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

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 blue 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

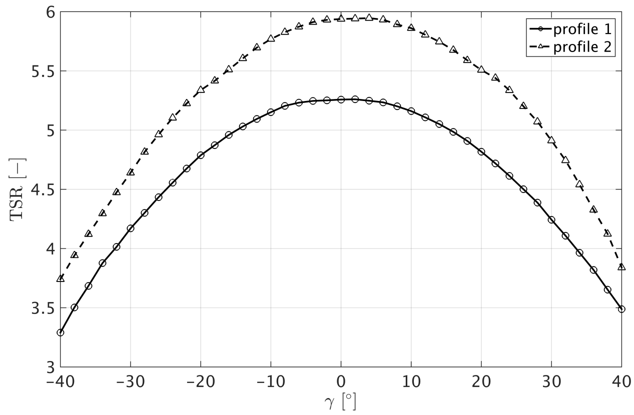

Figure 1. TSR λ_1 over the yaw angle γ_1, during constant control voltage U_{FET} and u $\approx$ 8ms^{-1}.

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 total 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 ($\gamma = 0°$), 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.

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, [4] and [9] 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 ~~. [10] and [4] 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 $+30°$ *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, [10] and [4] 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 $k = 79.9\mathrm{mN\,A^{-1}}$ taken from the generator's specifications. The current I is measured by the voltage drop across a shunt resistor of $100\,\mathrm{m\Omega}$. 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, $\mathrm{P} = \omega\mathrm{T}$, 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 $\mathrm{U_S}$ across a shunt-resistor of $0.1\,\Omega$. Therewith, the power becomes $\mathrm{P} := \omega\mathrm{k}\frac{\mathrm{U_S}}{0.1\,\Omega}$, where $\mathrm{k} = 79.9\,\mathrm{mN\,A^{-1}}$ is the proportionality constant relating the generator's electric current to its torque.

Figure 3. Screenshot 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 $u \approx 8\,\mathrm{m\,s^{-1}}$. 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

[a]Further 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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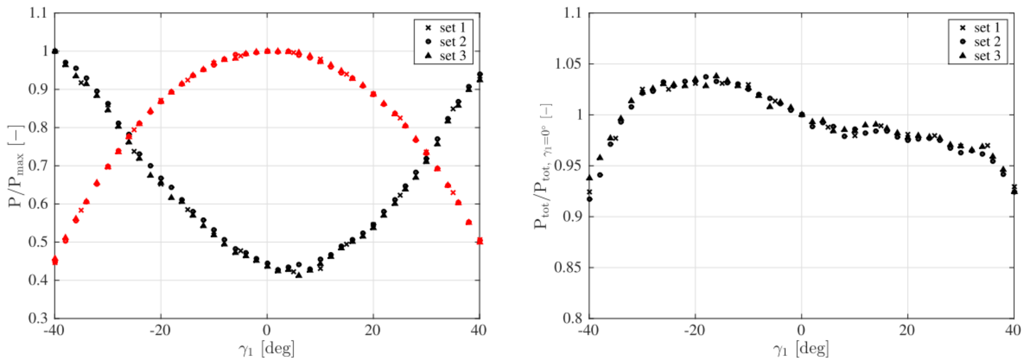
American Institute of Aeronautics and Astronautics

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 $1\,\mathrm{m} \times 0.8\,\mathrm{m} \times 5,\mathrm{m}$ *[*$\mathrm{w} \times \mathrm{h} \times \mathrm{l}$*]. Two model wind turbines as described by [3] were used in streamwise displacement. The turbines were separated by* $3D$*, with* $D = 0.58\,\mathrm{m}$ *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.



(a) Upstream (red) and downstream turbine (black).

(b) Total power output of both turbines.

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.

