Authors' response to Referee #1:

We would like to thank the referee for reviewing this manuscript, the valuable feedback and the very constructive comments. At this stage of the review process, we respond to the referee #1's comments and propose improvements 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

Main comment (1)

In this paper, the yaw-moment is measured as a main component for unsteady turbine loading. It would help motivate the research if the authors explain in the introduction why the yaw-moment is an important quantity.

Thank you for this very good comment. Indeed, the connection of the yaw-moment acting on a rotor to unsteady loading is not sufficiently explained in the text. 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 γ_{T1} and γ_{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 of the corresponding the rotational speed. Special focus is given to the concept of downstream turbine yawing (...).

Main comment (2)

Figures 2,6 and 10 are confusing because they show a measured velocity plane, but the text mentions that these results should only be considered as an illustration, and are not accurate. What is the reason for this? It should be mentioned that these measurements were performed with only turbine 1. It seems indeed useful to illustrate the expected wake impact for certain turbine placements. However, it is very confusing to show measurements that are not accurate. Furthermore, if these measurements are not reliable, they cannot be used in the text to explain certain observations, see P12L1. Therefore I suggest to either provide accurate wake measurements, for instance based on the previous publication, or to draw an illustration/sketch of the expected wake and turbine placement.

We agree with the reviewer, that the presented velocity planes in Figures 2, 6 and 10

of the manuscript might be confusing in this context. The shown velocity planes are considered to be accurate, but were measured behind a smaller version of the original rotor ($D_{small} = 0.45m$ vs. $D_{orig.} = 0.90m$). In the previous publication (Bartl et al., 2018) the wake deflections behind these two rotors were assessed to be very similar. Thus, the portion of the wake impacting the downstream turbine as shown in the Figures is deemed to be representative for the real situation.
As we do not intent to repeat wake measurements of the previous publication, we suggest to use sketches of the expected wake and turbine placement in the final version of the manuscript as shown below. The following text passages will be modified accordingly:

p.7, l.7:
The sketched wake flow contours in the xz-plane at hub height are ~~Laser Doppler Anemometry (LDA) measurements of an example case and are only~~ included for illustrative purposes. The location of the wake flow as sketched in gray is roughly estimated from previously performed measurements as presented in Bartl et al. (2018).

p.11, l.9 and p.12. l.1:
The reason for this is deemed to be a not perfectly axis-symmetric velocity deficit at $x/D = 3$ as indicated in ~~Figure 6 (a) and~~ Bartl et al. (2018).

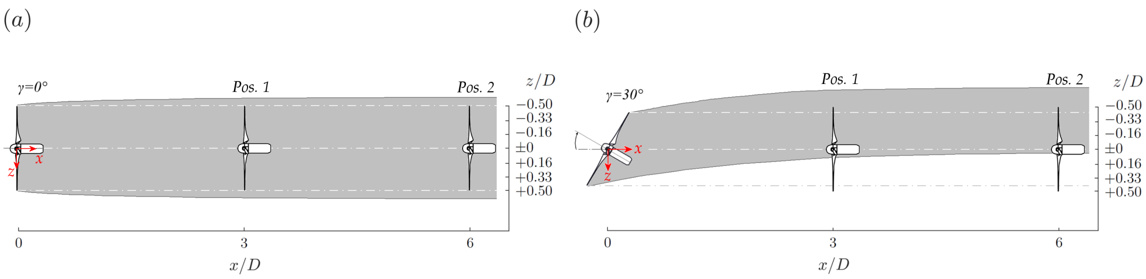

Figure 1: **Figure 2.** Topview of the aligned downstream turbine operated in the wake of an upstream turbine at the two different positions $x/D = 3$ and $x/D = 6$. The wake flow is indicated ~~by measured example cases~~ for **(a)** $\gamma_{T1} = 0°$ and **(b)** $\gamma_{T1} = 30°$.

