Authors reply to 3nd referee's comments to wes-2024-62

Thank you very much for your answer. We value your feedback and questions. We will answer any questions left open after reading our manuscript:

General comment

1. The main reason is the limitation of available computational resources. While the implementation of a "conservative" approach computes the AEP in fractions of seconds, adding the listed new methods slows the computation down significantly. This effect is negligible for one single AEP prediction. However, the duration of the optimization problem would be increased beyond tolerance. Ongoing work, which is the next step within this larger PhD project, includes the third dimension at reduced computation expense.

2. Those parameters are empirically fitted by the authors in the wake model's original publication [Ishihara & Qian, 2018]. The calibration was performed from a wind tunnel test, aerodynamic characteristics of a 2.4MW turbine, which is close to the Vest 2MW turbine used in this study, and a LES study. Further studies used by Ishihara & Qian to calibrate the parameters were LES simulations by Wu & Porté-Agel, 2011 & 2012.

3. In these LES studies Porté-Agel, 2013 and Wu & Porté-Agel, 2015, performed simulations of the wind farm Horns Rev 1 under neutral atmospheric conditions with $u_\infty = 8\frac{m}{s}, TI = 7.7\%$ and varying wind directions. The information is given in paragraph 4 "Study case". These boundary conditions apply for both studies, not just the study performed in 2015. We do agree that this should be made more clear in the manuscript and will add a sentence accordingly.
4. The reference used here is the wind farm modelled with Qwyn in its original layout, both with and without wake meandering. Figure 16 only depicts the case modelled with wake meandering. The black dashed line shows the modelled power output of the reference layout over various inflow angles. The optimization study does not include comparisons to measurement or LES data. We will clarify this with an additional sentence in the introduction paragraph of the optimization chapter.

   The estimated AEP is 758.62 GWh with meandering and 758.52 GWh without meandering. We emphasize that the absolute AEP value is less informative. While we use a relatively high-resolution of 2640 combinations of wind direction and speed, Kirchner-Bossi & Porté-Agel (2018) mention that the correct overall AEP prediction depends on the resolution of the atmospheric data. The result will therefore be refined, when the input of atmospheric data is refined.

   We agree, that the tool overpredicts the power output for most wind directions. This overestimation is likely due to the reduction of our modelling approach to two dimensions, which introduces errors in modelling partially overlapping wake cases. The wake shape is modelled more in a rectangular or linear rather than its actual circular shape. We will elaborate on this in the methodology section of the momentum-conserving superposition and the conclusion of the validation chapters.

Specific comments

1. The calibration and derivation of the equations has been performed by Ishihara & Qian in their original publication. We would like to refer to our answer of General comment No.2. We agree, that simply referring to the original publication of the model is not enough. In the second draft we will elaborate the model's calibration and refer to the original publication & it's references in a few additional sentences.
2. Ishihara & Qian do not specifically define a near and far wake region. They rather develop a model which is applicable in both far and near wake. The empirical parameters *a* and *b* are fitted to the far wake region with the use of wind tunnel & full-scale measurement data as well as LES simulations as discussed in "General comment: Answer 2". In the Ishihara-Qian (2018) wake model, there is no explicit mathematical definition for the near and far wake regions. The model incorporates several empirical parameters fitted to measurement and LES data. The parameters a and b (Eq. 6) are fitted to the far wake region, while parameter c (Eq. 8) is fitted to the near wake region, with its influence decaying due to the $(1 + x/D)^{-2}$ term in Eq. 7. Ishihara and Qian do not provide specific details on how they quantitatively distinguish between near and far wake regions. However, they describe the far wake region as where "the wake is fully developed and the velocity deficit and the added turbulence intensity can be assumed axisymmetric and have self-similar distributions in the wake cross-sections" (Ishihara & Qian, 2018), as noted by Vermeer et al. (2003). We, therefore, assume that the original authors evaluated measurement and LES data to determine the regions for fitting parameters a, b and c.

   For completeness: Qwyn incorporates a model extension for yawed wind turbines (wake deflection model) introduced by the same authors in Qian & Ishihara (2018). Here, Qian & Ishihara propose a quantitative estimation of near and far wake regions based on turbine yaw. This does not apply to any cases considered in this study, which is why we adhere to the previous explanation.

