Authors' response to Referee #2:

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 #2'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

Content-related remark (1)

In the introduction, p1.l20, you state wake redirection techniques, which intentionally apply an uneven load distribution. Instead of an uneven loading, I would say that key to wake steering is the tilting of the thrust vector. For instance, cyclic pitching results is a large uneven loading, but marginal steering, while yaw results in a much smaller uneven loading, but a large thrust vector tilting.

Thank you for the good comment. In our understanding a tilted thrust vector and an uneven rotor load distribution (or *uneven distribution of induction*, (Micallef and Sant, 2016)) are a direct consequence of each other. Intuitively, cyclic pitching results in an uneven (cyclic) rotor loading, which then causes an unevenly distributed thrust over the rotor plane (not tilted but varying in magnitude) and consequently a tilt or yaw moment. During yaw misalignment, the thrust vector is laterally tilted, creating a yaw moment and consequently uneven rotor loads.

This is in agreement with a description by Fleming et al (2014.):
During yaw misalignment *(...) the thrust force of the turbine is shown to act along the axis of the rotor shaft. When the wind inflow is at an angle to this direction, the thrust can be divided into components fx and fy. The component fx is parallel to the flow and slows the wind, while fy is perpendicular and applies the force that causes wake redirection. IPC creates an uneven distribution of thrust forces on the rotor blades over the course of a rotation (...). This creates a tilt or yaw moment on the turbine rotor. (...) Therefore the in-plane reaction forces of the rotor on the flow are also unbalanced resulting in the fact that the turbine applies a net force on the flow perpendicular to the thrust direction, which does cause the flow to be redirected and the wake structure to be skewed.*

We do however agree that *a tilted thrust vector* intuitively is a better description for the causes of wake redirection in the context of yaw misalignment. We therefore suggest the following small modification in the manuscript:

p.1, l.19 ff:

These methods include the reduction of the upstream turbine's axial-induction by varying its torque or blade pitch angle (Annoni et al., 2016; Bartl and Sætran, 2016) as well as wake redirection techniques, which intentionally apply ~~an uneven load distribution~~ a tilted thrust vector on the front row rotors. In Fleming et al. (2015) different wake deflection mechanisms have been discussed with respect to higher wind farm power production and rotor loads.

Content-related remark (2)

On page 11, in the subsection about the tower wake deflection, you discuss several factors that contribute to the tower shadow deflection. You mention the influence of the lateral offset between the rotor and the tower during yawing, and the effect of the CVP (Counter-rotating Vortex Pair) on the wake opposite tower wake direction. What I suspect here is that the bottom of the two counter-rotating vortices is in strong interaction with its mirror image underground (i.e. the ground effect), thereby forming another CVP, but in opposite direction to the main CVP involved in the wake steering. This could hypothetically boost the deflection of the wake shadow in opposite direction to the main wake deflection.

Thank you for this very interesting comment. We agree that the lateral offset between the rotor midpoint (center of yaw rotation) and the tower midpoint might only play a minor role in the significant deflection of the tower wake as shown in e.g. Figure 6 (a) of the manuscript. The main contribution is deemed to stem from a strong cross flow (caused by the lower vortex of the CVP) near the ground as shown in Figure 6 (b) of the manuscript.
The formation of another CVP due to the interaction with the ground as seen in Bastankhah and Porte-Agel (2016) or Berdowski et al. (2018), is not directly observed in our experimental study. An analysis of the streamwise vorticity ω_x in Figure 6 (c) of the manuscript does not clearly show the formation of another CVP near the ground. As discussed in detail in the answers to **Content-related remark (5)** later in this document, the ground effect is deemed not to play a significant role in our wind tunnel experiment. Apart from the tower, our setup is perfectly symmetrical, featuring the same distance of the rotor to the floor and the roof of the closed wind tunnel cross-section.
For a clearer distinction of the effects of the tower wake deflection, we suggest the following small additions to the text:

p.11, l.16 ff:

On the bottom of the wake contour plot~~s~~ in Figure 6 (a), the wake of the turbine tower is indicated. The tower wake is observed to be deflected in the opposite direction than the rotor wake when the turbine is yawed. The deflection of the tower wake in the opposite direction is believed to have two reasons. Firstly, the turbine tower has a slight offset from $z/D = 0$ as the center of yaw-rotation was set to the rotor midpoint and not the tower. Therefore, a minor offset from the central position is expected *for the tower wake. Secondly and more importantly, the tower wake experiences an additional deflection in opposite direction due to an adversely directed cross-flow component outside near the wind tunnel floor as depicted in the vector plot in ~~(~~Figure 6 (b)~~)~~. This cross-flow balances the counter-rotating vortex pair above and possibly deflects the tower wake further to the side.*