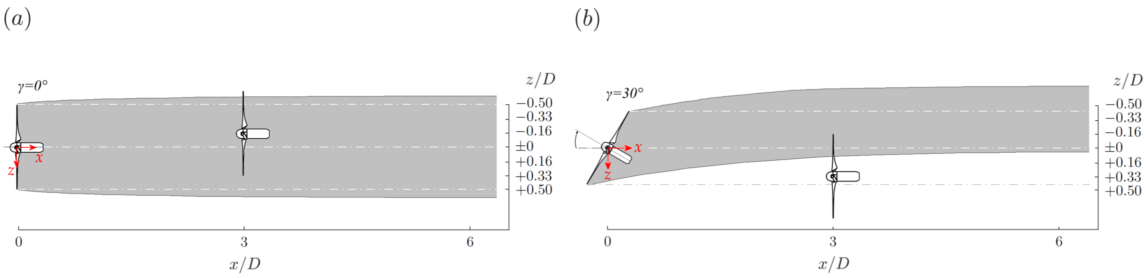

Figure 2: **Figure 6.** Topview of two lateral offset positions (**(a)** $z/D = -0.16$ and **(b)** $z/D = +0.33$) of the downstream turbine while operated in the wake of an upstream turbine at $x/D = 3$. The upstream turbine is operated at **(a)** $\gamma_{T1} = 0°$ and **(b)** $\gamma_{T1} = 30°$.

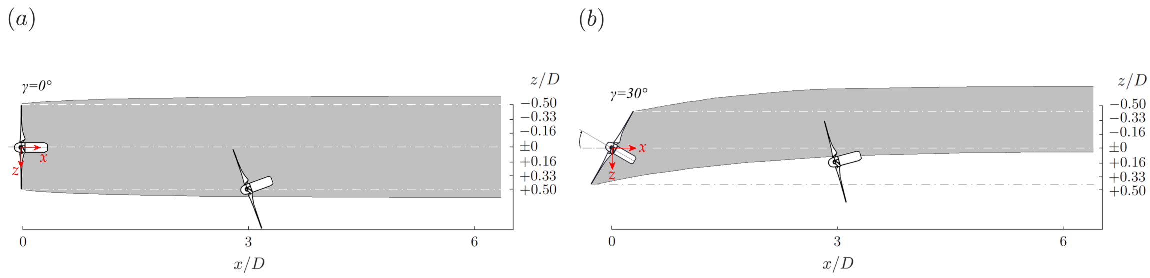

Figure 3: **Figure 10. (a)** Topview of the downstream turbine T2 operated at a lateral offset position $z/D = +0.50$ and a yaw angle of $\gamma_{T2} = -20°$ in the wake of an upstream turbine T1 operated at $\gamma_{T1} = 0°$. **(b)** Topview of the downstream turbine T2 operated at a lateral offset position ($z/D = +0.16$) and a yaw angle of $\gamma_{T2} = -15°$ in the wake of an upstream turbine T1 operated at $\gamma_{T1} = 30°$.

Main comment (3)

The Discussion section is too much of a repetition, and does not provide many new analyses. For example, P17L15-P18L21, do not provide any new information or observations. Therefore, the discussions seems unnecessary and more like a long conclusion. The reviewer suggests to move the few extra thoughts and references in the discussion to the corresponding parts in the main text.

Thank you for this constructive comment. We agree that the discussion mainly repeats previously presented results and only sparsely provides new information. We therefore follow the reviewers suggestion to completely omit the Discussion section and move the comparisons with external sources to the results section. These references are moved to the following sections in the text:

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.

Main comment (4)

The reviewer appreciates that the control of the turbines is described clearly. The downstream turbine is controlled to its optimal performance tip-speed-ratio, for each situations. However, the upstream turbine is controlled by keeping the tip-speed-ratio constant, even when yawed. When a turbine is yawed, it seems that the incoming velocity projected perpendicular to the rotor, decreases with the cosine of the yaw angle. By keeping the tip-speed-ratio constant to the reference velocity, one can thus expect that the yawed turbine actually operates at a relative higher tip-speed-ratio (compared to the perpendicular incoming velocity). Does this result in a less optimal performance? Because, this could mean that for a two turbine setup, with the first turbine yawed, even more optimal situations are possible with a higher aggregate power. It would be helpful if the authors discuss this in the text.