   It is also important to note that the near wake region does not play a significant role in the scope of the present study.

   We hope this clarifies the definition of near and far wake regions in the given approach.

3. This question aligns with the one under "general comments Nr.1". As mentioned, computational resources are the main driver for computing information only in a two-dimensional plane. Consequently, the integration can only be done in two dimensions. We are aware, that this introduces an error, which we will address more clearly in the second draft of the manuscript. We will provide additional explanations within the methodology section of the Zong – Porté-Agel model and in the validation conclusions. Despite this simplification, our reduced dimension model shows good agreement with the validation data, giving us confidence in the study's results. However, we plan to avoid this dimensional simplification in future work.
4. We define the worst-case operation scenarios as those with the most severe wake losses, occurring when a high number of turbines are aligned with the wind direction (particularly at 270° and symmetrically at 90°). In these scenarios, overlapping wakes significantly reduce the rate of wake recovery within the farm, leading to notable drops in performance, as seen in Figure 11. The most severe drop is at 270°, detailed in Figure 9, where there is

an overall loss of approximately 40% for all turbines behind the first one. To provide context, we propose citing Barthelmie et al., 2009, who demonstrated that these drops are most distinct when a large number of wakes align.

5. This is correct. We will clarify this in our manuscript.
6. The uncertainties are either quantitatively given in the cited reference (wind speed $\pm 0.5\ \mathrm{m}/s$) or estimated by us through evaluating the error bars provided in the source's graphs (Turbulence intensity $\pm 2\%$ and normalized power ± 0.1).
7. We believe that the observed differences are not due to the impact of wake meandering but rather indicate the limitations of the meandering correction model. Braunbehrens & Segalini (2019) validated their model on wide directional sectors, showing good results, which we were able to reproduce in our validation. However, when applied to narrow bins, the model performs significantly worse. This variability can make it challenging for users to determine when the meandering correction adds value. Therefore, we will conclude more decisively in the second draft that the correction is not universally applicable.
8. This is correct. We will revise this sentence for clarity. We have not plotted the graph with 5-degree bins to align with the available LES data, which does not include data points at the resolution necessary for such binning. Consequently, we cannot compare it to a high-fidelity study or measurement data at this time. However, we agree that conducting such an analysis would be valuable for future research.

Technical comments

Thank you for pointing out those slips (especially point 3). We will correct these in the second draft.

References:

Ishihara, T., Qian, G.-W., 2018 "A new Gaussian-based analytical wake model for wind turbines considering ambient turbulence intensities and thrust coefficient effects." Journal of Wind Engineering & Industrial Aerodynamics. 177, 275-292.

Wu, Y.T., Porté-Agel, F., 2011. "Large-eddy simulation of wind-turbine wakes: evaluation of turbine parametrisations." Boundary-Layer Meteorology. 138, 345–366.

Wu, Y.T., Porté-Agel, F., 2012. "Atmospheric turbulence effects on wind-turbine wakes: an LES study." Energies 5, 5340–5362. Xie, S.B., Archer, C., 2014. Self-similarity and turbulence characteristics of wind turbine wakes via large-eddy simulation. Wind Energy 17, 657–669.

Kirchner-Bossi, N. and Porté-Agel, F., 2018: "Realistic Wind Farm Layout Optimization through Genetic Algorithms Using a Gaussian Wake Model". Energies, 11, 3268.

Vermeer, L.J., Sørensen, J.N., Crespo, A., 2003. "Wind turbine wake aerodynamics. " Progress in Aerospace Sciences. 39, 467–510.

Qian, G.-W., Ishihara, T., 2018 "A New Analytical Wake Model for Yawed Wind Turbines." Energies. 11(3), 665-689.

Barthelmie, R. J., Hansen, K., Frandsen, S. T., Rathmann, O., Schepers, J. G., Schlez, W., Phillips, J., Rados, K., Zervos, A., Politis, E. S., and Chaviaropoulos, P. K., 2009: “Modelling and measuring flow and wind turbine wakes in large wind farms offshore.” Wind Energy, 12, 431–444.

Braunbehrens, R. and Segalini, A., 2019: “A statistical model for wake meandering behind wind turbines”. Journal of Wind Engineering and Industrial Aerodynamics, 193, 103954.