Content-related remark (3)

On page 12, the insignificant influence of the moderately sheared inflow on the wake shape is addressed. However, this can only be stated about the shear inflow under high turbulence conditions, as that is the only case you analysed. It might be the case that shear does have a significant contribution for low ambient turbulence levels, as the inflow shear in combination with the wake shear results in a distinctively high velocity gradient near the top of the wake (as shown by many researchers), thus increasing turbulence levels there. By the way, you mention this notion in the discussion about the TKE results later on in the paper.

Thank you for this very good comment. We do completely agree that the insignificant influence of the moderately sheared inflow on the wake only holds for the investigated highly turbulent inflow. This situation might not be very realistic, as in reality stronger vertical flow gradients are mostly present in stable atmospheric conditions featuring a low ambient turbulence level (Vollmer et al., 2016). However, it is very difficult to create a low-turbulent sheared inflow in a wind tunnel experiment with a limited wind tunnel length.
We agree that we have to be clearer about this at two passages in the text, and therefore suggest the following additions:

p.1, l.6 f:
Exposing the rotor to non-uniform highly turbulent shear inflow changes the mean and turbulent wake characteristics only insignificantly.

p.10, l.25 f:
Despite the sheared inflow the wake shapes for all three yaw angles and both downstream distances are observed to be very similar to those of test case B. The normalized velocity levels as well as the inner structure of the wake are almost identical. The influence of shear is however only investigated at high inflow turbulence levels, which does not allow for any conclusions at lower inflow turbulence levels.

Content-related remark (4)

For completeness, it is important that the parameter settings for the JMC and BPA models is provided.

Thank you for pointing this out. The parameter settings are, of course, very important for the reproducibility of the deflection calculations. The recommended default model-parameters were used in both cases. We suggest the following additions to the manuscript:

p.13, l.2 f:

Further, the results are compared with two different wake models by Jimenez et al. (2010) (JCM) and Bastankhah and Porte-Agel (2016) (BPA). The recommended default model-parameters were used in the implementation of both wake deflection models. For the JCM-model a linear wake expansion factor of $\beta = 0.125$ was applied, while $k_y = 0.022$, $k_z = 0.022$, $\alpha^* = 2.32$ and $\beta^* = 0.154$ were used in the case of the BPA-model. The comparisons of the wake deflections are shown in Figure 8.

Content-related remark (5)

On page 14, you note that the wake deflection of a non-yawed turbine is assumed to stem from the interaction of the rotating wake with the turbine tower. The fact that the wake of a counter-clockwise rotating turbine (thus with a clockwise rotating wake swirl) deflects in positive z direction, sounds to me as originating from the interaction between the wake swirl and the ground: the root vortex forms a CVP with its mirror image underground from the ground effect, with its deflection direction in positive z direction. This was also discussed by e.g. Fleming (2014) and BPA (2016).

This is a very good comment directed towards the core of manuscript, namely the asymmetrical interaction of the different vortices in the yawed wake. For a detailed discussion about the causes for an asymmetrical wake deflection it is also referred to the answers to **Overall comments (1b) and (1c)** in the **Authors' response to RC1**, in which a very similar comment was addressed.

The interaction of the ground with the counter-rotating vortex pair (CVP) in the wake of a yawed turbine has been discussed by Fleming et al. (2014), Bastankhah and Porte-Agel (2016) and Berdowski et al. (2018).

The study by Fleming et al. (2014) already discusses wake asymmetries influenced by the ground effect for a non-yawed turbine. *"The wake rotates counter-clockwise in these contour planes, i.e. opposite to the clockwise rotation of the turbine rotor, and the wake is like a vortex interacting with the ground. The clockwise-rotating image wake (when considering the ground plane as an image plane in potential flow) then induces motion on the actual wake, pushing it to the right."*

By the means of theoretical potential theory study Bastankhah and Porte-Agel (2016) observe a different *"wake-centre displacement (...) in both horizontal and vertical directions (...). This is due to the fact that the wake rotation and ground effects act against each other"* for one yaw direction, while they act in the same direction for the other yaw direction.