This is a very good thought and indeed requires a deeper discussion in the text. We have measured the operating characteristics of the upstream turbine in dependence of the yaw angle and tip speed ratio. For $\gamma_{T1} = 0°$ and $\pm 30°$ the operating characteristics for all inflow conditions are shown in the previous publication (Bartl et al., 2018), which already is referred to in the text. The complete characteristics for $\gamma_{T1} = 0°$ to $+40°$ (Inflow B) are shown here in Figure 4 for positive yaw angles only (note that negative yaw angles have a very similar TSR-dependency). It can observed that the maximum power coefficient is measured at $\lambda = 6.0$ for yaw angles between 0° and 30°. For the highest yaw angle of 40°, however, the optimum tip speed ratio is found at $\lambda = 5.5$, which makes sense according to the reasoning given by the reviewer. At this extreme yaw angle, a slightly higher combined power output could indeed have been achieved, if the upstream turbine would have been operated at $\lambda = 5.5$. However, a constant upstream turbine tip speed ratio of $\lambda = 6.0$ seems to be optimum for the most interesting region between 0° and 30°.
Nevertheless, we suggest to add some additional lines of text to the manuscript discussing the TSR-dependency.

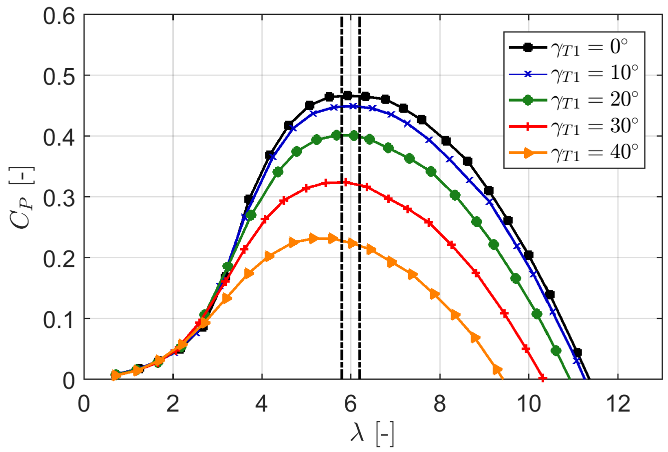

Figure 4: Tip-speed-ratio-dependent operating characteristics of the upstream turbine T1 operated at yaw angles from $\gamma_{T1} = 0°$ to $+40°$ at inflow B.

p.6, l.23 ff:
The model turbine is operated at a tip speed ratio of $\lambda_{T1} = 6.0$ for all yaw angles. ~~*The downstream turbine shows the exactly same operating characteristics when operated in undisturbed inflow.*~~ *For measurements showing the power and thrust coefficient depending on the tip speed ratio λ_{T1} it is referred to Bartl et al. (2018). There, the power coefficient is assessed to be maximum at $\lambda_{T1} = 6.0$ for all yaw angles between $\gamma_{T1} = 0°$ to $\pm 30°$. A slight shift towards a lower optimum tip speed ratio of $\lambda_{T1} = 5.5$ is measured for $\gamma_{T1} = \pm 40°$ (not shown in graph). As the difference in total power coefficient is observed to be very small, the upstream turbine is constantly operated at $\lambda_{T1} = 6.0$ also for these yaw angles. The downstream turbine shows exactly the same operating characteristics when operated in undisturbed inflow.*

Minor comment (1)

As there is no optimization in this study, it seems that the title can be made more clear by for example: 'Wind tunnel measurements of power output and yaw-moments for two yaw-controlled model wind turbines'

We agree that the term "optimization" does not reflect the content of this study, and therefore should be excluded from the title. We suggest to use a mixture of the reviewer's suggestion and the original title: "Wind tunnel study on power output and yaw-moments for two yaw-controlled model wind turbines"

p.1, l.0 (Title):

~~*Wind tunnel study on power and loads optimization of two yaw-controlled model wind turbines*~~

Wind tunnel study on power output and yaw-moments for two yaw-controlled model wind turbines

Minor comment (2)

Figures should be numbered according to their order of reference in the text. (figure 2 is the first to be referenced in the text).

