Authors' response to Referee #3:

We thank the referee for reviewing this manuscript and appreciate the constructive feedback and the improving comments. At this stage, we answer to referee #3's comments and propose changes for the final manuscript. The referee's original comments are printed in **bold** followed by the corresponding answers. Passages from the manuscript are printed in *italic writing*, in which proposed additions are indicated in blue and deleted parts in ~~red~~.
Thank you very much for your efforts,

Jan Bartl on behalf of all authors

Comment (1)

Page 5, Line 14-15: The sentence should be rewritten as follows: "The total uncertainties in power and thrust coefficient are 0.006 (2.5% of the absolute 15 CP -value) and 0.007 (0.9% of the absolute CT-value), respectively."

Thank you for the hint. We will change the sentence in the final version of the manuscript.

p.5, l.14 f:
The total uncertainties in power and thrust coefficient are 0.006 (2.5% of the absolute C_P-value) ~~respectively~~ 0.007 (0.9% of the absolute C_T-value), respectively.

Comment (2)

Page 8, line 2-3: "The asymmetric wake deflection is considered to be the main reason for the asymmetric distribution of T2's yaw moments.". It is quite clear that yawing the upstream wind turbine in two different direction leads to different power gain on the downstream one. The authors trace back this behavior to not-well specified asymmetric wake deflection. It would be interesting, for the readers, if the authors could provide a deeper insight into this topic, considering that the authors (previously cited publication) already measured the wake shed by the upstream WT for two different yaw misalignment. Is the observed asymmetry due to asymmetric wake displacement or wake recovery?

Thank you for this very constructive comment. This is indeed one of the most important observations in this publication, and we agree that the underlying reasons for the asymmetry require a more detailed explanation. A previous publication by Bartl et al. (2018) discussed the asymmetries in wake displacement in detail, but we consider it to be important to revive the main reason for the asymmetric wake deflection here. For clarification, the following changes are suggested for the manuscript:

p.8, l.2 f:

The asymmetric wake deflection for positive and negative yaw angles is considered to be the main reason for the asymmetric distribution of T2's yaw moments. As discussed in an analysis of the wake flow behind a yawed turbine by Bartl et al. (2018), the overall wake displacement for positive and negative yaw angles was observed to be slightly asymmetric. The interaction of the rotor wake with the turbine tower was identified to be the main contributor for the asymmetric wake flow. This finding is supported by a previous study on the non-yawed wake by Pierella and Sætran (2017), in which they attributed a significant displacement of the wake center to the interaction with the turbine tower.

Comment (3)

Page 9, line 4-5: "Moreover, the downstream turbine's power output at low inflow turbulence (inflow A) is observed to be more asymmetric with respect to T1 than at high inflow turbulence (B)." This is quite surprising since one would expect that as more homogenous the flow is, as higher the symmetry of the phenomena is. It would be interesting if the authors could argue more about the reasons behind the observed data.

This is a very good comment, that also needs some more detailed explanation in the text. As the downstream turbine is operated in the partial wake of the upstream turbine, the inflow to the downstream turbine is no longer homogeneous. As shown in the analysis of the wake flow in Bartl et al. (2018), the deflection of the wake for positive and negative yaw angles is more asymmetric for an inflow of low turbulence (Inflow A). This can be qualitatively observed in the comparison of the mean wake flow at $x/D = 6$ presented in Figure 1 below. For a quantification of the shape and deflection of the mean wake flow for different inflow conditions, it is referred to Figure 7 and Figure 9 in Bartl et al. (2018). In order to make a clearer connection to the asymmetries in the incoming wake flow, the following modifications in the text are suggested:

p.9, l.4 ff:
Moreover, the downstream turbine's power output at low inflow turbulence (inflow A) is observed to be more asymmetric with respect to than at high inflow turbulence (inflow B). Especially for $x/D = 6$, the downstream turbine power $C_{P,T2}$ is strongly asymmetric for inflow A. This observation corresponds well with the asymmetry in the mean streamwise wake flow measured for positive and negative yaw angles reported in Bartl et al. (2018). Therein, the wake flow behind a positively and negatively yawed turbine exposed to inflow A was observed to feature a higher degree of asymmetry than for the same turbine exposed to inflow B.

