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.*

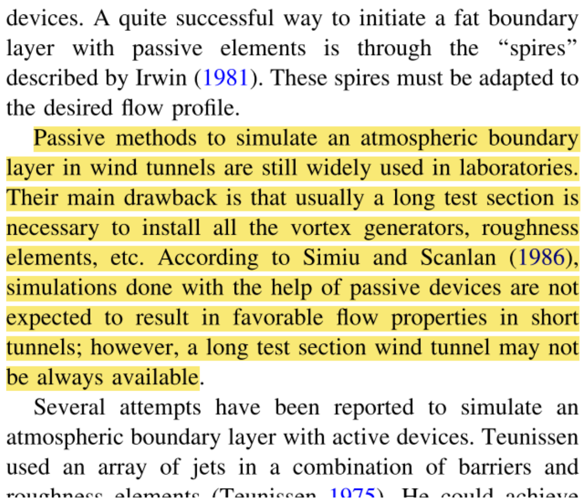
   We suggest to formulate this more clearly in the revised manuscript as done below:

   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

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 $\mathrm{u}(\mathrm{z}, \mathrm{t})$.

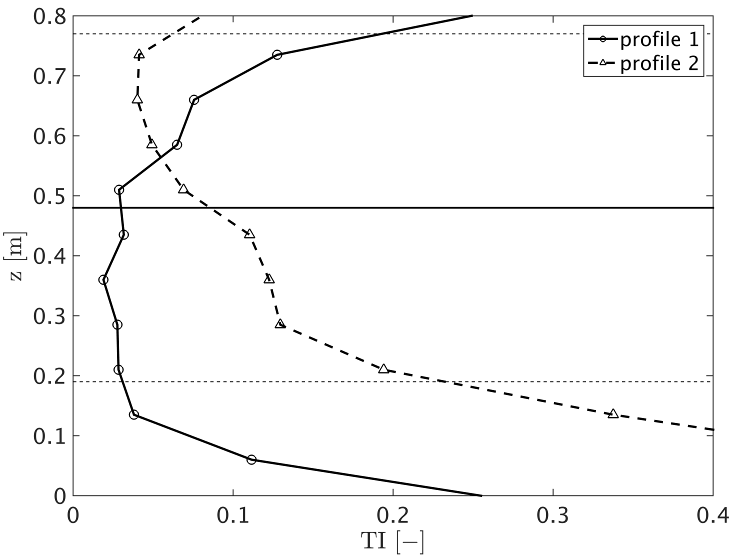
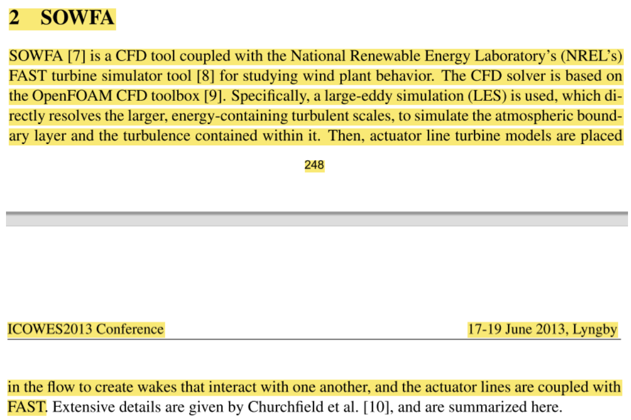


Figure 2. Turbulence intensities TI over height z for the respective mean values shown in Figure 1 of the manuscript.

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

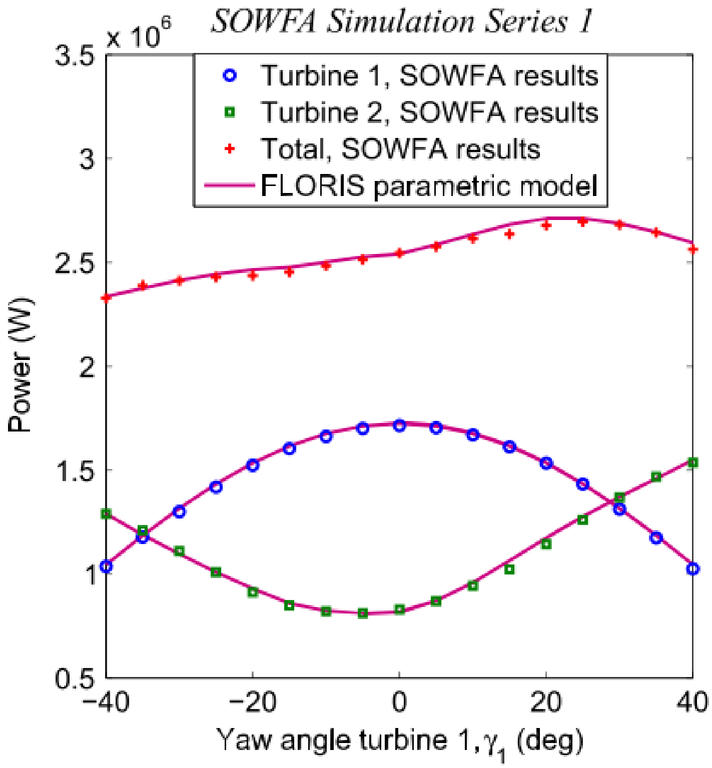

Figure 4. Screenshot taken from [4], Fig. 2, showing the power of an upstream turbine (blue), a downstream turbine (green, distance: 7D) and the total power of both (red) over the yaw angle of the upstream turbine.

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

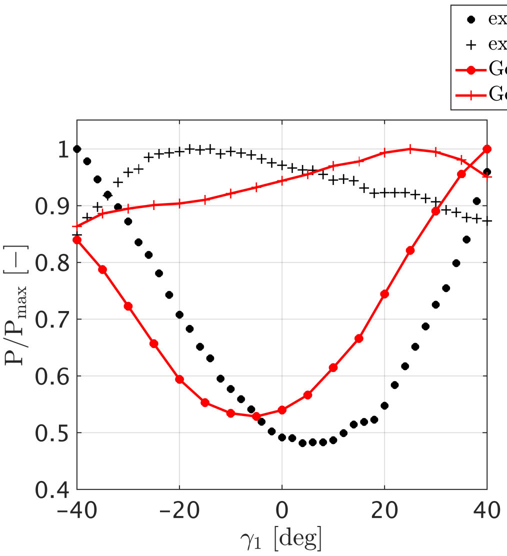

Figure 5. Comparison of the experimental results (left: profile 1, right: profile 2) and numerical results based on the data of [4]. All graphs are normalized to their maximum value.

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, [18] and [19] 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 [18] 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 [18] 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 [20] 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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