# Authors' response to Referee #2:

We would like to thank the referee for reviewing this manuscript, the constructive feedback and the valuable comments. At this stage, we respond to referee #2's comments and suggest changes for the final manuscript. The referee's original comments are printed in **bold** followed by the corresponding answers. Passages from the manuscript are printed in *italic writing*, in which proposed additions are indicated in blue and deleted parts in ~~red~~.
Thank you very much for your efforts,

Jan Bartl on behalf of all authors

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## Major comment (1)

**Figure 8(c): I found it very surprising that, for large lateral offset values such as 0.16 and 0.33 (normalized with the rotor diameter), the yaw moment of the downwind turbine is higher when the first turbine is yawed. On the contrary, I expect to see a lower moment in this case as the wake deflection essentially alleviates partial wake conditions.**

This is a good comment and may indeed seem surprising in the first place. In order to judge the exact inflow conditions to the downstream turbine, we need to take a closer look into the wake flow of the upstream turbine at $x/D = 3$ (plots taken from Bartl et al., 2018).
The red and pink circles in Figure 1 (a) and (b) indicate the locations of an imaginary downstream turbine operated at a lateral offset of $z/D = +0.16$ and $z/D = +0.33$, respectively. In Figure 1 (a) it can be observed a downstream turbine is still exposed to an almost full wake impingement for an offset of $x/D = +0.16$ and $\gamma_{T1} = 0°$, and therefore experiences a rather small yaw moment if $M_y^* \approx 0.012$ (Figure 8(c) of the manuscript) in this situation. At $x/D = 3$, they wake has slightly expanded to an area, which is wider than the rotor swept area. Even for a lateral offset of $z/D = +0.33$, the major part of the downstream turbine's rotor swept area (pink circle, Figure 1 (a)) is impinged by the low velocity field of the wake, while only about the outer 3rd of the blade tips pass the high velocity freestream flow outside the wake.
For an upstream turbine yaw angle of $\gamma_{T1} = 30°$, as shown in Figure 1 (b), the wake flow is significantly deflected. However, at this rather small downstream distance, the wake is not entirely deflected away from a downstream turbine. For both lateral offset positions $z/D = +0.16$ and $z/D = +0.33$ of the downstream turbine, roughly half of the rotor swept area is impinged by the low velocity wake, while the other halve is impinged by high velocity freestream flow. Consequently, very high yaw moments of $M_y^* \approx 0.042$ are measured for both situations (Figure 8(c) of the manuscript). At an even higher lateral offset of $z/D = +0.50$, the yaw moments are observed to decrease. But still, the wake cannot be entirely deflected away for this large offset $z/D$ and small separation distance $z/D$.