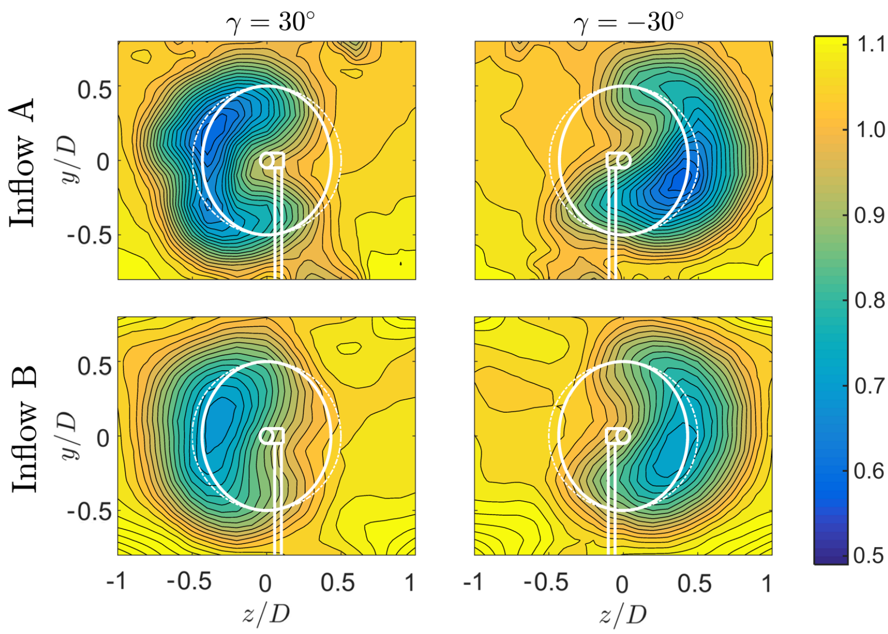

Figure 1: Mean streamwise velocity $\overline{u}/u_{ref}$ in cross-sectional cuts at $x/D = 6$ through the wake flow behind a single turbine for $\gamma_{T1} = 30°$ and $\gamma_{T1} = -30°$ for inflow conditions A (upper row) and B (lower row). The plots are adapted from Bartl et al. (2018) and were measured behind the same model turbine under the same boundary conditions.

Comment (4)

Page 10. In a previous sentence, the authors reported that quite substantial wake blockage was observed, leading to an increase of 10% of the speed outside the wake of the upstream model. How much is the blockage affecting the results presented in Figure 5? Moreover, the rotor speed of the upstream model was kept constant even for a very high yaw misalignment, which implies that the upstream model is operating at sub-optimal conditions. Indeed, when yawing a wind turbine it would have been better to keep constant the effective TSR, i.e. the TSR computed by using the component of the wind speed orthogonal to the rotor disk. How much power is lost, on the upstream model, due to the fact the model itself is operating, while yawed, at sub-optimal conditions? How this affects the results presented in figure 5?

Answer to first part of the question (how much blockage affects results): This is a very good comment, which points to one of the main weaknesses of the present study. In general, it is very difficult to quantify, how much the blockage of the wind tunnel walls affects the combined power results. For this study, we have not tried to use any kind of blockage correction models on our results.

It would be possible to correct the power and thrust of a single turbine operated in a wind tunnel. Different models have been proposed by, amongst others, Sørensen et al. (2006) and Ryi et al. (2015). However, wind tunnel blockage possibly also affects the deflection and expansion of the wake flow, which is more difficult to correct. A dedicated study on the effects of blockage on the wake development was presented by

Sarlak et al. (2016). In this study, a significant influence on the wake expansion was observed for a blockage ratio of 20%. The third and most difficult component of an assessment of the effects of blockage on the performance of a turbine array would be the performance of the downstream turbine operated in a (partial) wake of an upstream turbine. To our knowledge, there are currently no correction models available for this rather complex case. A comparative computational study of our setup in a domain, which includes and also omits the wind tunnel boundaries could be performed to shed light on this problem.
We are aware that our results do not represent a realistic, unblocked, full-scale wind turbine test case. They rather represent a model test case in defined boundary conditions, which can be used as a reference case for computational studies. In order elaborate more on this, we suggest to add the following lines to the manuscript:

p.4, l.5 ff:
Moreover, about 12.8% of the wind tunnel's cross sectional area are blocked by the turbines' rotor swept area. The wind tunnel width measures about three times the turbine's rotor diameter, which leaves sufficient space for lateral wake deflection and offset positions for T2. However, a speed-up of the flow in free-stream areas around the rotors is observed due to blockage effects as described in detail in Bartl et al. (2018). The impact of the wind tunnel blockage on the wake expansion behind the same model turbine rotor has furthermore been investigated in a computational study by Sarlak et al. (2016). For high blockage ratios, correction models e.g. by Sørensen et al. (2006) or Ryi et al. (2015) for the power output are available. In this study, however, no correction models have been applied, in order not to add another dimension of modeling uncertainty to the results.