Thank you for the hint. This line was obviously added in a revision of the text, violating the correct order. We therefore suggest to move this line to a later location in the text.

p.4, l.1:

(...) model wind turbines rotate counter-clockwise. ~~*Positive yaw is defined as indicated in Figure 2.*~~

p.7, l.6 f:

Figure 2 shows two example cases, in which the downstream turbine is operated in the upstream turbine's wake for $\gamma_{T1} = 0°$ *and* $\gamma_{T1} = 30°$. *Positive yaw is defined as indicated in Figure 2.*

Minor comment (3)

P4L14: In this section, it is in general not clear to which location the distances x/D refer. Is this compared to the beginning of the wind tunnel test-section? Where is the turbine located compared to the beginning of the test section?

We agree that this is not well explained in the text. $x/D = 0$ refers to the location of the upstream turbine, which is not clear before studying the sketches in Figure 2. In order to make this clearer, we suggest to make a small addition to the text:

p.4, l.13 f:

Inflow B is generated by a static grid at the wind tunnel inlet *($x/D = -2$) and is measured to amount TI_B = 10.0% at the location of the upstream turbine ($x/D = 0$)*.

The grid-generated turbulence decays with increasing downstream distance to about TI_B = 5.5% at $x/D = 3$ and to TI_B = 4.0% at $x/D = 6$.

Minor comment (4)

P17L17: '..,but can mostly by subscribed to lower average kinetic energy levels in wakes for turbines exposed to low inflow turbulence. This sentence doesn't provide any new information. Do the authors mean that wakes are more severe or recover more slowly when the ambient turbulence levels are lower? It is also better not to describe a wake as a kinetic energy sink, but rather as a region with low kinetic energy.

We agree that the sentence does not provide any new useful information. As already discussed in Major comment (3), the Discussion section is suggested to be omitted in the final version of the manuscript (with single comparisons being moved to the Results section).
Yes, the reviewer's interpretation of the sentence's meaning is correct, but that has already been discussed earlier in the text.

Minor comment (5)

'.. rather asymmetrical': It could be helpful to mention other studies in the literature that also observed an asymmetrical behavior and wake deflection from yawing.

We have now moved two references, which also observed asymmetries in the combined power output, from the Discussion section to the results section. Thus, this finding is now directly discussed in the text.

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.

Minor comment (6)

P8L21: "Obviously, the optimum downstream turbine T2's operating point shifts to higher tip speed ratios, the more kinetic energy is available in the wake." This is not obvious to the reviewer. Maybe the authors can elaborate on the reason for this?

Thank you for the comment. This is indeed not sufficiently explained in the text yet. The reason for higher optimum tip speed ratios of the downstream turbine is the fact, that also the power coefficient $C_{P,T2}$ is referred to the constant far upstream reference velocity U_{ref} and not the local inflow velocity to the downstream turbine (which is difficult to define due to its spatial non-uniformity). We therefore suggest to add two short sentences; one where we define the power, thrust and yaw moment coefficients and the other in the discussion of the results, respectively.

p.6, l.10:
For all test cases the power coefficient C_P , thrust coefficient C_T and normalized yaw moment M_y^* are assessed on T1 and T2. Note that the coefficients for both turbines are normalized with the reference inflow velocity U_{ref} measured far upstream of the turbine array at $x/D = -2$.

p.7, l.15 f:
~~Obviously, the~~The optimum downstream turbine T2's operating point shifts to higher tip speed ratios λ_{T2}, the more kinetic energy is available in the wake. As the downstream turbine power coefficient is referred to the constant far upstream reference velocity U_{ref}, the optimum operating conditions are measured for higher tip speed ratios as soon as the local inflow velocity increases.

