = 0$, Gaussian averaging as function of the wind speed and applying the wind direction offset to account for the wake drift).

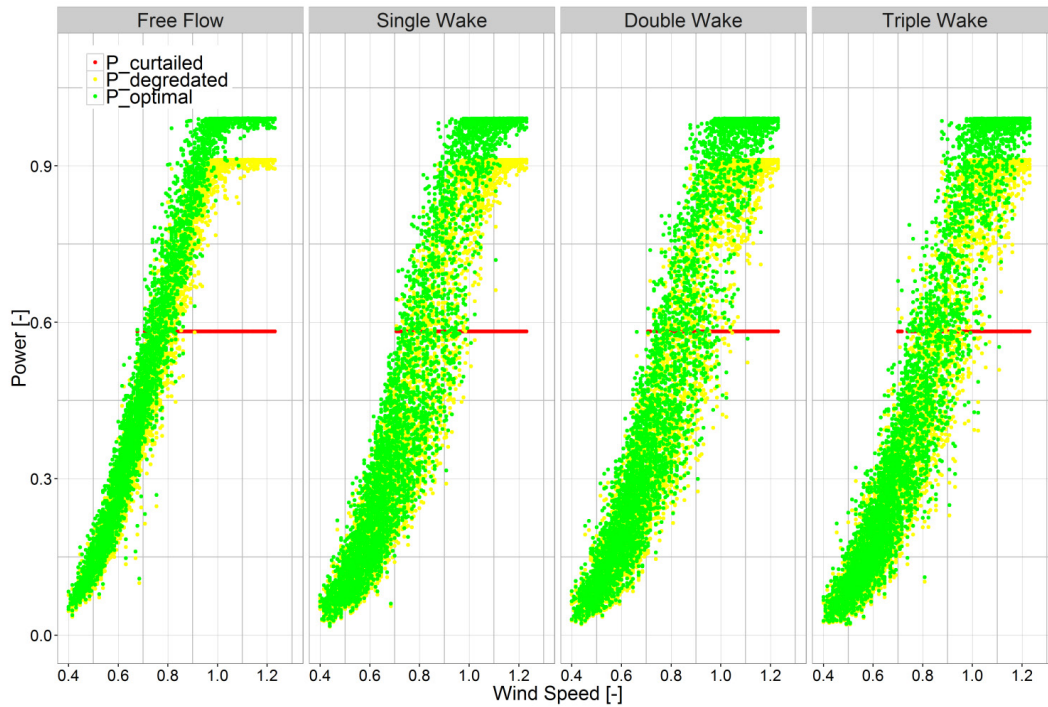


Figure 10: Scatterplot with normalized power as function of the normalized wind speed for four turbines in one row with two error test cases. Green dots are the measured power values and represent optimal operation. 8 % degradation of the power output is shown with yellow dots. A curtailment at 58 % is shown in red. Scatterplot with normalized power as function of the normalized wind speed for four turbines in one row with two error test cases.

Kommentar [MN90]: RC1: 67.
Figure 10: there should be some green points below 0.6, so perhaps it is better to degrade based on the best C_p curve