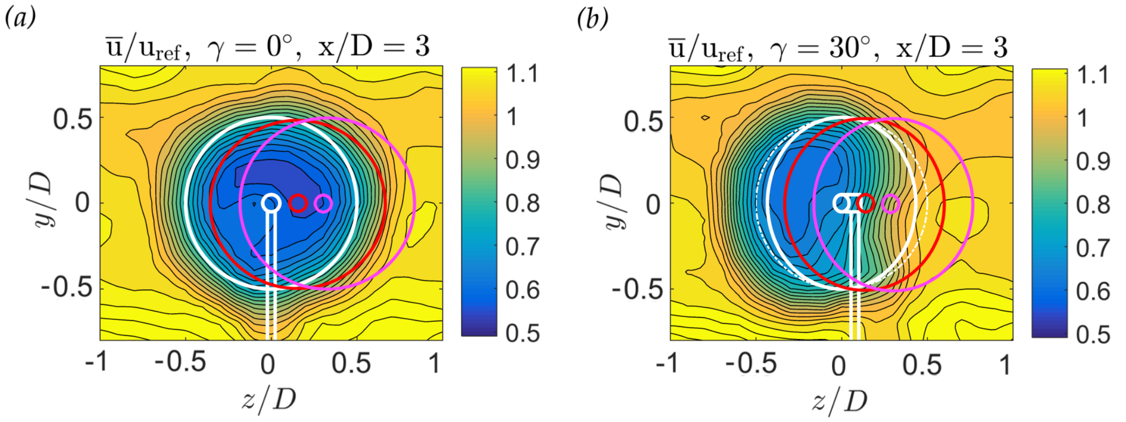


Figure 1: Mean streamwise velocity $\overline{u}/u_{ref}$ in a cross-sectional cut at $x/D = 3$ through the wake flow behind a single turbine for **(a)** $\gamma_{T1} = 0°$ and **(b)** $\gamma_{T1} = 30°$. The red and pink circles indicate the locations of an imaginary downstream turbine operated at a lateral offset of $z/D = +0.16$ and $z/D = +0.33$, respectively. The plots are adapted from Bartl et al. (2018) and were measured behind the same model turbine under the same boundary conditions.

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## Minor comment (1)

**It would be useful to mention that the yaw moment can only be an indicator of unsteady loads due to inflow shear or yaw misalignment. The effect of large turbulent structures (especially those in atmospheric boundary-layer flows) on turbine loads cannot be shown by the sole consideration of yaw moment.**

This is indeed something that should be discussed in more depth. As already mentioned by reviewer #1, the connection between yaw moments and unsteady blade loads should be commented on in the introduction. We therefore suggest the following addition to the introduction in the manuscript:

p.3, l.19 f:

*For this purpose the parameters turbine separation distance $x/D$, lateral turbine offset $z/D$ and turbine yaw settings $\gamma_{T1}$ and $\gamma_{T2}$ are systematically varied in this wind tunnel experiment. Aside from power output and rotor thrust, the yaw moments acting on the individual rotors are measured. Yaw moments are a representation of the imbalance of the forces acting on a rotor blade during the course of one rotation. High values of yaw moments thus indicate increased unsteady blade loading at a frequency corresponding the rotational speed. Special focus is given to the concept of downstream turbine yawing (...).*

## Minor comment (2)

**I agree with the other reviewer that the discussion part is relatively redundant, and it does not add new contribution to the paper.**

As mentioned in the answer to reviewer #1 already, we agree that the discussion mainly repeats previously presented results and only sparsely provides new information. We therefore will completely omit the Discussion section in the final version of the manuscript. References to external sources will be moved from the Discussion to the Results section. This concerns the following sections:

p.7, l.3 f:
*These asymmetries are slightly stronger for inflow A ($TI_A$ = 0.23%). Although it is not entirely clear where these stem from, the only reasonable source for an asymmetric load distribution in an uniform inflow is the rotor's interaction with the turbine tower. In the course of a revolution, the blades of a yawed turbine experience unsteady flow conditions, i.e. fluctuations in angle of attack and relative velocity. When superimposing an additional low-velocity zone, tower shadow or shear for example, the yaw-symmetry is disturbed. Asymmetric load distributions for turbines exposed to sheared inflow were recently reported by Damiani et al. (2017). They showed that vertical wind shear causes asymmetric distributions of angle of attack and relative flow velocity in the course of a blade revolution. They link these to rotor loads and conclude further consequences on wake characteristics and wind farm control strategies.*

p.10, l.14 f:
*Relative power gains of about 11% were measured at Inflow A, while only 8% were obtained for Inflow B at the same yaw angle of $\gamma_{T1} = -30°$. Asymmetries in the combined power output have been previously observed in a computational study Gebraad et al. (2016) and a similar experimental setup by Schottler et al. (2015). In a recent follow-up study, Schottler et al. (2017) attributed the asymmetry to a strong shear in the inflow to the two-turbine setup. As the inflow in the present study was measured to be spatially uniform, inflow shear is not a reason for the observed asymmetries.*