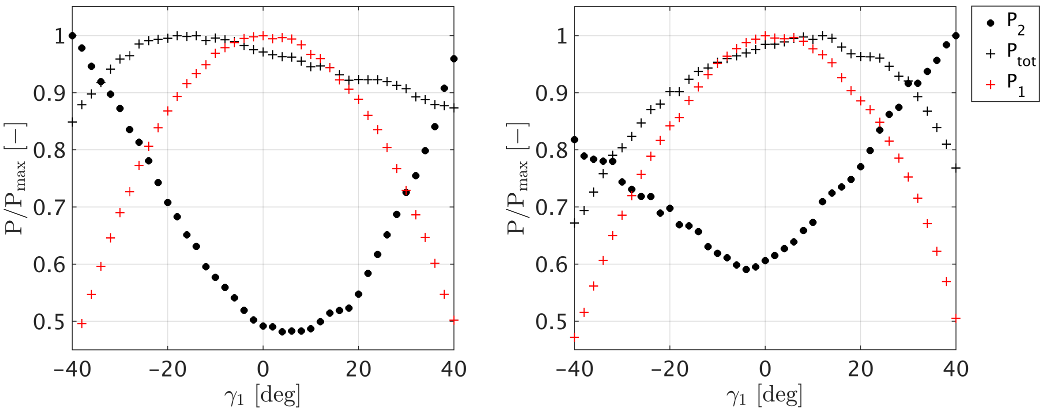


Figure 6. Mean values of P_1, P_2 and P_{tot} over γ_1 for profile 1 (left) and profile 2 (right).

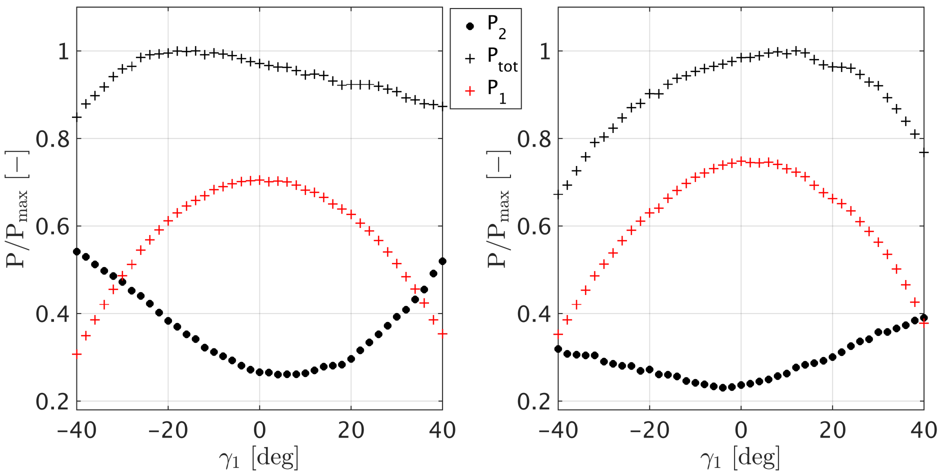


Figure 7. Mean values of P_1, P_2 and P_{tot} over γ_1 for profile 1 (left) and profile 2 (right).

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 [3] were used in stream-wise 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

[1] 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. 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.

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[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, Á., 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] 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.

[10] 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.

Authors' response to Referee #2, M. Paul van der Laan of DTU Wind Energy:

Dear Mr van der Laan, we, the authors, are very thankful for the detailed and constructive comments and greatly appreciate the willingness to review our manuscript. Especially, we would like to thank you for performing the numeric simulations shown in the comments. Please find our responses below. In this document, 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 blue 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. **Where are the profiles from Figure 1 measured with respect to the wind turbine positions and how do they develop from the first to the second wind turbine and further downstream (without the wind turbines present in the tunnel). My concern is that if the wind profiles are far from equilibrium, it could influence the wake deflection significantly.**
Thank you very much for the constructive concern. The hot wire array of the 13 sensors displaced vertically was installed at the upstream rotor's position, 1 m downstream of the inlet to the test section, before the turbine was installed. This is stated in p.2 ll.9-11 in the manuscript:

   The downstream position of the hot wire array was 1 m *from of the wind tunnel outlet, in agreement with the upstream turbine's rotor, which was installed after characterizing the inflow.*

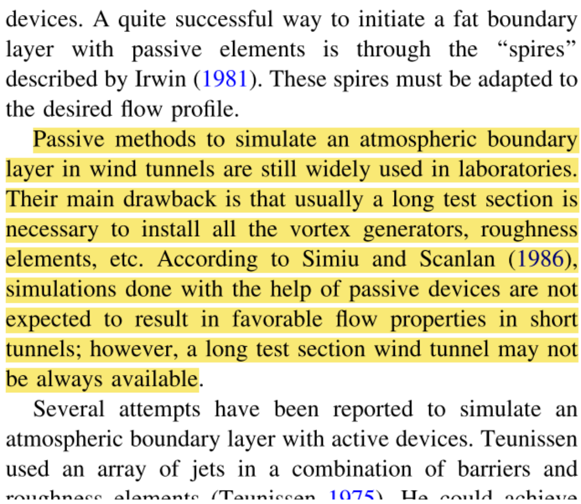
   We suggest to formulate this more clearly in the revised manuscript as done below:

