

Response to the anonymous referee #1:

Thanks a lot for the review. Here our response to the reviewer's comments. The response is given within XXX--- ---XXX

Regards,
The authors

The manuscript presents a comparison between an evaluation of wind turbine SCADA data and mesoscale model simulations for the Anholt wind farm. Assessing wakes in larger wind farms is an important topic that deserves attention. The efficiency of wind farms very much depends on a meaningful consideration of possible wake effects. Although wake properties are very much determined by atmospheric stability, the simulations for this manuscript have been made without taking atmospheric stratification into account. Unfortunately, I'm inclined to reject the manuscript in its present form. Reasons for this negative decision are:

(1) The Introduction does not present a thorough scientific discussion of the current problems regarding turbine wakes in larger wind farms and does not identify clearly formulated research issues which are to be addressed in this manuscript. The manuscript rather appears to be a collection of isolated evaluations made from the SCADA data, the Jensen park wake model and several mesoscale models (I found "Fuga", a linearized RANS model and WRF mentioned in the text without seeing a clear strategy how and why they have been used).

XXX--- We have modified the introduction to highlight the research issues addressed in this manuscript and some of the issues when modeling wakes in large offshore wind farms. As pointed out by the reviewer, we did not explain the motivation of using Fuga and WRF in the introduction of the original submission; we now try to explain why we use them for our analysis (please see the marked-up manuscript which highlights the changes and additions) ---XXX

(2) Page 12, line 2 declares the greatest deficiency of the manuscript: atmospheric stability is not accounted for in the simulations. Why do the authors present such incomplete simulations, although they state in the introduction the importance of atmospheric stability?

XXX--- The westerly and southerly flow cases are presented to show the ability of the wake models to predict the wake loss for particular inflow conditions only. The westerly case being the one where the effect of the land should be the highest and the southerly case being one of those cases with the highest wake losses due to the farm layout. Most of the manuscript is about the wake models being used in a long-time series fashion; it is rather difficult to include atmospheric stability in all the models used here and for the type of use we want them for in this paper, which is the prediction of the AEP. Most important, for the type of the analysis we are focused on (i.e. AEP-like analysis) and given the results we show in terms of AEP/Capacity factor, one can see that inclusion of these effects might not be that important for such analyses. This is because for AEP predictions, the over- and under-estimations we make with these models are generally compensated (unless the long-term atmospheric stability is far from neutral, which is not the case of the North Sea). In the introduction we state that it is important to include them when comparing the wake models for particular flow cases. Also there are no measurements available for stability estimation. Of course WRF provides modelled values of atmospheric stability but using them in a time-series basis is difficult in all wake models and highly uncertain (see Peña and Hahmann, 2012). We now add "We have atmospheric stability measures from the WRF simulations but 'instantaneous' WRF stability measures are highly uncertain (Peña and Hahmann, 2012)" ---XXX

(3) The last sentence of the Conclusions gives the final reason why I should not read this paper. Here, the authors clearly state that their results are wind farm specific and SCADA specific and cannot be transferred to other wind farms.

XXX--- We think that it is important to mention that our results are wind-farm specific because they are, as well as most wake evaluations in all literature (if not all). In our particular case, the relative model error is a function of the SCADA and the way SCADA have been treated. This is the reason of our statement. The study shows a way to perform-such an analysis, which can be done in all wind farms but the results are simply only valid for Anholt. It is though probable that the relative differences between models of the relative model error (in Fig. 9 of the original submission) will be similar for different offshore wind farms and configurations, with main differences in the bias from zero relative model error ---XXX

Further issues:

(4) Some references point to grey literature. This is not convenient for the possible reader (e.g., p. 7, line 20).

XXX--- We added this reference following the comments of the associate editor. We now use 'proper' referencing in this case ---XXX

(5) The denotation of the different wake model simulations is inconsistent. "Park 1" and "Larsen 2" have the same characteristics (as have "Park 2" and "Larsen 1"). This is irritating.

XXX--- This is now changed as suggested ---XXX

(6) What is meant by a "quadratic sum"? It would be helpful to give a few mathematical formulae in order to avoid unnecessary ambiguity.

XXX--- We now explain with formulae what is meant by linear and quadratic sum as suggested ---XXX

(7) The statement in line 20 on p. 2 needs references to the existing literature.

XXX--- References are added as suggested ---XXX

References:

Peña A. and Hahmann A.N. (2012) Atmospheric stability and turbulence fluxes at Horns Rev – an intercomparison of sonic, bulk and WRF model data. *Wind Energ.* 15:717–731

Response to the anonymous referee #2:

Thanks a lot for the review. Here our response to the reviewer's comments. The response is given within XXX--- ---XXX

Regards,
The authors

The paper provides an interesting evaluation of the effect of proximity to the coast on offshore wind farm wake losses which is clearly a relevant and topical area, though there are some points to address:

1) Given that the paper acknowledges that roughness change is the main driver to the change in wind speed offshore, why did the authors not compare the use of WRF with a simple roughness change model to confirm this?

XXX--- Although we understand the reviewer's point as it is an interesting comparison, we think that this is out of the scope of the paper and that it will divert the attention of the paper, which is on wake modelling. It will also make the paper much longer and difficult to digest. But for the reviewer's sake we have performed such analysis using the roughness model of WAsP engineering (Astrup et al. 1996) and as observed (qualitatively from the figure below) the model seems to be capable to reproduce the wind speed gradients on the wind farm due to the land nearby. A comparison of WRF and the results of a RANS model are also given in van der Laan et al. (2017a) (this is also now stated when this paper is mentioned in the introduction) ---XXX

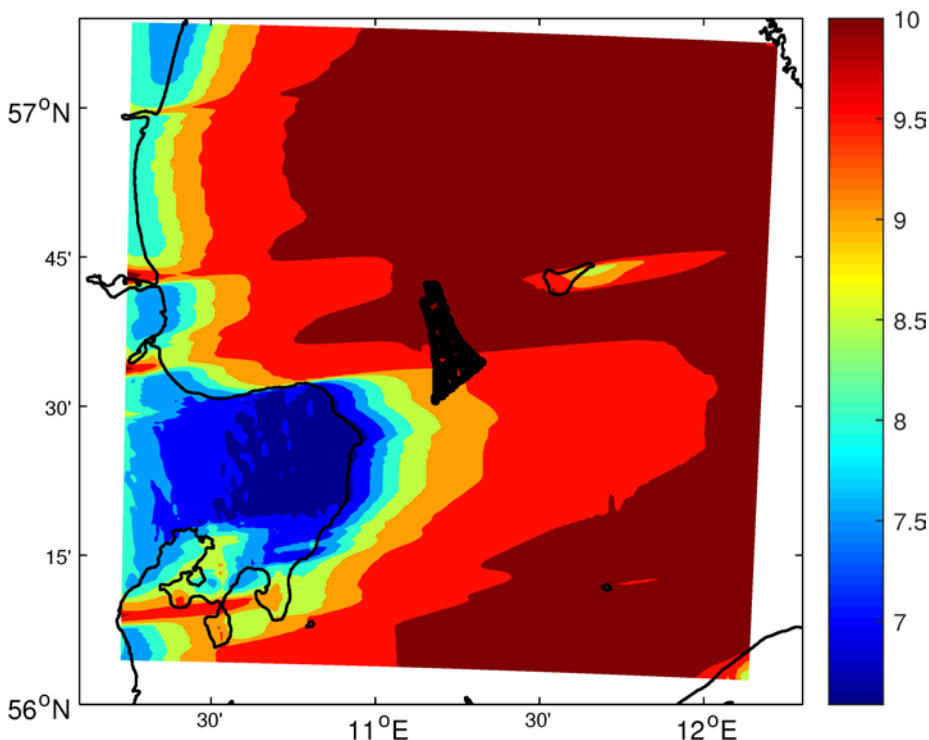


Figure. Wind speed simulated at hub height on the Anholt wind farm from a direction of 260 deg using WAsP Engineering.

2) It seems strange that a 'full' (non-linearised) RANS model was only used for the southerly flow case. Either such results should be shown for comparison in all cases or not at all.

XXX--- The RANS simulations are performed for the southerly flow case because, for this particular case, the SCADA does not match well the results of the “simple” wake models as we mention in the original submission (lines 10-12 Page 11). We wanted to investigate if this was because of the simplicity of the wake models. It is however too costly to perform 735 RANS simulations for the westerly flow cases since a single case takes about 3-4 hours using 153 CPUs (8 nodes). We think that is anyway valuable to show that the underestimation of the wake models is not due to the wake models per se but to the way that either data are treated or to conditions that we cannot extract from the SCADA such as atmospheric stability ---XXX

3) The discrepancy between the RANS model and the results in Fig. 7 was put down to a possible prevalence of stable conditions. It was stated that it was not possible to know this, but surely the WRF model results should have given enough information to at least estimate the stability conditions? Although not definitive, this could lend some weight to this hypothesis. Indeed, in all cases stability is likely to have played a role in wake recovery (and in the coastal transition), though this was not really commented on and would likely have affected the observed wake losses. Also, the RANS model could have been run under stable stratification (perhaps using a couple of z/L scenarios) to test whether a better fit was observed in this case.

XXX--- For the southerly flow case, the WRF simulations show a wide range of atmospheric stability conditions and in ‘average’ the atmosphere is actually close to neutral following the derived stability estimates from WRF. As we now mention in the revised paper, the instantaneous estimations of stability from WRF are rather uncertain (Pena and Hahmann, 2012). We acknowledge that it would be great to include RANS results with stability. However, our RANS model has only been validated with measurements and LES for neutral conditions (van der Laan et al., 2015a; van der Laan et al., 2015b). We have two published (Koblitz et al., 2015; van der Laan et al., 2017b) and one unpublished methods to account for atmospheric stability in RANS, which are all not yet validated to be used for wakes. We are currently conducting this research in a dedicated paper ---XXX

4) The results for the capacity factor in 3.2 used the WRF gradient wind speed with wake models. Given that previously, results were presented with both a WRF wind speed gradient and a single representative WRF wind speed, why was this not presented here?

XXX--- Given that the capacity factor is directly related to the AEP, one can estimate the difference in capacity factors when using different types of wind information by using the differences in AEP shown in table 3 of the original submission ---XXX

5) The authors suggest that an extension to the work would be to infer the wind speed gradient directly from the SCADA data. It seems odd that this was not already included in this work as it was such an obvious thing to do compared to trying to estimate the effect using a model. I would suggest that it would make this work much stronger if it were included.

XXX--- We guess the reviewer refers here to the last two sentences of the first paragraph of the original Discussion. In fact, this is more complicated than it sounds because we need to find all instances where all undisturbed turbines are concurrently operating showing quality-checked and calibrated yaw positions, power and pitch values. Also, and probably more difficult is it to define exactly what is a turbine under undisturbed inflow conditions when you have directions of all 111 individual turbines. This is partly the reason of the use of WRF since we can extract all 111 wake-free wind climates. The results in Fig. 5-right show that for most westerly directions, where the horizontal wind-speed gradient is the highest, WRF seems to do a fairly good job compared to individually-derived wind speeds for the most westerly row. We

have reformulated the sentences to clarify the aspects of such analysis and added a footnote to clarify that the wind-speed gradient cannot be infer from wake-affected turbines ---XXX

6) As suggested in other comments on this paper, the explanation of linear and quadratic wake addition would benefit from some equations and the order of '1' and '2' should be consistent between wake models.

