This document contains the responses to the reports of Referees #1 and #2 as well as a marked-up version of the manuscript showing the changes made to the previous version.

The authors want to thank the referees for their time of effort to review the revised version of the manuscript. This is greatly appreciated. Please find our responses below. The original comments are shown in **bold** with the respective answers below. Excerpts of the manuscript are written in *italic*, aspects added to the manuscript are written in blue.
Thank you very much,

Jannik Schottler on behalf of all authors

Responses to Referee #1:

1. **The authors have correctly responded to all the comments; however, I do believe that more discussion of the author's response can be added to the article. I would suggest to add the following to the discussion:**
   The downstream development of the inflow profiles has not been measured. A downstream development of the inflow profiles can have an impact on the wake deflection of the upstream wind turbine. This can also lead to asymmetries of the power of the downstream wind turbine with respect to yaw of the upstream turbine.

   Thank you very much, we strongly agree that parts of the discussion of the first round of reviews would improve the paper and should be added to the discussion in the manuscript. Stating that the downstream development of the flow was not investigated previously will be addressed in the revised version of the manuscript. Thus we add to the discussion section, p. 4:

   [...]. Further, due to spatial limitations of the wind tunnel, the profiles shown in Fig. 1 are expected to be not fully developed. Therefore, their downstream development, which was not investigated in this study, might impact the wake deflections. This effect could not be isolated. [...]

2. **It is good that you refer to observations of numerical large eddy simulations (LES); however, one should be aware of fol-**

lowing effects that can also lead to asymmetries of the wake deficit in LES:

(a) **In LES, the inflow wind direction is a distribution, which could have a mean wind direction that has a small offset at the wind turbine position.**

(b) **The referenced LES articles also include wind veer. You could consider to add these comments to the article if you find them relevant.**

Thank you for those comments. Regarding point (a), I think the fact that the yaw angle is a distribution and not fixed should be addressed. However, I believe this should not be limited to the LES simulations as neither [1] nor [2] give exact information about a distribution of the yaw angle. Also, it is of relevance when comparing full scale cases with experiments and probably an important topic on its own. We add to the end of the discussion, p. 4, ll 29 f:

[...], such as detailed wake measurements during different inflow gradients and yaw errors. As the yaw angle is a distribution in full scale cases, future works should address this issue and its impact on active wake redirection strategies.

Regarding point (b), the wind veer should be included in the discussion, as it is a relevant difference between the referenced LES simulations and the experiments. According to the comment we write (p. 4):

[...] It should be noted that the LES simulations performed in [1] and [3] include a wind veer, which was not reproduced experimentally and should be kept in mind when comparing the numerical and experimental studies. [...]

Responses to Referee #2:

1. **Based on the response of the authors, the upstream turbine operates under constant loading (constant U_{FET}). As a result, TSR decreases with the yaw angle as shown in Fig. 1 of the response letter. This means that comparison of the turbine**

power production at different yaw angles can be questionable as turbines operate at different (not necessarily optimum) TSRs. This may not affect asymmetry in the power output reported in the manuscript. However, the results are indeed more reliable if, first, the value of the load corresponding to the optimal TSR is found for each yaw angle.

Thank you for your comment. We agree that adding aspects of the peer-review discussion to the discussion of the manuscript would add quality to the paper. This should include a statement of the changing TSR due to yaw misalignment. The model turbine's controller can set a constant TSR by adapting the voltage U_{FET}, therewith the angle of attack at the blade is kept constant for $\gamma = 0°$ and idealized inflow conditions, with γ being the yaw angle. During yaw misalignment, a blade section experiences permanent angle of attack changes due to induced velocities, which makes the controller principle of keeping the TSR constant somewhat questionable and the *optimal* TSR becomes a non-trivial parameter. For example, Krogstad & Adaramola [4] report of a decreased optimal TSR (optimal = TSR($c_{P,max}$)) during yaw misalignment. This is likely to be dependent on the airfoil / blade design used. We add this aspect to the manuscript (p. 4):

[...]. It should also be noted that the upstream turbine's tip speed ratio (TSR) is not constant for varying angles γ_1. As shown by [4], the TSR maximizing the power is subject to change with the yaw angle. Therefore, the load control utilized by the downstream turbine was not used for the upstream turbine, which was operated at constant electrical load for both profiles. However, as the upstream turbine's TSR is symmetric with respect to γ_1, this is not expected to affect the asymmetries observed in this work.