   For both settings of the grid, data were recorded for 120 s *at a sampling frequency of 2* kHz. *The ~~downstream position of the hot wire array was~~ array was installed 1* m *~~from of the wind tunnel outlet, in agreement~~*

~~with~~ downstream of the grid at the position of the upstream turbine's rotor, which was installed after characterizing the inflow.

We believe that stating the inflows are 'not in equilibrium' means that they will evolve further / change when moving downstream in the test section, even without any turbine installed. If that is what is meant, we fully agree with this concern and appreciate the constructive critic.

To create a boundary layer in a wind tunnel for experimental studies, often very long test sections (>10 m) are used to let a boundary layer develop due to inserted surface roughness elements, examples include Chamorro et al. (2009) [1] or Bastankhah and Porté-Agel (2016) [2]. Additionally, the cross sectional area is often adjusted for a zero pressure gradient. The work of Cekli and van de Water (2010) [3] gives a thorough overview and summarizes the problem precisely as quoted in Figure 1 of this document.



devices. A quite successful way to initiate a fat boundary layer with passive elements is through the "spires" described by Irwin (1981). These spires must be adapted to the desired flow profile.

Passive methods to simulate an atmospheric boundary layer in wind tunnels are still widely used in laboratories. Their main drawback is that usually a long test section is necessary to install all the vortex generators, roughness elements, etc. According to Simiu and Scanlan (1986), simulations done with the help of passive devices are not expected to result in favorable flow properties in short tunnels; however, a long test section wind tunnel may not be always available.

Several attempts have been reported to simulate an atmospheric boundary layer with active devices. Teunissen used an array of jets in a combination of barriers and roughness elements (Teunissen 1975). He could achieve

Figure 1. Screenshot taken from [3].

In our experimental setup, we are limited by the extension of the test section. However, the focus is not to create a realistic boundary layer profile, but to create inverse profiles by the usage of an active grid (used passively here). We do agree that in an ideal case both experimental capabilities, a long test section and therewith rather stable boundary layer as well as the possibility to inverse a profile, need to be combined. Achieving this experimentally is rather difficult and beyond our

experimental possibilities, which are limited by the test section length. However, using an active grid passively offers a great flexibility to purposely tune inflow gradients in shorter test sections. This is further described in [3]. It is important to notice that our work does not aim to create two realistic but inverted boundary layer profiles. It focuses on inverting an extreme shear profile, sacrificing certainty about the downstream development of the profiles.
We are aware of those limitations and therefore characterize the inflow profile at the exact same position as the upstream turbine in order to grasp the most appropriate inflow characteristics.
Depending on the downstream development, an influence on the wake deflection is possible. However, we do believe that the influence should be similar in both cases, profile 1 and profile 2. Unfortunately, we cannot prove this by measurement data. In order to minimize the possibility of wind tunnel effects to impair the findings significantly, we believe that it is a strength of the present study that between both tests cases, profile 1 and profile 2, all other aspects were kept the same, isolating the effect of the difference in inflow. Nevertheless, due to experimental limitations, it is hardly possible to fully distinguish the contribution of all parameters of the inflow, including turbulence parameters, all three velocity components, downstream development etc.

2. **What is the turbulence intensity and/or how do the turbulence profiles look like that correspond to profile 1 and 2 from Figure 1?**
The profiles of the turbulence intensities $\mathrm{TI} = \sigma_\mathrm{u}/\overline{\mathrm{u}}$ corresponding to Figure 1 of the manuscript are shown in Figure 2 of this document. As expected, the turbulence intensities increase where the flaps of the grid were not aligned with the main flow direction, e.g. lower velocities correspond to higher turbulence intensities. At the respective opposite side, where the flaps of the grid were in alignment with the main flow direction, the turbulence intensities are rather low, approximately 2-4 %.
Due to the briefness of the manuscript, we suggest to leave Figure 1 of the manuscript as it is and restrain it the mean values of $\mathrm{u}(\mathrm{z}, \mathrm{t})$.