XXX--- We have done this as suggested ---XXX

References

Astrup P., Jensen N.O. and Mikkelsen T. (1996) Surface roughness model for LINCOM. Risø-R-900(EN). Risø National Laboratory, Roskilde, Denmark

van der Laan M.P., Peña A., Volker P., Hansen K.S., Sørensen N.N., Ott S. and Hasager C.B. (2017a) Challenges in simulating coastal effects on an offshore wind farm. *J. Phys.: Conf. Ser.*, 854, 012046

Peña A. and Hahmann A.N. (2012) Atmospheric stability and turbulence fluxes at Horns Rev – an intercomparison of sonic, bulk and WRF model data. *Wind Energ.* 15:717–731

van der Laan, M. P., Sørensen, N. N., Réthoré, P.-E., Mann, J., Kelly, M. C., Troldborg, N., Schepers, J. G., and Macheaux, E. (2015) An improved k- ϵ model applied to a wind turbine wake in atmospheric turbulence. *Wind Energy*, 18, 889-489

van der Laan, M. P., Sørensen, N. N., Réthoré, P.-E., Mann, J., Kelly, M. C., Troldborg, N., Hansen, K. S. and Murcia, J. P. (2015) The k- ϵ -fP model applied to wind farms. *Wind Energy*, 18, 2065-2084

Koblitz, T., Bechmann, A., Sogachev, A., Sørensen, N. and Réthoré, P.-E. (2015) Computational Fluid Dynamics model of stratified atmospheric boundary-layer flow. *Wind Energy*, 18, 75-89

van der Laan, M. P.; Sørensen, N. N. & Kelly, M. C. (2017b) A new k-epsilon model consistent with Monin-Obukhov similarity theory. *Wind Energy*, 20, 479-489

Response to the anonymous referee #3:

Thanks a lot for the review. Here our response to the reviewer's comments. The response is given within XXX--- ---XXX

Regards,
The authors

General comments:

The authors conducted a large number of simulations using a wide variety of models, and compared simulated values with observations from SCADA. These results can be of use to the scientific community, particularly in regards to the coupling of WRF and wake models, and to the effect of the nearby continent on the wind farm production. However, the abstract, methods, results, and conclusions are not well organized and the reader is left wondering what the real contribution of the work is, and what exactly was done when it comes to specific details of the results and their relevance to the scientific community. The manuscript can be greatly improved by overhauling the organization and text, at which point it can be considered for publication.

Specific comments:

Abstract: Very scattered text. Please rewrite. This is very confusing: *“accounting for the horizontal wind-speed gradient gives nearly the same results as averaging all the wake-free wind climates at the turbines' positions or using the wind climate of a position in the middle of the wind farm”*. Results of what? AEP? CF? Can you be more direct with the “take home messages” you include in the abstract?

XXX--- The abstract has largely been changed taking the suggestions of the reviewer. The changes and additions can be clearly seen in the marked-up version of the manuscript ---XXX

This does not belong in the abstract but rather in the discussion section: *“These results are specific for this wind farm, the available dataset, and the derived inflow conditions.”*

XXX--- Given that we provide quantitative results, we think that is very important to say that the numbers are specific for this wind farm, these inflow conditions and this dataset---XXX

Can you be quantitative in the abstract, e.g. the model uncertainty is on average x%? What are the relevant results for the greater scientific community?

XXX--- See our previous two responses ---XXX

The motivation on page 2, lines 20-26 should be included in a reduced manner in the abstract to give a greater context to why this work is relevant and needed. Below is a rewording that you can use as you rewrite your abstract.

In this work, a wide range of models is used to investigate wake effects at the Anholt offshore wind farm. Undisturbed atmospheric conditions are simulated with WRF for an entire year, and wake effects are simulated with two engineering models (Park and Larsen) and with a linearized Reynolds-Averaged Navier-Stokes solver (Fuga). For the engineering models, linear and quadratic approaches are considered for lateral merging of wake deficits. The effect of the horizontal wind speed gradient over the wind farm on the annual energy production and on the capacity factor is quantified by coupling the WRF and wake models and by comparing the derived predictions to SCADA. Additionally, the ability of the wake models in estimating power losses is evaluated, and the relative uncertainty of each wake model is quantified by bootstrapping the SCADA and to estimate the model-specific error distributions. We find that accounting for the horizontal wind speed gradient is important when estimating the annual energy production but not critical to estimating...? We propose methods for estimating freestream flow conditions based on SCADA, when no measurements are available upstream of the wind farm and quantify their relative performance using the turbines power curve...?

XXX--- We appreciate the suggestion of abstract by the reviewer. We now use some of the suggestion to write a revised abstract with what we consider has a better flow. We also add some of the text regarding motivation as suggested ---XXX

Similarly for the discussion and summary, be more specific with your take home messages. Even after carefully reading the entire manuscript, it is not clear to me by the end what your main results are, and what your contribution is. Results are fragmented and scattered.

XXX--- We think this was partly because of the way the abstract and introduction were written and also because of the rather `disruptive` last paragraph in the original discussion. We have removed this last paragraph. We think the abstract and conclusions provide with the important take home messages; a sentence has been added to the second paragraph of the conclusions to link the results for the individual flow cases with the overall power loss. ---XXX

“Background” is not a good title for section 2.

XXX--- We change it for “Methods” ---XXX

Please get rid of “Park1” and “Park2”, “Larsen1” and “Larsen2” and choose more descriptive names such as “Park_Linear” and “Park_Quadratic”, “Larsen_Linear” and “Larsen_Quadratic”.

XXX--- This is now changed as suggested by the reviewers ---XXX

Remove from all figure captions where you have something like “details in main text”.

XXX--- Removed as suggested by the reviewer ---XXX

Be consistent with your verb tenses – either present or past. Example of inconsistency, page 14 line 1: “we use and found”

XXX--- We have gone through the paper to find such inconsistencies ---XXX

Technical corrections:

Section	Page/Line	Comment
Entire manuscript		Don't hyphenate “wind speed” and “wind direction”. You also use hyphens in other various terms that do not call for it, e.g. wind-farm.
		XXX—hyphenation is a matter of style and we think that it is the editor who decides whether this is appropriate. You will not find (if you do it is a typo) two isolated words hyphenated, e.g. wind-farm but wind-farm gradients ---XXX
		Remove the figure references that are left/right and top/bottom and instead use (a), (b), ...
		XXX—This is the style we use and we have used it previously in other publications in the same journal ---XXX
Introduction	2/22	“relatively close by” – be quantitative, how many km?
		XXX—We add the number as recommended ---XXX
Background	3/9	Even after being done reading your manuscript, I still don't understand what is the “ensemble” that you are using for your average. Please explain more clearly: is it an ensemble of turbines? Of grid points? Of models? Of runs?
		XXX--- Since it is not necessary that the values that we average are equally separated in a time-series form, we clarify that these averages are ensemble averages. In the particular case of Eqn. (2) of the original submission it is an average of power values ---XXX
	3/14-16	Please give range of wind turbine spacings within the farm, to make it easier for the reader to understand what your model grid spacing means later on. I was left wondering how much spatial interpolation is being done on a 2 km grid, when you place your turbines on the model grid.
		XXX--- We add “The smallest distance between the turbines is 4.9 rotor diameters”---XXX

3/21	The dataset exclude periods where “any” turbine was parked/idling/etc.? Or only where at least some n number of turbines was parked/idling/etc.?
	XXX--- “any” is added as suggested ---XXX
22	The “;” is confusing, please make two sentences there. I don’t understand this: “power is 5% above rated power for turbines nr. 1, 36, 65, and 68.”
	XXX--- We now split the sentence into two and reformulated the last part to avoid confusion ---XXX
23	How many of these 10-minute time stamps are in 2014, which is the portion you consider in your analysis?
	XXX--- If the type of analysis is performed with the filtered SCADA time series, then all the time series is considered (not only 2014) except for the results regarding the capacity factor, in which we use all non-filtered SCADA for 2014 as stated in the section “Capacity factor” ---XXX
26-27	This is really confusing. Can you have a more lengthy explanation or an equation for $u_{\text{equivalent}}$? Also, you say how the “inflow reference wind speed” is estimated but what is it defined to be? How about it is defined as ... , estimated as ... , and used for ...?
	XXX--- We have reformulated these sentences and provided an extended explanation of the equivalent wind speed ---XXX
4/Fig. 1	Can you color the turbines that are used in those groups you define in Tables 1 and 2, to estimate the “inflow wind speed” and direction? Is this what you call the “inflow reference wind speed”? Does “reference” stand for undisturbed, freestream wind speed?
	XXX--- Colors are added as suggested. As it is stated in line 27/p 3 of the original submission, the inflow reference speed is estimated from wake-free groups of turbines, so yes, it is an undisturbed freestream speed ---XXX
4	Please explain why a group of 4 turbines is used to estimate the wind speed, and only a group of two is used to estimate wind direction? And why are the sectors defined differently? Can you please combine these two tables in one?
	XXX--- The two tables are now combined as suggested. We have extended the explanation of the computation of the inflow wind direction as suggested ---XXX
5/2-12	How long was the simulation run for?
	XXX--- The simulations were originally performed for another project and are described in detail in the reference we provide in the text. For the reviewer’s knowledge, the model was run during nearly 4 months and is a 30-year mesoscale model simulation ---XXX
5/10	Is the model output linearly or logarithmically interpolated to hub height? Please explain. “(the mean wind speed is 9.23 m s^{-1})” over these sectors or over the entire rose? How does that compare to the “inflow reference wind direction” estimated with your method and your two turbines by region?
	XXX--- We add “The model output is logarithmically interpolated to hub height” as suggested. The mean wind speed is an all-sector mean wind speed so this information is now added. It is not important how well the simulated mean wind speed compares to that estimated by us from the SCADA since the latter is less than an ideal time series due to the filtering we apply (described in the SCADA section) ---XXX
6/1-6	Why would you do Park1/Larsen2 for quadratic, and Park2/Larsen1 for linear? Confusing! This entire paragraph is just hard to follow, please rewrite. “We consider three different wake models: the Park wake model with the commonly-used offshore value of $k = 0.04$; the G. C. Larsen model (Larsen, 2009); and Fuga (Ott et al., 2011). Two methods of laterally merging the wake deficits are considered in the first two models: a linear sum and a quadratic sum.”
	XXX--- We have changed the names of Park 1/2 and Larsen 1/2 to linear and quadratic to avoid confusion as suggested and we also take the suggestion of the reviewer regarding the paragraph ---XXX
6/7	What is “a time series basis”? Reword.