A recent computational free-wake vortex filament study by Berdowski et al. (2018) investigated the ground effect for a yawed actuator disc. In this study, ground effects could be isolated by running two different simulations, of which only one was including a symmetry plane on the ground. For this case they observed that *"the bottom vortex of the CVP forms another CVP with its mirror vortex underground and in opposite* *direction"* (Berdowski et al., 2018).

The experimental setup investigated in this manuscript, however, is perfectly symmetrical, i.e. the rotor is located in the center of the wind tunnel, meaning that it has the same distance to wind tunnel floor and roof respectively the right and left sidewall. Our model turbine ($D \approx 90cm$) is installed with a hub height ($h_{hub,exp} = 89cm$) adjusted to the center of the wind tunnel ($h_{tunnel} \approx 180cm$), such that the setup is almost perfectly symmetrical. As shown in Fig. 6 (c) in the manuscript, we did not observe a formation of another CVP in our experimental setup.

As explained in the **Authors' response to RC1, Comment (1b)**, the effect of the tower wake on the rotor wake is deemed to be the main influence factor introducing asymmetries to the setup. However, the tower wake in this model scale experiment is deemed to be significantly stronger in the Reynolds-number-range of model-scale experiments than in full-scale situations. As this is a very critical issue, we suggest to add some more lines to the explanation on p.14 (as suggested in the answers to RC1 already):

p.14, l.5 ff:
The wake shows a higher deflection for negative yaw angles in all inflow cases. Also the wake behind the non-yawed turbine is seen to be slightly deflected in positive z-direction, which is assumed to stem from the interaction of the rotating wake with the turbine tower. As discussed by Pierella and Sætran (2017) who performed experiments on the same rotor with a slightly larger tower, the tower-wake interaction ~~can lead~~ leads to an uneven momentum entrainment in the wake. For the non-yawed case Pierella and Sætran (2017) observed both a lateral and vertical displacement of the wake vortex center, induced by an interaction with the tower wake. It can therefore be assumed that also the interaction of the counter-rotating vortex pair with the tower wake slightly displaced wake vortex in the yawed cases might be influence by an interaction with the tower wake, which is the only source of asymmetry in an otherwise perfectly symmetrical setup.

Content-related remark (6)

On page 14, you mention that the differences are small for the wake deflection as compared between a high and low turbulence inflow. Here it would be helpful to present results of the streamwise vorticity for both cases and for several downstream positions. Maybe the diffusion of vorticity under self-induced turbulence is already very significant for low ambient turbulence levels, which would explain why both cases are then so similar. In the end, the analysis of streamwise vorticity is key to understand, as the streamwise vorticity forms the CVP which is the driving force behind both the wake deflection and the shape deformation.

This is a very good idea for a deeper analysis. We agree the diffusion of vorticity in a field of rotor-generated turbulence for low inflow turbulence levels might be very similar to that of higher inflow turbulence levels. However, a more detailed analysis would be needed to support this assumption.

Unfortunately, we are not able present and analyze the streamwise vorticity for all wake scans at this stage, as our Laser-Doppler-Anemometer (LDA) only allowed recording two velocity components at a time. We decided to record the streamwise component u and the vertical component v. For an assessment of the streamwise vorticity ω_x, also the lateral velocity component w would be needed. This component was additionally measured for one wake scan only, which included in the parameters presented in Figure 6 of the manuscript.

As the vorticity is deemed to be of major interest for an assessment of the different diffusion in the flow, we suggest to add a line one that issue in the discussion section of the manuscript, motivating a deeper analysis of this in future studies.

p.18, l.19:

Our study moreover indicates that the wake shape and deflection is affected by inflow turbulence. The overall wake deflection was observed to be similar for both investigated turbulence levels. For a more detailed investigation of diffusion mechanisms in the wake, however, a vorticity analysis in the wake of a turbine exposed to low and high turbulence is motivated for future studies. The inflow turbulence is furthermore implemented ~~This confirms the implementation of the inflow turbulence~~ as an input parameter in the recently developed wake model by Bastankhah and Porte-Agel (2016).

Content-related remark (7)

In figure 11, vertical lines of the standard deviation are given, but it is unclear how the mean and standard deviation are defined here. After all, the Gaussian fit curves applied here are clearly not symmetric, thus I assume those are from a fit with multiple Gaussians, for which it is less trivial to define a mean and standard deviation. Apart from that, there is a lot of information in this figure, and it took me a while to comprehend it fully.

