Authors' response to Anonymous Referee #1:

We, the authors, are very thankful for the detailed and constructive comments and greatly appreciate the willingness to review our manuscript. Please find our responses below. The original comments are shown in **bold** with the respective answers below. Excerpts of the manuscript are shown in *italic writing*, whereas additions are written in <u>blue</u> and deleted parts in red.

Please note that the format of citations in manuscript excerpts might be changed.

Thank you very much for your efforts,

Jannik Schottler on behalf of all authors

Major comments:

1. One of the main criticism to the paper is the fact that is suffers from the lack of velocity and thrust measurements. For instance, wake measurements at different yaw angles can provide more insights on the asymmetric behavior observed in the power of the downwind turbine. Even only thrust measurements for the upwind turbine can shed lights on the overall strength of the turbine wake, and consequently the performance of the downwind turbine. However, I do appreciate that the authors are motivated to perform velocity measurements in their future research.

Thank you very much for the constructive criticism. We do agree that wake velocity measurements and thrust measurements along with the presented power data would give an overall insight in the scenario as a whole. However, wake velocity measurements were not performed in the scope of this manuscript. The focus of this paper are power measurements of both turbines in relation to the upstream turbine's yaw angle and two inflow profiles. In this brief manuscript, we focus on one main message, which is how both inflow profiles affect the asymmetries in the powers during yaw misalignment differently.

We believe that the *whole picture* of active wake control by yaw misalignment can only be grasped by studying the wake evolutions by means of numerous turbulence parameters along with turbine data such as power and loads for various inflow conditions, both experimentally and numerically. In our opinion it is hardly possible nor desirable to cover all of these aspects in one publication. Instead, we believe that it adds clarity, intelligibility and systematics to literature when focusing on few if not one main message only, especially in the manuscript type "Brief communications".

In our manuscript, the main quantity of interest is the power. The reasons for the shapes of the powers in relation to the yaw angle is believed to be complex and cannot be covered in one publication. Recent works such as Bastankhah and Porté-Agel (2016) [1] or Vollmer at al. (2016) [2] show that solely the wake velocities of deflected wakes due to yaw misalignment comprises a challenging complexity.

In our study, the power and therewith the performance of the downstream turbine is measured directly, thus thrust measurements of the upstream turbine would, in our opinion, not contribute significantly to information regarding the downstream turbine's performance.

2. Apart from the yaw angle, the operational tip-speed ratio is very important as it significantly affects the turbine power. It is not clear in the manuscript if the turbine always operate a the optimal tip-speed ratio (i.e., the one at which the turbine power is maximum) or a constant tip-speed ratio is used for all the different yaw angles. In other words, please explain how the effect of yaw angle on power production is isolated from the effect of the other parameters such as the operating tip-speed ratio.

Thank you for pointing this out, indeed the TSR is affecting the wake of a wind turbine and therewith its deflection. In the present setup, the rotational speed of the model wind turbine(s) is controlled using a field effect transistor (FET) within the electric circuit. By applying an external voltage U_{FET} to the FET, the electric current is manipulated and therewith the electric load and the rotational speed are controlled. The concept and the settings during the experiment are described in [3], which is why this information is missing the current manuscript, the reference to the description in [3] is given in p.2, ll. 5-6.

During the experiment, the downstream turbine utilizes the active load control, where a PI-controller controls the load by continuously adapting the voltage U_{FET}. Therewith, the turbine automatically adapts to changing inflow conditions, keeping the TSR of the downstream turbine constant. For the upstream turbine, however, the control voltage U_{FET} was kept constant for each yaw angle γ_1 and both inflow profiles. This results in a variation of the TSR with γ_1 , which is shown in Fig. 1 of this document. Unfortunately, the TSR is not equal for both profiles



Figure 1. TSR λ_1 over the yaw angle γ_1 , during constant control voltage U_{FET} and $u \approx 8 \text{ms}^{-1}$.

used. However, both profiles do not show any distinct asymmetries. Herewith it is shown that the asymmetries in the power output, which are the focus of this paper, do not result from the TSR variations.

