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

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Abstract. 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~~. Power, thrust force and yaw moment are measured on both the upstream and downstream turbine. The influence of inflow turbulence level and streamwise turbine separation distance are analyzed for full wake overlap~~situations~~. For partial wake overlap the concept of downstream turbine yawing for yaw moment mitigation is examined for different lateral offset positions.

Results indicate that upstream turbine yaw misalignment is able to increase the combined power production of the two turbines for both partial and full wake overlap~~setups~~. For aligned turbine setups the combined power is increased between 3.5% and 11% depending on the inflow turbulence level and turbine separation distance. The increase in combined power is at the expense of increased yaw moments on both upstream and downstream turbine. For partial wake overlap~~situations~~, yaw moments on the downstream turbine can be mitigated through upstream turbine yawing~~, while simultaneously increasing~~ . Simultaneously, the combined power ~~production~~output of the turbine array is increased. 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.

1 Introduction

In wind farms the individual wind turbines interact aerodynamically through their wakes. Besides significant power losses, rotors exposed to upstream turbines' wakes experience higher unsteady loading (Kim et al., 2015). The reduced power and increased rotor loads are dependent on the downstream turbine's lateral and streamwise location in the wake, the upstream turbine's control settings and the characteristics of the incoming wind. The inflow characteristics are governed by the atmospheric stability, in which the turbulence level as well as the degree of shear and veer are important parameters. In combination with the wind farm layout, the site dependent wind statistic, such as wind speed and direction distributions, define the occurrence for downstream turbines to be fully or partially exposed to the upstream turbine's wake.

In order to mitigate power losses and wake induced loads on downstream turbines, different upstream turbine control strategies have recently been suggested (Knudsen et al., 2014; Gebraad et al., 2015). These include methods to reduce the axial-induction of an upstream turbine and thus also mean and turbulent gradients in the wake (Annoni et al., 2016; Bartl and Sætran, 2016) as well as wake redirection techniques (Fleming et al., 2015). The most discussed wake deflection mechanisms include individual pitch angle control, tilt angle variation and yaw angle actuation. In a computational fluid dynamics (CFD) study Fleming et al. (2015) compare these techniques with regards to power gains and blade out-of-plane bending loads on a two turbine setup. Individual pitch control was observed to cause high structural loads. Most current turbine designs do not feature tilt mechanisms, while yaw actuation is concluded to be a promising technique due to its simple implementability. As all modern wind turbines are equipped with yaw actuators, intentional yaw misalignment can be used to laterally deflect the wake flow and potentially increase the wind farm power output.

A number of recent research focused on the wake characteristics behind a yawed wind turbine. In a combined experimental and computational study Howland et al. (2016) measured the wake of yawed small drag disc and conducted a Large-Eddy-Simulation (LES) behind an actuator disc/line modeled rotor. They discussed different quantifications for wake deflection and characterized the formation of a curled wake shape due to a counter-rotating vortex pair. A similar wake shape was found in a LES study by Vollmer et al. (2016), who found a significant variation of wake shape and deflection depending on the atmospheric stability. The yawed wake characteristics' dependency on inflow turbulence and shear were investigated in an experimental study by Bartl et al. (2018). The inflow turbulence level was observed to influence the shape and deflection of the wake, in contrast to a moderate shear in the inflow. Schottler et al. (2018) highlight the importance of considering non-Gaussian distributions of velocity increments in wind farm control and layout optimizations. A ring of strongly intermittent flow is shown to surround the mean velocity deficit locations, suggesting a much wider wake expansion as based on the mean velocity. An extensive theoretical and experimental study on yaw wakes was performed by Bastankhah and Porté-Agel (2016). They presented a theoretical description for the formation of the counter-rotating vortex pair in the wake and developed a sophisticated analytical model for the far wake of a yawed turbine. Including inflow turbulence as an additional input parameter makes Bastankhah and Porté-Agel's model a favorable alternative to the wake deflection model by Jiménez et al. (2010).

Moreover, various research investigated the potential of overall wind farm power gains through intentional yaw misalignment. An experimental study by Adaramola and Krogstad (2011) on two aligned model wind turbines ($x/D = 3$) demonstrated an increase in combined efficiency with increasing upstream turbine yaw angle. For a yaw angle of $30°$, they measured an increase of 12% in combined power compared to the reference case at $0°$. For the same separation distance ~~?~~ Schottler et al. (2016) measured a combined power increase of about 4% for an upstream turbine yaw angle of $-18°$. Their experimental study on two aligned model turbines furthermore pointed out clear asymmetries of the downstream turbine power output with regards to the upstream turbine yaw angle. Another experimental study on three model wind turbines was presented by Campagnolo et al. (2016), who measured a combined power increase of 21% for an lateral offset of $\Delta z/D = 0.45$ between the turbines. Comprehensive studies on yaw misalignment for optimized full wind farm control haven been presented by Fleming et al. (2014) and Gebraad et al. (2016). They analyzed wake mitigation strategies by using both the LES code SOWFA as well as a parametric wake model. A ~~dedicated~~ comprehensive full-scale study by McKay et al. (2013) investigated the connection of yaw alignment and power output of a downstream turbine operated in the wake of an upstream turbine. They found ~~an independent yaw alignment~~

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

Most of these studies focus on the possibilities for power optimization through yaw control; however, the discussion of increased structural loads is often left open. Yet, yaw misalignment of an undisturbed turbine was observed to create increased unsteady loading on the yawed rotor. In a simulation by Kragh and Hansen (2014) these loads are quantified for different inflow conditions. It is furthermore shown that load variations due to wind shear can potentially be alleviated by yaw misalignment. Load characteristics on a yawed model turbine rotor were compared to various computational approaches by Schepers et al. (2014). The so-called Mexnext project revealed modeling deficiencies while shedding light on complex unsteady flow phenomena during yaw. In a recent paper by Damiani et al. (2018) damage equivalent loads and extreme loads under yaw misalignment are measured and predicted for a fully instrumented wind turbine. They observed rather complex, inflow-dependent load distributions for yaw angle offsets. In a computational setup of ten aligned ~~, non-yawed wind turbines Andersen et al. (2017) recently~~ turbines Andersen et al. (2017) investigated the influence of inflow ~~velocity, turbulence intensity and streamwise~~ conditions and turbine spacing on ~~the yaw moments and other equivalent loads on~~ yaw moments of downstream turbines operated in the wake. The study shows up unexpected load peaks for every second or third downstream turbine in below-rated operating conditions. A way to utilize measured rotor loads such as yaw moments to estimate rotor yaw misalignment, inflow shear or partial wake rotor operation is investigated by Schreiber et al. (2016). Using a computational framework of a wake model, BEM model for power and loads and a gradient-based optimizer ~~van Dijk et al. (2017)~~ **?** investigated the effects of yaw misalignment on power production and loads in full and partial wake overlap~~situations~~. They found that upstream turbine yaw-misalignment is able to increase the total power production of their modeled wind farm, while reducing the loads in partial wake overlap~~situations~~.

The objective of the present study is to analyze potentials of yaw control for the often contradicting goals of combined power gains and load mitigation. Balancing the benefits of power gains and costs of increased rotor loads is of utmost importance for the design of cost-effective wind farm control strategies. For this purpose the parameters turbine separation distance x/D, lateral turbine offset $\Delta z/D$ 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 in partial wake situations for the purpose of load reduction and combined power gains. Together with the inflow-dependent wake flow measurements on the same experimental setup presented in Bartl et al. (2018), this study completes the link between detailed wake flow characteristics and power, yaw moments and thrust forces on a turbine operated in the wake.

2 Experimental setup

2.1 Wind turbine models

Two wind turbine models of the exactly same rotor geometry were used for this study. The rotor was designed based on the NREL S826 aifoil and has a total diameter of $D = 0.894\,m$. The tower and nacelle structure of the upstream turbine (T1) is slightly slimmer than that of the downstream turbine (T2), in order to minimize the effect on the wake flow behind the yawed upstream turbine. The maximum power point of both turbines is reached at a tip speed ratio of $\lambda_{T1} = \lambda_{T2} = 6.0$ in undisturbed inflow. In this experiment T2 is controlled to its optimum power point, which strongly varies for different positions and upstream turbine operational parameters. The exact geometry and detailed performance curves of T1 are described in Bartl et al. (2018), while T2's characteristics can be found in Bartl and Sætran (2017). In contrast to most other turbines, the investigated model turbines rotate counter-clockwise. ~~Positive yaw is defined as indicated in Figure 2.~~

The experiments were performed in the closed-loop wind tunnel at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. The tunnel's cross-section measures $2.71\,m$ in width, $1.81\,m$ in height and $11.15\,m$ in length. The turbine models are operated at a blade tip Reynolds numbers of approximately $Re_{\text{tip}} \approx 10^5$.

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~~ freestream 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.