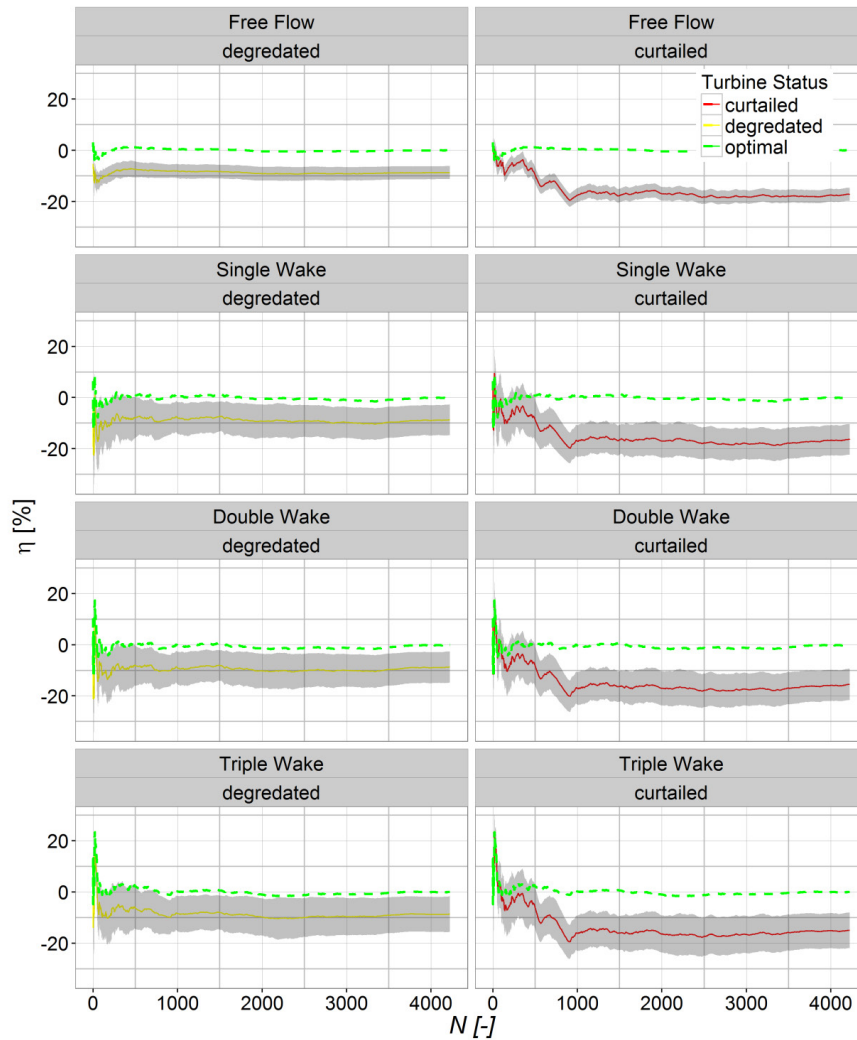


Figure 11: Underperformance detection for curtailment (right column) and degradation (left column) at turbines with different levels of wake influence. The displayed values represent the underperformance indicator η as function of the number of values N . We highlight the first time of underperformance detection when the green dotted line is outside of the grey uncertainty bandwidth. Underperformance detection for curtailment and degradation at turbines with different levels of wake influence.

Formatiert: Schriftart: Kursiv

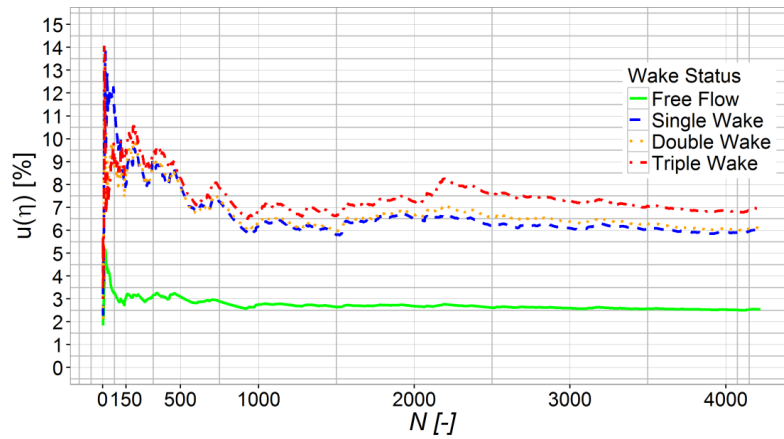


Figure 12: Uncertainties for the underperformance indicator $u(\eta)$ as function of N values for free flow, single wake, double wake and triple wake situation. Uncertainties for free flow conditions (green) are much lower than the uncertainties for the waked turbines. Uncertainties for the underperformance indicator $u(\eta)$ as function of N values for free flow, single wake, double wake and triple wake situation.