3. The literature review has to be improved. Some very relevant experimental and numerical studies in the literature (e.g. Jimenet et al. 2010, Howland et al. 2016, Bastankhah and Porte-Agel 2016) are not mentioned in the manuscript. In particular, Bastankhah and Porte-Agel (2016) has recently showed that, in addition to the lateral deflection, the wake of a yawed turbine moves vertically, and the magnitude and the direction of both horizontal and vertical displacements depend on the yaw-angle direction. This can explain why the power of the downwind turbine (or the combined power) depends on the yaw-angle direction of the upwind turbine.

Thank you very much for pointing this out. We fully agree that the mentioned studies, especially Bastankhah and Porté-Agel [1] did some very interesting work on the topic, which should be included in the literature review. Amongst other aspects, it was found that the direction of yaw misalignment results in a upward or downward movement of the examined model turbine wakes. A method based on potential theory was used to show that this asymmetric wake deflection for positive and negative yaw angles result of an interaction between a pair of counter rotating voracities, the ground and the wake rotation. For details, please see chapter 3 in [1]. This finding supports our conclusion, that the asymmetry in power of the downstream (and therewith the to-

tal power) turbine with respect to γ_1 is the result of the wake rotation interacting with shear. Similar assumptions are stated by Gebraad et al (2014) [4]. There, reasons for an initial wake deflection without yaw misalignment ($\gamma = 0^{\circ}$), are given as shown in the quote in Figure 2 of this document. Similar to Bastankhah and Porté-Agel, a combination of the wake's rotation and the interaction with the ground/wind shear is pointed out.

$$\frac{D_{i}}{D_{i}} \left[\frac{2\kappa_{d} \left[x - A_{l} \right]}{D_{i}} + 1 \right]$$

In addition, in the simulations described by Fleming *et al.*,²³ it was shown that a small lateral wake deflection occurs when the turbine is not yawed (i.e., $\gamma_i = 0$). This deflection can be explained by vertical shear in the boundary layer and wake rotation. In reaction to the rotor rotating clockwise, the wake will rotate counterclockwise. As a result, the low-speed flow in the lower part of the boundary layer will be rotated up and to the right, and high-speed flow in the upper part of the boundary layer will be rotated down and to the left. Consequently, the velocity deficit at the right part of the wake (looking downstream) increases, so the wake deflects to the right. Because in *SOWFA Simulation Series 1* and 2, the wake behavior was tested for a single mean wind velocity with a limited velocity variation caused by turbulence, the exact dependence of the wake deflection on the rotor speed could not be derived from the power data obtained. Therefore, this rotation-induced wake lateral offset is parameterized through a simple linear function of the downstream distance from the rotor:

Figure 2. Screenshot taken from [4].

Jimenéz et al. did important work on the topic of wake deflection by yawing in general. However, only one direction of yaw misalignment was studied in the mentioned paper and asymmetries are therefore not reported. Nevertheless, this important piece of work should be mentioned in the manuscript.

We suggest to add this works to the literature review as done below:

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 [5], in wind tunnel experiments [6, 7] and in numerical simulations [4, 2][8, 4, 2]. Further, [9] and [10] applied the concept to wind farm control strategies using large-eddy simulation (LES) methods, showing a potential power increase in wind farm applications.

[2] and [4] report on an asymmetric deflection of a turbine's wake with respect to its direction of yaw misalignment . [11] and [9] 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 has been confirmed by [3] 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 numeric studies. Similarly, [1] 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 vorticies formed in yawed conditions with the ground. [2] studied the influence of atmospheric stabilities on the wake deflection by yaw misalignment. The results showed that different stratifications indeed resulted 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 $+30^{\circ}$ and -30° were significantly different considering different atmospheric stratifications and therewith different vertical velocity gradients. 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 turbine array, [11] and [9] 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 has been confirmed by [3] 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 velocity gradient has a direct effect on the wake's asymmetry during yaw misalignment using two model wind turbines in a wind tunnel study.

4. Please explain why a relatively unrealistic spacing between turbines (3D) is selected. In wind farms, turbine spacing usually falls in the range of 5D to 7D depending on terrain and flow conditions.

The experiments were performed at a wind tunnel of the University of Oldenburg, having a test section of 5 m length or ≈ 8.6 rotor diameters, whereas 5 m corresponds to the location of the collector. However, the spacing from the outlet/grid to the front turbine as well as the free stream configuration of the wind tunnel set limits the distance separating both turbines. In order to minimize wind tunnel effects due to the increasing shear layer of the free stream, the experiments were performed at a distance of x/D=3. We do agree that increasing distances would add valuable information, however, those were not performed due to the described wind tunnel limitations.