	XXX--- This has been reworded as suggested ---XXX	
6/9	What is a “free” wind speed/direction? Reword.	
	XXX--- Changed to “undisturbed” ---XXX	
6/11	“(≈160/340 and 45/235 deg)” confusing – write in words.	
	XXX--- We do not really understand why is this confusing but we now use more words anyway ---XXX	
6/15	Remove this bit starting with “;for the Anholt...AEP analysis”	
	XXX--- Removed as suggested ---XXX	
7/1-12	These two paragraphs are very confusing. Please rewrite the whole thing, even if you need to be more wordy and/or use equations.	
	XXX--- We have rewritten both paragraphs, in particular the first one, which is the one providing the details of how we account for the horizontal wind gradient. Here it is also now defined what a gradient-based analysis is ---XXX	
7/10	What is a gradient-based AEP analysis?	
	XXX--- See our previous response ---XXX	
7/10-12	I don’t understand this last sentence...	
	XXX--- He have also rewritten this sentence so that it is clear what we mean with calculations using pre-computed LUTs ---XXX	
7/20	I assume you can reference this pdf in a better way...	
	XXX--- Corrected as suggested ---XXX	
Results	7/23	Why 2014? Why is half of the year in 2013 for which you do have data, ignored here?
		XXX--- It is simply to have a complete year and not bias the AEP estimation ---XXX
	8/2	By information you mean the WRF simulated wind direction at hub height? Be specific.
		XXX--- We replace “information” by “simulated wind direction at hub height” as suggested ---XXX
	8/5-7	Be quantitative – how small is the effect of the small island relative to the Djursland effect in percentage?
		XXX--- We have added a sentence with numbers regarding the differences between the influence of both land bodies on the farm ---XXX
	8/9	Everywhere in the manuscript change “all directions” to “omnidirectional” “wind gradient” change to “wind speed gradient”
		XXX--- Corrected as suggested ---XXX
	8/10	How does the magnitude of the WRF gradients compare to those in Paul’s RANS work?
		XXX--- For the reviewer’s knowledge: WRF and RANS predict comparable trends of the velocity gradient with respect to wind direction. However, the gradient calculated by WRF is more wide spread with respect to the RANS results (see van der Laan et al., 2017) ---XXX
	9/1	“a effect” change to “an effect”
		XXX--- Corrected as suggested ---XXX
	9/1-4	You need to rewrite this to make it sound a bit more scientific/less speculative. It seems like you are giving a justification for the wind farm wall effect justification for this, but it is poorly worded. Also, this “similar effect” that you are using in your justification is not
	shown, so maybe say that?	
	XXX--- We add “(not shown)” as suggested and use some rewording to sound less speculative as recommended ---XXX	
9/Fig. 5	Left panel: add small markers to points where each turbine is; Do not connect line as we move from one row to the next (e.g. turbine 30 to 31). Legend... “omnidirectional flow”	
	XXX--- Changed as suggested ---XXX	
9/7	“that that” change to “that which” “assuming a horizontally homogeneous”	
	XXX--- Changed as suggested ---XXX	
9/9	“highest impact” of what on what?	
	XXX--- Changed to “difference” and so it is self-explanatory ---XXX	
9/6-9	This sentence is long and confusing.	
	XXX--- We slightly reword and shorten the sentence as suggested ---XXX	

9/13	“larger than 1%” – by how much? XXX--- We provide later (line 14 page 9 of the original submission) the AEP reference value
9/14	“significant” may be not the best term – is this statistical significant? I’m guessing not. XXX--- Changed to “large” in two instances as suggested---XXX
9/12-17	In Section 2 (which may be best called “Methodology”) please explain the choices of these turbines #1, #54, #65 in your analysis, as it seems very arbitrary. XXX--- We do not think that it seems arbitrary. As the original submission states in lines 13, 15 and 17 page 9, these turbines are chosen either because of their strategic location or because in case of 1 the wind speed is the lowest observed---XXX
10/1	Change to “although accounting for the wind farm gradient is important, it does not” XXX--- Changed as suggested ---XXX
10/3-4	This sentence doesn’t belong here? XXX--- This value is here provided so that the reader can see how different the wind of turbines nr. 1, 54 and 65 is compared to the average homogenous wind ---XXX
10/5	This sentence is too informal, please use scientific writing practices. XXX--- We have rewritten the sentence as suggested ---XXX
10/8	By “simulated wind climate” you mean the WRF simulated wind climate? Since you are using so many models, please be very specific when referencing your results. XXX--- We have added “WRF” as suggested ---XXX
10/15-18	So confusing! Reword. XXX--- The sentence has been split into two and reworded ---XXX
10/footnote	I still don’t understand what your ensemble is... time series at each wind turbine location? At all the WRF grid points in the innermost domain? XXX--- The footnote has been removed---XXX
11/Fig. 6	Don’t use these abbreviations “grad” and “homo” – just spell out the entire term, there is space. What is the SCADA standard “error”? I assume this is the same as “standard deviation” but the term “error” is not usually used in this context, especially when error means something else here (simulations-observations). XXX--- We changed to “standard error of the mean” which is equal to σ/\sqrt{n} , with n being the number of samples. We also avoid the abbreviations as suggested ---XXX
11/1-2	Why, if the flow is from the west? I don’t understand the P3<P31. Is this circling back to your blockage comment earlier on? If so, please remind the reader. XXX--- There are couple of possible reasons: first it is a large wind sector, second distances are large between these two archs and so wakes are small , third the wake meanders, and fourth the inflow is not uniform ---XXX
11/5	Why this weird number, 168.7? Explain. Be more specific on which information from Table 1 is used, which group? I still don’t understand your entire process of estimating these “reference” inflows, when they are used and what for. XXX--- We now add “, which is the direction where turbines nr. 45 and 46 are aligned”. We also rephrased the text so that it reads “that are derived from the SCADA of turbines nr. 45 and 67–68 (Table 1)” to be more explicit---XXX
12/3	Yes you do, you can use WRF output to estimate stability. Please comment on why not do it? XXX--- We do not have observations of atmospheric stability. We add “We have atmospheric stability measures from the WRF simulations but ‘instantaneous’ WRF stability measures are highly uncertain (Peña and Hahmann, 2012)” ---XXX
12/4	Why is this interesting? Why are the differences so large? XXX--- We delete “interesting” from the sentence. As we mention, the period is different from that used by Nygaard (2014) ---XXX
12/15	“performing the best” – reword this. XXX--- See next response ---XXX

12/15-17	Confusing, reword. Why is it not “fair”? Maybe “fair” is not an adequate word here?	
	XXX--- We reword the sentences as suggested: “However, it is important to note that wind turbines are not always working and underperform when compared to the manufacturer's power curve. The predicted AEP/capacity factor of a combined mesoscale-wake model is typically lower than the observed value; however, we want to know the capacity factor of a wind farm regardless of the operating conditions.”---XXX	
13/3	Instead of having these numbers in the text can you add them as another column to Table 4, just noting that for PL estimation WRF is not used just the wake models?	
	XXX--- We think that this will be confusing as WRF is not used for the PL estimations and because these are two different datasets --- XXX	
13/7-13	I’m not sure about this paragraph – it sounds like a justification of your methodology and not really a result. Does it belong elsewhere, maybe Section 2?	
	XXX--- In section 2 we do not show any results that involve the analysis of SCADA so we choose this place as the power loss is directly dependent on the derived undisturbed inflow conditions ---XXX	
13/17-20	What does this mean for your analysis?	
	XXX--- We respond to this question in the first paragraph of the original discussion ---XXX	
14/2-3	It is counter-intuitive to say that positive values mean under-estimation, so reword this a bit: “where positive ϵ values denote a model that overestimates the power (i.e. underestimates the wake loss)”	
	XXX--- Changed as suggested ---XXX	
14/3	“mean $\langle \epsilon \rangle$ and standard deviation σ_{ϵ} of the distributions”	
	XXX--- Changed to “The mean and standard deviation of the distributions of ϵ , $\langle \epsilon \rangle$ and σ_{ϵ} ” ---XXX	
14/Table 5	Get rid of this table and add these numbers to Fig. 9.	
	XXX--- Corrected as suggested ---XXX	
16/1-5	This paragraph is completely irrelevant.	
	XXX--- Removed as suggested ---XXX	
Conclusions	16/7	We “confirm” or “reiterate” – you don’t really “show” since previous work had already shown this.
		XXX--- Changed to “confirm” as suggested ---XXX

References:

- Peña A. and Hahmann A.N. (2012) Atmospheric stability and turbulence fluxes at Horns Rev – an intercomparison of sonic, bulk and WRF model data. *Wind Energ.* 15:717–73
- van der Laan M.P., Peña A, Volker P., Hansen K.S., Sørensen N.N., Ott S., and Hasager C.B. (2017) Challenges in simulating coastal effects on an offshore wind farm. *J. Phys.: Conf. Series* 854, 012046

On wake modeling, wind-farm gradients and AEP predictions at the Anholt wind farm

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Abstract.

We investigate wake effects at the Anholt offshore wind farm in Denmark. ~~We perform the analysis, which is a farm experiencing strong horizontal wind-speed gradients because of its size and relatively closeness to land. Mesoscale model simulations are used to study the horizontal wind-speed gradients over the wind farm. From analysis of the mesoscale simulations and SCADA, we show that for westerly flow in particular, there is a clear horizontal wind-speed gradient over the wind farm. We also use the mesoscale simulations to derive the undisturbed inflow conditions that are coupled~~ with three commonly-used wake models; two engineering approaches (the Park and G. C. Larsen models) and a linearized Reynolds-averaged Navier-Stokes approach (Fuga). ~~From analysis of SCADA and mesoscale model simulations, we show that for westerly flow in particular, there is a clear~~ The effect of the horizontal wind-speed gradient ~~over the wind farm, which results from the effect of the land nearby. We also show that for~~ on annual energy production estimates ~~, in which a wake model is run with inflow conditions derived from mesoscale model outputs, accounting for the horizontal wind-speed gradient gives nearly the same results as averaging all the wake-free wind climates at the~~ is not found to be critical compared to estimates from both the average undisturbed wind climate of all turbines' positions ~~or using the~~ and the undisturbed wind climate of a position in the middle of the wind farm. However, annual energy production estimates can largely differ when using wind climates at positions that are strongly influenced by the horizontal wind-speed gradient. When looking at westerly flow wake cases, where the impact of the horizontal wind-speed gradient on the power of the undisturbed turbines is largest, the wake models agree with the SCADA fairly well; when looking at a southerly flow case, where the wake losses are highest, ~~they~~ the wake models tend to underestimate the wake loss. With the mesoscale-wake model setup, we are also able to estimate the capacity factor of the wind farm rather well when compared to that derived from the SCADA. Finally, we estimate the uncertainty of the wake models ~~and some of its variants~~ by bootstrapping the SCADA. The models tend to underestimate the wake losses (the median relative model error is 8.75%) and the engineering wake models are as uncertain as Fuga. These results are specific for this wind farm, the available dataset, and the derived inflow conditions.

1 Introduction

The Anholt wind farm is currently the fourth largest offshore wind farm in the world power-wise. The layout of the Anholt wind farm was optimized to minimize wake losses. The number of wind turbines (111), the wind-turbine type and the maximum

allowed wind-farm area for turbine deployment (88 km²) are examples of chosen constraints. The employed optimization tool has a tendency to place most wind turbines at the edges of the wind-farm area, while the remaining wind turbines are placed inside the wind farm with a relative large interspacing. For the particular case of Anholt, a number of wind turbines were relocated from the optimized layout due to seabed that turned to be too soft (Nicolai Gayle Nygaard, 2017, personal communication).

So far the only reported studies on the wake effects of this wind farm are those of Nygaard (2014), Nygaard et al. (2014), and van der Laan et al. (2017). In the former, there is a comparison between the Park wake model (Katic et al., 1986) and SCADA for a row of turbines in the middle of the wind farm for a given wind-direction and wind-speed range. The wake model ~~does not underestimate~~ estimates fairly well the wake losses, ~~which is commonly argued as an issue of the engineering~~ wake models when predicting wakes in large arrays. The study also presents the results of the Park model for ~~different other~~ large offshore wind farms, clearly showing that this wake model agrees with the SCADA for different inflow conditions rather well. ~~In the next mentioned study~~ These are interesting findings because engineering wake models do not generally include coupling with the vertical structure of the atmospheric boundary layer, thus, they should tend to underpredict wake losses in large offshore arrays (Stevens et al., 2016). However, the studies showing wake-model underprediction in large offshore wind farms (Barthelmie et al., 2009) analyze the wake observations using narrow wind direction sectors and do not account for wind direction variability. In the study by Nygaard et al. (2014), a comparison of two wake models, Park and the eddy viscosity model of WindFarmer (GL Garrad Hassan, 2013), is performed against SCADA, revealing that Park, with a wake-decay coefficient $k = 0.04$, gives the best results better results than the model of WindFarmer with and without a large wind-farm correction. In the ~~third study~~ study by van der Laan et al. (2017), the effect of the coastline on the wind farm is investigated with a Reynolds-averaged Navier-Stokes (RANS) model, showing that such RANS setup is able to predict the horizontal wind-speed gradient over the wind farm when compared to the SCADA and mesoscale model simulations.