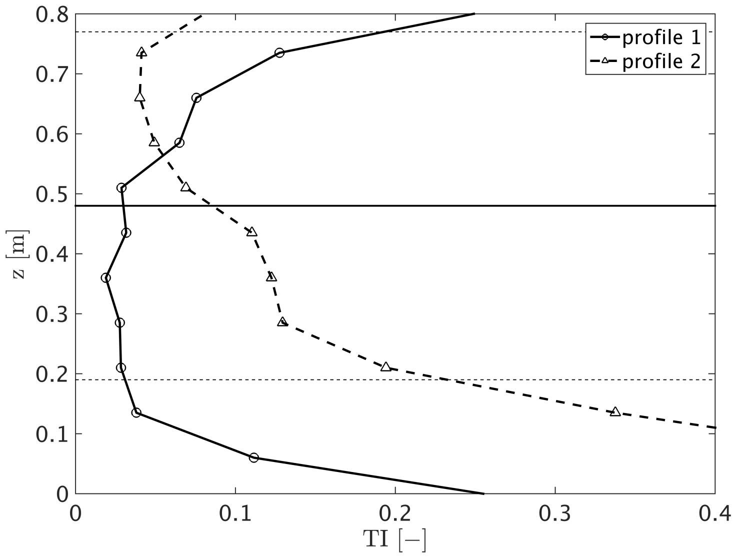
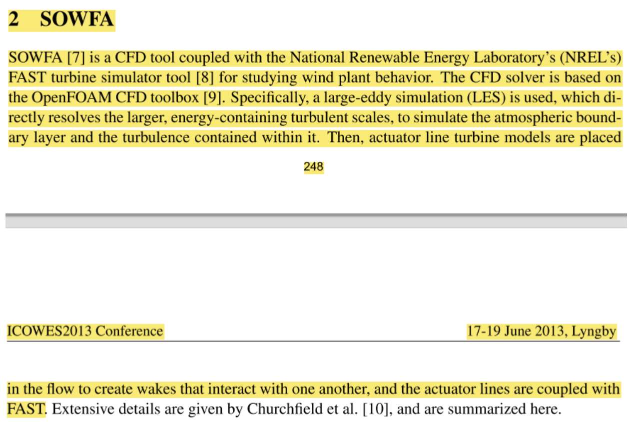


Figure 2. Turbulence intensities TI over height z for the respective mean values shown in Figure 1 of the manuscript.

We want to thank the Reviewer for performing numeric simulations of a comparable scenario. We do agree, that it needs a combination of numeric, experimental (and field studies) to fully understand complex phenomena such as wake effects of/on wind turbines. In previous works by Gebraad et al. [4] and Fleming at al. [5], SOWFA[1] simulations were performed using a very similar setup of two aligned wind turbines, examining the power during a yaw misalignment of the upstream turbine. Here, large eddy simulations (LES) are linked to the aeroelastic tool FAST [8]. The SOFWA tool has been validated for example for an offshore wind farm by Chruchfield et al. (2012) [9]. Further studies include [10].
As in the simulations performed by the Referee, two NREL 5MW reference turbines were used, the distance separating both turbines was 7 rotor diameters, being notably larger than in the manuscript. At an inflow of $\mathrm{u} = 8\,\mathrm{m\,s^{-1}}$, the vertical wind shear was $1.46\,\mathrm{m\,s^{-1}}$ across the rotor, corresponding to a natural boundary layer. For further details about the simulations, please refer to Fleming et al. (2014) [5]. For more details on SOFWA, see Figure 3 of this document.

Amongst others, the powers of both turbines were examined by Gebraad

[1]Simulator for Off/Onshore Wind Farm Applications, for further details, please see [6] or [7].


2 SOWFA

SOWFA [7] is a CFD tool coupled with the National Renewable Energy Laboratory's (NREL's) FAST turbine simulator tool [8] for studying wind plant behavior. The CFD solver is based on the OpenFOAM CFD toolbox [9]. Specifically, a large-eddy simulation (LES) is used, which directly resolves the larger, energy-containing turbulent scales, to simulate the atmospheric boundary layer and the turbulence contained within it. Then, actuator line turbine models are placed

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in the flow to create wakes that interact with one another, and the actuator lines are coupled with FAST. Extensive details are given by Churchfield et al. [10], and are summarized here.

