Author response to Rebecca Barthelmie

The authors response is shown in red.
Changes implemented in the new version of the manuscript are in blue.

This paper describes a useful set of measurements used to examine wake deflection. Overall it is interesting and has a good message. It could be improved to make it substantially easier to follow and compare the different cases and data sets and models. A data access statement is required by journal policy.

We thank Prof. Barthelmie for her comments, which helped to improve the manuscript. Based on the comments from her and Dr. van Dooren we implemented the following changes to the manuscript:

- An overview of the wake-steering cases and the control cases was added the beginning of Sect. 3 (Table1).
- The validation of the inflow measurements uses the wake-steering cases and the control cases to make the usage of measurement data uniform throughout the results (Sect. 3.1).
- The validation of the analytical model distinguishes various error sources (Sect. 3.3.2)
- The effect of the wake steering on the power is estimated based on the wake-scanning lidar in addition to the analytical model (Sect. 3.4.2).
- The abstract and conclusion were modified to provide more room for the evaluation of the wake-steering setup.
- Numerous minor changes (additions and clarification within the methods section, spelling and phrasing throughout the manuscript).

The line numbers in our replies refer to the revised manuscript. In addition to the revised manuscript, we also provide a tracked-changes manuscript that visually highlights the changes made.

Please see comments below.

- Introduction: Could this be quantitative? Rather than listing the papers, wouldn't it be helpful if the introduction gave a background in terms of answering: How big are power losses due to wakes? What could be expected in terms of the gains from wake steering? What have other modeling studies and the few available field studies indicated are those magnitudes? You could then follow up in the conclusions to evaluate whether a consensus is being reached on the viability of wake steering for power gain for example.

  The power losses from wake effects depend on turbine spacing, wind direction, atmospheric stability and turbulence levels. A single fully waked wind turbine can produce 40% less power than a wind turbine in the free stream (Simley et al., 2020; Barthelmie et al. 2010). On a wind farm scale, the power losses also depend on the above mentioned variables, but additionally on how deep a wind turbine is behind the leading row of wind turbines (Barthelmie et al, 2010, Porté-Agel et al. 2013).

  For a pair of upstream-downstream turbines, the possible power improvement with wake steering given in literature ranges from 3.5% to 11% (Bartl et al. 2016) depending on turbulence levels and turbine distances. Field experiments showed values improvements of 3.5% (Simley et al. 2020) and 4% (Fleming et al. 2019).

We included quantitative information on the wake losses and the power gains with wake steering to the introduction (lines 17-19 and 29-33).

- Figure 1. The google map figure needs a scale.

  A scale was added to the overview map (Fig. 1).

- Figure 2 needs an idea at least of how LONG a measurement period this represents. Is it the whole data period i.e. six months of data, from every direction?, every wind speed and turbulence condition? is it a case study?

  Figure 2 uses all available data from 6 January until 9 April 2019, which is consistent with the period used in the results. All wind speeds and turbulence levels are included as long as the wind turbine and the WindCube were operational.

  This information was added to the caption of Figure 2.

- Section 2: How was the target yaw offset determined? How were the wind directions determined from the lidar data? What is the purpose of the analytical models? (beyond 'comparison with data'? what is the objective?) Please elaborate why and how you used the models. What are the errors in the wind speed direction comparison? How does that propagate into the uncertainty in the wake deflection analysis?

  We believe that some of the raised questions resulted from a bad structure of the section. Therefore, we modified Sect. 2.1 to introduce the measurement site only, and the instruments and measurements are then introduced in Sect. 2.2, separately. To answer the above questions here directly:

  - The target yaw offset was precomputed before the campaign based on an optimization with the Flow Redirection and Induction in Steady State (FLORIS) software from NREL as described in Fleming et al. (2019).
  - The wind directions were determined from the WindCube using the Doppler beam swinging technique (similar to the profiling lidar used in Lundquist et al., 2017).
  - The analytical models are compared with the measurements for the purpose of the validation of the models themselves and to evaluate the efficiency of the wake steering. One-to-one comparisons with the wake scanning Doppler lidars are made by computing the analytical models with the input variables measured by the WindCube and WindIris during each wake steering case.
  - The errors of the wind speed and the wind direction measurements are analyzed in section 3.1 (which was modified heavily to make it easier to follow and uniform in terms of used measurement data).
  - We assume that the RMSE between the WindCube and the WindIris as the error of the yaw angle, which is then propagated to the resulting error of the wake deflection using geometry. The resulting error is shown in Fig. 9b as errorbars.

  A reference to the section introducing the instruments and their measurements was added to section 2.1 (lines 56-57). We added how the target yaw offset function was determined (lines

62-63). The purpose of analytical models and how they are computed were added to Sect. 2.4 (lines 190-191, 193-195, and 203-206).