2. **Based on Fig. 2 in the response letter, the value of the turbulence intensity of Profile 2 at the turbine hub height level is more than two times of the one for Profile 1. Due to this significant difference in the turbulence level between Profiles 1 & 2, the wake of the upstream turbine can have a totally different recovery rate depending on the incoming profile. This in turn affects the power production of the downstream turbine. One has to therefore compare the power output for Profiles 1 and 2 with caution.**

   Thank you for pointing this out. We do recognize that statistical properties of the flow beyond its mean values (over height) are of importance regarding wake effects, including wake recovery. Those properties include the turbulence intensity. In order to ideally isolate an effect, all other relevant properties should be equal. However, using the active grid to create both profiles experimentally sets limits to what flow properties can be controlled simultaneously. Indeed, due to the different TIs, one has to be careful when comparing absolute power values. However, we do not expect the asymmetries of the powers for the respective profiles to be affected. We fully agree that this should be stated in the discussion section, we therefore add to the manuscript, p.4:

[...]. Next, the inflow profiles vary regarding their turbulence intensity. This is expected to impact the wake recovery [5], but not the asymmetries in power reported.

3. **In response to the other reviewer, the authors acknowledged that the incoming boundary layers are not fully developed. I think it is useful if the authors mention this limitation in the manuscript with more quantitative information (e.g., variation of velocity in the streamwise direction without the presence of the turbines). This helps readers to bear this limitation in mind when they try to interpret the presented results.**

   We agree with this comment and will add this point to the discussion section of the manuscript, p.4:

   [...]. Further, due to spatial limitations of the wind tunnel, the profiles shown in Fig. 1 are expected to be not fully developed. Therefore, their downstream development, which was not investigated in this study, might impact the wake deflections. This effect could not be isolated. [...]

4. **Please update the caption of Fig. 2 in the manuscript, following the changes made in this figure.**

   Thank you for the hint, this will be corrected.

References

[1] Fleming, P., Gebraad, P. M., Lee, S., Wingerden, J.-W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P., and Moriarty, P., "Simulation comparison of wake mitigation control strategies for a two-turbine case," *Wind Energy*, 2014.

[2] Churchfield, M. J., Lee, S., Michalakes, J., and Moriarty, P. J., "A numerical study of the effects of atmospheric and wake turbulence on wind turbine dynamics," *Journal of Turbulence*, Vol. 13, No. June 2015, 2012, pp. N14.

[3] Gebraad, P. M. O., Teeuwisse, F. W., van Wingerden, J. W., Fleming, P. A., Ruben, S. D., Marden, J. R., and Pao, L. Y., "Wind plant power optimization through yaw control using a parametric model for wake effects-a CFD simulation study," *Wind Energy*, Vol. 19, No. 1, jan 2014, pp. 95–114.

[4] Krogstad, P.-Å. and Adaramola, M. S., "Performance and near wake measurements of a model horizontal axis wind turbine," *Wind Energy*, Vol. 15, No. 5, 2012, pp. 743–756.

[5] Wu, Y. T. and Porté-Agel, F., "Atmospheric turbulence effects on wind-turbine wakes: An LES study," *Energies*, Vol. 5, No. 12, 2012, pp. 5340–5362.

Brief Communication: On the influence of vertical wind shear on the combined power output of two model wind turbines in yaw

Jannik Schottler, Agnieszka Hölling, Joachim Peinke, and Michael Hölling

ForWind, University of Oldenburg, Institute of Physics, Oldenburg, Germany

Correspondence to: Jannik Schottler (jannik.schottler@forwind.de)

Abstract. The effect of vertical wind shear on the total power output of two aligned model wind turbines as a function of yaw misalignment of the upstream turbine is studied experimentally. It is shown that asymmetries of the power output of the downstream turbine and the combined power of both with respect to the upstream turbine's yaw misalignment angle can be linked to the vertical wind shear of the inflow.