Answer to second part of the question (how much additional upstream turbine TSR-control would affect results): Also this second part of the question is a very good comment. A similar comment was given by reviewer #1. We have measured the operating characteristics of the upstream turbine in dependence of the yaw angle and tip speed ratio. For $\gamma_{T1} = 0°$ and $\pm 30°$ the operating characteristics for all inflow conditions are shown in the previous publication (Bartl et al., 2018), which already is referred to in the text. The complete characteristics for $\gamma_{T1} = 0°$ to $+40°$ (Inflow B) are shown here in Figure 2 for positive yaw angles only (note that negative yaw angles have an insignificantly higher magnitude, but very similar TSR-dependency). It can observed that the maximum power coefficient is measured at $\lambda = 6.0$ for yaw angles between 0° and 30°. For the highest yaw angle of 40°, however, the optimum tip speed ratio is found at $\lambda = 5.5$, which makes sense according to the reasoning given by the reviewer. At this extreme yaw angle, a slightly higher combined power output could indeed have been achieved, if the upstream turbine would have been operated at $\lambda = 5.5$. However, a constant upstream turbine tip speed ratio of $\lambda = 6.0$ seems to be optimum for the most interesting region between 0° and 30°. In conclusion, we think that only the results for the extreme yaw angles of $\pm 40°$ could slightly be affected by a non-optimum TSR control of the upstream turbine (ref. Figure 5 of the manuscript). Fore all other yaw angles, the upstream turbine was operated very close to its optimum.

Nevertheless, we suggest to add some additional lines of text to the manuscript discussing the TSR-dependency.

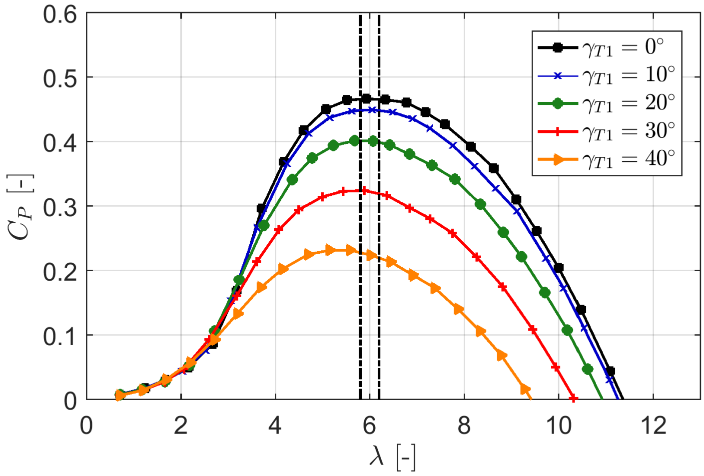

Figure 2: Tip-speed-ratio-dependent operating characteristics of the upstream turbine T1 operated at yaw angles from $\gamma_{T1} = 0°$ to $+40°$ at inflow B.

p.6, l.23 ff:
The model turbine is operated at a tip speed ratio of $\lambda_{T1} = 6.0$ for all yaw angles. ~~*The downstream turbine shows the exactly same operating characteristics when operated in undisturbed inflow.*~~ *For measurements showing the power and thrust coefficient depending on the tip speed ratio λ_{T1} it is referred to Bartl et al. (2018). There, the power coefficient is assessed to be maximum at $\lambda_{T1} = 6.0$ for all yaw angles between $\gamma_{T1} = 0°$ to $\pm 30°$. A slight shift towards a lower optimum tip speed ratio of $\lambda_{T1} = 5.5$ is measured for $\gamma_{T1} = \pm 40°$ (not shown in graph). As the difference in total power coefficient is observed to be very small, the upstream turbine is constantly operated at $\lambda_{T1} = 6.0$ also for these yaw angles. The downstream turbine shows exactly the same operating characteristics when operated in undisturbed inflow.*

Comment (5)

Page 11, line 1: the authors claim that the lack of symmetry, in the power output, for a downstream model placed on the right or left side of the upstream one, is due to "not perfectly axis-symmetric velocity deficit at x/D = 3". Since the authors measured the wake shed by the upstream wind turbine, it would be beneficial to add also a quantitative comparison: could the measured not perfectly axis-symmetric velocity deficit quantitatively explain the observed difference of power output?