- Section 3.2 How were these wake deflection cases selected? Are you saying it is an analysis of all of the data from January to April? Please rewrite this section to help readers understand what you mean? What is a favorite in this context?
  'First, the wake deflection is verified for non-yawed control cases, where no wake deflection is expected. The distribution of the normalized wake deflection using the WindIris has a RMSE of 0:08 (Fig. 9a) and using the wind direction of the Wind-Cube with the nacelle position of T2 provides a RMSE of 0:07 (Fig. 9b). These errors agree with the RMSE of the yaw angle between 235 the two instruments (4sin(1:30_) =0:09) and both distributions have mean value that is not significantly different from zero. The consistency between the yaw angle errors and wake deflection distribution shows that the wake scanning and its spatial positioning were working well, and the absence of a bias shows that the alignment of the wake scanning lidar with the rotor axis is correct (the measured offset of 0:15_ during the installation was taken into account in the processing). Since we could not identify a clear favourite between the WindIris and the WindCube for the yaw angle, the average of both will be used for 240 the remainder of the article.'

  Both, the wake-steering cases and the control cases, are selected based on the criteria outlined in section 2.3.1. Briefly summarized:
  - The wake-steering cases require a northwestern wind direction with T3 downstream of T2 and active wake steering.
  - The control cases require a northeastern wind direction such that T2 will not yaw (limiting to northeaster directions also ensures that the inflow is undisturbed by other wind turbine wakes or topography as for the wake steering cases).

  There are 81 wake-steering cases and 76 control cases between 6 January 2019 and 9 April 2019 that fulfill the criteria of section 2.3.1. Their numbers are then further reduced by removing cases with unsuccessful wake center detections (due to insufficient SNR or bad Gaussian fits). A summary is presented in Table 1 below. We reworked Sect. 3.1, to use only the wake-steering cases and the control cases to be consistent with the remainder of the results section (it used all measurement data previously).

  With "no clear favorite", we wanted to express that the yaw angles measured by the WindIris and the WindCube compared well with each other and had no biases or any other apparent problem. Therefore, we had no reason to pick one over the other and instead used the average of both.

  An overview of the cases has been added at the beginning of the results section (lines 212-213 and Table 1). Section 3.1 was modified to use data of the wake-steering cases and the control cases to make it consistent with remainder of the manuscript. Fig. 8 was modified to include the 3D scans of the control cases (analog to Fig. 9 for the wake-steering cases). It is specified in each figure caption which data is used (Fig. 5, 6 and 7). Section 3.2 was restructured and rephrased (lines 243-251).

Table 1: Overview of wake-steering cases and control cases. From top to bottom: the number of 30-minute periods that met the requirements of Sect. 2.3.1, the number of cases with a sufficient SNR of the wake-scanning lidar, the number of cases with a successful detection of the wake center based on the correlation threshold (Sect. 2.3.3), and the number of cases for

which the model prediction of u_{mod} was possible (Sect. 2.4). The numbers outside of the brackets are the total number of cases, and the numbers inside the brackets are the 2D scans and 3D scans of the wake-scanning lidar, respectively.

	Wake-steering cases	Control cases
Cases based on Sect. 2.3.1	81 (36+45)	76 (27+45)
Cases with a sufficient SNR	56 (27+29)	66 (26+40)
Cases with a successful wake center detection	29 (16+13)	55 (21+34)
Cases with a prediction of u_{mod}	41 (19+22)	-

- Figure 7. Please add some quantitative comparison e.g. correlation coefficients, RMSE? How many measurements are included? Or excluded? How were they selected? It looks like about 30 measured points?

  Quantitative measures of the comparison have been added and the data is selected according to the criteria outlined in section 2.3.1, which is now stated at the beginning of the results section (see our response to the previous comment). The figure shows 29 data points for the wake-steering cases and 55 for the control cases.

  The RMSE and the correlation coefficient have been included to Fig. 7 and the caption states which data is used.

- Figure 8. This figure is probably key but again its very difficult to understand. Describe how you chose this case, describe how and where the measurements are located, describe how and where the models were implanted including the derivation of the freestream and its errors. Is tis a totally random case? Was it selected for some specific purpose?

  This case was chosen, because it has the largest yaw offset of the data set and therefore the largest magnitude of the wake deflection, which has two benefits: (i) the errors of the wake deflection are smallest relative to the wake deflection and (ii) the deflection is easy to visually observe. The models were computed from the inflow measurements of the WindCube and WindIris taken at the same time as the wake scanning as described in Sect. 2.4.