Figure 3. Screenshot taken from [11].

et al. in [4] for different angles of yaw misalignment of the upstream turbine, γ_1. Figure 4 of this document shows the results, taken from [4]. The

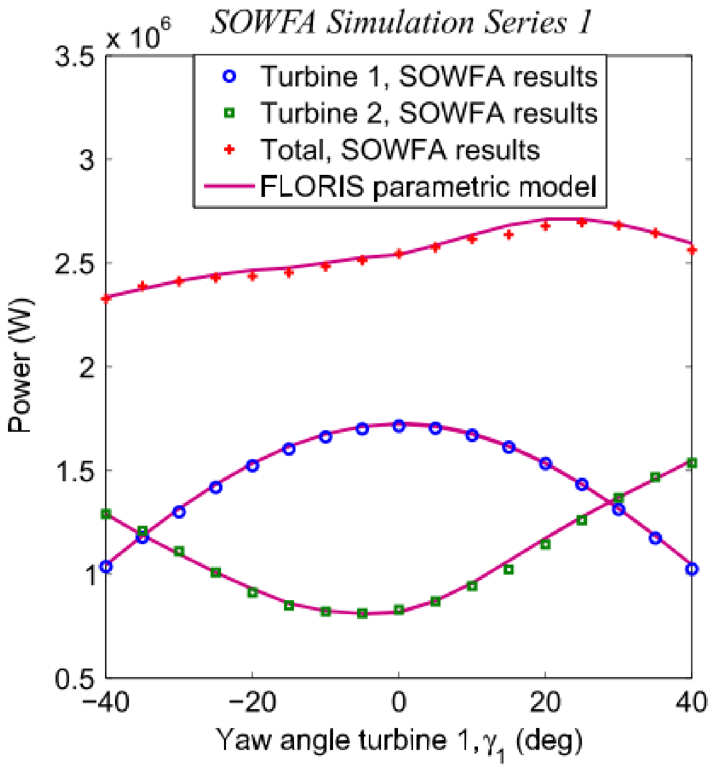

Figure 4. Screenshot taken from [4], Fig. 2, showing the power of an upstream turbine (blue), a downstream turbine (green, distance: 7D) and the total power of both (red) over the yaw angle of the upstream turbine.

power of the upstream turbine shows nearly symmetric variations with γ_1. The power of the downstream turbine, P_2 and the sum of both, P_{tot}, show distinct asymmetries. The minimum of P_2 is clearly shifted towards negative angles, resulting in an asymmetric total power. P_{tot} is maximal at $\gamma_1 = 25°$, resulting in a power gain ($\approx$ 6%) as compared to $\gamma_1 = 0°$. Further, the opposite direction of yaw misalignment $\gamma_1 = -25°$ shows a power decrease compared to $\gamma_1 = 0°$.
Those principle shapes are in agreement with our experimental results presented in the manuscript as well as the results shown in [12]. To further show, Figure 5 of this document shows the normalized data taken from Gebraad et al. (2014) [4] and our experimental results for better comparison. The numerical data were received from P. Gebraad as a result of personal communications on this matter. It should be noted that the vertical wind