Minor comment (7)

P8L21: Wake recovery is not directly measured in this study. Therefore, it seems more correct to say: 'these results indicate a faster wake recovery..' + cite papers that have shown that wakes recover more quickly when turbulence levels are higher.

We not completely sure, if we are looking at the same sentence in the text here, as there is no P8L21 in the manuscript. Referring to P8L9, we agree that this is not a result of the presented study, but rather the previous wake study (Bartl et al., 2018). We therefore suggest to add a reference here.

p.8, l.9:
As previously observed in Bartl et al. (2018), the ~~The~~ wake flow recovers at a higher rate, leaving more kinetic energy for the downstream turbine to extract.

Technical correction (1)

Abstract: - 'wake overlap' instead of 'wake overlap situations'.

Thank you for pointing out a number of technical mistakes. All of them will be included in the final version of the manuscript, in order to make the text easier to read.

p.1, l.1 f:

In this experimental wind tunnel study the effects of intentional yaw misalignment on the power production and loads of a downstream turbine are investigated for full and partial wake overlap ~~situations~~.

Technical correction (2)

Abstract: - "For partial wake overlap the concept of downstream turbine yawing for yaw moment mitigation is examined for different lateral offset positions." - consider splitting up this sentence to make it more easy to read.

The referred sentence is actually from the conclusions. But an even longer, more complicated sentence is found in the abstract. We agree that both sentences are too long and complicated. We suggest to split up the abtract's sentence and to omit the second part of the conclusion's sentence:

p.1, l.9 ff:

For partial wake overlap ~~situations~~, yaw moments on the downstream turbine can be mitigated through upstream turbine yawing ~~, while simultaneously increasing the combined power production~~. Simultaneously, the combined power output of the turbine array is increased.

p.19, l.3 f:

For partial wake overlap the concept of downstream turbine yawing for the purpose of yaw-moment mitigation is examined ~~for different lateral offset positions~~.

Technical correction (3)

Abstract: - "Opposed downstream turbine yawing" is not clear in the abstract. It may be more clear to say something like: "the measurements show that for a turbine with partial wake overlap, the power can be increased and the yaw moment decreased, by yawing it intentionally 10 degrees in the opposite direction."?

We agree that this concept of "opposed downstream turbine yawing" is not yet introduced, and therefore not suited in the abstract. We suggest the following wording:

p.1, l.11 f:

A final test case demonstrates ~~the concept of opposed~~benefits for power and loads through downstream turbine yawing in partial wake ~~situations, which is shown to~~

~~*reduce its yaw moments and increasing its power production by up to 5%.*~~*overlap. Yaw moments can be decreased and the power increased by intentionally yawing the downstream turbine in the opposite direction.*

Technical correction (4)

Main text: - P4L12 'low turbulence' instead of 'very low'

We agree.

p.4, l.12:
(...) an inflow of ~~*very*~~ *low turbulence intensity (...)*

Technical correction (5)

Main text: - P4L22: keep model number as 1 part "T20W-N/2-Nm".

Yes. Thank you for the hint.

p.17, l.18 ff:
(...) HBM torque transducer of the type "T20W-N/2-Nm".

Technical correction (6)

Main text: - Table 1: it would be helpful to indicate that yaw angles are considered from -40 to 40 in steps of 10 degrees.

We will add an additional number to indicate the steps of 10 degrees.

Table 1:
$[-40°, -30°, ..., +40°]$

Technical correction (7)

Main text: - P2L 32: "dedicated full-scale", what is meant with dedicated?

The wording is probably not well chosen here. We suggest to use "comprehensive" instead of "dedicated" here.

p.2, l.32:
A ~~*dedicated*~~*comprehensive full-scale study by McKay et al. (2013) (...)*

Technical correction (8)

Main text: - P2L33: "They found an independent yaw alignment for the purpose of individual power increase of downstream turbines.." is not clear.

We agree that this sentence is not clear at all. We suggest a new wording and sentence structure:

p.2, l.33 f:

They found ~~an independent yaw alignment for the purpose of individual power increase of~~ a power increase for downstream turbines, which independently misaligned their yaw angle from the main wind direction when operated in partial wake situations.