1 Introduction

Lately, different concepts of active wake control are discussed throughout the research community. One promising concept is the wake deflection by intentional yaw misalignment of single wind turbines. The principle of deflecting the velocity deficit behind a wind turbine was observed in field measurements by Trujillo et al. (2016), in wind tunnel experiments (e.g. Medici and Alfredsson, 2006; Krogstad and Adaramola, 2012) and in numerical simulations (e.g. Jiménez et al., 2010; Gebraad et al., 2014; Vollmer et al., 2016). Further, Gebraad et al. (2014) and Fleming et al. (2016) applied the concept to wind farm control strategies using large-eddy simulation (LES) methods, showing a potential power increase in wind farm applications.

Vollmer et al. (2016) report on an asymmetric deflection of a turbine's wake with respect to its direction of yaw misalignment in numeric studies. Similarly, Bastankhah and Porté-Agel (2016) found that a wake moves upwards or downwards depending on the direction of a yaw misalignment using PIV measurements behind a small turbine model. This observation is explained by an interaction of the wake's rotation and a pair of counter-rotating vortices formed in yawed conditions with the ground.

Vollmer et al. (2016) studied the influence of atmospheric stabilities on the wake deflection by yaw misalignment. The results show that different stratifications indeed result in varying deflections of the wake behind the rotor of a numeric turbine model. More precisely, disparities between wake deflections due to yaw misalignments of $+30°$ and $-30°$ were significantly different considering different atmospheric stratifications and therewith different shears. It is believed that a combination of a vertical inflow gradient, the wake's rotation and the wind veer cause asymmetric wake deflections with respect to the rotor's yaw angle.

Examining the power of a turbine array, Fleming et al. (2014) and Gebraad et al. (2014) showed that only one direction of yaw misalignment resulted in a power increase of a two turbine array, while the exact opposite direction caused a power decrease. This finding was confirmed by Schottler et al. (2016) experimentally using two model wind turbines. As those findings impact the applicability of the concept significantly, reasons for the asymmetry need to be understood.

In this study, we show that a vertical wind shear has a direct effect on the power's asymmetry of two model wind turbines during yaw misalignment.

2 Methods

The experiments were performed at a wind tunnel of the University of Oldenburg, with an open test section of $1\,\mathrm{m} \times 0.8\,\mathrm{m} \times 5\,\mathrm{m}$ $[\mathrm{w} \times \mathrm{h} \times \mathrm{l}]$. Two model wind turbines as described by Schottler et al. (2016) were used in streamwise displacement. The turbines were separated by $3D$, with $D = 0.58\,\mathrm{m}$ being the rotor diameter and rotate clockwise when observed from upstream. The upstream turbine is placed on a turning table allowing for yaw misalignment, where a positive yaw angle is a counter-clockwise rotation of the rotor when seen from above. The downstream turbine utilizes a partial load control and therewith adapts to the changing inflow conditions. Power measurements are based on the rotational speed and the torque, being proportional to the electric current of the generator. Further details about the setup, power measurements and turbine control are described by Schottler et al. (2016). In order to isolate the effect of a vertical wind shear in the inflow, the horizontal axes of an active grid (see Weitemeyer et al. (2013)) at the wind tunnel outlet were set statically to create two different inflow profiles, which were characterized prior to the experiments. 13 hot wire probes were used simultaneously in a vertical line arrangement with a distance of $75\,\mathrm{mm}$ separating two sensors. For both settings of the grid, data were recorded for 120 s at a sampling frequency of 2 kHz. The array was installed 1 m downstream from the grid at the position of the upstream turbine's rotor, which was installed after characterizing the inflow. Fig. 1 shows mean wind speeds over the height z, whereas $\mathrm{z} = 0\,\mathrm{m}$ corresponds to the bottom of the wind tunnel outlet. The reproducibility of time averaged velocity profiles for one grid setting has been investigated and confirmed. Further, mean values have been checked for statistical convergence. As of now, we refer to the inflow conditions