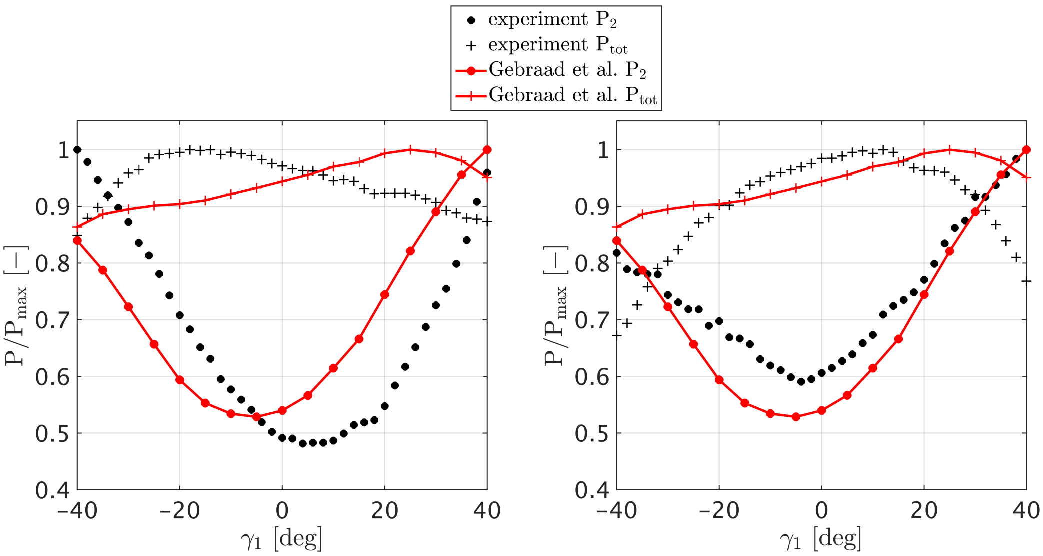

Figure 5. Comparison of the experimental results (left: profile 1, right: profile 2) and numerical results based on the data of [4]. All graphs are normalized to their maximum value.

shears are of *opposite* direction in the left plot of Figure 5 and of the *same* direction in the right.
Comparing our experimental results to the simulations of the Referee and the simulations from literature shown in Figures 4 and 5 reveal multiple aspects listed below:

- The simulations performed by Gebraad et al. show distinct asymmetries, although both turbines were (in the simulation environment)

aligned with the main flow direction *without* lateral offset. As shown by the reviewer, a lateral offsets could possibly cause asymmetries. However, this should not mean in turn that the asymmetries indicate a lateral offset of the turbines. This is shown by the simulation results in Figure 4. of this document.
The setup is sensitive to boundary conditions, but the turbines were aligned to our best possibilities.

- Comparing the simulations performed by the referee and the results shown in Figure 4, differences become apparent regarding the asymmetry of $P_2(\gamma_1)$ and $P_{tot}(\gamma_1)$. Although the same NREL 5 MW reference turbines were used, disparities seem to arise from other simulation set-ups, i.e. a different level of detail by using actuator line or actuator disc, boundary conditions of the setup, and/or turbine spacing. We believe those disparities show the need for further validation studies, either code-to-code validation or experimental work as done in our manuscript.

- Comparing simulations and experiment shown in Figure 5 of this document show similar trends. Looking at the left plot, both vertical wind shears are of *opposite* direction resulting in a very similar asymmetric shape but of reversed sign. On the right plot, both inflow shears were of the *same* direction, resulting in asymmetries where the minimum of P_2 is shifted to negative yaw angles and the total power P_{tot} to positive yaw angles. Although full scale 5 MW turbines were simulated, having a larger spacing of 7D, the general shapes agree with the laboratory experiment using model turbines of much smaller scale and different spacing.

Minor comments:

1. **A few references include duplicated links.**
   This will be corrected in the updated manuscript.

2. **Page 1, lines 12-14: I am not able to find a discussion on asymmetries of wake deflection in Gebraad et al. (2016)**
   We appreciate pointing out this mistake, what was meant is the study of Gebraad et al. (2014) [4], not (2016). However, we want to be more precise in the updated manuscript. Vollmer et al. [13] investigated

wake deflections, while Gebraad et al. investigated the *power*, not the velocities, which was formulated somewhat unclear in the manuscript. We updated the manuscript accordingly as shown below. Please note that some other changes resulted from the comments of Reviewer#1.

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 [14], in wind tunnel experiments [15, 16] and in numerical simulations ~~[4, 13]~~ [17, 4, 13] . Further, [4] and [18] applied the concept to wind farm control strategies using large-eddy simulation (LES) methods, showing a potential power increase in wind farm applications.
[13] ~~and [4]~~ report on an asymmetric deflection of a turbine's wake with respect to its direction of yaw misalignment ~~. [5] and [?] 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 [12] 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, [2] 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.
[13] 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 $+30°$ *and* $-30°$ *were significantly different considering different atmospheric stratifications and therewith different ~~vertical velocity gradients~~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 turbine array, [5] and [4] 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 [12] 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~~ wind shear has a direct effect on the wake's asymmetry during yaw misalignment using two model wind turbines in a wind tunnel study.

3. **I would call vertical velocity gradient simply wind shear.**
   Thank you for suggesting this simpler formulation. In order to be precise about the direction of shear, we suggest to reformulate this to *vertical wind shear* in the updated version of the manuscript.