  We analyzed the influence of the measurement errors on the model error. The analytical models require γ, TI_{WI}, $u_{WC}(z)$, and the nacelle position of T2 from the SCADA data as input. In Sect. 3.1., the RMSE for γ and u_{WC} were determined as 1.42° and 0.42 m/s, respectively. We assume that the nacelle position from the SCADA data is virtually free of errors based on agreement with the position of hard targets in the scan field of the wake-scanning lidar. We could not do a validation for TI_{WI} and assume an accuracy of 0.015 as given in the manufacturer specifications instead. We quantified the error propagation by varying the model input based on the measurement errors for all investigated wake-steering cases. The errors resulting from TI_{WC} and γ led to uncertainties of 20 kW and 6 kW, respectively. The error resulting from u_{WC} resulted in the largest uncertainty with 61 kW.

  A detailed description of the example case was added to the manuscript text (lines 252-260). After the restructuring section 3.2, the example case is now shown in Fig. 9a.

- Can you start by laying out the various cases in a table? Are there are examples, wake steering cases and the complete data set. Are there more? Like the wide case and the narrow case? It is difficult to follow and make comparisons. All of the comparisons should be in a table with the model results to allow a better evaluation? So for example, how does Table 2 compare with Table 1?

We added a table with an overview of the cases at the beginning of the results section. In addition, we made the usage of the measurement data uniform by modifying Sect. 3.1. Now, the results only use the wake-steering cases and the control cases (and examples chosen from the wake-steering cases).
Only Section 3.4 deviates from this structure as explained at the beginning of its subsections (which includes Fig. 12 and Table 2). In Sect. 3.4.2, we compare a period with wake steering to a period without wake steering, which is not possible based on the definition of the wake-steering cases. In Sect. 3.4.2, we only subdivide the wake-steering cases based on the wind direction to illustrate that the wake steering setup was suboptimal.

An overview of the used measurement data was added at the beginning of the results section (lines 212-213 and Table 1). Section 3.1 was reworked overall to make usage of the measurement data uniform and easier to follow. The captions of Figures 5, 6, 10, 11, 13, and 14 as well as Table 3 were updated to state which date they are using.

- In the conclusions please evaluate this study in terms of: 1) Measurement errors vs model errors 2) Magnitude of wake steering vs errors 3) Comparison with other data sets – what is the overall assessment in terms of the viability of wake steering.

Regarding the model errors and the magnitude of the wake steering effect:
  - The effect of wake steering on the power is now also estimated from the wake-scanning Doppler lidar independent from the model (Fig. 14a and Table 3). These results show the same behavior as the analytical model. Especially, a reduced wake steering success for wind directions outside a narrow wind direction range between 325° and 335° is consistent with results of the analytical model.
  - The effect of wake steering depends mainly on the deflection of the wake, which the model can predict fairly well. The model errors for the power prediction also includes contributions from the power coefficient and nonstationary conditions, that do not directly enter into the model-to-model comparison from which the wake steering is evaluated. The shortcomings of the power coefficient for a partially waked turbine is responsible for a third of the model error. We reworked Sect. 3.3.2 to better distinguish the various error sources.

In summary, the found model errors do include contributions from the measurement errors, but they do not prevent the evaluation of the wake-steering setup. We believe that the identified problem areas of the model are important conclusions themselves. E.g., a study by Walker et al. (2016) does not list the power coefficient as an important error source in a model validation for wake losses.

Another important conclusion of the paper is that the implemented wake steering was performing suboptimal due to a bias of the wind direction perceived by the wind turbine once it had a yaw offset among other issues. This point is better highlighted in the conclusions, now. We believe that our study is not suited to provide an overall assessment of the viability of wake steering for two reasons: (i) as mentioned above, the investigated wake-steering setup was

not working as intended, and (ii) the investigated wake-steering cases only cover a limited range of atmospheric conditions (e.g., the employed methods limited the analysis to stationary conditions). However, we found that the wake steering improved the power output in some cases despite the issues with the wind vane on top of the nacelle.
This conclusion is in line with other studies. For example Vollmer et al. (2016) already concluded that the wake steering success is sensitive to the wind direction input. Simley (2020) came to similar conclusions based on a SCADA data driven approach, but without the wake-scanning lidar showing the wake position relative to the downstream turbine.

The conclusions were modified to and place a stronger emphasis on the suboptimal wake-steering setup and possible remedies (lines 376-387). The influence of measurement conditions and measurement errors on the model errors is included to the conclusions (lines 372-375).

- Please provide a data access statement.

A data statement is now included in the manuscript (line 394).

- Please check for typos.

A lot of typos were corrected throughout the manuscript based on feedback of a native English speaker. The changes are too numerous to be listed fully.

Literature

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