2.2 Inflow conditions

The influence of different inflow turbulence levels is investigated in this study. For this purpose the turbines are exposed to an inflow of ~~very~~ low turbulence intensity $TI_A = 0.23\%$ (Inflow A) as well as high turbulence intensity $TI_B = 10.0\%$ (Inflow B). 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 $x/D = 6$. The profiles of streamwise mean velocity and turbulence intensity measured in the empty wind tunnel for different downstream positions are presented in Bartl et al. (2018). Inflow A is assessed to be uniform within $\pm 0.8\%$ over the rotor swept area. 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 within $\pm 1.0\%$. Both test cases were performed at the constant reference velocity of $u_{ref} = 10.0 m/s$.

2.3 Measurement techniques

The mechanical power on both rotors was measured in separate steps with a HBM torque transducer of the type "T20W-N/2-Nm", which is installed in the nacelle of the downstream turbine T2. The transducer is connected to the rotor shaft through flexible couplings. An optical photo cell inside the nacelle makes the rotor's rotational speed assessable. On the test rig of T1 the rotational speed is controlled via a servo motor, ensuring the same power and load characteristics as for T2.

For the purpose of thrust force and yaw moment measurements the model turbines are separately installed on a six-component force balance by Carl Schenck AG. By constantly recording signals obtained from the three horizontal force cells, the yaw moments referred to the rotor center can be calculated. For the assessment of the rotor thrust, the drag force on tower and nacelle is measured isolated and then subtracted from the total thrust. No such correction is applied for the assessment of the yaw moments.

2.4 Statistical measurement uncertainties

The statistical measurement uncertainties for power coefficients, thrust coefficient and normalized yaw moments have been calculated following the procedure described by Wheeler and Ganji (2004). Random errors are computed from repeated measurements of various representative measurement points based on a 95 % confidence interval. Furthermore, the match of power and thrust values of the baseline cases (e.g. $\gamma_{T1} = 0°$, $x/D = 3$, $\Delta z/D = 0$) with previous results e.g. by Bartl and Sætran (2016, 2017) has been checked for consistency.

For the purpose of clarity, errorbars are not shown in the resulting graphs in Section 3. Instead, a short overview of uncertainties for the different measures is given here. The total uncertainty in T1's power coefficient is 0.011 (1.9%) for non-yawed operation, rising up to about 0.017 (3.9%) for a yaw angle of $\gamma_{T1} = 30°$. The uncertainty in T1's thrust coefficient is assessed to be very similar, varying from 0.013 (1.4%) to 0.018 (3.1%) for yaw angles 0° and ±40°, respectively. The uncertainty in normalized yaw moments M_y^* is 0.0032, which corresponds to almost 15% of the absolute measurement value at $\gamma_{T1} = 30°$. Due to very small absolute values of the yaw moments, the relative uncertainty is rather high. In the case of T2, the uncertainties are presented representatively for the aligned test case, in which the upstream turbine is operated at $\gamma_{T1} = 30°$ and T2 located at $x/D = 3$ and operated at $\gamma_{T2} = 0°$. The total uncertainties in power and thrust coefficient are 0.006 (2.5% of the absolute C_P-value) ~~respectively~~ and 0.007 (0.9% of the absolute C_T-value), respectively. The normalized yaw moment of the downstream turbine for this case is amounts 0.0019 (about 8% of the absolute value).

2.5 Test case definition

Three main test cases are investigated in this study. In a first test case the two model turbines are installed in an aligned arrangement in the wind tunnel, i.e. T2 is immersed in the full wake of T1 (for $\gamma_{T1} = 0°$). The upstream turbine's yaw angle is then systematically varied at nine different values $\gamma_{T1} = [-40°, -30°, -20°, -10°, 0°, +10°, +20°, +30°, +40°]$. Moreover, the streamwise separation distance between the turbines is varied from x/D=3 to x/D=6. Finally, the inflow turbulence intensity

Table 1. Overview of test cases.

Test case		Parameter variation	Inflow turbulence	Yaw angle γ_{T1}	Streamwise separation x/D	Lateral offset $\Delta z/D$	Yaw angle γ_{T2}
1 (a)	Aligned turbines	γ_{T1} & x/D	0.23%	[-40°,..., +40°]	3 & 6	0	0°
1 (b)	Aligned turbines	γ_{T1} & x/D	10.0%	[-40°,..., +40°]	3 & 6	0	0°
2 (a)	Offset turbines	$\Delta z/D$	10.0%	0°	3	[-0.5,...+0.5]	0°
2 (b)	Offset turbines	$\Delta z/D$	10.0%	+30°	3	[-0.5,...+0.5]	0°
3 (a)	Downstream turbine yaw	$\Delta z/D$ & γ_{T2}	10.0%	0°	3	[-0.5,...+0.5]	[-30°,...,+30°]
3 (b)	Downstream turbine yaw	$\Delta z/D$ & γ_{T2}	10.0%	+30°	3	[-0.5,...+0.5]	[-30°,...,+30°]

is varied from $TI_A = 0.23\%$ (Inflow A) to $TI_B = 10.0\%$ (Inflow B).

In a second test case, the effect of the lateral offset position $\Delta z/D$ of the downstream turbine T2 in the wake of an upstream turbine T1 is investigated. That means that T2 is in most cases exposed to partial wake situations. For this purpose, the lateral offset is set to seven different positions ranging from $\Delta z/D = [-0.50, -0.33, -0.16, 0, +0.16, +0.33, +0.50]$. This is done for two upstream turbine yaw angles $\gamma_{T1} = 0°$ and $\gamma_{T1} = +30°$. The turbine separation distance is kept constant at $x/D = 3$ and only the highly turbulent inflow condition (Inflow B) is investigated.

In a third and final test case the downstream turbine yaw angle γ_{T2} is varied as an additional parameter while it is operated at different lateral offset positions $\Delta z/D$. This concept intends to demonstrate the possibility for yaw moment mitigation in partial wake situations by opposed yawing of the downstream turbine. In this test case T2 is therefore operated at 13 different yaw angles ranging from $\gamma_{T2} = [-30°, ..., +30°]$. An overview of all investigated test cases is presented in Table 1.

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 $x/D = -2$. The power coefficient is the measured mechanical power normalized with the kinetic power of the wind in a streamtube of the same diameter:

$$C_P = \frac{P}{1/8\,\rho\,\pi\,D^2\,U_{ref}^3}. \tag{1}$$

The thrust coefficient is defined as the thrust force normal to the rotor plane normalized with the momentum of the wind in a streamtube:

$$C_T = \frac{F_T}{1/8\,\rho\,\pi\,D^2\,U_{ref}^2}. \tag{2}$$

The yaw moment M_y is normalized in a similar way as the thrust force with an additional rotor diameter D to account for the normalization of the yaw moment's lever:

$$M_y^* = \frac{M_y}{1/8\,\rho\,\pi\,D^3\,U_{ref}^2}. \tag{3}$$

3 Results

3.1 Operating characteristics of T1

At first the yaw-angle dependent operating characteristics of the upstream wind turbine are presented for two inflow conditions in Figure 1. The model turbine is operated at a tip speed ratio of $\lambda_{T1} = 6.0$ for all yaw angles. 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 ~~the exactly~~ exactly the 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).

At $\gamma_{T1} = 0$ the upstream turbine reaches a power coefficient of about $C_{P,T1} = 0.460$ for both inflow conditions. It is observed that an increase in inflow turbulence results in the same performance characteristics. 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 α 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 slightly smaller exponent of $\beta = 1.5$ for the thrust coefficient.

The normalized yaw moment shows an almost linear behavior around the origin. However, minor asymmetries between positive and corresponding negative yaw angles are observed. 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. (2018). 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.