This is a very good comment. Until now, the statement was only based on a qualitative assessment of the kinetic energy available in the wake. As observed in Figure 3, the left part (negative z/D) of the wake at $x/D = 3$ seems to contain slightly more kinetic energy than the right part (positive z/D).
As we are also able to calculate the available kinetic power contained in the wake (see

"available power method" described in Bartl et al. (2018)), we can quantify the power contained in circular areas at different positions in the wake. If we now laterally traverse an imaginary downstream turbine (red circle) from $z/D = -0.5$ to $z/D = +0.5$ through the wake and integrate over all measured and interpolated velocity points, we can assess the theoretical power contained in the wake for all lateral offset positions. The results for the calculated available power for 50 offset positions is shown in the red triangles in Figure 4. This curve is compared to the actually measured power of the downstream turbine in the wake (7 positions, 7 red circular dots) in Figure 4. Although the curves do not perfectly match (due to simplifications in the calculation of the power; the kinetic energy is not converted by a "real" rotor), the general trends of both curves confirm the initial assumption that more kinetic energy is available in the left part of the wake (negative z/D) than in the right part (positive z/D). Aside from the measured $C_{P,T2}$ values, also the calculated Available power values from the wake measurements confirm higher power contained for negative z/D-values.
We will add some lines to the passage in the text to support this statement, but suggest not to include further plots at this stage.

p.11, l.8 ff:

T2's power coefficient is observed not to be entirely symmetric with respect to its lateral position in the wake. Slightly higher power coefficients are measured for negative offset positions. The reason for this is deemed to be a not perfectly axis-symmetric velocity deficit at $x/D = 3$ as indicated in ~~Figure 6 (a) and~~ Bartl et al. (2018). An analysis of the available kinetic energy contained in the wake at $x/D = 3$ behind a non-yawed upstream turbine confirmed a higher kinetic energy over an imaginary rotor swept area for negative lateral offsets z/D than for positive offsets.

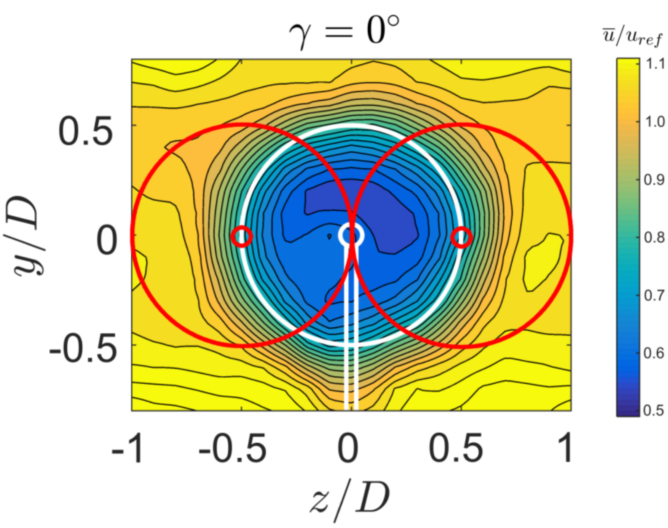

Figure 3: Mean streamwise velocity $\overline{u}/u_{ref}$ in a cross-sectional cut at $x/D = 3$ through the wake flow behind a single turbine for $\gamma_{T1} = 0°$ exposed to inflow conditions B. The plot is adapted from Bartl et al. (2018) and was measured behind the same model turbine under the same boundary conditions.