Thank you for this good comment. We agree that Figure 11 of the manuscript can be misunderstood and needs to be simplified. The mean and the standard deviation are defined from a single Gaussian fit function of the mean velocity profile at hub height. Confusingly, this single Gaussian fit was not shown in the original version of Figure 11 of the manuscript. The original version included a couple of multiple Gaussian fits for the mean velocity and TKE profiles, which might have been misleading. For a clearer presentation, a new version of Figure 11 is suggested including the single Gaussian fit of the velocity profiles, while all other multiple-fitted curves are omitted. A suggested modified version of the manuscript's Fig. 11 is shown in Figure 2 of this answer document.

Additionally, small changes in the caption and text are suggested to also make the description clearer:

p.17, l.18 ff:

~~Effects of yawing on~~ Approximation for turbulent kinetic energy distributions in yaw

The levels of peak turbulence are observed to decrease considerably when the rotor is yawed. For a direct case-to-case comparison, TKE-profiles at hub height $y=0$ at $x/D=6$ are presented for $\gamma = 0^\circ$ and $\gamma = -30^\circ$ in the lower plots of Figure 11.

For a yawed turbine, the rotor thrust reduces with approximately $cos^2(\gamma)$ as previously shown in Figure 3. Multiplying also the TKE levels generated by the non-yawed rotor with $cos^2(\gamma)$ is observed to result in a decent first order approximation of the turbulence levels behind the yawed rotor. The reduced TKE levels for $\gamma = -30^\circ$ are indicated by the chain-dotted lines in the lower left plot of Figure 11. ~~In order to also find~~For an approximation of the lateral deflection of the turbulence peaks for yawed rotors, ~~another first order approximation of~~their location can be estimated as proposed by Schottler et al. (2018)~~ is applied~~. In this approach the expected value and standard deviation of ~~the fitted~~ a Gaussian fit of the velocity profile behind a yawed rotor is calculated. Adding the standard deviation to the expected value $\mu \pm \sigma_u$ gives a rough estimate of the ~~corresponding TKE peak~~locations of the corresponding TKE peaks, as shown by the vertical ~~dashed~~lines in Figure 11. Thus, it is possible to ~~rescale the~~ approximate both TKE peak locations and levels by knowing TKE and mean velocity for the now-yawed case.

