Author response to Marijn Floris van Dooren

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

This paper presents an interesting study on the characterisation and validation of analytical yawed wake models. The writing is of high quality, the figures are nice and in general the paper is very informative. However, in some aspects the paper could be a bit more 'to the point'. I will illustrate that with further comments. I suggest a minor revision.

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

- The abstract and conclusion were modified to provide more room for the evaluation of the wake-steering setup.
- 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).
- 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.

General comments:

- The conclusions mainly address the errors in the power prediction for different experimental and analytical methods/models. Even the lowest value of 12% is higher than the expected power improvements reached by wake steering (Sect.3.3.3). Maybe this could be elaborated a bit more in a broader scope, addressing how these findings contribute to the research field that attempts to increase power production of turbines in an array or wind farm and what are your recommendations on how and with which methods to proceed.

  We have two points concerning the issue of the large model errors in comparison to the power increase due to wake steering:

  1. The effect of wake steering on the power is now also estimated from the wake-scanning Doppler lidar independent from the analytical model (new Fig. 14 and Table 3). These results show the same behavior as the model. Especially, a reduced wake steering success for wind directions outside a narrow sector between 325° and 335° is consistent with results of the analytical model.
  2. The increase in power due to wake steering results from the wake deflection, which the model reproduces fairly well. On the other hand, the errors of the analytical model includes the shortcomings of the power curve (one third of the error) and missing atmospheric effects (nonstationary conditions, wind veer etc.), which do not affect the findings for the increase in power directly, because it is gained from a comparison of model vs. model.

We believe the manuscript provides a meaning full contribution to the research field by demonstrating that the implemented wake steering was suboptimal and pointing out the causes. Concerning the latter, the found wind direction bias when the wind turbine is yawed is especially important, because it points to the general problem that the standard instrumentation of a wind turbine seems not sufficient to provide the required input for the wake-steering controller with the needed quality. We assume that the bias of the wind vane comes from the flow in close proximity of the nacelle while it is yawed (i.e. it is not an instrument fault, but the flow at instrument location is systematically not aligned with the wind direction of the free stream during yawed operation). We avoided drawing general conclusions about the success of wake steering, because the wake steering setup was not working as intended as mentioned above. Nevertheless, the wake steering increased the power output in some cases, but probably not as much as possible.

Using a narrower wind direction sector, to which a yaw angle offset is applied, only reduced the impact of the suboptimal wake steering, but is not an optimal solution. A correction of the bias might be possible if it only depends on the yaw angle and the wind speed. A proven solution would be a forward facing Doppler lidar to provide the input measurements (that adds other benefits, too).

The effect of wake steering on the power is computed from the wake-scanning lidar (methods in lines 185-188; results shown in Fig. 14, Table 3, and lines 354-359). We made changes to the abstract and conclusions to give more room for the wake steering (lines 376-387).

- On the other hand the length of the paper could be reduced a little. I like the fact that the paper is very informative, but sometimes it provides information not directly necessary for the take-away message. One example is Sect. 3.4 on the shape of the wake. Please consider whether it is a vital concern or whether it could be omitted.

  The section was included for two reasons: (i) after looking at position and depth of the wake, its shape would be the next logical property to investigate, and (ii) it provides insights on the dominant effects that are important to be considered in modeling. However, we are aware that the section is only a side note to the findings, and we decided to move the section into an appendix and reference it in the conclusions.

  We moved Sect. 3.4 from the main body of the manuscript into Appendix B and referenced in the conclusions (lines 390-391). The former Sect. 3.3 is now subdivided into a new Sect. 3.3 that only contains the model validation and a new Sect. 3.4 that contains the effect of wake steering on the power.

- You state that ’studies of yawed wind turbines using field data are rare’. Although this may be true, I recommend you to look into and perhaps cite the work of Bromm (2018), DOI: 10.1002/we.2210 in addition to the other references.

  Thank you for pointing out this paper. It was extremely relevant in the context of this paper and was an interesting read.

  We added Bromm et al. (2018) into the literature review of the introduction (lines 41-42).

Specific comments:

- P2, L50: What kind of WindCube was used? There are various short-range and long-range WindCube models.

It was a WindCube-V2 profiling lidar (details have been added in Sect. 2.2.1).

Additional information on the Wind Cube added in lines 76, and 81-82).

- P11, Fig. 5 and Fig. 6: It would be very good for the overview to see the goodness of fit (correlation) coefficient displayed within the correlations plots.

  We added quantitative information on errors and goodness of fits to all figures. Further, in response to comments of Reviewer #2, section 3.1 was modified extensively to make the usage of measurement data uniform throughout the paper.

  We included the correlation coefficient in the legends of Fig. 5. The new Fig. 6 includes the RMSE and parameters of a fitted Gaussian.

- P14, Fig. 8: Does the wake center detection function as it should? It seems to jump between the wakes of T2, T3 and T4. Wouldn't it make more sense to try to follow the far wake of T2 instead? Maybe this could be adjusted.

  Only the solid part of the white line was the successfully detected wake center. Instances where the wake center detection jumps between the wakes were detected and rejected based on the correlation threshold (the rejected parts were shown as the dashed part of the white line in the original figure).

  We removed the dashed part of the white line and show only the solid part to avoid confusion (new Fig. 9a).

- P17, Fig. 10 and Fig. 11: Again it would be nice to see the correlation coefficient displayed within the figures.

  We included the correlation coefficient and RMSE in the legends of Fig. 10 and Fig. 11.

Technical corrections:

- P2, L52: Replace 'thrid' by 'third'.

  The sentence about the third wake-scanning lidar was removed.

- P3, L59: Replace 'nacelle' by 'the nacelle'.

  Inserted "the" (line 64).

- P5, L82: Add 'direction' at the end of the sentence.

  Inserted "direction" (line 88).

- P6, L106: Replace 'StreamLine' with 'Stream Line'.

  Inserted a space (line 112).

- P9, L191: Rewrite 'data of either the WindIris or the WindCube was missing'.

  Corrected (lines 208-209).

- P9, L204: Remove 'the' in front of '07 February 2019'.

  This sentence became obsolete after reworking section 3.1 to use only the wake-steering cases and control cases.

- P10, L212: Remove ’the’ in front of ’11 February 2019’.

  Removed "the" (line 228).
- P12, L235: Add ’a’ in front of ’mean value’.

  Inserted "a" (line 246).
- P14, L264: Add ’a’ in front of ’correlation coefficient’.

  After adding the correlation coefficient and RMSE to the Fig. 10, we removed this sentence.
- P16, L268: Replace ’reasons’ with ’reason’

  Removed the "s" (line 283).