3.2 Test case 1: Aligned turbines

In the first test case both rotors are installed in the center of the wind tunnel at $(y,z) = (0,0)$ aligned with the main inflow direction. The downstream turbine position is varied from $x/D = 3$ to $x/D = 6$, while the upstream turbine yaw angle is systematically changed in steps of $\Delta\gamma_{T1} = 10°$ from $\gamma_{T1} = [-40°, ..., +40°]$. 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. The sketched wake flow contours in the xz-plane at hub height ~~are Laser Doppler Anemometry (LDA)~~

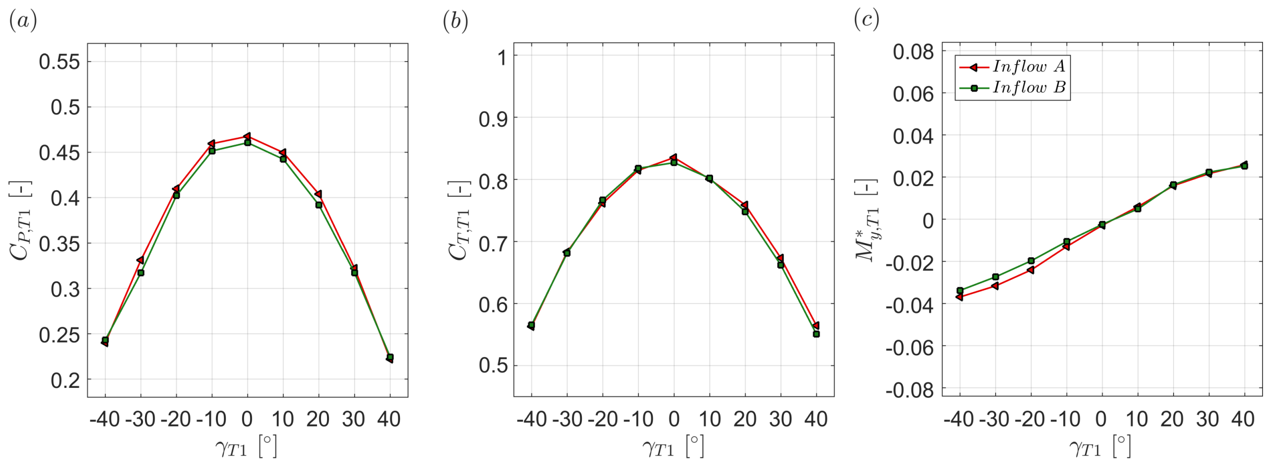

Figure 1. (a) Power coefficient $C_{P,T1}$ **(b)** thrust coefficient $C_{T,T1}$ and **(c)** normalized yaw moment $M^*_{y,T1}$ of the undisturbed upstream turbine T1 for different inflow conditions. The turbine is operated at $\lambda_{opt,T1} = 6.0$ for all yaw angles.

~~measurements of an example case and are only~~ included for illustrative purposes. ~~An exact quantification~~ The location of the wake ~~can be obtained from cross-sectional measurements in the yz-plane~~ flow as sketched in gray is roughly estimated from previously performed measurements as presented in Bartl et al. (2018). The results for the downstream turbine $C_{P,T2}$, $C_{T,T2}$ and $M^*_{y,T2}$ at inflow B in dependency of its tip speed ratio λ_{T2} are shown in Figure 3. The downstream turbine's power is observed to increase with an increasing absolute value of the upstream turbine yaw angle. As the wake is laterally deflected, the downstream turbine is partly exposed to higher flow velocities in the freestream. The power ~~recovery~~ output of the downstream turbine is observed to be asymmetric with respect to the upstream turbine yaw angle. Higher downstream turbine power coefficients are measured for negative upstream turbine yaw angles. ~~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. A corresponding asymmetry between positive and negative upstream turbine yaw angles is also observed in T2's thrust coefficient, showing higher values for negative upstream turbine yaw angles. The yaw moments experienced by the downstream turbine are observed to grow with increasing upstream turbine yaw angle. As expected, downstream turbine yaw moments are positive for positive upstream turbine yaw angles and vice versa. For low tip speed ratios, i.e. during stall the yaw moments are seen to be small and below 0.01. As soon as the flow is attached the absolute value of the yaw moments is observed to strongly rise. Again, an asymmetry between negative and positive upstream turbine yaw angles is observed. The asymmetric wake deflection for positive and negative yaw angles is considered to be the main reason for the asymmetric distribution of T2's yaw moments. As discussed in an analysis of the wake flow behind a yawed turbine by Bartl et al. (2018), the overall wake displacement for positive and negative yaw angles was observed to be slightly asymmetric. The interaction of the rotor wake with the turbine tower is identified to be the main contributor for the asymmetric wake flow. This finding is supported by a previous study on the non-yawed wake by

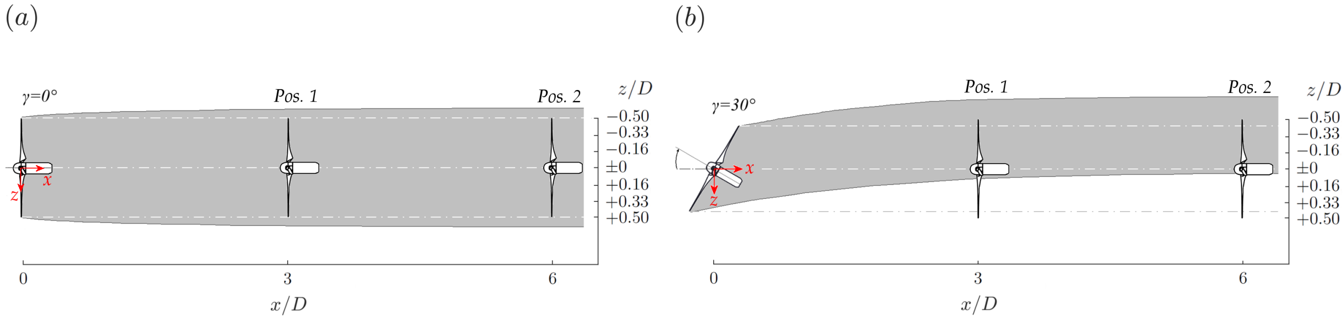

Figure 2. Topview of the aligned downstream turbine operated in the wake of an upstream turbine at the two different positions $x/D = 3$ and $x/D = 6$. The wake flow is indicated ~~by measured example cases~~ for **(a)** $\gamma_{T1} = 0°$ and **(b)** $\gamma_{T1} = 30°$.

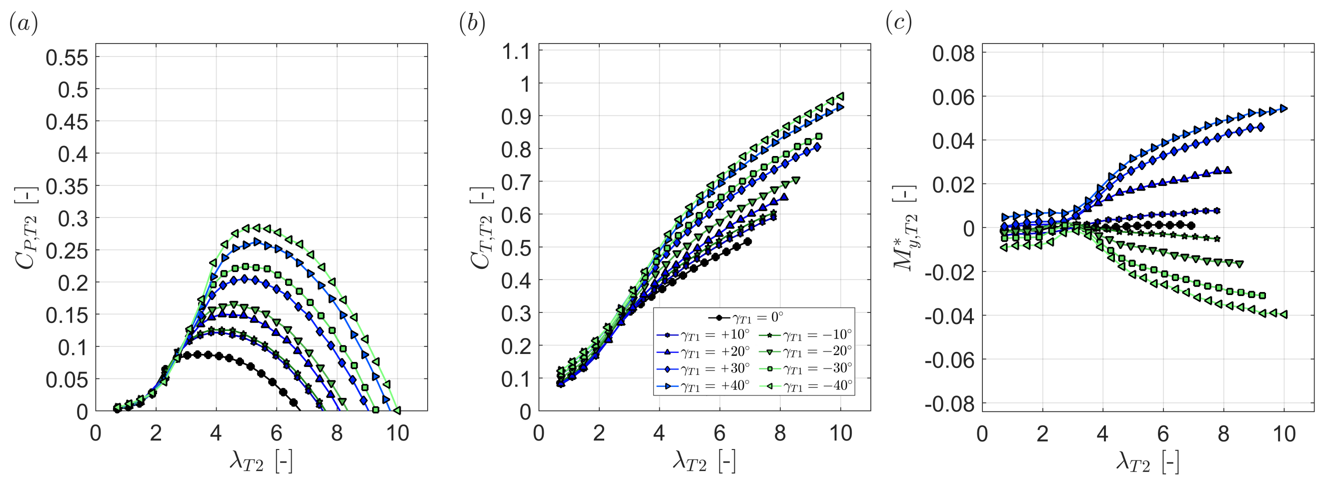

Figure 3. Downstream turbine **(a)** power coefficient, **(b)** thrust coefficient and **(c)** normalized yaw moment as a function of its tip speed ratio λ_{T2} for different upstream turbine yaw angles γ_{T1}. The downstream turbine T2 is located at $x/D = 3$. The turbines are exposed to inflow B.

Pierella and Sætran (2017), in which they attributed a significant displacement of the wake center to the interaction with the turbine tower.

The effect of a variation in inflow turbulence level ($TI_A = 0.23\%$ versus $TI_B = 10.0\%$) on the downstream turbine's $C_{P,T2}$, $C_{T,T2}$ and $M^*_{y,T2}$ is shown in Figure 4. The results are presented for varying upstream turbine yaw angle γ_{T1}. The downstream turbine T2 is operated at a λ_{T2}, for which $C_{P,T2}$ was maximum for the specific conditions. Note that for $x/D = 6$ neither thrust nor yaw moments were measured.