p.14, l.3 ff:
*In conclusion, is has been demonstrated that intentional upstream turbine yaw control is favorable in offset situations when considering both, the power output and yaw moments on a downstream turbine. Depending on the downstream turbine's streamwise and lateral position, the wake can be partly or even fully deflected away from its rotor swept area. This finding experimentally confirms results of a similar test case recently computed with a model-framework by van Dijk et al. (2017).*

p.14, l.18 f:
*Simultaneously, the yaw moment is measured to be around zero at this yaw angle. The potential of load reductions of a single turbine by yawing has been previously discussed by Kragh and Hansen (2014), in situations where the rotor was exposed to vertically sheared inflows. In the present test case, however, the partial wake impingement on the rotor represents a situation of a strongly horizontally sheared flow. Whether the shear in the incoming wind field is horizontal or vertical obviously makes a big difference, but mitigation of loads and maximization of power might be possible with yaw adjustments in both cases.*

p.14, l.20 f:

*The simultaneous power increase for the oppositely yawed downstream rotor is a positive side effect, although the exact reasons for the power increase are not entirely clear at this stage. A power increase by downstream turbine yawing has previously been reported in a full-scale data evaluation by McKay et al. (2013), who found an offset in the downstream turbine's yaw alignment for the purpose of optimized power output when operated in a partial wake of an upstream turbine. The downstream turbine yaw angle was observed to adjust itself opposed to the velocity gradient in the partial wake impinging the downstream rotor. These findings are in total agreement with the optimal downstream turbine yaw angle measured in our wind tunnel experiment.*

## Minor comment (3)

**Please compare your wind tunnel blockage ratio with commonly acceptable values in the literature.**

This is a very good comment, which points to one of the weaknesses of the presented study. Commonly, a solid body should block less than 10% of the wind tunnel's cross sectional area. However, the blockage of a wind turbine rotor is dependent on the tip speed ratio. Dedicated studies investigating the influence of blockage on the performance of a wind turbine have been proposed by Sørensen et al. (2006) and Ryi et al. (2015). The proposed models are able to correct the power output of a single turbine. For an array of two aligned (and especially offset) turbines, no models have been developed yet to our knowledge. Recently, a dedicated computational study on the influence of the blockage ratio on the wake development for different inflow conditions was presented by Sarlak et al. (2016). In this study, a significant influence on the wake expansion was observed for a blockage ratio of 20%. In the present study, we intentionally do not use any blockage correction models, as we do not want to add another dimension of modeling uncertainty to our results. We are aware that our results do not represent a realistic, unblocked, full-scale wind turbine test case. They rather represent a model test case in defined boundary conditions, which can be used as a reference case for computational studies. In order elaborate more on this, we suggest to add the following lines to the manuscript:

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

## Minor comment (4)

**Page 6, Lines 28 and 29: Please compare your results with those reported in the literature (e.g., Ozbay et al. 2012 and Bastankhah and Porté-Agel 2017).**

Thank you for this valuable comment. This is indeed still a widely discussed topic in research, and should be discussed in more detail. Four more external sources are referred to for comparison:

p.6, l.28 f:

*As discussed by Bartl et al. (2018), the decrease in power coefficient can be approximated $C_{P,\gamma_{T1}=0} \cdot cos^3(\gamma_{T1})$ when the turbine yaw angle is varied. The thrust coefficient's reduction through yawing is observed to match well with $C_{T,\gamma_{T1}=0} \cdot cos^2(\gamma_{T1})$. Despite the commonly assumed exponent of $\alpha = 3$ for the power coefficient $C_P(\gamma) = C_{P,\gamma=0} \cdot cos^\alpha$, Micallef and Sant (2016) refer to different values of $\alpha$ between 1.8 and 5 measured in different full-scale tests. The measured relations of our study, however, correspond well with previous measurements on the same rotor by Krogstad and Adaramola (2012) and another experimental study on a smaller rotor by Ozbay et al. (2012). Another recent experimental study on a very small rotor by Bastankhah and Porté-Agel (2017) confirmed the $\alpha = 3$ for the power coefficient, but found an slighly smaller exponent of $\beta = 1.5$ for the thrust coefficient.*