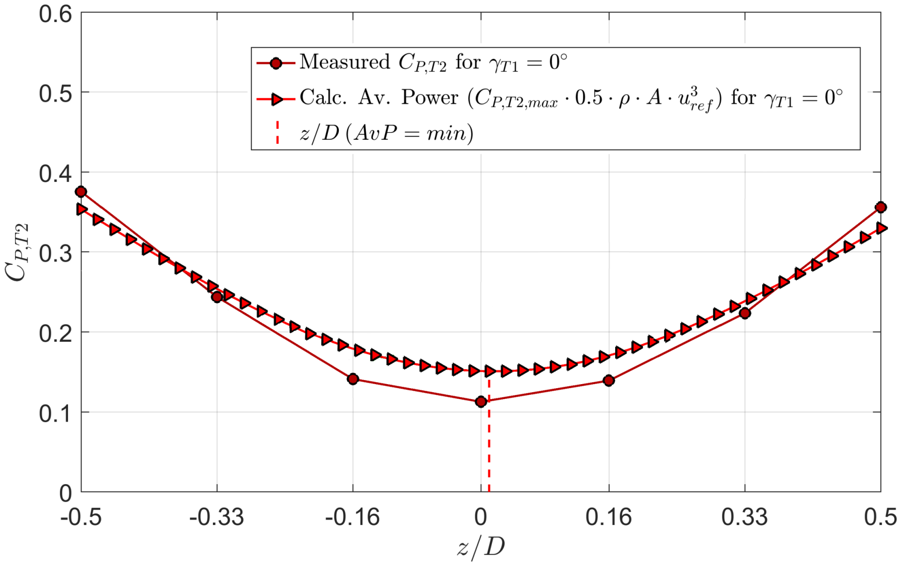

Figure 4: Comparison of the actually measured power of a downstream turbine and calculated kinetic power from wake flow measurements of an imaginary downstream turbine for different lateral offset positions z/D = [-0.5, ..., +0.5]

Comment (6)

Page 12: which is the effect of wake blockage on the data reported in Figure 8? As the authors properly write, the high Cp, measured on the downstream turbine experiencing partial-wake conditions, is due to blockage. How would the plots in figure 8 look like if the effects of blockage were compensated?

This comment is following up on the issue of wind tunnel blockage already discussed in Comment (4). As already mentioned in the answer to Comment (4), it is not possible to compensate for blockage effects on the power output of the downstream turbine operated in a partial wake with simple correction models. Advanced CFD techniques could simulate the flow around the turbine array with and without wind tunnel walls, but that would be a rather expensive study on its own.

One can use rough estimates for the power of the downstream turbine for cases, in which the wake is almost entirely deflected away from the downstream rotor, e.g. for $\gamma_{TI} = 30°$ and $z/D = +0.5$ (blue point furthest to the right in Figure 8 (a) of the manuscript). Instead of a power coefficient of $C_{P,T2;uncorr.} = 0.52$ one would obtain a blockage-corrected power coefficient of $C_{P,T2,corr.} = 0.39$, assuming that the downstream rotor is mostly exposed to undisturbed but blocked freestream flow ($C_{P,T2,corr.} = C_{P,T2;uncorr.}/(u_{wake}/u_{ref})^3 = 0.52/1.10^3 = 0.39$). For smaller lateral offsets, however, the situation is unfortunately more complex, as the downstream rotor is impinged by a partial wake.

For clarification, we suggest also to add a sentence in this passage of the manuscript:

p.12, l.22 f:

A power coefficient of $C_{P,T2} > 0.50$ *can be explained by increased freestream velocity lev-*

els of $u/u_{ref} = 1.10$ (Bartl et al., 2018) caused by wind tunnel blockage. Unfortunately, it is not possible to correct for blockage effects on the downstream turbine power, thrust and yaw moments with simple correction models. The influence of wind tunnel blockage on the highly complex inflow to the downstream turbine operated in a partial wake would have to be quantified by dedicated experiments or high-fidelity simulations.

Comment (7)

Page 13, Figure 8. The caption reports: "The upstream turbine yaw angle is kept constant at gamma = 0". It should be "The downstream turbine yaw angle is kept constant at gamma = 0"

Thank you for pointing at this mistake. It is indeed the downstream turbine yaw angle, which is referred to.

p.13, caption of Figure 8:
The ~~upstream~~ downstream turbine yaw angle is kept constant at $\cancel{\gamma_{T1} = 0°}$ $\gamma_{T2} = 0°$.

Comment (8)

Page 16: quite surprisingly, it is found that the downstream wind turbine should be yawed by 10-15 degrees (quite a lot!) in order to improve its power production. However, again the TSR of the second turbine was not changed while varying its misalignment angle. This could again lead to sub-optimal operating conditions. If the models were operated as full-scale wind turbines are (constant effective TSR) the conclusions could have been quite different. The authors should comment on this.