Engineering wake models are also often regarded as too simplistic for the estimation of wake losses, yet they are those that are most used when planning wind-farm layouts and for annual energy production (AEP) estimations. This is because they can be easily implemented and optimized in terms of computational performance. One cannot expect to characterize wakes in detail with such models but for the estimation of power and energy production means, they are sufficiently accurate when used properly (Nygaard, 2014; Nygaard et al., 2014). Peña et al. (2014) show that the Park model is able to predict the wake losses of the Horns Rev I wind farm in the North Sea for different atmospheric stability conditions when using a stability-dependent wake-decay coefficient. Peña et al. (2016) show that the Park model is in good agreement with the Sexbierum cases where two more sophisticated wake models are also tested: a linearized RANS solution (Fuga) and a nonlinear solution of the RANS equations that uses a modified $k-\varepsilon$ turbulence model. In the latter two studies, the goodness of the results of the Park model is partly a result of accounting for the variability of the wind direction (Gaumont et al., 2014).

~~The layout of the Anholt wind farm was optimized to minimize wake losses. The number of wind turbines (111),~~ Since Fuga is a computationally efficient wake model, whose results (in terms of wind-speed deficits) are nearly equal to those of a nonlinear solution of the RANS equations (Ott et al., 2011), we want to find out how different AEP and capacity factor estimates are when compared to those of Park and of another wake model that is a simple solution of the ~~wind-turbine type~~

and the maximum allowed wind-farm area for turbine deployment (88 km²) are examples of chosen constraints. The employed optimization tool has a tendency to place most wind turbines at the edges of the wind-farm area, while the remaining wind turbines are placed inside the wind farm with a relative large interspacing. For the particular case of Anholt, a number of wind turbines were relocated from the optimized layout due to seabed that turned to be too soft (Nicolai Nygaard, 2017, personal communication). RANS equations, the G. C. Larsen model (Larsen, 2009).

Wake models of all types have been mainly evaluated against offshore wind farms that are well off the coast or where the effect of the land is assumed to be minimal (Barthelmie et al., 2009; Réthoré et al., 2013; Stevens et al., 2016). The Anholt wind farm can therefore help us investigating such effect as the land is relatively close by (≈ 20 km) and within the direction of the predominant winds. We are aware that the Anholt wind farm experiences strong horizontal wind-speed gradients, which are translated into power gradients for turbines that are not experiencing wakes (Damgaard, 2015). The challenge is therefore to find out how such gradients interfere with the wake losses and how these affect the production and the annual energy production (AEP). This can be performed by simple ‘coupling’ of undisturbed wind climates at some (or all) turbines’ positions, in which the horizontal wind-speed gradient is embedded, with the wake models. To the authors knowledge, there has not been attempts to study the impact of the horizontal wind-speed gradient on wakes of wind farms using engineering wake models yet, although there is an attempt to include wind-direction gradients (Hasager et al., 2017). An obvious choice to derive the wind climate is the use of a mesoscale model such as the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008), which is nowadays often used multi-purposely in the wind-energy community (Storm and Basu, 2010; Hahmann et al., 2015). In the present work, we also want to investigate the ability of WRF to model the horizontal wind-speed gradient over the wind farm.

In this study, we first present (Sect. 2) a general background regarding the Anholt wind farm, the WRF mesoscale runs that we use to estimate the wind-farm climate, the wind-farm SCADA, the wake models, and the ways in which we account for the horizontal wind-speed gradient and estimate the wake-models uncertainty. Section 3 presents the results regarding the influence of the wind-speed gradient on flow cases, on the AEP, those showing the evaluation of the wake models for two flow cases, and the analyses of the capacity factor, power loss and model uncertainty. Finally, discussion and conclusions are given in the last two sections.

2 Background Methods

2.1 Definitions

We define the efficiency of the wind farm at a given wind speed U as

$$\eta_U = \frac{\sum_i P_i}{n_t P_U}, \quad (1)$$

where P_i the power of each individual turbine in the farm, P_U the power of the turbine from the power curve at U , and n_t the number of turbines in the wind farm.

We define the power loss of the wind farm as

$$PL = 1 - \frac{\langle \sum_i P_i \rangle}{n_t \langle P_{free} \rangle}, \quad (2)$$

where $\langle \rangle$ means ensemble average and P_{free} is the power of the free-stream turbines (these are defined in Sect. 2.2.2).

We define the relative wake model error as

$$\epsilon = \frac{PL_{obs} - PL_{mod}}{PL_{obs}}, \quad (3)$$

where the subscript obs and mod refer to observations and model, respectively.

2.2 Anholt wind farm

The Anholt wind farm is located in the Kattegat strait between Djursland and the island of Anholt in Denmark (see Fig. 1-left).

It consists of 111 Siemens 3.6 MW-120 turbines with hub height of 81.6 m and a rotor diameter of 120 m (Fig. 1-right). The

10 smallest distance between the turbines is 4.9 rotor diameters. The water has depths of 15–19 m, the wind farm area is 88 km² and full operation started since summer 2013.

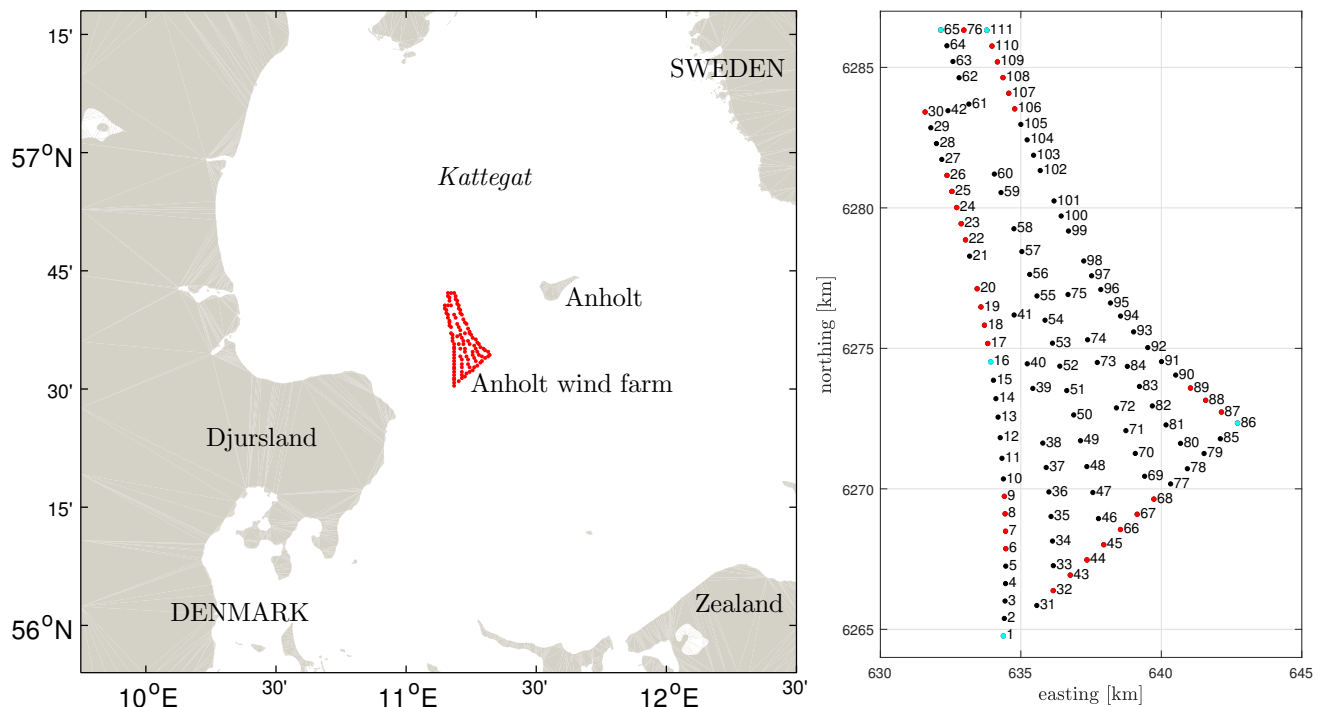


Figure 1. (Left) the Anholt wind farm (red markers) in the Kattegat. (Right) The layout and numbering of the turbines of the Anholt wind farm in UTM32 WGS84. Turbines used to derived the inflow conditions are shown in red and cyan markers

2.2.1 SCADA

We have access to 10-min means of SCADA for the period January 1, 2013 to June 30, 2015. Data include nacelle wind speed, yaw position, pitch angle, rotor speed, power reference, air temperature, rotor inflow speed, and active power. We also produce a filtered SCADA dataset by identifying periods where each turbine was grid connected and produced power during the entire 10-min period. The dataset excludes periods where ~~turbines were any turbine was~~ either parked or idling, those with starting and stopping events, where power was curtailed, or boosted; ~~power is 5% above rated power for.~~ We find turbines nr. 1, 36, 65, and ~~68. 68 to be boosted with power values 5% above the rated value.~~ The result is a time series of 7440 10-min values starting in July 2013 until December 2014.

2.2.2 Inflow conditions

Due to the lack of ~~wake-free undisturbed~~ mast measurements in the SCADA, we derive the inflow conditions from the filtered SCADA dataset. We estimate an ‘equivalent’ wind speed ~~from based on either the~~ 10-min ~~power and pitch values combined~~ SCADA’s power or pitch angle values in combination with the manufacturer’s power curve or the average pitch curve extracted from the SCADA. The inflow reference wind speed is ~~estimated computed~~ as the average equivalent wind speed for ~~wake-free~~ groups of four undisturbed turbines as shown in Table 1. A group of four turbines is used to robustly estimate the inflow wind speed and 10 different sectors are needed to avoid the influence of Djursland and the island of Anholt. The inflow reference wind direction is ~~estimated as the average of the calibrated, undisturbed wind turbine yaw position of two turbines as shown in Table ??.~~ Due to the large wind farm extension, we also use an additional constraint requiring that nearby wake generating turbines are online during the analysis. computed as an average yaw position for pairs of undisturbed wind turbines listed in Table 1. The yaw position calibration is performed as in Rodrigo and Moriarty (2015). The turbines that we use to derive the inflow conditions are shown in Fig. 1-right.