The downstream turbine's power coefficient $C_{P,T2}$ is in general observed to be higher for a higher inflow turbulence (Inflow B). ~~The~~ As previously observed in Bartl et al. (2018), the wake flow recovers at a higher rate, leaving more kinetic energy for the downstream turbine to extract. The difference in T2's power extraction between the two inflow turbulence levels is observed to be highest at small upstream turbine yaw angles γ_{T1}. At high yaw angles $\gamma_{T1} \geq 30°$, however, the power coefficient $C_{P,T2}$

is very similar for the two different inflow turbulence levels. For these high yaw angles the wake's mean velocity deficit has the largest lateral deflection, exposing about half of T2's rotor swept area to the freestream. The kinetic energy content in the freestream is about the same for both inflows, which brings T2's power levels closer together. Moreover, the downstream turbine's power output at low inflow turbulence (inflow A) is observed to be more asymmetric with respect to γ_{T1} than at high inflow turbulence (inflow B). Especially for $x/D = 6$, the downstream turbine power $C_{P,T2}$ is strongly asymmetric for inflow A. This observation corresponds well with the asymmetry in the mean streamwise wake flow measured for positive and negative yaw angles reported in Bartl et al. (2018). Therein, the wake flow behind a positively and negatively yawed turbine exposed to inflow A was observed to feature a higher degree of asymmetry than for the same turbine exposed to inflow B. For extreme yaw angles $\gamma_{T1} = \pm 40°$, T2's power coefficient reaches levels of $C_{P,T2} = 0.45 - 0.46$, which is about the same magnitude of $C_{P,T1}$ at $\gamma_{T1} = 0°$. 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 $\overline{u}/u_{ref} = 1.10$~~ higher wind speeds outside of the wake lift the downstream turbine's power to these levels.
Similar trends are observed for the downstream turbine thrust coefficient $C_{P,T2}$ (Figure 4 (b)), where higher thrust forces are measured for the higher turbulence level in Inflow B. Inflow A implicates a higher asymmetry in $C_{T,T2}$ with respect to γ_{T1}. As previously discussed, the downstream turbine yaw moments $M^*_{y,T2}$ are observed to increase with larger upstream turbine yaw angles γ_{T1}. For both inflow cases, the yaw moments' absolute values are seen to be higher for positive γ_{T1} than for negative γ_{T1}. Larger yaw moments are measured for Inflow A than for Inflow B, which possibly stems from stronger mean velocity gradients in the wake flow in Inflow A. The yaw moments $M^*_{y,T2}$ on the downstream turbine located at $x/D = 3$ have approximately the same magnitude as the yaw moments measured on the upstream turbine $M^*_{y,T1}$. Consequently, an intentional upstream turbine yaw misalignment implicates significant yaw moments on the upstream turbine it self as well as an aligned downstream turbine.

A main goal of this study is to find out if upstream turbine yawing can positively affect the total power output. As observed in Figure 1 yawing the upstream turbine reduces its power output, while Figure 4 shows that the downstream turbine's power increases simultaneously. In order to quantify if the gain in T2 power can make up for the losses in T1, we define the combined relative power output of the two turbine array

$$P^*_{T1+T2} = \frac{P_{T1}(\gamma_{T1}) + P_{T2}(\gamma_{T1})}{P_{T1,\gamma_{T1}=0} + P_{T2,\gamma_{T1}=0}}. \tag{4}$$

The results for the combined relative power are presented in Figure 5 for both inflow conditions and two turbine separation distances. In all of these four setups an increase in combined power between 3.5% and 11% was measured for upstream turbine yawing. For both turbine spacings, the maximum combined efficiencies were measured for $\gamma_{T1} = -30°$. The combination of a larger wake deflection and a progressed wake recovery at higher separation distances are seen to shift the optimum of the energy balance between T1 and T2 to higher yaw angles γ_{T1}. Moreover, the combined relative power is seen to be asymmetric

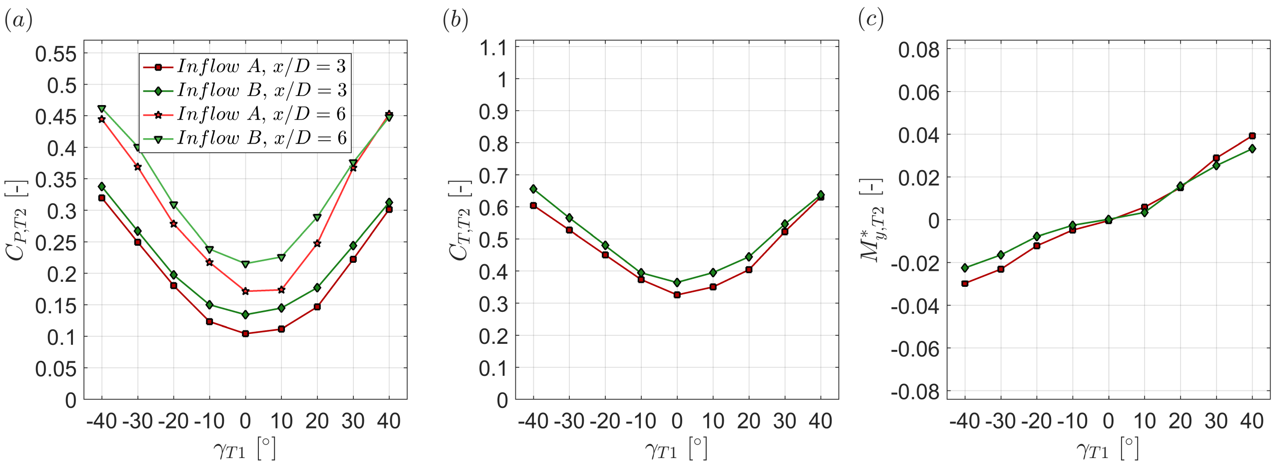

Figure 4. Downstream turbine **(a)** power coefficient, **(b)** thrust coefficient and **(c)** normalized yaw moment as a function of the upstream turbine's yaw angle γ_{T1}. The downstream turbine T2 is located at $x/D = 3$ and $x/D = 6$ respectively. The turbines are exposed to inflows A and B.

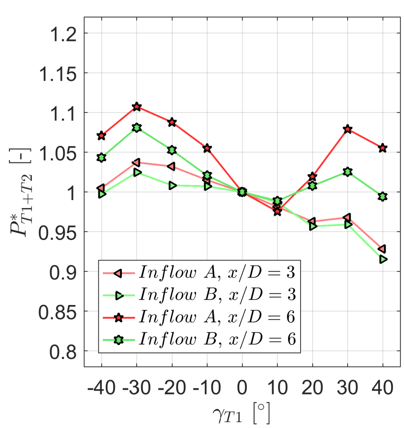

Figure 5. Combined relative power P^*_{T1+T2} of two turbines for different upstream turbine yaw angles γ_{T1}. The downstream turbine T2 is located at $x/D = 3$ and $x/D = 6$ respectively. The turbines are exposed to inflows A and B.

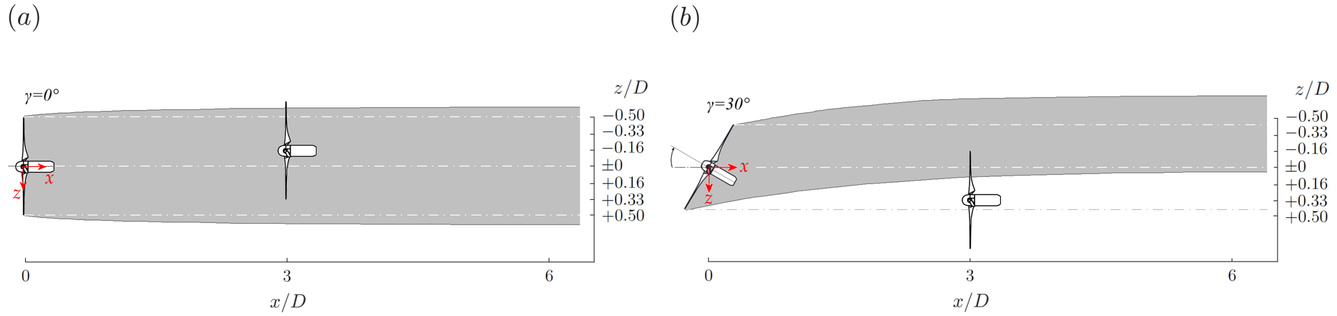

Figure 6. Topview of two lateral offset positions (**(a)** $\Delta z/D = -0.16$ and **(b)** $\Delta z/D = +0.33$) of the downstream turbine while operated in the wake of an upstream turbine at $x/D = 3$. The upstream turbine is operated at **(a)** $\gamma_{T1} = 0°$ and **(b)** $\gamma_{T1} = 30°$.

with higher values for negative yaw angles γ_{T1}. 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. Furthermore, the relative power gains are observed to be significantly larger for lower inflow turbulence levels (Inflow A). 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. (2016). 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.

3.3 Test case 2: Offset turbines

The power and loads of the downstream turbine T2 are dependent on many different parameters, such as the inflow conditions, the operating point of the upstream turbine T1, its relative streamwise and lateral position with respect to T1 as well as its operating point. In a second test case we therefore investigate the downstream turbine's performance in lateral offset. That means that T2 experiences partial wake situations. The turbine separation distance is in this test case fixed to $x/D = 3$, while different offset positions $\Delta z/D = [-0.50, -0.33, -0.16, \pm 0, +0.16, +0.33, +0.50]$ are investigated. This is done for Inflow B ($TI_B = 10.0\%$) only, while upstream turbine yaw angles of $\gamma_{T1} = 0°$ and $\gamma_{T1} = +30°$ are investigated. In Figure 6 two example positions of the downstream turbine are sketched, illustrating two different wake impingement situations.