## Minor comment (5)

**Page 4, Line 17: Please add space between ": : : still detectable." and "At".**

Thank you for the hint. The typing mistake is fixed for the final version of the manuscript.

p.4, l.16 ff:

*A velocity variation of $\pm 2.5\%$ is measured at $x/D = 0$ for Inflow B, as the footprint of the grid's single bars are still detectable. At $x/D = 3$, however, the grid-generated turbulent flow is seen to be uniform...*

## Minor comment (6)

**Page 5, Line 15: It should be written as ": : : and 0.007 (0.9% of the absolute CT value), respectively".**

Thank you for pointing at this. This will be fixed in the final version of the manuscript.

p.5, l.14 f:

*The total uncertainties in power and thrust coefficient are 0.006 (2.5% of the absolute $C_P$-value) ~~respectively~~ 0.007 (0.9% of the absolute $C_T$-value), respectively.*

## Minor comment (7)

**Figure 3: I recommend using colors with more contrast.**

Thank you for this legitimate comment. We agree that the different shades of green and blue are not well distinguishable in the plot. However, the use of different symbols should make it possible to identify the curves corresponding to the different yaw angles.

## Minor comment (8)

**Page 9, Line 9: Can it be shown using velocity measurements?**

This is a good comment, which has been pointed to by reviewer #1 as well. We suggest to add a some text explaining the effects of the wall blockage on the freestream velocity outside of the wake in more detail. Wake flow measurements showing this effect are presented in a previous publication on Wind Energy Science (companion paper) by Bartl et al. (2018).

p.9, l.7 ff:
*These high downstream power coefficients $C_{P,T2}$ can be explained by increased velocity levels of $u/u_{ref} = 1.10$ in the freestream outside of the wake as a result of wind tunnel blockage (Bartl et al., 2018). The downstream turbine power coefficient is, however, still referred to the undisturbed far upstream reference velocity $u_{ref}$. Although a considerable part of the downstream turbine rotor is impinged by T1's wake, ~~blockage-increase freestream velocity levels of $u/u_{ref} = 1.10$~~ higher wind speeds outside of the wake lift the downstream turbine's power to these levels.*

## Minor comment (9)

**Additional references:**
**Ozbay, A., Tian, W., Yang, Z. and Hu, H., 2012. Interference of wind turbines with different yaw angles of the upstream wind turbine. In 42nd AIAA Fluid Dynamics Conference and Exhibit (p. 2719).**
**Bastankhah, M. and Porté-Agel, F., 2017. Wind tunnel study of the wind turbine interaction with a boundary-layer flow: Upwind region, turbine performance, and wake region. Physics of Fluids, 29(6), p.065105.**

Thank you for alluding these two valuable references. They have been included to the manuscript in the discussion of the dependency of the power and thrust coeffient on the yaw angle (see Minor comment (4)).

# References

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

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

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

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

[5] Micallef, D. and Sant, T.: A Review of Wind Turbine Yaw Aerodynamics, Chapter 2 in Wind Turbines - Design, Control and Applications, InTech, doi: 10.5772/63445, 2016.

[6] Krogstad, P.-AA. and Adaramola, M. S.: Performance and near wake measurements of a model horizontal axis wind turbine, Wind Energy, 15, 743–756, doi:10.1002/we.502, 2012.

[7] Ozbay, A., Tian, W., Yang, Z. and Hu, H.: Interference of wind turbines with different yaw angles of the upstream wind turbine, AIAA Fluid Dynamics Conference and Exhibit, AIAA 2012-2719, 2012.

[8] Bastankhah, M. and Porté-Agel, F.: Wind tunnel study of the wind turbine interaction with a boundary-layer flow: Upwind region, turbine performance, and wake region. Physics of Fluids, 29, 65105, 2017.