Table 1. Free-stream turbines used to determine the inflow wind speed (first two columns) and the inflow wind direction (second two columns) as function of wind direction

dir [deg]	turbine nr.		
0–35	65 76 110 111		
35–55	106 107 108 109		
55–90	86 87 88 89		
90–180	45 66 67 68		
180–215	32 43 44 45		
215–230	6 7 8 9		
230–270	22 23 24 25		
270–280	17 18 19 20		
280–310	23 24 25 26		
310–360	30 65 76 111	Free-stream turbines used to determine the inflow wind direction as function of wind direction dir deg	turbine nr. 0–30 65

2.3 Wind-farm climate

We perform simulations of the wind climate over a region covering the Anholt wind farm using the [Weather-Research-and-Forecasting \(WRF\)-WRF](#) version 3.5.1 model. Simulations are carried out on an outer grid with horizontal spacing of 18 km \times 18 km (121 \times 87 grid points), a first nested domain of 6 km \times 6 km (280 \times 178 grid points), and a second nest with center in the middle of Jutland, Denmark of 2 km \times 2 km (427 \times 304 grid points). The simulations use 41 vertical levels from the ground to about 20 km. The lowest 12 levels are within the 1000 m of the surface with the first level at \approx 14 m. Initial, boundary conditions, and fields for grid nudging come from the European Centre for Medium Range Forecast ERA-Interim Reanalysis (Dee et al., 2011) at $0.7^\circ \times 0.7^\circ$ resolution. Other choices in the model setup are standard and commonly used in the modelling community. Further details regarding the simulations are provided in Peña and Hahmann (2017). Figure 2 shows the Anholt wind climate at hub height at a WRF grid point in the middle of the wind farm based on the WRF hourly outputs for 2014. [The model output is logarithmically interpolated to hub height.](#) Most winds come from the west, south-southwest, and southeast directions and winds between 5 and 15 m s⁻¹ are the most frequent (the [all-sector](#) mean wind speed is 9.23 m s⁻¹).

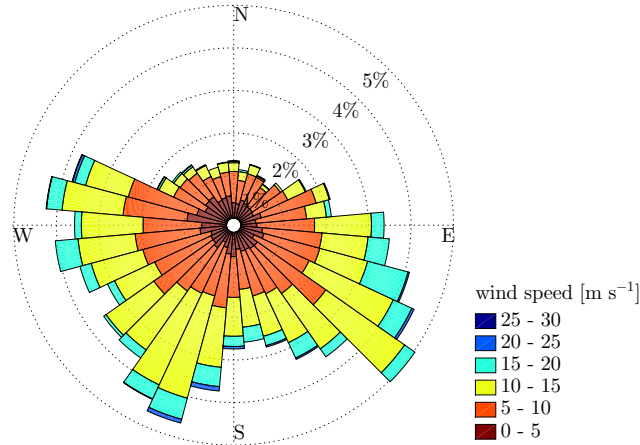


Figure 2. The wind climate at hub height in the middle of the Anholt wind farm for the year 2014 based on WRF simulations

2.4 Wake models

We use three different wake models: the Park wake model with the commonly-used offshore value of $k = 0.04$ [with two variants; adding the wake deficits as a quadratic sum \(hereafter Park 1\) and linearly \(hereafter Park 2\)](#), the G. C. Larsen model (Larsen, 2009) [adding the wake deficits linearly \(hereafter Larsen 1\) and as a quadratic sum \(hereafter Larsen 2\)](#), and Fuga (Ott et al., 2011). The first two are engineering wake models and Fuga is a linearized flow solver of the steady-state RANS equations using an actuator-disk approach. [For the two engineering wake models, the local wake deficits \$\delta_i\$ are superposed to compute the speed deficit at the \$n\$ th turbine. This is performed in two different ways: linearly \$\sum_{i=1}^n \delta_i\$ and as a quadratic sum \$\(\sum_{i=1}^n \delta_i^2\)^{1/2}\$.](#)

Due to the high computational efficiency of these wake models, we can easily perform wake analysis over given wind-speed and wind-direction ranges and AEP-like calculations ~~in a time series basis using the values in the time series (no need for distributions)~~. For the latter calculations, we create look-up-tables (LUTs) for each wake model, which contain the total wind-farm power output for specific ~~free-undisturbed~~ wind directions and wind speeds. Figure 3 shows a comparison of the efficiency of the wind farm (Eqn. 1) predicted by the wake models. All wake models show the highest wake losses at the directions where most wind turbines are aligned (~~i.e. at ≈ 160 and 340 deg, and 45 and 235 deg~~). At 5 m s^{-1} , the ~~Park-2-Park-linear~~ model generally shows the highest wake losses followed by ~~Larsen-1-Larsen-linear~~ and Fuga (within the direction where turbines are most aligned). At ~~5 and~~ 10 m s^{-1} , $\eta \approx 0.9$ for all wake models excluding the most aligned directions, being ~~Larsen-2 and Park-2-Larsen-quadratic and Park-linear~~ the models showing the highest and lowest efficiencies, respectively; ~~for the Anholt wind climate (Fig. 2) these two models will most probably be the most and less optimistic models, respectively, when performing AEP analysis.~~

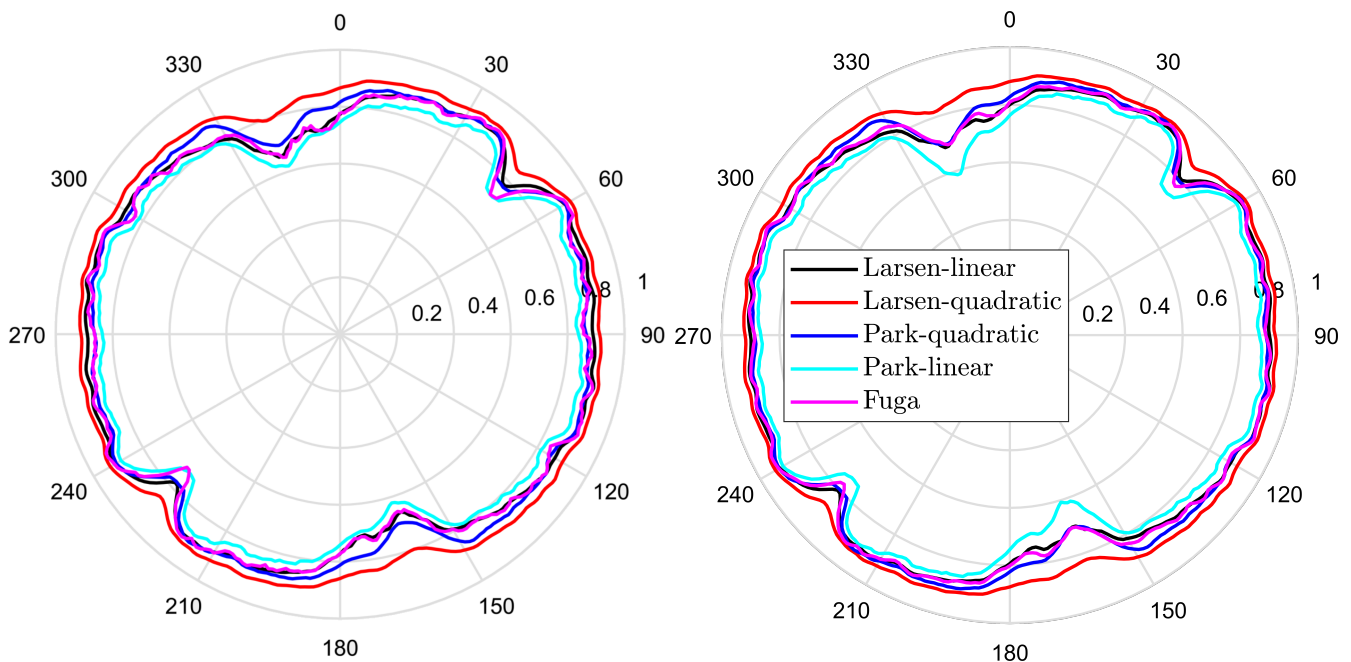


Figure 3. The efficiency of the Anholt wind farm predicted by the wake models at 5 m s^{-1} (left frame) and 10 m s^{-1} (right frame)

2.5 Accounting for the wind-farm gradient

One way to account for the ~~effect of the~~ horizontal wind-speed gradient within a wind farm is ~~to estimate the wake, which is not the result of wake effects themselves, on the wind-farm power output~~ is by estimating the wake losses using the ~~undisturbed~~ wind speed and direction at each ~~turbine individual turbine position for each time realization~~ as inflow condition ~~and then average the power estimated at~~ instead of using a single undisturbed wind speed and direction as it is commonly performed.

At each turbine position (the average is thus computed for the number of, we will therefore have both a time series of velocity deficits (and thus power values) because of the change with time of inflow conditions and a series, with a number of members equal to the number of turbines in the farm). The wind, of velocity deficits for each inflow condition experienced by each turbine for each time realization. Then, the wind-farm power time series, as an example, can be estimated by averaging the power resulting from all inflow conditions for the same time realization (for the Anholt case this means 111 conditions) and then averaging the results of all turbines. This is hereafter known as a gradient-based analysis. The wind/inflow at each turbine must be wake-free undisturbed and so mesoscale model simulations over the wind-farm area (without the wind farm) are an obvious option to estimate the wind climate at each turbine position.

Due to the very high efficiency of the Park model (in a Matlab script it takes ≈ 55 ms milliseconds to perform one simulation of Anholt for a given single inflow wind speed and direction), when using the WRF hourly time series, we can perform 111 simulations (i.e. 111 different inflow conditions that are interpolated from the WRF grid into the turbine positions) in ≈ 6.1 couple of seconds. Thus, we can perform a gradient-based AEP analysis with hourly WRF winds in ≈ 15 h just few hours. It is important to note that we can perform traditional¹ AEP calculations with all wake models much faster using the LUTs but these contain the total wind-farm power output only and not the AEP of each individual turbine pre-computed LUTs.

2.6 Uncertainty estimation

We quantify the uncertainty of the wake models using a nonparametric circular-block bootstrap similar to Nygaard (2015). The idea is to ‘wrap’ the power-output time series (from both measurements and simulations) of the wind farm around a circle. Blocks of the time series with a given size, which is here selected according to Politis and White (2004) based on the wind-speed time series, are then randomly sampled. The number of sampled blocks is given by the total size of the time series and the block size. The number of bootstrap replications should be large enough to ensure a close to zero Monte Carlo error. By bootstrapping the power-output time series, we can estimate the bootstrapped PL and so estimate a distribution of ϵ . Details and code implementations of a number of bootstrapping techniques can be found at in Sheppard (2014).

3 Results

The analysis of the influence of the horizontal wind-speed gradient in Sect. 3.1 is performed with the WRF model outputs for 2014 and the filtered SCADA dataset. For AEP estimations (Sect. 3.1.1), we only use WRF model outputs for 2014. The westerly flow case in Sect. 3.1.2 uses the filtered SCADA dataset, as well as the south flow case in Sect. 3.1.3, and the WRF model outputs for 2014. For the capacity factor calculations in Sect. 3.2, we use all the SCADA available for 2014 and the WRF model outputs for the same year. The analyses of the power loss and model uncertainty in Sects. 3.3 and 3.4 are performed on the filtered SCADA.