Figure 7 shows the downstream turbine's $C_{P,T2}$, $C_{T,T2}$ and $M^*_{y,T2}$ while operated in the wake of the upstream turbine at $\gamma_{T1} = 0°$ in dependency of its tip speed ratio λ_{T2} and lateral offset position $\Delta z/D$. As expected, the power coefficient is seen to increase with increasing lateral offset $\Delta z/D$ as the downstream turbine is partly exposed to a flow of higher kinetic energy. T2's power coefficient is observed not to be entirely symmetric with respect to its lateral position in the wake. Slightly higher power coefficients are measured for negative offset positions. The reason for this is deemed to be a not perfectly axis-symmetric

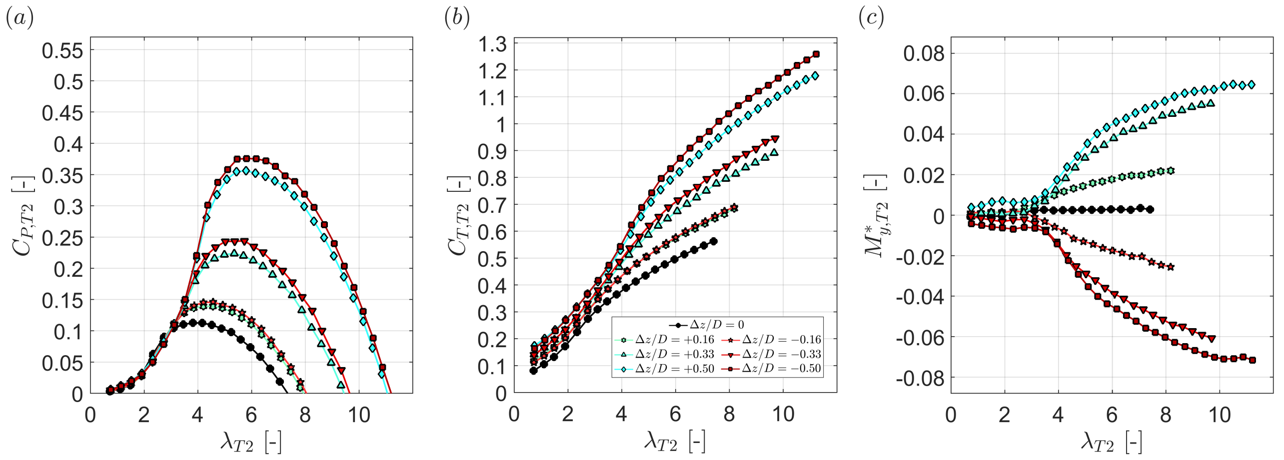

Figure 7. Downstream turbine **(a)** power coefficient, **(b)** thrust coefficient and **(c)** normalized yaw moment as a function of its tip speed ratio λ_{T2} for different lateral offset positions $\Delta z/D$. The upstream turbine yaw angle is kept constant at $\gamma_{T1} = 0°$. The downstream turbine T2 is located at $x/D = 3$. The turbines are exposed to inflow B.

velocity deficit at $x/D = 3$ as indicated in ~~Figure 6 (a) and Bartl et al. (2018).~~ Bartl et al. (2018). An analysis of the available kinetic energy contained in the wake at $x/D = 3$ behind a non-yawed upstream turbine confirmed a higher kinetic energy over an imaginary rotor swept area for negative lateral offsets z/D than for positive offsets. As observed earlier, T2's optimum operating point shifts to higher tip speed ratios λ_{T2} with increasing kinetic energy being available in the wake.

Similar trends are observed for the downstream turbine thrust coefficient $C_{T,T2}$, which was measured to be slightly higher for negative offset positions. The yaw moments experienced by the downstream turbine are seen to increase for larger lateral offsets as the rotor is impinged by stronger mean velocity gradients. The largest increases are detected for a change from $\Delta z/D = \pm 0$ to ± 0.16 and from ± 0.16 to ± 0.33, while a position change from ± 0.33 to ± 0.50 only causes a small increase in yaw moment. The curves are generally observed to be almost symmetric with respect to the offset position, but also show slightly higher absolute values for negative offset positions.

The effect of a variation in upstream turbine yaw angle from $\gamma_{T1} = 0°$ to $\gamma_{T1} = 30°$ on the downstream turbine's characteristics in different lateral offset positions is presented in Figure 8. For the shown results the downstream turbine T2 is operated at a its optimum λ_{T2}, which differs for each offset position.

The red curves summarize the results for $\gamma_{T1} = 0°$ already shown in Figure 7 for their optimum operating point, while the blue curves represent a setup, in which T1 is operated at $\gamma_{T1} = 30°$ (see Figure 6). For this upstream turbine yaw angle, the wake center is shifted to $\Delta z/D = -0.167$ (Bartl et al., 2018) and correspondingly the blue curves minima in $C_{P,T2}$ and $C_{T,T2}$ are shifted to $\Delta z/D = -0.16$ (Figure 8 (a) and (b)). The yaw moment $M^*_{y,T2}$ as depicted in Figure 8 (c) is observed to be around zero for this offset position, as the rotor is approximately impinged by a full wake. For an offset position around $\Delta z/D = +0.16$ to $\Delta z/D = +0.33$ 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~~. At a lateral offset

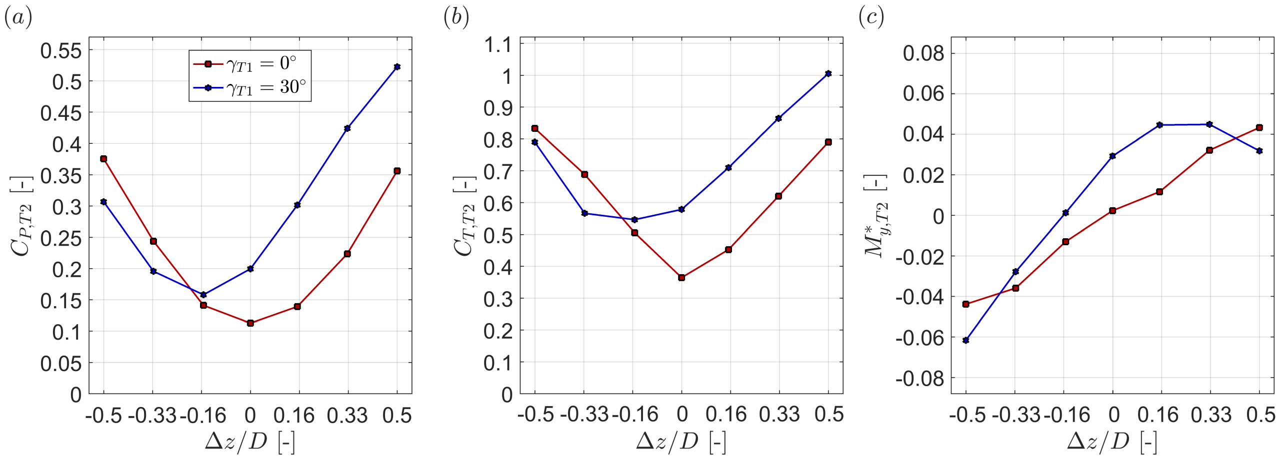

Figure 8. Downstream turbine **(a)** power coefficient, **(b)** thrust coefficient and **(c)** normalized yaw moment as a function of its lateral offset position $\Delta z/D$. The ~~upstream~~ downstream turbine yaw angle is kept constant at $\cancel{\gamma_{T1} = 0°}$ $\gamma_{T2} = 0°$. The downstream turbine T2 is located at $x/D = 3$. The turbines are exposed to inflow B.

of $\Delta z/D = +0.50$ the yaw moments on T2 are observed to decrease again. A large part of the rotor is exposed to the freestream flow; however, the wake is not yet entirely deflected away from T2. For this offset position the power and thrust coefficient are seen to reach very high levels as the rotor is exposed to a large portion of high kinetic energy freestream flow. A power coefficient of $C_{P,T2} > 0.50$ can be explained by increased freestream velocity levels of $\overline{u}/u_{ref} = 1.10$ (Bartl et al., 2018) caused by wind tunnel blockage. The power and thrust coefficient still are referred to u_{ref} measured $x/D = -2$ upstream of T1. Unfortunately, it is not possible to correct for blockage effects on the downstream turbine power, thrust and yaw moments with simple correction models. The influence of wind tunnel blockage on the highly complex inflow to the downstream turbine operated in a partial wake would have to be quantified by dedicated experiments or high-fidelity simulations.