All of the following comments (5-9) address a lack of information that has been published in [3], where the same experimental setup was used apart from the sheared inflow profiles. Due to the limitations to 4 pages in length of the manuscript type 'Brief communication', we described only the most important aspects of the setup with the reference to [3] for more details. In general, we prefer to follow this principle due to the limitations and avoid describing details already published. However, we fully agree with the referee that some more very important aspects should be mentioned in the manuscript. In the following, a point-by-point response to the comments is given.

5. There is no information on how the turbine power is measured. Is it the electrical? Or the mechanical power extracted by the turbine form the wind?

The turbine power is $P = T \cdot \omega$, where ω is the rotational speed and $T = k \cdot I$ the torque based on the electric current I and the constant k = 79.9mN A⁻¹ taken from the generator's specifications. The current I is measured by the voltage drop across a shunt resistor of 100 mΩ. Therewith, the power becomes $P = \omega T = \omega k \frac{U_s}{0.1\Omega}$.

This concept is described in [3] as shown by the screenshot in Figure 3 of this document, please refer to comment number 6 for the suggested update of the manuscript.

Data acquisition and turbine control were realized by a National Instruments NI-9074 cRIO real time controller equipped with modules for stepper motor control (NI-9512), analog input (NI-9215), analog output (NI-9264) and digital input/output (NI-9401) in combination with in-house built LabView software. The power of the model turbines, $P = \omega T$, is based on the generator's torque T, which is proportional to the electric current I according to the generator's specifications. I is obtained by measuring the voltage drop U_S across a shunt-resistor of 0.1 Ω . Therewith, the power becomes $P := \omega k \frac{U_S}{0.1 \Omega}$, where $k = 79.9 \text{ mN A}^{-1}$ is the proportionality constant relating the generator's electric current to its torque.

Figure 3. Schreenshot taken from [3], description of power measurements.

6. Please provide more information on about the wind tunnel (e.g. wind-tunnel type, test section size, and blockage ratio).

We agree that this information is of importance and needs to be mentioned to a larger extent. The manuscript describes an experiments using the same setup is in a previous study [3], apart from the vertical velocity profiles. In [3], more detailed information about the setup are giving, which is shown in Figure 4 of this document.

III. Experimental Setup

Both turbines were placed in the wind tunnel of the University of Oldenburg with an outlet of 1 m x 0.8 m (width x height) and an open test section of 5 m length, displaced in streamwise direction as sketched in Figure 5. The distance x is variable, in this study we investigate the case x/D = 3. The outlet of the wind tunnel was equipped with an active grid as described by Weitemeier et al.¹⁷ The grid was used passively in open configuration with a blockage of nearly 4.8%, which resulted in a turbulence intensity of approx. 3% at hub height and $u \approx 8 \text{ m s}^{-1}$. The front turbine T1 was placed on a stepper motor driven turning table that allows a variation of the yaw angle. The wind speed u_2 , which was the input wind speed for the load control of T2 as described in section B, was measured by a Prandtl tube 0.35 m in front of the downstream

^aFurther characterizations showed that the maximal power coefficient achievable increases with the prevailing wind speed. Most likely, this is caused by mechanical losses, whose impact becomes less significant with increasing velocity.

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Figure 4. Screenshot taken from [3], describing the setup.

Therefore, some aspect already described there were purposely not included in the current manuscript in order to keep the paper brief. A suggested update of Section 2 is given below:

p.2, ll.2 ff.:

The experiments were performed at a wind tunnel of the University of Oldenburg, with an open test section of $1 \text{ m} \times 0.8 \text{ m} \times 5$, m [w × h × 1]. Two model wind turbines as described by [12] were used in streamwise displacement. The turbines were separated by 3D, with D = 0.58 m being the rotor diameter. The upstream turbine is placed on a turning table allowing a yaw misalignment, while the where a positive yaw angle is a counter-clockwise rotation of the rotor observed from above. The downstream turbine utilizes a partial load control and therewith adapts to the changing inflow conditions. Power measurement are based on the rotational speed and the torque, being proportional to the electric current of the generator. Further details about the setup and power measurements are described by Schottler et al. (2016) [3]. In order to isolate ...