¹traditional here implying AEP calculations with a single inflow condition per time realization

3.1 Influence of the wind-farm gradient

Figure 4 shows the mean horizontal wind-speed gradient at hub height in and surrounding the Anholt wind farm based on simulations from the WRF model for the year 2014. The left frame shows the average for all wind speeds and directions and the right frame the average for all wind speeds and directions within 270 ± 30 deg, which have been filtered using the [information-at-simulated-wind-direction-at-hub-height-at](#) the position of turbine 15. It is clear the influence of Djursland (see [Fig. 1-left](#)) on the wind at the farm even for the [all-directions-omnidirectional](#) case. The impact of Djursland is much stronger when looking at westerly winds so we could expect an impact on the results of wake models when the flow is particularly from these directions. The horizontal wind-speed gradient is mainly due to the roughness effect of the land surrounding the wind farm (van der Laan et al., 2017). Although it is not shown, the island of Anholt east of the farm also has an impact on the wind speed at the wind farm for northeasterly flow but this is not as strong as that of Djursland for westerly flow. [For westerly winds \(\$270 \pm 30^\circ\$ \), the WRF-simulated average hub-height wind-speed difference between turbines nr. 1 and 30 is \$0.62 \text{ m s}^{-1}\$, whereas for easterly winds \(\$90 \pm 30^\circ\$ \) it is \$0.12 \text{ m s}^{-1}\$ between turbines nr. 86 and 111.](#)

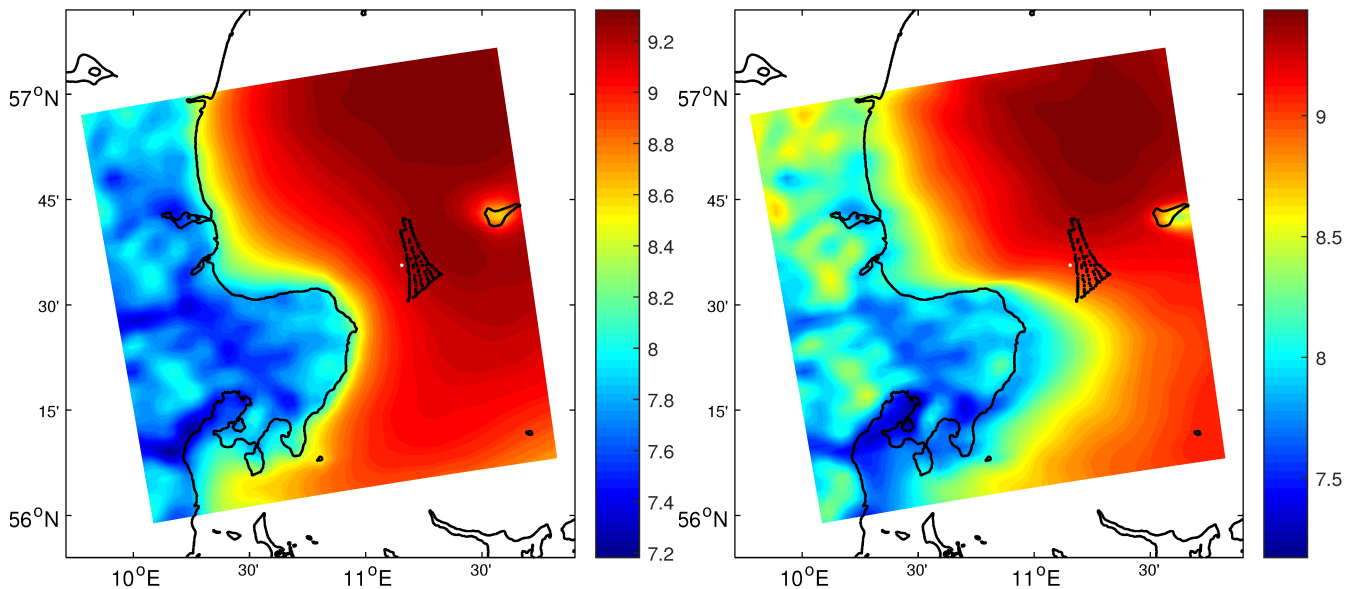


Figure 4. WRF-simulated mean wind speed at hub height on the Anholt wind farm area for the year 2014. All data are shown in the left frame and data within the directions $270 \pm 30^\circ$ at the position of turbine nr. 15 in the right frame. Colorbars are in m s^{-1}

In Fig. 5-left we extract the values from Fig. 4 at each turbine position by linearly interpolating the WRF winds to the turbine positions. For the [all-directions-omnidirectional](#) case, the [wind-horizontal-wind-speed](#) gradient is lower than for westerly winds, as expected, and for both cases the strongest gradient is observed for the first row of turbines (1–30), which are those closer to Djursland.

Figure 5-right shows SCADA-derived and WRF-simulated average wind speeds at hub height for turbines nr. 1–30 for a number of westerly flow cases. We select filtered SCADA based on the inflow conditions described in Sect. 2.2.2 within the wind-speed range $5\text{--}10\text{ m s}^{-1}$ and use the manufacturer's power curve to derive each turbine's wind speed from the power output. For the comparison, we extract the WRF-simulated winds by averaging the horizontal wind-speed components on the corresponding free-stream turbines for each direction range as given in Table 1. We also select WRF-simulated winds within the same wind-speed range $5\text{--}10\text{ m s}^{-1}$. It is observed that the horizontal wind-speed gradient for westerly winds depends on the particular direction. The strongest simulated and observed gradients are found at $265 \pm 5\text{ deg}$, being the winds at turbines nr. 1–15 lower than those at turbines nr. 15–30. Generally, the simulated gradient agrees with the observations fairly well, except for the range $295 \pm 5\text{ deg}$, where the SCADA show the highest winds at the southern turbines. This ~~might be a~~ can be an effect of the topography on the turbines, which is not captured by WRF, ~~but it is more plausible that this is~~. It could also be a wind-farm wall effect (Mitraszewski et al., 2012). A similar effect (not shown) is observed when analyzing the SCADA-derived wind speeds of the turbines at the south of each row for a direction $80\text{--}90\text{ deg}$: the wind speed at turbine nr. 1 is about 6% higher than that at turbine nr. 86.

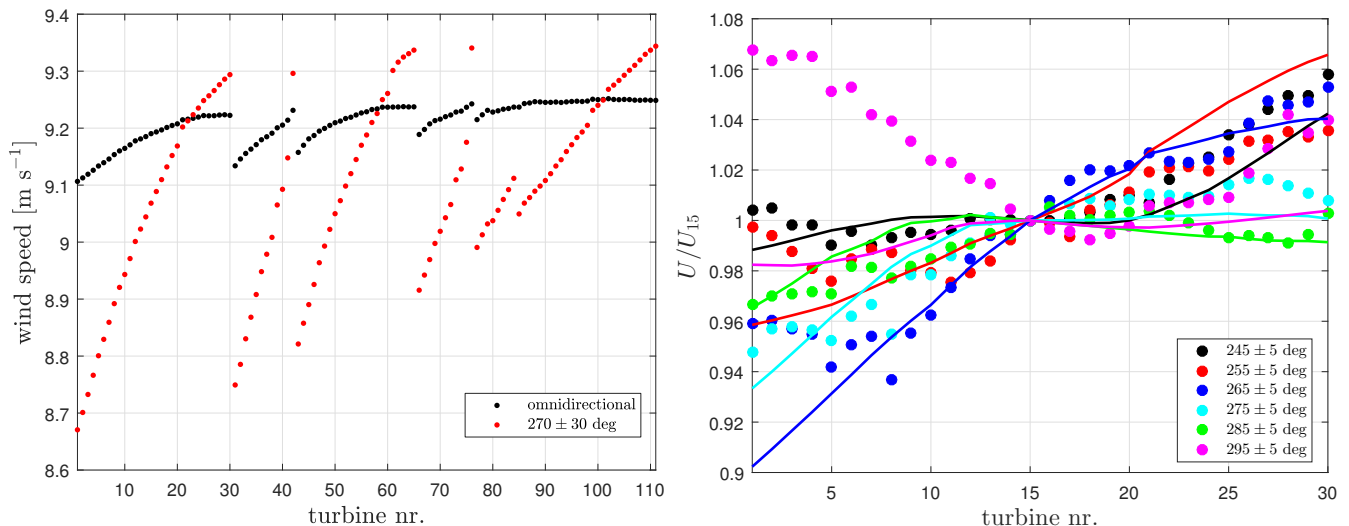


Figure 5. (Left) WRF simulated average wind speed at hub height at the turbine positions of the Anholt wind farm. (Right) Average wind speed at hub height (normalized by that of turbine 15) at the most westerly row of the wind farm for a number of westerly flow cases: WRF winds in solid lines and SCADA-derived winds in markers (details in the main text)

3.1.1 Annual energy production

15 The difference in AEP when accounting for the wind-farm gradient information ~~as described in Sect. 2.5, to perform the AEP analysis and that that results by assuming a~~ and when assuming a horizontally homogenous wind field (estimated each

hour by taking the average of the horizontal wind-speed gradient over each turbine of the farm)² is not larger than 1% when using the 2014 hourly WRF wind fields during 2014 combined with the wake models ('average wind field' column in Table 2). The highest impact difference is observed for the WRF-Fuga setup, in which the estimation using the 'average wind' does not compensate for the low energy yield of the turbines in the south of the farm and the high energy yield of those in the north as it does for the other WRF-wake model setups.

Table 2. Difference (in percentage) between different type of AEP calculations and that using the horizontal wind-speed gradient information from the WRF simulations

model setup	average wind field	turbine nr. 1	turbine nr. 54	turbine nr. 65
WRF-Park 1 WRF-Park-quadratic	0.05	-1.29	0.08	0.26
WRF-Park 2 WRF-Park-linear	0.05	-1.33	0.07	0.26
WRF-Larsen 1 WRF-Larsen-linear	0.05	-1.28	0.08	0.27
WRF-Larsen 2 WRF-Larsen-quadratic	0.06	-1.24	0.08	0.27
WRF-Fuga	0.76	-0.59	0.77	0.98

The difference in the AEP estimation by accounting for the wind-speed gradient and that by using the wind climate of turbine nr. 1, which is the position with the lowest average wind speed, is larger than 1% for the engineering wake models. Such difference is significant rather large considering that the AEP of the wind farm is ≈ 1889.3 GW h when averaging all models' AEP estimations using the wind-gradient information. The same exercise using the information of turbine nr. 54 (in the middle of the farm) results in differences very close to those using the average wind field. Using the information of turbine nr. 65 (at the top of the farm), the difference is also significant large but positive as expected. For the Anholt wind farm and its wind climate, in particular, these results show that although it is important, accounting for the wind-farm gradient is important, it does not change largely the AEP estimations compared to those based on a one-point wind climate, unless the latter is not close to the average wind climate within the wind-farm area. For comparison purposes (e.g. with the results in Fig. 5-left) the yearly average wind speed of the 'homogenous' wind is 9.21 m s^{-1} .

3.1.2 Westerly flow cases

So, is the Given the impact of the horizontal wind-speed gradient important when studying on the AEP estimations (Sect. 3.1.1), it is relevant to study the wake losses under westerly flow conditions?-. Figure 6-top shows the average³ ~~WRF-Park 1,~~ for 2014, the average ~~WRF-Park-quadratic~~ power of each turbine in the wind farm when filtering for westerly wind directions (using the WRF simulated wind climate at turbine nr. 15), both accounting for the wind-speed gradient, as described in Sect. 2.5, and assuming a homogenous wind field (the average of the wind climates at each turbine). For a broad wind-direction range, both results are nearly identical and only small differences at specific turbines (up to 27.2 kW) are found when the wind-direction range is reduced; in this latter case we use the range that shows the largest gradients in Fig. 5-right. It is important to

² estimated each hour by taking the average of the horizontal wind-speed gradient over each turbine of the farm

³ ensemble average of the 2014 time-series

note that, although it is not seen, the normalized average power of turbines 1–30 for the two ‘gradient’ cases in Figure 6-top is slightly lower than one.