The combined relative power output of the two-turbine array is in this case calculated for a change of upstream turbine yaw angle from $\gamma_{T1} = 0°$ to $+30°$. It has to be kept in mind, that the upstream turbine power is constant, independent of the downstream turbine position. The combined power for each offset position is calculated as

$$P^*_{T1+T2} = \frac{P_{T1,\gamma_{T1}=30} + P_{T2,\gamma_{T1}=30}(z/D)}{P_{T1,\gamma_{T1}=0} + P_{T2,\gamma_{T1}=0}(z/D)}. \tag{5}$$

Figure 9 shows the resultant combined relative power output. For an offset position of $\Delta z/D = +0.33$ a maximum combined power increase of 13% is measured, as a major part is deflected away from the downstream rotor. Surprisingly, the relative power gains measured for an offset $\Delta z/D = +0.50$ are measured to be smaller, amounting about 6%. This can be explained by significantly larger $C_{P,T2}$-values in the non-yawed case for $\Delta z/D = +0.50$ than for $\Delta z/D = +0.33$, allowing smaller relative gains. For zero lateral offset, about 5% in combined power are lost when yawing T1 to $\gamma_{T1} = +30°$ as previously observed in Figure 5. In the case of the downstream turbine being located at negative offset positions $\Delta z/D$, the wake is

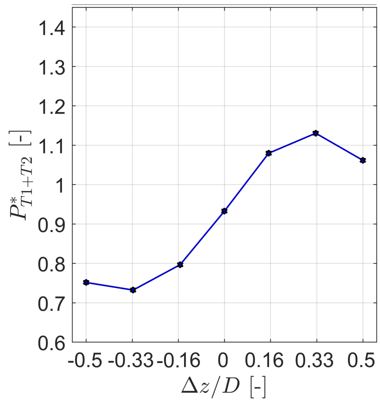

Figure 9. Combined relative power P^*_{T1+T2} of the two-turbine-array for different lateral offset positions $\Delta z/D$. The combined power is calculated for a change of upstream turbine yaw angle from $\gamma_{T1} = 0°$ to $+30°$ for each position. The downstream turbine T2 is located at $x/D = 3$. The turbines are exposed to inflow B.

deflected directly on T2's rotor, significantly reducing its power output and consequently also the combined power.

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 **?**.

3.4 Test case3: Downstream turbine yawing

The third and final test case investigates whether a variation in downstream turbine yaw angle γ_{T2} contributes to a yaw-load mitigation and power optimization. As previously seen, both partial wake impingement and turbine yaw misalignment are possible sources for increased yaw moments. An intentional yaw misalignment opposed to the partial wake impingement is therefore considered to cancel out yaw loading on the turbine. For this purpose, the downstream turbine yaw angle is systematically varied from γ_{T2}=$[-30°, ..., +30°]$ in steps of $5°$ for all seven lateral offset positions and upstream turbine yaw angles γ_{T1}=$[0°, +30°]$. A sketch of two downstream turbine yaw angles at two offset positions is presented in Figure 10.

The resulting $C_{P,T2}$, $C_{T,T2}$ and $M^*_{y,T2}$ of the downstream turbine in dependency of its yaw angle γ_{T2} and lateral offset position $\Delta z/D$ for a constant upstream turbine yaw angle of $\gamma_{T1} = 0°$ are shown in Figure 11. The points for $\gamma_{T2} = 0°$ correspond to the previously shown red lines in Figure 8. In case the downstream turbine rotor is fully impinged by the upstream turbine's wake, i.e. $\Delta z/D = 0$, a variation of its yaw angle γ_{T2} reduces its power output and increases uneven yaw moments. During a lateral offset however, the maximum power output and minimum yaw moments are found for yaw angles $\gamma_{T2} \neq 0°$. At a lateral offset position of $\Delta z/D = +0.16$, for instance, the maximum $C_{P,T2}$ is assessed for $\gamma_{T2} = -10°$. Simultaneously, the yaw moment is measured to be around zero at this yaw angle. The ~~downstream turbine is exposed to a strong shear flowin the partial wake situation, mitigating yaw moments~~ potential of load reductions of a single turbine by yawing has been previously

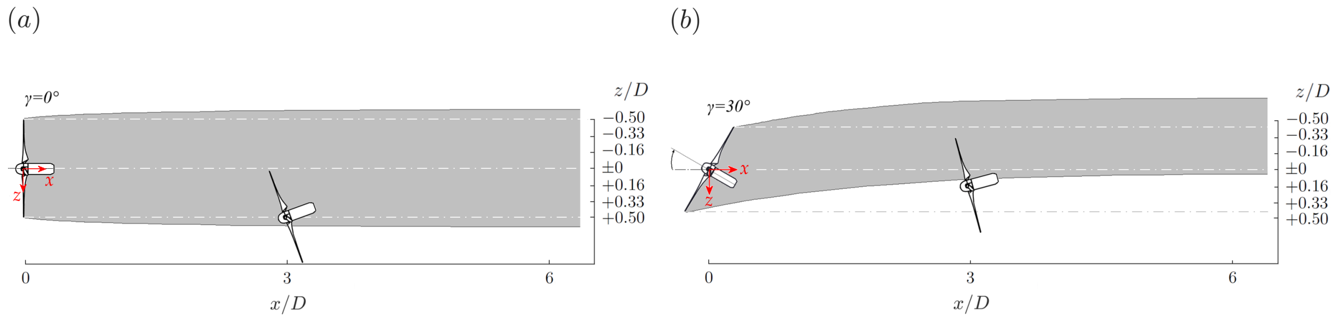

Figure 10. (a) Topview of the downstream turbine T2 operated at a lateral offset position $\Delta z/D = +0.50$ and a yaw angle of $\gamma_{T2} = -20°$ in the wake of an upstream turbine T1 operated at $\gamma_{T1} = 0°$. **(b)** Topview of the downstream turbine T2 operated at a lateral offset position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

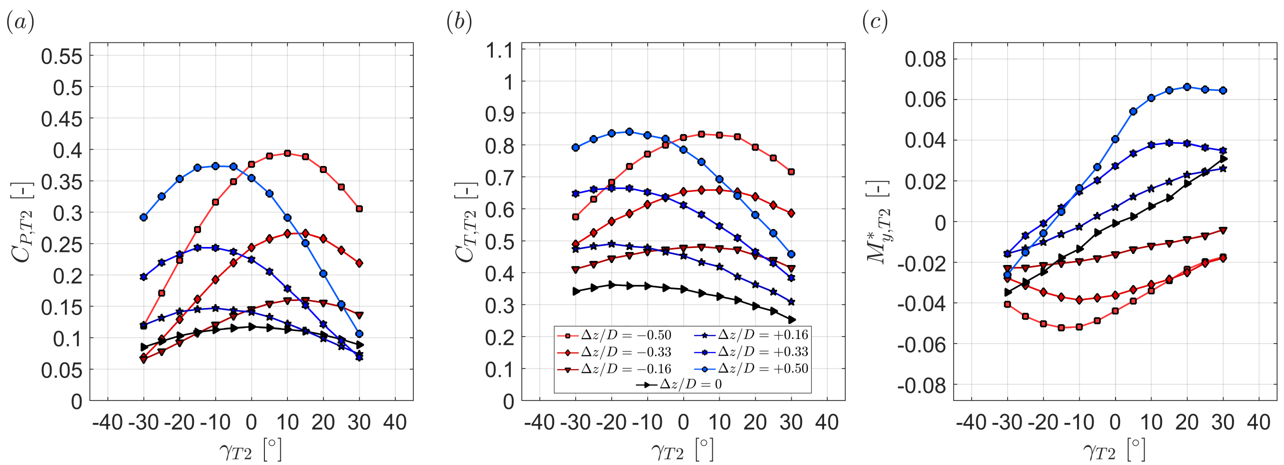

Figure 11. Downstream turbine **(a)** power coefficient, **(b)** thrust coefficient and **(c)** normalized yaw moment as a function of its yaw angle γ_{T2} for different lateral offset positions $\Delta z/D$. The upstream turbine yaw angle is kept constant at $\gamma_{T1} = 0°$. The downstream turbine T2 is located at $x/D = 3$. The turbines are exposed to inflow B.

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. As the downstream turbine operated in the partial wake is exposed to a strongly sheared inflow, yaw moments can be mitigated by actively yawing ~~opposed to that~~ the rotor in the opposite direction to the incoming shear. 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. Higher power outputs and decreased yaw moments are also measured for moderate yaw angles around $\gamma_{T2} = -10°$ at larger lateral offsets of $\Delta z/D = +0.33$ and $\Delta z/D = +0.50$. The slope of the power curves in Figure 11 (a) and yaw moment curves in Figure 11 (c) are observed to be even steeper for larger lateral offsets. The power gains when yawing the turbine from $\gamma_{T2} = 0°$ to $\gamma_{T2} = -10°$ are larger for higher lateral offsets. 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.

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 γ_{T2}. The power output and yaw moment distribution is however not completely symmetrical with respect to yaw angle γ_{T2} and offset position $\Delta z/D$.