7. I suggest the authors to also test the performance of the turbines under uniform inflow conditions as a reference case. This can strengthen the authors' arguments. Moreover, Profile 2 down not have a good quality. It has a positive slope at

lower heights and a fairly negative slope a higher heights. A profile with a clearly negative slope (in contrast to profile 1) is more constructive.

The study [3] describes a very similar setup with the same grid installed, but all flaps being *open*, e.g. aligned with the main flow direction. Please refer to Figure 4 of this document for the exact passage. The results for the upstream and downstream turbine's power under uniform inflow conditions are discussed in this study. Figure 5 of this document shows a screenshot with the upstream and downstream turbine's power along with their sum. Here, also an asymmetry in $P_2(\gamma_1)$ and $P_{tot}(\gamma_1)$ is observed. The power of the upstream turbine $P_1(\gamma_1)$ is shown to be close to symmetric. The three different sets show three measurements, showing the reproducibility of the results.



Figure 5. P_1 and P_2 (a) and P_{tot} (b) over γ_1 during uniform inflow conditions, taken from [3].

8. Figure 2: Please add the variation of the power with the yaw angle for the upstream turbine. This helps readers to easier realize how yawing the upwind turbine reduces its own power and increases the power of the downwind one.

Figure 6 of this document shows Figure 2 of the manuscript with the power of the upstream turbine added to the plots. In our opinion, the plots appear a bit crowded now with three graphs overlapping. We suggest to normalize all graphs to the maximum value of P_{tot} , as done in Figure 7 of this document.



Figure 6. Mean values of P_1 , P_2 and P_{tot} over γ_1 for profile 1 (left) and profile 2 (right).



Figure 7. Mean values of P_1 , P_2 and P_{tot} over γ_1 for profile 1 (left) and profile 2 (right).

9. Please define which yaw-angle direction is assumed to be positive in this study. Moreover, please specify in the manuscript the rotational direction of the turbine.

We do agree that this should be mentioned in the manuscript besides the reference to [3]. We suggest to update the manuscript as done below:

p.2 ll. 4 ff.:

Two model wind turbines as described by [12] were used in streamwise displacement. The turbines were separated by 3D, with D = 0.58 m being the rotor diameter and rotate clockwise when observed form upstream. The upstream turbine is placed on a turning table allowing a yaw misalignment, while the where a positive yaw angle is a counter-clockwise rotation of the rotor observed from above. The downstream turbine utilizes a partial load control and therewith adapts to the changing inflow conditions. Power measurement are based on the rotational speed and the torque, being proportional to the electric current of the generator. Further details about the setup and power measurements are described by Schottler et al. (2016) [3].

Minor comments:

All minor comments were considered in the revised version of the manuscript.

References

- Bastankhah, M. and Porté-Agel, F., "Experimental and theoretical study of wind turbine wakes in yawed conditions," *Journal of Fluid Mechanics*, Vol. 806, No. 1, nov 2016, pp. 506–541.
- [2] 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*, Vol. 1, No. 2, sep 2016, pp. 129–141.
- [3] Schottler, J., Hölling, A., Peinke, J., and Hölling, M., "Wind tunnel tests on controllable model wind turbines in yaw," 34th Wind Energy Symposium, , No. January, 2016, pp. 1523.
- [4] Gebraad, P., Teeuwisse, F., Wingerden, J., Fleming, P., Ruben, S., Marden, J., and Pao, L., "Wind plant power optimization through yaw control using a parametric model for wake effects—a CFD simulation study," Wind Energy, 2014.
- [5] 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*, , No. January, 2016, pp. 1–17.

- [6] Medici, D. and Alfredsson, P., "Measurements on a wind turbine wake: 3D effects and bluff body vortex shedding," *Wind Energy*, Vol. 9, No. 3, 2006, pp. 219–236.
- [7] 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.
- [8] Jiménez, A., Crespo, A., and Migoya, E., "Application of a LES technique to characterize the wake deflection of a wind turbine in yaw," *Wind energy*, Vol. 13, No. 6, 2010, pp. 559–572.
- [9] 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.
- [10] 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*, Vol. 19, No. 2, feb 2016, pp. 329–344.
- [11] 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.
- [12] Schottler, J., Hölling, A., Peinke, J., and Hölling, M., "Design and implementation of a controllable model wind turbine for experimental studies," *Journal of Physics: Conference Series*, Vol. 753, sep 2016, pp. 072030.