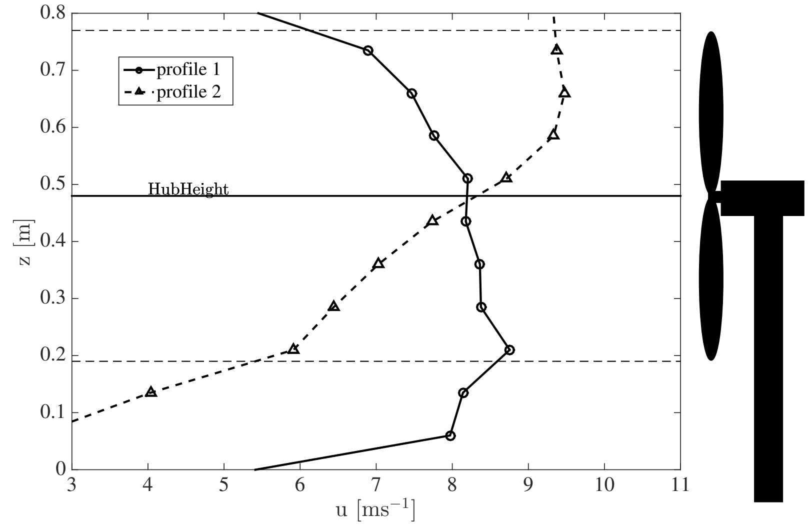

Figure 1. Mean velocity values of the vertical wind speed profiles 1 and 2 that were used as inflow conditions. The dashed, vertical lines mark the heights of the rotor tips of the turbine that was installed after characterizing the inflow profiles.

shown in Fig. 1 as *profile 1* and *profile 2*. Using two inflows which feature a vertical wind shear of opposite direction over the rotor area allows for an investigation of the gradient's influence on the asymmetric power output of the two turbines with respect to the upstream turbine's yaw angle, γ_1.

3 Results

Mean values of the ~~combined power P_{tot} and the power of the downstream turbine~~upstream turbine's power P_1, the downstream turbine's power P_2 and their sum P_{tot} are shown as a function of the yaw angle γ_1 in Fig. 2. Data points are normalized to the respective maximum of P_{tot}. Looking at Fig. 2(a), asymmetries of P_2 and P_{tot} with respect to γ_1 become obvious. The minimum of the downstream turbine's power P_2 is shifted towards positive angles. The maximum of the combined power P_{tot} is at $\gamma_1 \approx -18°$, being approx. 4 % larger compared to the case of no yaw misalignment $\gamma_1 = 0°$. Also the combined power shows a distinct asymmetry with respect to γ_1. While the power is maximal at $\gamma_1 \approx -18°$, it further decreases for larger values of γ_1. For positive yaw angles, the total power output is smaller compared to the case of no yaw misalignment. The results support that the direction of a purposeful yaw misalignment is of great relevance regarding the application of this concept to wind farm control. Further, the general shape of the graphs are in good agreement with numeric simulations of full size turbines reported by Gebraad et al. (2014) and Fleming et al. (2014).