The concept of downstream turbine yawing in partial wake impingement situations is moreover investigated for an upstream turbine yaw angle of $\gamma_{T1} = +30°$. The wake flow features a significantly higher asymmetry in this case. The results for $C_{P,T2}$, $C_{T,T2}$ and $M^*_{y,T2}$ are shown in Figure 12. As previously observed, an offset of $\Delta z/D = -0.16$ approximately corresponds to an impingement of the full wake. Thus, the power coefficient has an almost symmetric distribution with respect to downstream turbine yaw angle γ_{T2}. The yaw moments are observed to be rather low for this offset position and around zero for $\gamma_{T2} = 0$. For partial wake impingement situations at $\Delta z/D \geq 0$, negative downstream turbine yaw angles are again seen to reduce the yaw moments acting on the rotor. The gradients in yaw moment reduction per degree of yaw angle are observed to be steeper for larger lateral offsets. The maximum power coefficients are again measured for moderate downstream turbine yaw angles around $\gamma_{T2} \pm 10°$.

Power gains by downstream turbine yawing are assessed by a relative combined power of the two-turbine array

$$P^*_{T1+T2} = \frac{P_{T1} + P_{T2}(\gamma_{T2}, z/D)}{P_{T1,\gamma_{T1}=0,z/D=0} + P_{T2,\gamma_{T1}=0,\gamma_{T2}=0,z/D=0}}. \tag{6}$$

As a reference the power measured for the non-yawed upstream turbine, a non-yawed downstream turbine in an aligned setup ($\Delta z/D = 0$) is used. The results are shown in Figure 13. For an upstream turbine yaw angle of $\gamma_{T1} = 0°$ (Figure 13 (a))

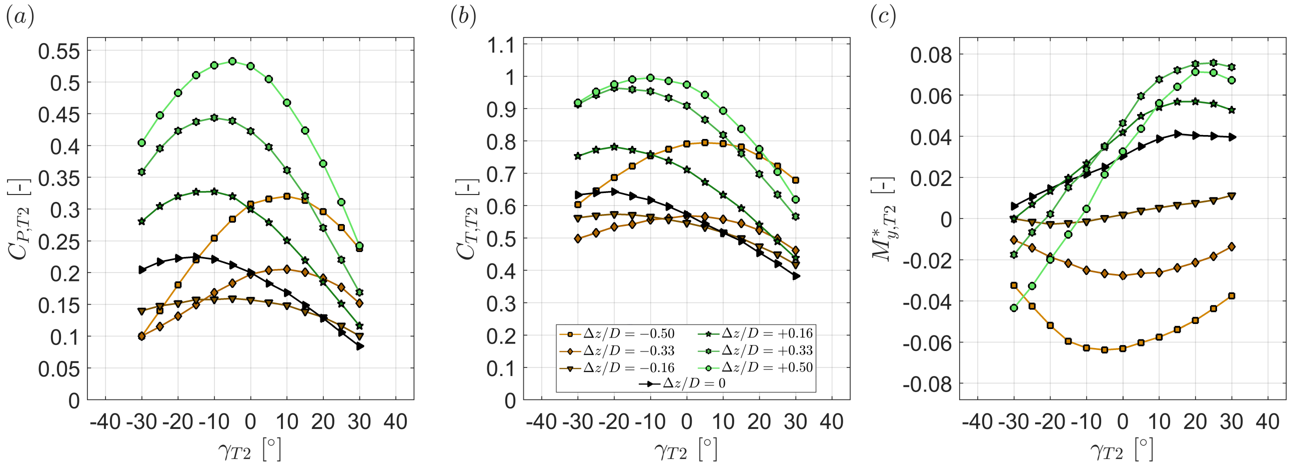

Figure 12. Downstream turbine **(a)** power coefficient, **(b)** thrust coefficient and **(c)** normalized yaw moment as a function of its yaw angle γ_{T2} for different lateral offset position $\Delta z/D$. The upstream turbine yaw angle is kept constant at $\gamma_{T1} = 30°$. The downstream turbine T2 is located at $x/D = 3$. The turbines are exposed to inflow B.

combined power gains of approximately 3% are measured for a moderate downstream turbine yaw angles ($\gamma_{T2} \pm 10 - \pm 15°$). The combined power characteristics are observed to be quite symmetrical with respect to downstream turbine offset and its yaw angle. Slightly higher relative power gains are obtained for the case of an upstream turbine yaw angle of $\gamma_{T1} = +30°$ (Figure 13 (b)). A maximum power gain of about 5% is measured for offset positions $\Delta z/D = 0$ and $+0.16$ and a downstream turbine yaw angle between $\gamma_{T1} = -10°$ and $-15°$. Note that the downstream turbine's tip speed ratio λ_{T2} is kept constant when the downstream turbine is yawed. As no change in optimum tip speed ratio was measured for yaw angle variations up to $\gamma = \pm 30°$ in undisturbed inflow, it is at this stage assumed, that no further adjustments of the tip speed ratio in a partial wake are needed for an optimal downstream turbine power output.

~~In conclusion, this third test case demonstrates that~~ In conclusion, this third test case demonstrates that moderate downstream turbine ~~yawing can be an effective method to mitigate yaw moments acting on the rotor in partial wake situations, while simultaneously obtaining slight power gains.~~ yawing can be an effective method to mitigate yaw moments acting on the rotor in partial wake situations, while simultaneously obtaining slight power gains.

4 ~~Discussion~~

~~When assessing the operational characteristics of the upstream turbine in dependency of its yaw angle, some asymmetries were apparent. While the power and thrust curves only showed slight deviations for positive and the corresponding negative yaw angle, higher asymmetries were found for the yaw moment. 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~~

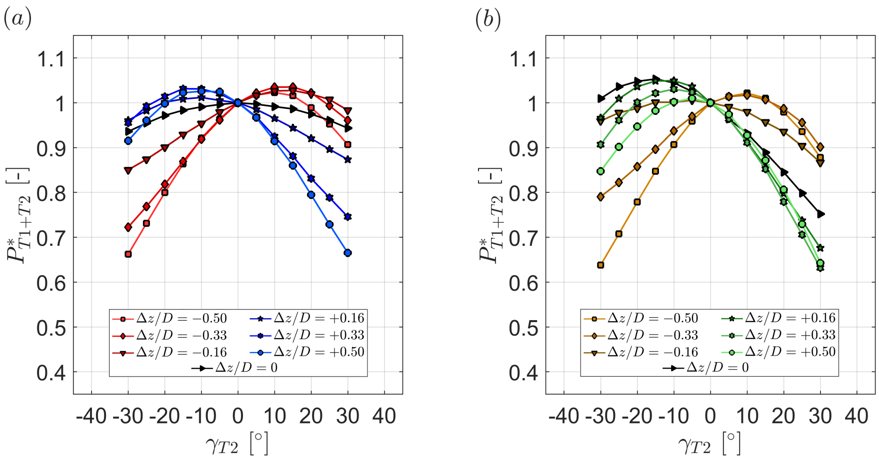

Figure 13. Combined relative power P^*_{T1+T2} of two turbines as a function of the downstream turbine yaw angle γ_{T2} for different lateral offset positions $\Delta z/D$. The upstream turbine yaw angle is kept constant at **(a)** $\gamma_{T1} = 0°$ and **(b)** $\gamma_{T1} = 30°$ respectively. The downstream turbine T2 is located at $x/D = 3$. The turbines are exposed to inflow B.

~~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. (2018). 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.Moreover, our study emphasized even stronger asymmetries in loads and power on an aligned downstream turbine . The combined power output of a two turbine setup consequently also featured an asymmetric distribution, which has been previously observed in an computational study Gebraad et al. (2016) and a similar experimental setup by **?**. 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. The major contributor to an asymmetric combined power distribution was seen to be the downstream turbine power. The yaw angle dependency of downstream turbine power is in direct relation to an asymmetric wake deflection observed on the same setup by in Bartl et al. (2018). Therein, the wake deflection is slightly larger for negative yaw angles than for the corresponding positive yaw angles, a trend which is seen to directly affect the downstream turbine power, thrust and yaw moment distribution.The present results further demonstrate a significant influence of the inflow turbulence level on the effectiveness of wake steering by yaw. The relative power gains were observed to be significantly larger for lower inflow turbulence levels (11% versus 8%). The reason might to a small degree be differences in wake deflection (Bartl et al., 2018), but can mostly be subscribed to lower average kinetic energy levels in wakes for turbines exposed to low inflow turbulence. When deflecting a kinetic energy sink away from the downstream rotor, the relative gains in combined power are higher. Alongside with combined power increases, the results demonstrated a linear increase in the upstream turbine's yaw moments with its yaw angle. For wake steering behind an upstream turbine, partial wake impingement~~

