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. July 26, 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. 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 /***

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 EuropeanWind 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 now 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., (March), 1–23, doi:10.5194/wes-2016-4, 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

$$\vartheta = nacelle\ position + wind\ vane\ position$$

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.

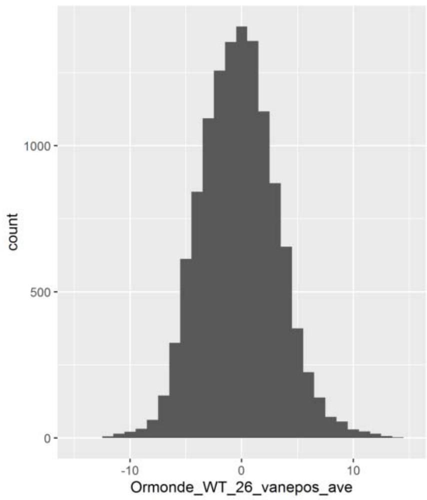


Figure x: Histogram of the wind vane position signal from turbine 26 showing all data that has been used for wake model calibration. Resulting in a mean value of -0.2 and a median of -0.3.

A systematic yaw error resulting from the sensor alignment can be estimated to ±2° 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., Kühn M.: Estimating the wake deflection downstream of a wind turbine in different atmospheric stabilities: An LES study, doi:10.5194/wes-2016-4, 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 thing 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 Pnpi and Pnmu”

***/ 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 a 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 neta_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. **Fehler! Verweisquelle konnte nicht gefunden werden.**.” /***

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., (March), 1–23, doi:10.5194/wes-2016-4, 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.

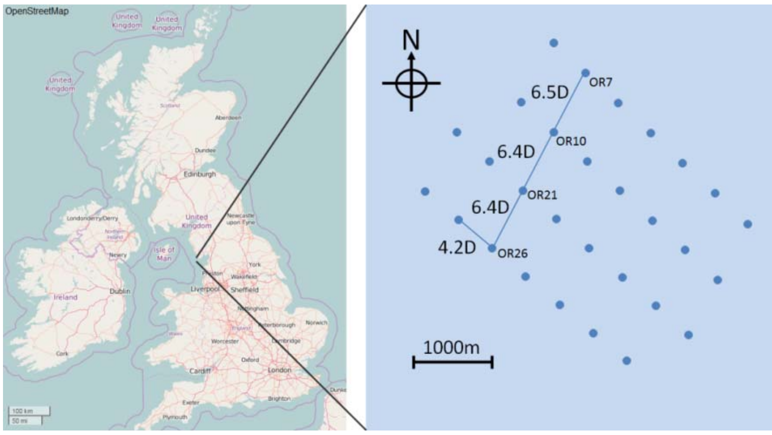
/***

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

***/New wording:
"The uncertainty derived by Eq. **Fehler! Verweisquelle konnte nicht gefunden werden.**) 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 where 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° ±15°. 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. Therefor 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., (March), 1–23, doi:10.5194/wes-2016-4, 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 ±5° 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”?

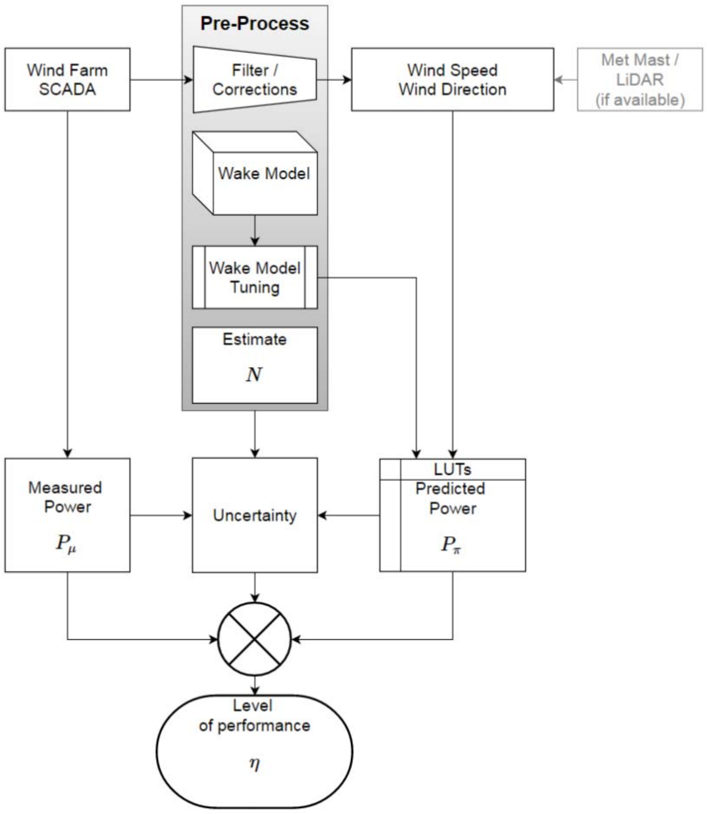
***/ “Working with ::: wind speeds. Therefore ::: 5 m/s.” is replaced by:
“Below 5m/s we have realized a strong increase in wind direction variation among the turbines compared to the artificial wind direction from the virtual met mast. This variation increases the uncertainty of the model and therefore 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.