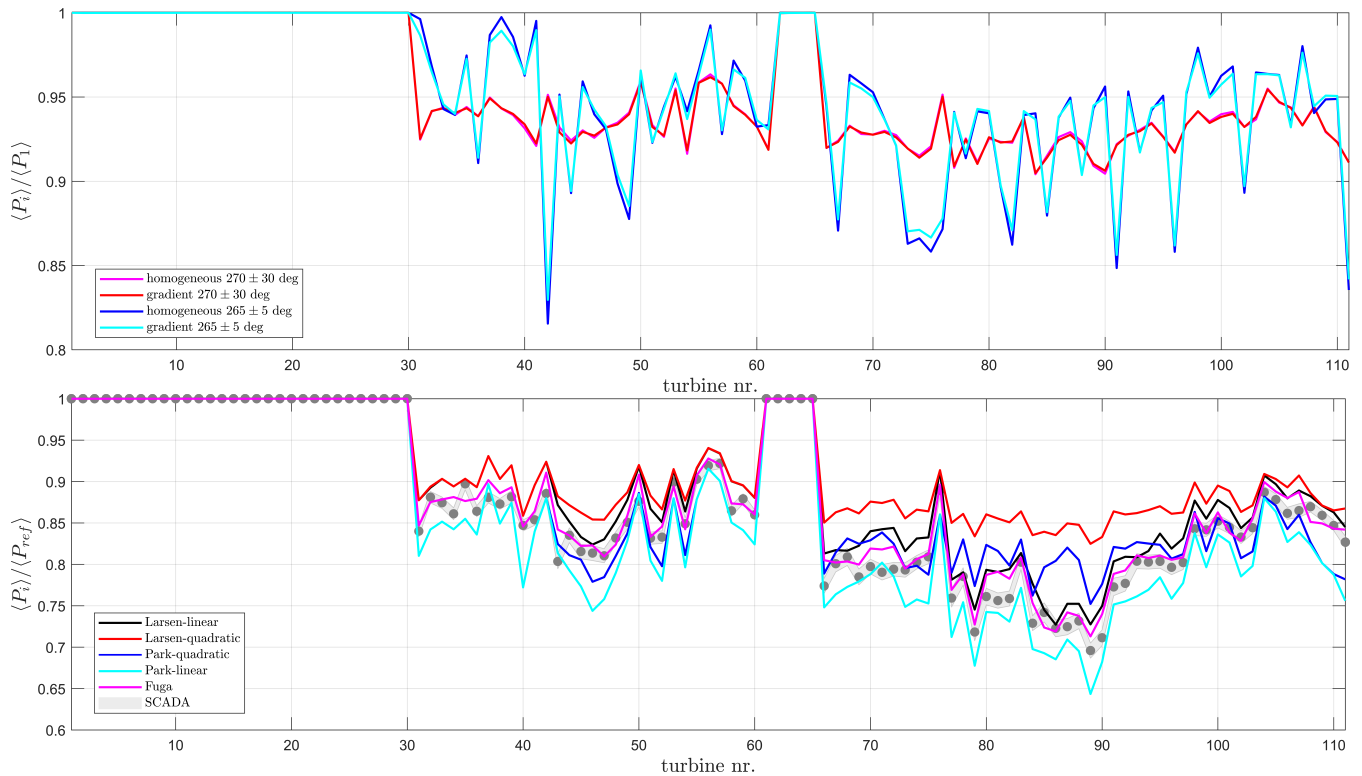


Figure 6. Normalized average power of each turbine in the wind farm for westerly flow conditions. (Top) from simulations using the 2014 WRF time-series and [Park-1 Park-quadratic](#) with ([grad-gradient](#)) and without ([homo-homogeneous](#)) the horizontal wind-speed gradient information. (Bottom) from SCADA and simulations from the wake models within the range 270 ± 30 deg and hub-height inflow wind speed of $5\text{--}10 \text{ m s}^{-1}$ ([details in the main text](#)). For the SCADA, the shaded region indicates \pm the standard error [of the mean](#)

Since the [horizontal-wind-speed-horizontal wind-speed](#) gradient does not seem to strongly impact the wake behavior for broad wind-directions ranges, we compare the SCADA that have been wind-speed and direction filtered with the wake models in Fig. 6-bottom. The inflow conditions are derived from the SCADA (see Table 1) and are used to run the wake models. 735 10-min cases are left after filtering for wind speed and direction ($5\text{--}10 \text{ m s}^{-1}$ and 270 ± 30 deg). In this case the [normalization is not made](#) power values are not normalized with the power of [one of the turbines in the west row \(1–30\) a unique turbine](#), as we [did do](#) for the plot in the top frame, [but with a reference turbine, which is the turbine](#). Instead, we use the undisturbed turbine that is closest to that where we [compute are extracting](#) the power from [the speed deficit](#). This aids to levelize the SCADA at turbines nr. 1–30 mainly. The wake models generally agree with the SCADA, particularly Fuga, being this and the engineering wake models’ variants using the linear sum of wake deficits those showing the highest wake losses generally. For turbines nr. 31–60, where the wind farm experiences single and double wakes mostly, the SCADA are between the models’ results. For

turbines nr. 66–111, where multiple wakes occur, [Larsen-2](#)-[Larsen-quadratic](#) highly underestimates the wake and the linear ‘variants’ and Fuga seem to generally agree better with the SCADA. However, the comparison is not completely fair with the wake models because the reference power is not always higher or equal to that of the individual turbines when these are supposed to be in the wake of a turbine. E.g. in the case of turbine nr. 31, we use turbine nr. 3 as reference and [in](#) $\approx 19\%$ of the cases with the inflow conditions analyzed in Fig. 6-bottom, $P_3 < P_{31}$.

3.1.3 Southerly flow case

Figure 7 illustrates the wake loss for the north-south row in the middle of the wind farm (turbines nr. 45–65) filtering for inflow conditions ($9 \pm 0.5 \text{ m s}^{-1}$ and $168.7 \pm 15 \text{ deg}$, [which is the direction where turbines nr. 45 and 46 are aligned](#)) that are derived [using the information of the turbines from Table 1 from the SCADA of turbines nr. 45 and 66–68 \(Table 1\)](#). 26 10-min cases are left after filtering for wind speed and direction. As expected from the results in Fig. 6-bottom, for this multiple wake case, the models using the ‘linear’ variant agree better with the SCADA than those using the ‘quadratic’ variant when going deeper in the row. The [Park-1](#)-[Park-quadratic](#) model predicts the wake loss of the three first turbines rather well but underpredicts it when moving deeper in the row. The results from Fuga are between the engineering model’s variants.

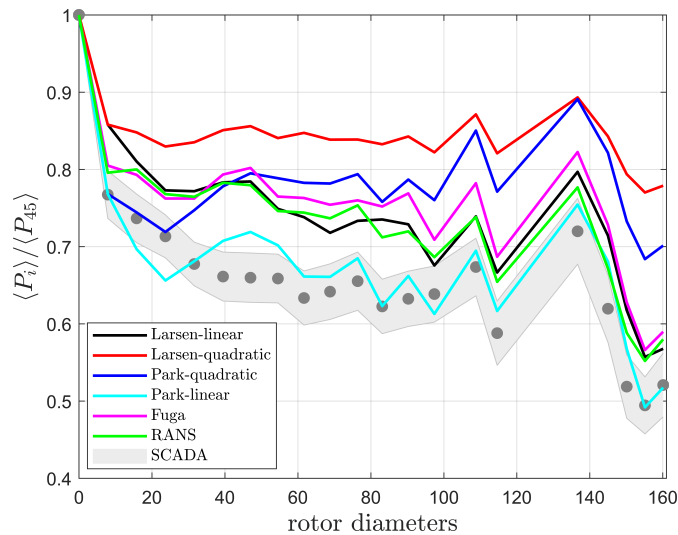


Figure 7. Normalized average power of the north-south row of turbines in the middle of the wind farm for southerly flow conditions from SCADA and simulations from the wake models within the range $168.7 \pm 15 \text{ deg}$ and hub-height inflow wind speed of $9 \pm 0.5 \text{ m s}^{-1}$ ([details in the main text](#)). For the SCADA, the shaded region indicates \pm the standard error [of the mean](#)

Because the differences between SCADA and models in Fig. 7 are relatively large and the amount of 10-min periods for the southerly flow case are 26 only, we also perform actuator-disk RANS simulations in EllipSys3D (Sørensen, 2003) using a modified $k-\varepsilon$ turbulence model (van der Laan et al., 2015). The results of the RANS model are very close to those of Fuga and [Larsen-1](#)-[Larsen-linear](#) also underestimating the wake loss. We can only speculate that for this particular case, the high wake

loss from the SCADA is due to atmospheric conditions, in particular from periods under a rather stable atmosphere, that we are not accounting for in the simulations. However, we do not have useful observations to directly derive stability. Interestingly, We have atmospheric stability measures from the WRF simulations but ‘instantaneous’ WRF stability measures are highly uncertain (Peña and Hahmann, 2012). Nygaard (2014) shows the same case using another SCADA period and the wake losses are $\approx 10\%$ lower than those we observe.

3.2 Capacity factor

Being able to estimate the AEP (Sect. 3.1.1) is important but it is more interesting to find out whether we are able to predict it, in our particular case, with the combined mesoscale-wake setup. For the exercise, the capacity factor is a better choice than the AEP, since we can compare Anholt with other offshore wind farms.

We use all the SCADA data that are available for 2014. Theoretically, there should be 52560 10-min samples for this year. However, the amount of samples per turbine available in the SCADA varies and is never the theoretical one; the turbine with the highest amount of samples is nr. 7 (51648) and that with the lowest is nr. 77 (49512). The average availability, taking into account all turbines, of observed samples is 98.10%. Table 3 shows the observed and estimated capacity factors, which are predicted by the WRF-wake model setup and that account for both the wind-farm gradient and the observed average availability of samples.

Table 3. Observed and estimated (from the WRF-wake model setup) capacity factors of the Anholt wind farm for 2014. The estimated values account for the observed average availability of samples

source	capacity factor [%]
SCADA	51.75
WRF-Park-1 <u>WRF-Park-quadratic</u>	53.19
WRF-Park-2 <u>WRF-Park-linear</u>	51.89
WRF-Larsen-1 <u>WRF-Larsen-linear</u>	52.87
WRF-Larsen-2 <u>WRF-Larsen-quadratic</u>	54.13
WRF-Fuga	52.51

It is clear that we can estimate fairly well the observed capacity factor using the WRF-wake model setup. However, it is important to note that the wind turbines are not always working or performing the best so comparing the observed and the and underperform when compared to the manufacturer’s power curve. The predicted AEP/capacity factors is not fair for the factor of a combined mesoscale-wake model , although is typically lower than the observed value; however, we want to know the capacity factor of a wind farm regardless of the operating conditions.

3.3 Power loss

Based on the SCADA’s 7440 10-min values and using Eqn. (2) with the inflow conditions as defined in Table 1, the wind farm PL is 4.08%. The estimated PL_s of the wake models are 3.64%, 5.05%, 3.87%, 2.60%, and 3.70% for ~~Park-1, Park-2, Larsen-1,~~

[Larsen-2](#), [Park-quadratic](#), [Park-linear](#), [Larsen-linear](#), [Larsen-quadratic](#), and Fuga, respectively. The results for the wake models are computed interpolating the models' LUTs with the same inflow conditions derived from the SCADA. All models, except for [Park-2](#), [Park-linear](#), predict lower PLs than the SCADA; [Park-1](#), [Larsen-1](#), [Park-quadratic](#), [Larsen-linear](#) and Fuga slightly underestimating the wake loss.

- 5 One way to show that the estimations of power of the free-stream turbines are sound is to compare the manufacturer power curve with the SCADA-derived power (averaging the power of the turbines in Table 1) and SCADA-derived inflow wind speed. This is illustrated in Fig. 8-left, where we show the power curve of the turbine and the SCADA-derived free values (no interpolation is made). Figure 8-right shows a similar comparison but in this case we derive the gross wind-farm power (i.e. 111 times the power of the free-stream turbines) and that derived from the power curve at the estimated free wind speed. Both
- 10 figures show that our definition of the free-stream turbines is sound (no evident wake effects are observed) and that the turbines do follow the manufacturer's power curve.