Technical correction (9)

Main text: - P3L8: This is a long and complicated sentence.

We agree and suggest to shorten down the sentence by deleting needless parts of it.

p.3, l.8 ff:

In a computational setup of ten aligned ~~, non-yawed wind~~ turbines, Andersen et al. (2017) ~~recently~~ investigated the influence of inflow conditions ~~velocity, turbulence intensity~~ and ~~streamwise~~ turbine spacing on ~~the~~ yaw moments ~~and other equivalent loads on~~ of downstream turbines operated in the wake.

Technical correction (10)

Main text: - P7L13: The term 'power recovery' is not clear.

This is indeed not clear. We suggest to use the word "output" instead.

p.7, l.13 ff:

The power ~~recovery~~ output of the downstream turbine is observed to be asymmetric with respect to the upstream turbine yaw angle.

Technical correction (11)

Main text: - P9L7: fix '.., blockage-increase freestream velocity levels of u/uref = 1.10 lift the downstream turbine's power to these levels.'

We agree, that this is again not very well-explained. We consider a full revision of this sentence, adding a deeper explanation of the assumed effects.

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.

Technical correction (12)

Main text: - P10L11: fix 'have seen not to be'

This is indeed bad language and will be fixed in the manuscript. Also, the rather long sentence is split up into two parts.

p.10, l.11 ff:

Both, upstream turbine power $C_{P,T1}$ and downstream turbine power $C_{P,T2}$ ~~have seen not to be perfectly symmetrical, the~~ are observed to be asymmetrically distributed. The larger portion can however be subscribed to the power extraction of downstream turbine, which is exposed to asymmetric wake flow fields for positive and negative yaw angles.

Technical correction (13)

Main text: - P12L13: 'other have' is 'other halve'?

This is indeed a typing mistake. We suggest to omit the second part of the sentence, as it only makes the sentence unnecessarily long.

p.12, l.16 ff:

For an offset position around $z/D = +0.16$ to $z/D = +0.33$ the yaw moments reach a maximum level, as roughly half the rotor swept area is impinged by the low velocity region of the wake~~, while the other have is impinged by the high velocity freestream flow~~.

Technical correction (14)

Main text: - P14L19: fix: 'The downstream turbine is exposed to a strong shear flow in the partial wake situation, mitigating yaw moment by actively yawing opposed to that shear'.

We agree that this sentence grammatically does not make any sense. We suggest the following correction:

p.14, l.19 f:

As the ~~The~~ downstream turbine operated in the partial wake is exposed to a strongly sheared inflow, ~~in the partial wake situation, mitigating~~ yaw moments can be mitigated by actively yawing the rotor in the opposite direction to the incoming ~~opposed to that~~ shear.

Technical correction (15)

Main text: - P15L4: 'deemed': 'expected' may be better?

We agree and pick up the suggested correction.

p.15, l.4 ff:

At the same time, the relative yaw moment reduction is larger, implying that opposed *downstream yawing is ~~deemed~~ expected to be even more effective for higher lateral offsets.*

Technical correction (16)

Main text: - P15L6: remove 'obviously'.

We agree that 'obviously' does not fit here.

p.15, l.6 f:

For negative lateral offset positions, ~~obviously~~ the opposite trends are observed, i.e. maximum power and smallest absolute yaw moments are measured for positive downstream turbine yaw angles.

References

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[6] van Dijk, M., van Wingerden, J.-W., Ashuri, T., and Li, Y.: Wind farm multi-objective wake redirection for optimizing power production and loads, Energy, 121, 561–569, doi:10.1016/j.energy.2017.01.051, 2017.

[7] Kragh, K. A. and Hansen, M. H.: Load alleviation of wind turbines by yaw misalignment, Wind Energy, 17, 971–982, doi:10.1002/we.1612, 2014.

[8] McKay, P., Carriveau, R., and Ting, D. S.-K.: Wake impacts on downstream wind turbine performance and yaw alignment,Wind Energy, 16, 221–234, doi:10.1002/we.554, 2013.