4. **How is your yaw angle defined?**
   Thank you very much for this hint. Some information about the setup were left out as the study [12] uses the same setup apart from the inflow variations. However, we absolutely agree that this should be mentioned in the manuscript besides the reference to [12]. We suggest to update the manuscript as done below. It should be noted that other changes in this paragraph result from the comments of the first referee.

   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 $D = 0.58\,\mathrm{m}$ 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) [12].

5. **Page 2, lines 14-16: I would add over the rotor area to be more precise: Using two inflows which feature a vertical velocity gradient in opposite direction over the rotor area allows an investigation of ....**

   We do agree that this formulation would add clarity. This will be done in the updated version of the manuscript as shown below:

   P.2, ll. 14-16:
   Using two inflows which feature a vertical velocity gradient in opposite direction over the rotor area allows 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.

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Brief Communication: On the influence of vertical velocity profiles 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 velocity gradients 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 velocity gradient 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. Gebraad et al., 2014; Vollmer et al., 2016) (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) and Gebraad et al. (2014) report on an asymmetric deflection of a turbine's wake with respect to its direction of yaw misalignment . Fleming et al. (2014) and ? 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 Schottler et al. (2016a) 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, 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 showed show that different stratifications indeed resulted 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 vertical velocity gradients 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. (2016a) 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~~ wind shear has a direct effect on the ~~wake~~power's asymmetry ~~during yaw misalignment using~~ of two model wind turbines ~~in a wind tunnel study.~~ 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. (2016b)~~ Schottler et al. (2016a) were used in streamwise displacement. The turbines ~~where~~ 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 ~~a~~ for yaw misalignment, ~~while the~~ 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. (2016a)~~ Schottler et al. (2016a) . In order to isolate the effect of a vertical ~~velocity gradient~~ 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 $120\,\mathrm{s}$ at a sampling frequency of $2\,\mathrm{kHz}$. The ~~downstream position of the hot wire array was~~ array was installed 1 m ~~from of the wind tunnel outlet, in agreement with the~~ 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 shown in Fig. 1 as *profile 1* and *profile 2*. Using two inflows which feature a vertical ~~velocity gradient in opposite direction allows~~ 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.

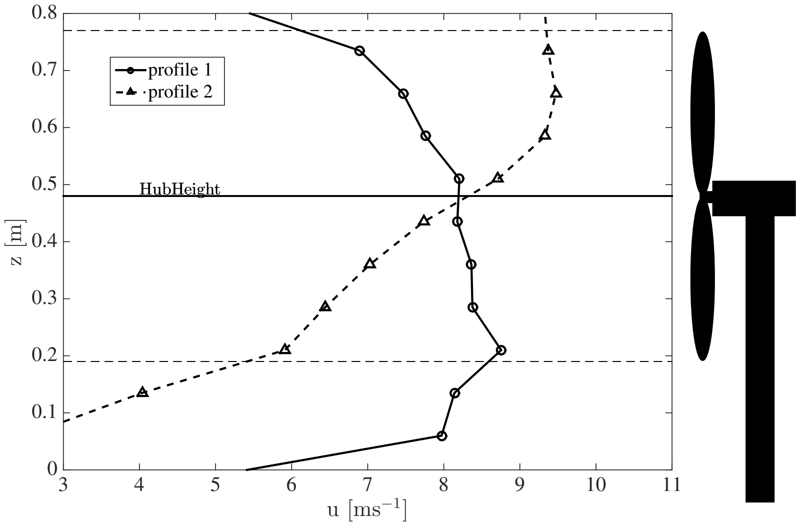

Figure 1. Mean velocity values of the vertical wind speed profiles ~~profiles~~ 1 and 2 that were used as inflow conditions. The dashed, vertical lines mark the heights of the rotor tips of the turbine that was installed after characterizing the inflow profiles.