Thank you for this very good comment. In our experiment, we pursued the following sequence :
(1) we scanned all tip speed ratios λ_{T2} for the downstream turbine located at a certain offset position,
(2) we operated the downstream turbine at its optimum tip speed ratio $\lambda_{T2,opt}$ for this offset,
(3) we varied the downstream turbine yaw angle in steps of $\Delta\gamma_{T2} = 5°$.
When exposed to undisturbed inflow conditions the downstream turbine T2 has exactly the same operating characteristics (λ, γ) as the upstream turbine T1. These are shown in Figure 2 in this "Answers document". It is observed that the optimum tip speed ratio is more or less constant ($\lambda = 6.0$ in undisturbed inflow) up to yaw angles of $\gamma = \pm 30°$. Therefore, it can be assumed, that also the optimum tip speed ratio of the downstream turbine does not significantly change as soon as the downstream turbine is yawed in a partial wake. At this stage, we do not see any indication, why the downstream turbine should have been operated at sub-optimal conditions. However, we cannot be 100% sure about this, as we do not completely know the three-dimensional inflow field of the partial wake and if the turbine's operating conditions change in such

an environment. Assuming that it could be possible, that an additional adjustment of the tip speed ratio λ_{T2} would optimize the turbine's performance, this would have resulted in an even bigger power gain for the downstream turbine.
In any case, our intention was to show that downstream turbine yawing in a partial wake situation can benefit the power output (similar results were reported by McKay et al. (2013) in a full-scale test). In case additional TSR-control would have resulted in an additional power gain, our results would still be conservative. The general concept of power gains through downstream turbine yawing in a partial wake is therefore not in doubt.
Nevertheless, we agree that this concept requires further research, in order to completely understand the underlying physics. For this purpose, it would be helpful to have all three velocity components measured in the shear layer surrounding the wake to identify possible lateral flow components in this region. Also, additional TSR-variations of the yawed downstream turbine should be investigated.
We suggested to add some more lines to the manuscript:

p.16, l.7 f:
A maximum power gain of about 5% is measured for offset positions $z/D = 0$ *and* $+0.16$ *and a downstream turbine yaw angle between* $\gamma_{T1} = -10°$ *and* $-15°$. *Note that the downstream turbine's tip speed ratio* λ_{T2} *is kept constant when the downstream turbine is yawed. As no change in optimum tip speed ratio was measured for yaw angle variations up to* $\gamma = \pm 30°$ *in undisturbed inflow, it is at this stage assumed, that no further adjustments of the tip speed ratio in a partial wake are needed for an optimal downstream turbine power output.*

References

[1] Bartl, J., Mühle, F., Schottler, J., Hölling, M., Peinke, J., Adaramola, M., and Sætran, L.: Wind tunnel experiments on wind turbine wakes in yaw: Influence of inflow turbulence and shear, Wind Energ. Sci., 3, 329–343, doi:10.5194/wes-3-329-2018, 2018.

[2] Pierella, F. and Sætran, L.: Wind tunnel investigation on the effect of the turbine tower on wind turbines wake symmetry, Wind Energy, 20, 1753-–1769, doi: 10.1002/we.2120, 2017.

[3] Sørensen, J.N., Shen, W.Z., Mikkelsen, R.: Wall correction model for wind tunnels with open test section, AIAA J., 44 (8), 1890–1894, 2006.

[4] Ryi, J., Rhee, W., Hwang, U.C., Choi, J.-S.: Blockage effect correction for a scaled wind turbine rotor by using wind tunnel test data, Renewable Energy, 79, 227–235, doi:10.1016/j.renene.2014.11.057, 2015.

[5] Sarlak, H., Nishino, T., Martinez-Tossas, L.A., Meneveau, C., and Sørensen, J.N.: Assessment of blockage effects on the wake characteristics and power of wind turbines, Renewable Energy 93, 340–352, doi: 10.1016/j.renene.2016.01.101, 2016.

[6] McKay, P., Carriveau, R., and Ting, D. S.-K.: Wake impacts on downstream wind turbine performance and yaw alignment,Wind Energy, 16, 221–234, doi:10.1002/we.554, 2013.