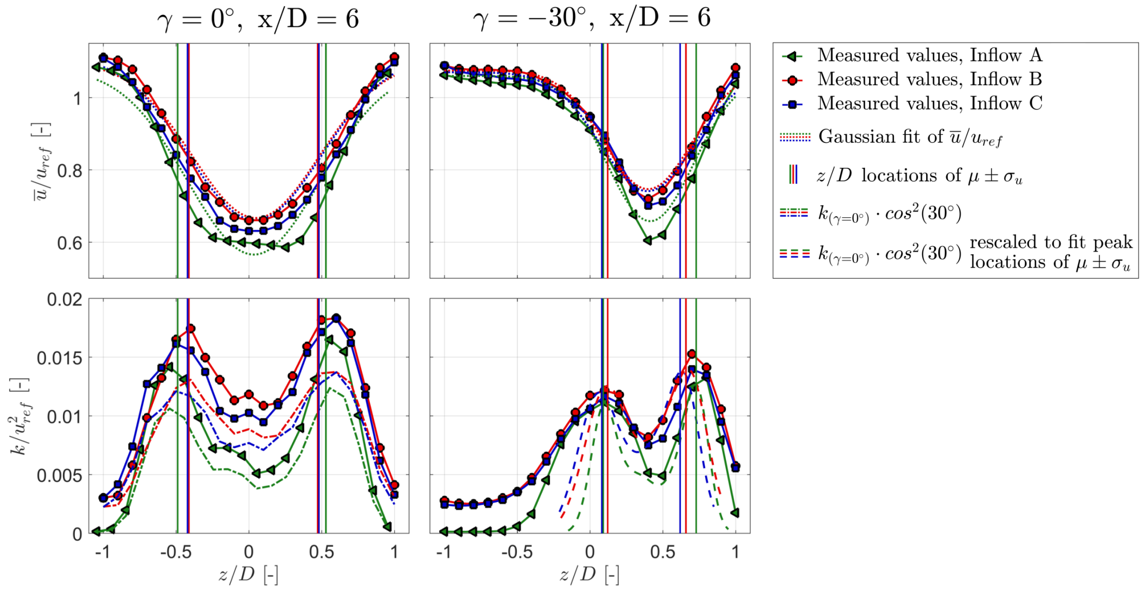

Figure 1: **Suggested simplified version of Figure 11:** Normalized mean velocity and turbulent kinetic energy k/u_{ref}^2 profiles at hub height $y=0$ and x/D=6. The yaw angles are set to $\gamma = 0^\circ$ and $\gamma = -30^\circ$. Vertical lines indicate the borders of standard deviations of Gaussian-fitted velocity profiles $\mu \pm \sigma_u$. Chain-dotted lines indicate a TKE profiles at $\gamma = 0^\circ$ multiplied by $cos^2(-30^\circ)$. Dashed lines in the lower right subplot have the same magnitude as the chain-dotted lines, but are linearly scaled in z to fit the peak locations of $\mu \pm \sigma_u$.

Technical remark (1)

P3.l4 – "donstream" → "downstream"
P3.l24 – remove "used in"
P3.l27 – "a NREL" → "an NREL"
Table 1 – add full stop
Figure 2 – add full stop
Table 2 – "CT" → "C_T"
Table 2 – add full stop
P7.l3 – "a HBM" → "an HBM"
P8.l14 – "a eight" → "an eight"
P8.l16 – remove "these" before "all these"
P8.l16 – remove "as a result" (duplication with "is obtained")
P9.l22 – "an solid" → "a solid"
P11.l10 – add "been" in between "previously investigated"
P12.l13 – remove "in"
P13.l9 – add "the" before "BPA-model"
P13.l9 – lowercase for "Available"
P13.l16 – duplicate of the word "complex"
P13.l20 – "a input" → "an input"
P15.l13 – remove "and"
Figure 10 – add full stop
Figure 11 – remove "a" before "TKE profiles"
P18.l16 – "slight" → "slightly"
P19.l2 – "shown" → "show"

Thank you for indicating these technical errors. We corrected all of them in the revised version of the manuscript.

Technical remark (2)

Comma's could be used more extensively to increase readability. For instance, see the first paragraph of section 4.1: "At the top, the"; "As the rotor thrust is reduced, a"; "For a yawed rotor, a"; "Due to this lateral force component, the"; "Comparing the wake contours [: : :] , an asymmetry": : :

Thank you for pointing this out. Commas have been added at the suggested passages in the text. Special attention will be given to commas in a final proof-reading of the manuscript.

Technical remark (3)

Sometimes it would make the text more easily readable if the text would be broken up into several paragraphs. For instance, p13.l18: "Secondly, the wake: : :" is a confusing construction, as there is no "firstly" defined in your text. Moreover, this sentence refers to a new comparison, so to clarify the text it would be better to break it up into two sections.

This is indeed an incorrect use of the word "Secondly,...". We replaced it with "Further,..." in the revised version of the manuscript.

Technical remark (4)

At p2.l18, "The measured circulation in the wake showed clear asymmetries for positive and negative yaw angles". This is about the asymmetry of the wake regarding the kidney shape, but this sentence could also be read as an asymmetry between the values for positive and negative yaw (i.e. yaw dependency).

We agree that the wording of the addressed sentence is equivocal. We therefore suggest a clearer wording:

p.2, l.17 ff:

In a follow-up study, Grant and Parkin (2000) presented phase-locked particle image velocimetry (PIV) measurements in the wake. The measured circulation in the wake showed clear asymmetries in the wake shape for positive and negative yaw angles.

Technical remark (5)

In figure 1, a clockwise rotating turbine is presented in the left subfigure, while the other two subfigures depict an anti-clockwise rotating turbine. Although it was clearly mentioned in the text that the results were for a turbine that is anti-clockwise rotating, it was a bit confusing for me at first to see the picture for the clockwise rotating turbine (which I assume is the second turbine used for the experiments later on in the paper).

Well observed. The rotor depicted in Figure 1.(a) of the manuscript turns clockwise and therefore is wrong in this setting. We updated the figure with a counter-clockwise turning rotor as shown in Figure 2, which now should be correct.