3 Results

Mean values of the combined power P_{tot} and the power of the downstream turbine P_2 are shown ~~for every examined~~ as a function of the yaw angle γ_1 in Fig. 2. ~~For each curve, data~~ Data points are normalized to the respective maximum of P_{tot}. Looking at Fig. 2(a), asymmetries of ~~both curves~~ P_2 and P_{tot} with respect to γ_1 become obvious. The minimum of the

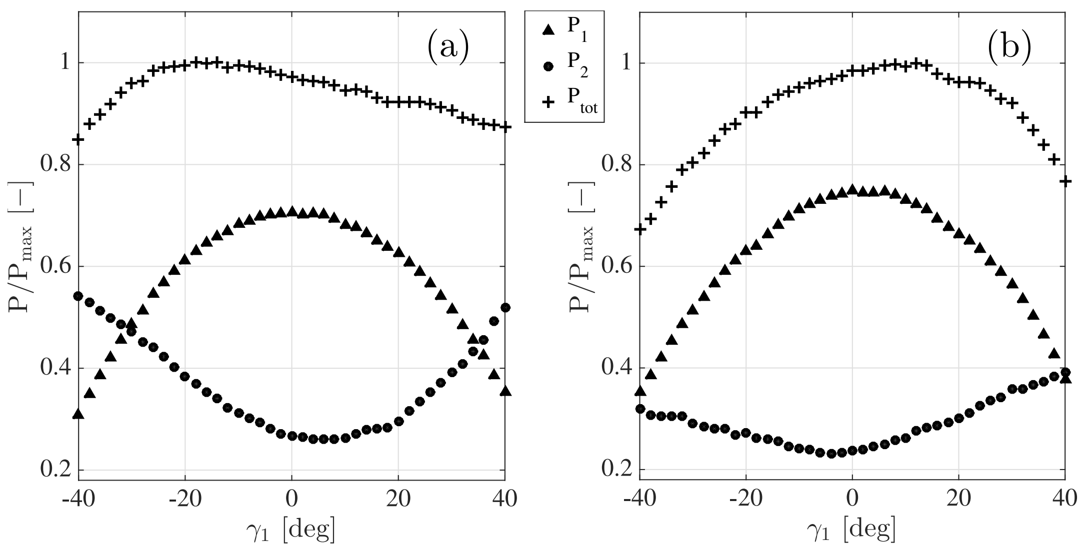

Figure 2. Mean values of P_2 and P_{tot} for each examined value of γ_1 during the both inflow condition profile 1 (a) and profile 2 (b).

downstream turbine's power P_2 is shifted towards positive angles. The maximum of the combined power P_{tot} is maximal at $\gamma_1 \approx -18°$, being approx. 4 % larger compared to the case with perfect yaw alignment 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 is are in good agreement with numeric simulations of full size turbines reported by Gebraad et al. (2014) and Fleming et al. (2014).

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. (2016a) Schottler et al. (2016a) , the effect of the changed inflow is isolated. As can be seen, asymmetric shapes of both graphs P_2 and P_{tot} are still observed. More importantly, the direction of the asymmetry changed with the direction of the inflow's vertical velocity gradientshear. Now, in Fig. 2(b), the minimum of P_2 is located at negative yaw angles, $\gamma_1 \approx -4°$. Also for the total power output, the sign of the maximum's location Moreover, the yaw angle direction at which the combined power is maximum changed, being positive ($\gamma_1 \approx 12°$) during for inflow profile 2. Our results suggest, show that the reason for the asymmetric shapes of the graphs in Fig. 2 is related to the inflowvelocity gradient's vertical wind shear, which is further discussed in Sec. 4.

4 Discussion and conclusion

In this study, we investigate the influence of vertical velocity gradients 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., 2016a) (Schottler et al., 2016a) as well as in full scale numeric simulations (Fleming et al., 2016; Vollmer et al., 2016) (Gebraad et al., 2014; Fleming et al., 2014) . Only one direction of yaw misalignment resulted in a power increase, whereas the causes were not fully 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 further investigate the reasons for the asymmetric wake deflection power output of a two turbine array and isolate the effect of a vertical inflow gradient's orientationon the power output of a two turbine array. A strong linkage between the asymmetry and the velocity gradient's orientation was found. For a potential application of active wake control by intentional yawing, the effect itself needs to be understood. If the reported asymmetry depends on boundary conditions of the surroundings, which our results suggest, than then this drastically impacts the applicability to real world wind farm control scenarios. In this study, the downstream turbineis used and conclusions about the wake deflection of the upstream turbine is based on power measurements's power is used as indicator. The interesting results regarding the asymmetry and its linkage to the inflow conditions motivate further examinationsin , 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. (2016a) Schottler et al. (2016a) with simulations of a full scale case (Fleming et al., 2014; Gebraad et al., 2014) (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.

Acknowledgements. Parts of this work was 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.

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