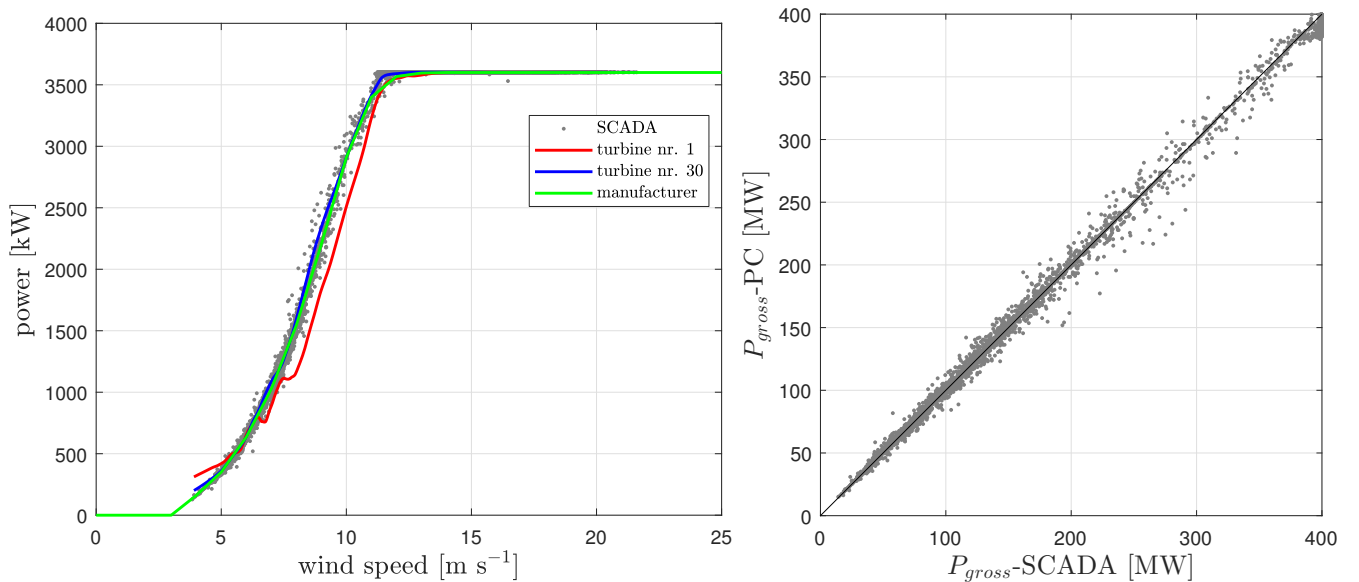


Figure 8. (Left) power curve of the turbines at the Anholt wind farm. (Right) gross wind-farm power derived from the SCADA for the free-stream turbines compared to the that derived from the power curve (PC)

- However, this does not give us an idea about the validity of the SCADA-derived inflow conditions for the turbines that are far from those we use to derive the inflow conditions. [Filtering-By filtering](#) the SCADA-derived inflow conditions for westerly flow (270 ± 30 deg), so that no wakes are observed for turbines nr. 1–30, we can derive power curves for the turbines at the beginning and end of that row (i.e. [nr.](#) 1 and 30) and compare them to, e.g. the manufacturer's power curve. As expected, the
- 15 power curves for turbines nr. 1 and 30 are below and above the manufacturer's one, being the difference as high as 500 kW for turbine nr. 1, which is the turbine with the lowest average wind speed according to the WRF simulations (Fig. 5-left). Within the wind-speed range where we observe such differences in power, the difference in wind speed is about 1 m s^{-1} .

3.4 Model uncertainty

Also based on the SCADA's 7440 10-min values, we ~~found~~find an optimal block length for the circular bootstrap of 242 samples. In average, such sample length corresponds to about 10 days, which is long enough to capture the correlation between samples. We use 10000 bootstrap replications and ~~found~~find that, e.g. ϵ for the ~~Park-1~~Park-quadratic model stabilizes after 5 2000 replications. Figure 9 shows the distribution of ϵ for all models where positive ϵ values denote a model that overestimates the power (underestimates the wake loss), whereas negative ϵ values a model that underestimate the power (overestimates the wake loss). ~~The mean and standard deviation σ of the distributions of ϵ are given in Table ??.~~

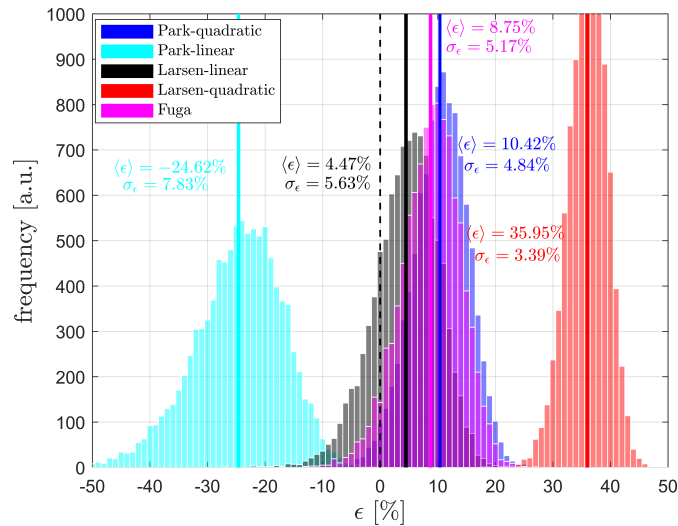


Figure 9. Distribution of the relative model error ϵ (Eqn. 3) of three wake models using 7440 10-min bootstrapped samples from the Anholt wind-farm SCADA. The mean of each distribution is shown with a thicker vertical line. The mean and standard deviation of the distributions of ϵ , $\langle \epsilon \rangle$ and σ_ϵ , are also given

~~Mean and standard deviation σ of the distribution of the relative error of the wake models~~
~~Model $\langle \epsilon \rangle$ % σ_ϵ %~~
~~Park-1 10.42 4.84~~
~~Park-2 -24.62 7.83~~
~~Larsen-1 4.47 5.63~~
~~Larsen-2 35.95 3.39~~
~~Fuga 8.75 5.17~~

10 For the particular case of the Anholt wind farm and for the filtered SCADA used in the analysis, ~~Larsen-1~~Larsen-linear has the distribution with lowest bias and the largest σ values together with ~~Park-2~~ (both the ‘linear’ variants), whereas ~~Larsen-2~~Park-linear, whereas ~~Larsen-quadratic~~ has the highest bias and lowest σ values. The results for ~~Park-1~~Park-quadratic and Fuga are very similar, both bias and σ . ~~Park-2~~Park-linear, as expected due to the previous results, is the only model systematically overestimating the wake loss. If we could extrapolate these results to an AEP analysis, we would expect non-conservative AEP
15 estimations (except for ~~Park-2~~Park-linear), being ~~Park-1~~Park-quadratic, Fuga and ~~Larsen-1~~Larsen-linear slightly optimistic and ~~Larsen-2~~Larsen-quadratic too optimistic.

4 Discussion

~~Some~~ It is important to note that some of our results depend on the methods we use to derive the ~~wind-farm inflow conditions~~ undisturbed inflow conditions of the wind farm. We show that for ~~the individual turbines~~ power analyses of individual turbines, whose inflow conditions are greatly affected by the horizontal wind-speed gradient (like turbines nr. 1 or 30), this is an important matter (see Fig. 8-left), ~~but for~~. For this particular wind farm and wind climate, the differences between the ~~inflow-undisturbed inflow conditions~~ derived from turbines in the middle of the long rows and the inflow conditions derived from turbines to either side of the rows ~~seem to~~ compensate for the overall wind-farm long-term analyses (e.g. AEP and capacity factor). One way to further analyze the impact of different inflow conditions is to derive them for each individual ~~wake-free~~ undisturbed turbine. We can then potentially perform analyses (flow cases, power loss, and capacity factor) in a similar fashion as that we use for accounting for the horizontal wind-speed gradient³ and validate our findings.

We also estimate the power loss and the uncertainty of the wake models based on a rather discontinuous and short filtered SCADA dataset. Therefore, our results might be biased and caution must be taken when generalizing our findings. A clear example is that related to the model uncertainty where we find that most wake models underestimate the wake losses. With a longer dataset, the biases can change (and models might start to produce conservative results) but the relative position of the ~~modes~~ models will most probably be maintained, ~~Park 2 and Larsen 2~~ Park-linear and Larsen-quadratic being the most conservative and most optimistic models, respectively. ~~This can also happen if~~ If the same models are evaluated with SCADA from other wind farms, the biases will most probably change.

We show that our WRF-wake model setup is able to predict rather accurately the capacity factor of the Anholt wind farm. Anholt is the offshore wind farm with the highest all-life capacity factor in Denmark (48.7%) and the highest in the world for a wind farm older than 2 y, outperforming Horns Rev II that has in principle more favourable wind conditions. One of the reasons for this is the Anholt wind-farm layout, which highly minimizes the wake losses.

~~The placement of a wind turbine row on an arch instead of on a straight line could have a contribution to the minimized wake losses. Wind directions aligned with a straight wind turbine row typically show well pronounced power deficits for the entire row. When turbines are placed on an arch, the power deficit of the row is less pronounced but smeared out over a larger range of wind directions. In other words, placing wind turbines on an arch has a peak-shaving effect of the power deficit of the wind turbine row.~~

5 Conclusions

For the Anholt wind farm, we show from both the SCADA and WRF model simulations that for a number of wind directions, there is a clear influence of the land on the free-stream wind speed at the positions of the turbines closer to the coast. However, for AEP calculations where we run three different wake models using mesoscale model outputs as inflow conditions, accounting for the horizontal wind-speed gradient (also derived from the mesoscale model results) does not have a large impact on the

³although we cannot derive the undisturbed horizontal wind-speed gradient from wake-affected turbines without a wake model

results when compared to AEP calculations based on first, a wind climate that is the average of all wind climates at the turbines' positions, ~~or~~ and second, a wind climate correspondent to a position in the middle of the wind farm. It does, however, differ from the calculation using a wind climate that is strongly influenced by the horizontal wind-speed gradient particularly for the engineering wake models.

5 We look at two flow wake cases with two different engineering wake models and some of its variants and a linearized RANS model. The first case corresponds to westerly winds, where the influence of the horizontal wind-speed gradient is largest. Here the wake models, and Fuga in particular, agree with the SCADA fairly well. The second case corresponds to southerly winds, where the wake losses are highest. Here, the wake models tend to underestimate the wake deficit when compared to the SCADA. This is also translated into a wake-model tendency to underestimate the observed power loss; in average 0.31% less
10 than that derived from the SCADA.

Using our mesoscale-wake model setup, we find that the estimated capacity factors are 0.27–4.60% biased when compared to that computed from the SCADA. Finally, using inflow conditions derived from the SCADA and by circularly block-bootstrapping these, we estimate the relative error of the wake models. We find that these models tend to underestimate the wake losses, except for one wake model variant. The engineering wake models are found to be as good as the linearized RANS
15 fuga model. However, these are results that are wind-farm and SCADA specific, and that depend on the definition of inflow conditions; therefore similar analyses need to be reproduced at different wind farms, using more SCADA and different methods to derive the inflow conditions.

Data availability. The Anholt SCADA can be made available by Ørsted upon request to Miriam Marchante Jiménez (mirji@orsted.dk). The WRF data can be made available by DTU Wind Energy upon request to Andrea N. Hahmann (ahah@dtu.dk).

20 *Competing interests.* The authors declare that they have no conflict of interest.

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