Formatiert: Schriftart: Kursiv

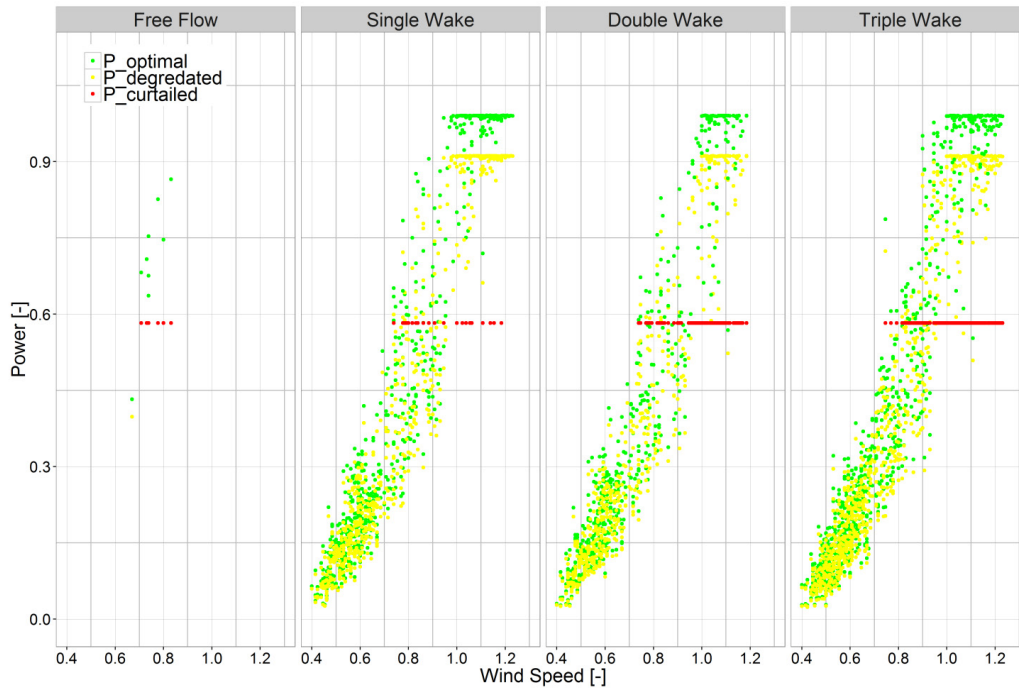


Figure 13: Scatterplot of each turbine's normalized power curve. The quantity $N = 754$ equals to the estimated sample size for the first detection of degradation at a turbine in triple wake situation.

Table 1: Type B uncertainties of the predicted power P_π

k	Uncertainty Component	Sensitivity $c_{k,i,j}$	Uncertainty $u_{k,i,j}$
1	Wind speed estimation	$\frac{P_{\pi i,j} - P_{\pi i-1,j}}{V_{i,j} - V_{i-1,j}}$	One standard deviation of the averaged anemometers
2	Wind direction estimation	$\frac{P_{\pi i,j} - P_{\pi i-1,j}}{\vartheta_{i,j} - \vartheta_{i-1,j}}$	One standard deviation of the averaged wind direction

Table 2: Type B uncertainties of the measured power P_μ (values as suggested by IEC 61400-12-1)

k	Uncertainty Component	Sensitivity $c_{k,i,j}$	Uncertainty $u_{k,i,j}$
1	Current transformer	1	0.0043 P [kW]
2	Voltage transformer	1	0.003 P [kW]
3	Power transducer	1	0.003 P_{rated} [kW]
4	Power data acquisition	1	0.001 P_{rated} [kW]

Kommentar [NM91]: RC3: Table 2: Is the source of that the IEC Annex D uncertainty estimation, or own values?

Table 3: N values to the first detection of underperformance with certainty of one standard deviation. Values in brackets indicate N with wind speeds above the curtailment.

Wake situation	N degradation $N_{\text{degradation}}$ [-]	N curtailment $N_{\text{curtailment}}$ [-]
Free Flow	1	51 (8)
Single Wake	187 577	497-149 (40928)
Double Wake	378 502	498-501 (403106)
Triple Wake	731 754	526-655 (426164)

Feldfunktion geändert

Formatiert: Schriftart: Kursiv

Formatiert: Schriftart: Kursiv

Formatiert: Schriftart: Kursiv

5 Table 4: Uncertainty U at quantity N of first detection of underperformance with certainty of one standard deviation.

Wake situation	U degradation $U_{\text{degradation}}$ [%]	U curtailment $U_{\text{curtailment}}$ [%]
Free Flow	1.8	3.6
Single Wake	86 .9	7.9
Double Wake	87 .78	7.8
Triple Wake	87 .08	7.83

Feldfunktion geändert

Formatiert: Schriftart: Kursiv

Formatiert: Schriftart: Kursiv