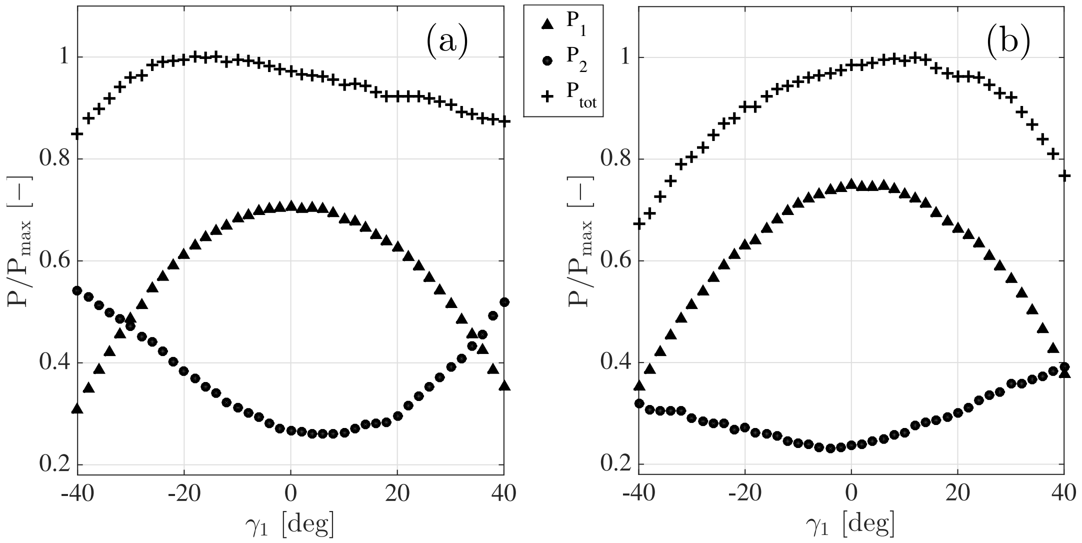

Figure 2. Mean values of P_1, P_2 and P_{tot} for each examined value of γ_1 during the both inflow condition profile 1 (a) and profile 2 (b).

Fig. 2(b) shows the results of the same experiment, whereas nothing but the inflow conditions was changed to profile 2. Since the reproducibility of results was proven by Schottler et al. (2016), the effect of the changed inflow is isolated. As can be seen, asymmetric shapes of P_2 and P_{tot} are still observed. More importantly, the direction of the asymmetry changed with the direction of the inflow's vertical shear. Now, in Fig. 2(b), the minimum of P_2 is located at negative yaw angles, $\gamma_1 \approx -4°$.

Moreover, the yaw angle direction at which the combined power is maximum changed, being positive ($\gamma_1 \approx 12°$) for inflow profile 2. Our results show that the reason for the asymmetric shapes of the graphs in Fig. 2 is related to the inflow's vertical wind shear, which is further discussed in Sec. 4.

4 Discussion and conclusion

~~In this study, the~~ The vast majority of model wind turbine experiments face a Reynolds number mismatch between the laboratory and full scale case, which is nearly a factor of 170 in this study. However, due to the good agreement of the general shapes of the turbines' normalized powers comparing the present study and Schottler et al. (2016) with simulations of a full scale case (Fleming et al., 2014; Gebraad et al., 2014) , the Reynolds number dependence is assumed to be rather insignificant when judging general effects of wake deflection. It should be noted that the LES simulations performed in (Fleming et al., 2014) and (Gebraad et al., 2014) include a wind veer, which was not reproduced experimentally and should be kept in mind when comparing the numerical and experimental studies. Further, due to spatial limitations of the wind tunnel, the profiles shown in Fig. 1 are expected to be not fully developed. Therefore, their downstream development, which was not investigated in this study, might impact the wake deflections. This effect could not be isolated. Next, the inflow profiles vary regarding their turbulence intensity. This is expected to impact the wake recovery (Wu and Porté-Agel, 2012) , but not the asymmetries in power reported. It should also be noted that the upstream turbine's tip speed ratio (TSR) is not constant for varying angles γ_1. As shown by Krogstad and Adaramola (2012) , the TSR maximizing the power is subject to change with the yaw angle. Therefore, the load control utilized by the downstream turbine was not used for the upstream turbine, which was operated at constant electrical load for both profiles. However, as the upstream turbine's TSR is symmetric with respect to γ_1, this is not expected to affect the asymmetries observed in this work.

This study investigates the influence of vertical wind shears on the power output of two aligned model wind turbines~~is investigated~~. An asymmetry of the power output with respect to the upstream turbine's yaw angle was found in prior experiments on laboratory scale (Schottler et al., 2016) as well as in full scale numeric simulations (Gebraad et al., 2014; Fleming et al., 2014). Only one direction of yaw misalignment resulted in a power increase, whereas the exact opposite direction caused a power decrease of the turbine array. For a potential application of active wake control by intentional yawing, this effect needs to be understood. With the present methods, we investigate the reasons for the asymmetric power output of a two turbine array and isolate the effect of a vertical inflow gradient's orientation. A strong linkage between the asymmetry and the velocity gradient's orientation was found. If the reported asymmetry depends on boundary conditions of the surroundings, which our results suggest, then this drastically impacts the applicability to real world wind farm control scenarios. In this study, the downstream turbine's power is used as indicator. The interesting results regarding the asymmetry and its linkage to the inflow conditions motivate further examinations, such as detailed wake measurements during different inflow gradients and yaw errors. ~~The vast majority of model wind turbine experiments face a Reynolds number mismatch between the laboratory and full scale case, which is nearly a factor of 170 in this study. However, due to the good agreement of the general shape of the turbines' normalized power comparing the present study and Schottler et al. (2016) with simulations of a full scale~~