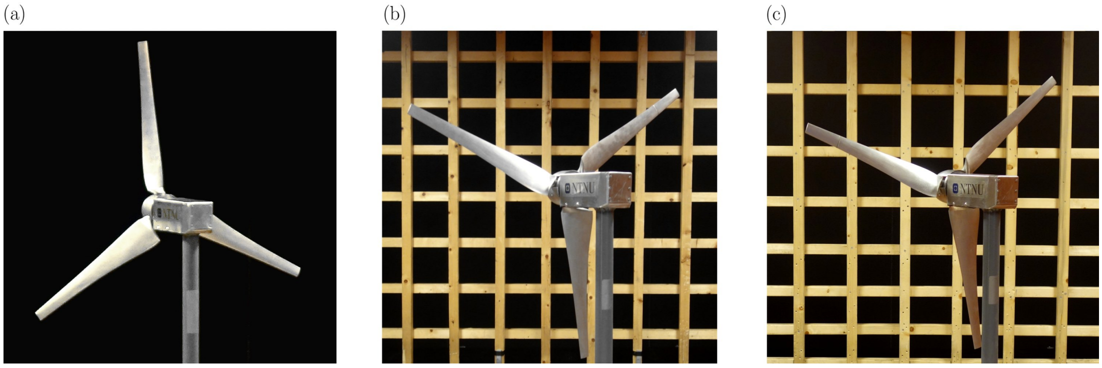

Figure 2: Yawed model wind turbine exposed to different inflow conditions: **(a)** $TI_A = 0.23\%$, uniform **(b)** $TI_B = 10.0\%$, uniform **(c)** $TI_C = 10.0\%$, non-uniform shear.

Technical remark (6)

At page 6, it would be good to add the approximate values for cos2(30) and cos3(30) in the main text to get a feeling for their magnitude (0.75 and 0.65 respectively).

That is a good idea. Although the approximated and actually measured values already are compared in Figure 3 of the manuscript, the approximated values are never mentioned in the text. For a value-to-value comparison with the measured $C_{P/T,\gamma=30}$ as presented in Table 2 of the manuscript, we propose the following small additions to the text:

p.6, l.12 ff:

An approximation of this reduction can be obtained with sufficient accuracy by multiplying the maximum power of the non-yawed turbine by $C_{P,A} \cdot cos^3(30°) \approx 0.304$. *An adequate estimate of the thrust coefficient of the yawed rotor can be obtained assuming a reduction by* $C_{T,A} \cdot cos^2(30°) \approx 0.670$ *on the thrust of the non-yawed rotor. This corresponds well to previous measurements by Krogstad and Adaramola (2012).*

Technical remark (7)

In figure 5 you apply a very fine gradient scaling with contour lines added, but it is hard to extract the true magnitude from these plots. You might change these plots to one where you have much fewer gradient colors (let's say about 10), and change the colorbar accordingly (which is completely smooth in the current visualization).

Thank you for this good comment. Matlab offers a number of different pre-defined and the option for custom defined colormaps. The most commonly used pre-defined maps are ”jet” and ”parula”. ”Jet” offers a wider spectrum of colors, which makes it easier to extract the magnitude of the values from a plot. ”Parula”, on the other hand, appears more linear to the eye. We therefore decided to plot our wake results using the ”parula” colormap.

We deem it is very important that the colormaps are consistent with our earlier publications (e.g. Bartl et al. (2017), Schottler et al. (2018)) and therefore propose to keep the colormaps as they are in the manuscript. However, we now made all our experimental wake data publicly available on a web-platform including a digital object identifier (doi). This enables everyone to download the wake data and adjust the colormaps according to their specific preferences. We propose to add a short line called *”Data availability”* in the end of the manuscript:

p.19, l.26:

Data availability. All presented wake data in this paper is available on *https://doi.org/10.5281/zenodo.1193656* .

Technical remark (8)

In section 4.1, the subsection about the curled wake shape, you mention ": : : a kidneyshaped velocity deficit is observed: : :", without referring to a figure number. The same applies for the subsection about the tower wake deflection on the next page.

Thank you for pointing this out. We suggest to add a reference to the specific figures in both cases:

p.10, l.32:
At x/D=6 a kidney-shaped velocity deficit is observed (Figure 5), showing a higher local velocities behind the rotor center.

p.11, l.16:
On the bottom of the wake contour plot~~s~~ in Figure 6 (a), the wake of the turbine tower is indicated.

Technical remark (9)

In general, it comes more natural for the understanding of the reader if the lateral direction was defined as y and the vertical direction as z instead.

This is a legitimate comment, which has also been addressed by referee 1. Despite the unfortunate inconsistency of our coordinate system with most other definitions, we think that it is important to be consistent with our earlier publications (e.g. Bartl and Sætran (2017), Schottler et al. (2017), Schottler et al. (2018)). We therefore carefully define the coordinate system in a clear sketch (Fig. 4 of the manuscript) before going into the results.

References

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