~~case (Fleming et al., 2014; Gebraad et al., 2014) , the Reynolds number dependence is assumed to be rather insignificant when judging general effects of wake deflection.~~ As the yaw angle is a distribution in full scale cases, future works should address this issue and its impact on active wake redirection strategies.

Acknowledgements. Parts of this work ~~was~~ were funded by the Reiner Lemoine Stiftung (RLS), Germany, which is greatly appreciated. The authors thank Stefan Ivanell for providing the rotor blade design as well as Jan Bartl and Lukas Vollmer for fruitful discussions.

References

Bastankhah, M. and Porté-Agel, F.: Experimental and theoretical study of wind turbine wakes in yawed conditions, Journal of Fluid Mechanics, 806, 506–541, doi:10.1017/jfm.2016.595, http://stacks.iop.org/1742-6596/625/i=1/a=012014, 2016.

Fleming, P., Gebraad, P. M., Lee, S., Wingerden, J.-W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P., and Moriarty, P.: Simulation comparison of wake mitigation control strategies for a two-turbine case, Wind Energy, 2014.

Fleming, P. A., Ning, A., Gebraad, P. M. O., and Dykes, K.: Wind plant system engineering through optimization of layout and yaw control, Wind Energy, 19, 329–344, doi:10.1002/we.1836, http://doi.wiley.com/10.1002/we.1836, 2016.

Gebraad, P. M. O., Teeuwisse, F. W., van Wingerden, J. W., Fleming, P. A., Ruben, S. D., Marden, J. R., and Pao, L. Y.: Wind plant power optimization through yaw control using a parametric model for wake effects-a CFD simulation study, Wind Energy, 19, 95–114, doi:10.1002/we.1822, http://doi.wiley.com/10.1002/we.1822, 2014.

Jiménez, Á., Crespo, A., and Migoya, E.: Application of a LES technique to characterize the wake deflection of a wind turbine in yaw, Wind energy, 13, 559–572, 2010.

Krogstad, P.-Å. and Adaramola, M. S.: Performance and near wake measurements of a model horizontal axis wind turbine, Wind Energy, 15, 743–756, 2012.

Medici, D. and Alfredsson, P.: Measurements on a wind turbine wake: 3D effects and bluff body vortex shedding, Wind Energy, 9, 219–236, 2006.

Schottler, J., Hölling, A., Peinke, J., and Hölling, M.: Wind tunnel tests on controllable model wind turbines in yaw, 34th Wind Energy Symposium, p. 1523, 2016.

Trujillo, J.-J., Seifert, J. K., Würth, I., Schlipf, D., and Kühn, M.: Full field assessment of wind turbine near wake deviation in relation to yaw misalignment, Wind Energy Science Discussions, pp. 1–17, doi:10.5194/wes-2015-5, http://www.wind-energ-sci-discuss.net/wes-2015-5/, 2016.

Vollmer, L., Steinfeld, G., Heinemann, D., and Kühn, M.: Estimating the wake deflection downstream of a wind turbine in different atmospheric stabilities: an LES study, Wind Energy Science, 1, 129–141, doi:10.5194/wes-1-129-2016, http://www.wind-energ-sci.net/1/129/2016/, 2016.

Weitemeyer, S., Reinke, N., Peinke, J., and Hölling, M.: Multi-scale generation of turbulence with fractal grids and an active grid, Fluid Dynamics Research, 45, 061 407, doi:10.1088/0169-5983/45/6/061407, http://stacks.iop.org/1873-7005/45/i=6/a=061407?key=crossref.8476ac727119acae00736461833aca18, 2013.

Wu, Y. T. and Porté-Agel, F.: Atmospheric turbulence effects on wind-turbine wakes: An LES study, Energies, 5, 5340–5362, doi:10.3390/en5125340, 2012.