~~situations arise for an aligned downstream turbine , resulting in increased yaw moments also on the downstream turbine.In a real wind farm exposed to varying wind directions, however, partial wake situations, in which the downstream turbine is laterally offset are just as important as the aligned case . For a lateral offset of half a rotor diameter, for instance, it is demonstrated, that upstream turbine yaw control is able to steer most of the wake flow away from an offset downstream turbine . Consequently, both the combined power increases and yaw moments on the downstream turbine are significantly mitigated. This finding experimentally confirms results of a similar test case recently computed with a model-framework by van Dijk et al. (2017). For an offset of $\Delta z/D = +0.33$, we measured a maximum power increase of about 13% for when yawing the upstream turbine from $\gamma_{T1} = 0°$ to $+30°$. Although not directly comparable, this result is estimated to be at the same order of magnitude as power gains experimentally obtained by Campagnolo et al. (2016), who measured a combined power increase of 21% for a setup of three model turbines with an lateral offset of $\Delta z/D = +0.45$. Furthermore, our results indicated a not perfectly symmetrical distribution of the downstream turbine power and thrust coefficients with respect to its positive or negative offset position, as slightly higher power coefficients were obtained for negative offset positions. The reason for this is deemed to be an asymmetric velocity deficit in the non-yawed wake as indicated in Pierella and Sætran (2017) and Bartl et al. (2018).In a final test case, we introduced the concept of downstream turbine yawing in partial wake overlap situations for the purpose of load mitigation. The concept suggests that yawing a downstream turbine opposed to a strong horizontally sheared flow is able to mitigate rotor's yaw moments while simultaneously increasing the rotor 's power output. The horizontally sheared flow is in this case the transition zone between the low- velocity wake flow to the high-velocity freestream flow. A mitigation of yaw moments by yawing the rotor opposed to the shear is intuitively imaginable, while the simultaneous power increase might be surprising. Similar effects have, however, been reported in 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. The potential of load reductions of a single turbine by yawing has been previously discussed by Kragh and Hansen (2014), in situationswhere 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. The power output and yaw moment distribution was however not completely symmetrical with respect to yaw angle γ_{T2} and offset position $\Delta z/D$. Besides the slightly asymmetric streamwise wake flow, also the interaction of the downstream turbine with respect to the wake rotation of the upstream turbine might cause this asymmetry. A characterization of the wake rotation and asymmetric freestream flow entrainment in the wake behind the same rotor is given by Pierella and Sætran (2017). As a yawed operation of a downstream rotor in a partial wake of an upstream turbine is highly complex, a combination of a number of different factors are assumed to influence wake-rotor interaction, making a clear conclusion difficult at this stage.~~

4 Conclusions

A wind tunnel experiment studying the effects of intentional yaw misalignment on the power production and yaw moments of a downstream turbine was presented. Both, full wake impingement and partial wake overlap ~~situations~~ were investigated. For partial wake overlap, the concept of downstream turbine yawing for the purpose of yaw moment mitigation ~~was investigated for different lateral offset positions~~is examined.

It is demonstrated that upstream turbine yaw misalignment is able to increase the combined power production of the two turbines for both partial and full wake overlap setups. For aligned turbines the combined array power was increased up to 11% for a separation distance of $x/D = 6$ and low inflow turbulence levels ($TI_A = 0.23\%$). At a higher inflow turbulence of $TI_B = 10.0\%$, however, the relative power increase was assessed to be only 8%. For smaller turbine separation distances, combined power gains were assessed to be even smaller. The distribution of combined power gains in dependency of the upstream turbine yaw angle was observed to be rather asymmetrical. The formation of not entirely symmetric velocity deficit shapes in the wake was deemed to be the main reason for that finding.

The obtained power gains were assessed to be at the cost of increased yaw moments on the upstream rotor. The yaw moments on the upstream rotor are observed to increase roughly linearly with increasing yaw angle, but are not entirely symmetrical distributed. Upstream turbine yaw control is moreover seen to directly influence the yaw moments on a downstream rotor. For aligned turbine positions, the downstream turbine yaw moments are observed to increase to similar magnitudes as for the upstream turbine. These results highlight the importance of also taking loads into account when optimizing layout and control of a wind farm.

Further, we demonstrate advantages of upstream turbine yaw control for load reduction and power increases on an offset downstream turbine. For situations, in which the downstream turbine is impinged by a partial wake, upstream turbine yaw control can redirect the wake either on or away from the downstream rotor. In case the wake is directed onto the downstream turbine's rotor swept area, its yaw moments and power production reduce. If the lateral offset between the turbines is large enough, the wake can be deflected entirely away from the downstream turbine, maximizing its power and canceling out yaw moments.

Moreover, a final test case proved the concept of yaw control for yaw moment mitigation on a downstream turbine operated in ~~a~~ partial wake overlap~~situation~~. While yaw moments are observed to decrease when yawing the rotor opposed to the shear layer in the incoming wake flow, also the turbine's power output is seen to increase. These results illustrate the importance for combined power and load optimization on all turbines in a wind farm.

Competing interests. The authors declare that there are no competing interests.

References

Adaramola, M. and Krogstad, P.-Å.: Experimental investigation of wake effects on wind turbine performance, Renewable Energy, 36, 2078–2086, doi:10.1016/j.renene.2011.01.024, 2011.

Andersen, S., Sørensen, J., and Mikkelsen, R.: Performance and Equivalent Loads of Wind Turbines in Large Wind Farms, Journal of Physics: Conference Series, 854, 012 001, doi:10.1088/1742-6596/854/1/012001, 2017.

Annoni, J., Gebraad, P., Scholbrock, A., Fleming, P., and van Wingerden, J.: Analysis of axial-induction-based wind plant control using an engineering and a high-order wind plant model, Wind Energy, 19, 1135–1150, doi:10.1002/we.1891, 2016.

Bartl, J. and Sætran, L.: Experimental testing of axial induction based control strategies for wake control and wind farm optimization, Journal of Physics: Conference Series, 753, 032 035, doi:10.1088/1742-6596/753/3/032035, 2016.

Bartl, J. and Sætran, L.: Blind test comparison of the performance and wake flow between two in-line wind turbines exposed to different turbulent inflow conditions, Wind Energy Science, 2, 55–76, doi:10.5194/wes-2-55-2017, 2017.

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

Bastankhah, M. and Porté-Agel, F.: Experimental and theoretical study of wind turbine wakes in yawed conditions, Journal of Fluid Mechanics, 806, 506–541, doi:10.1017/jfm.2016.595, 2016.

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, 65 105, doi:10.1063/1.4984078, 2017.

Campagnolo, F., Petrović, V., Bottasso, C., and Croce, A.: Wind Tunnel Testing of Wake Control Strategies, American Control Conference, doi:10.1109/ACC.2016.7524965, 2016.

Damiani, R., Dana, S., Annoni, J., Fleming, P., Roadman, J., van Dam, J., and Dykes, K.: Assessment of wind turbine component loads under yaw-offset conditions, Wind Energ. Sci., 3, 173–189, doi:10.5194/wes-3-173-2018, 2018.

Fleming, P., Gebraad, P., Lee, S., van Wingerden, J.-W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P., and Moriarty, P.: Evaluating techniques for redirecting turbine wakes using SOWFA, Renewable Energy, 70, 211–218, doi:10.1016/j.renene.2014.02.015, 2014.

Fleming, P., Gebraad, P. M., Lee, S., van 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, 18, 2135–2143, doi:10.1002/we.1810, 2015.

Gebraad, P. M. O., Fleming, P. A., and Wingerden, J. W. v.: Comparison of Actuation Methods for Wake Control in Wind Plants, American Control Conference, doi:10.1109/ACC.2015.7170977, 2015.

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, 19, 95–114, doi:10.1002/we.1822, 2016.

Howland, M., Bossuyt, J., Martinez-Tossas, L., Meyers, J., and Meneveau, C.: Wake Structure of Wind Turbines in Yaw under Uniform Inflow Conditions, Journal of Renewable and Sustainable Energy, 8, 043 301, doi:10.1063/1.4955091, 2016.

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, 13, 559–572, doi:10.1002/we.380, 2010.

Kim, S.-H., Shin, H.-K., Joo, Y.-C., and Kim, K.-H.: A study of the wake effects on the wind characteristics and fatigue loads for the turbines in a wind farm, Renewable Energy, 74, 536–543, doi:10.1016/j.renene.2014.08.054, 2015.

Knudsen, T., Bak, T., and Svenstrup, M.: Survey of wind farm control—power and fatigue optimization, Wind Energy, 18, 1333–1351, doi:10.1002/we.1760, 2014.

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.

Krogstad, P.-A. 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.

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.

Micallef, D. and Sant, T.: Wind Turbines - Design, Control and Applications, InTech, doi:10.5772/63445, 2016.

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.

Pierella, F. and Sætran, L.: Wind tunnel investigation on the effect of the turbine tower on wind turbines wake symmetry, Wind Energy, 20, 1753–1769, doi:10.1002/we.2120, 2017.

Ryi, J., Rhee, W., Hwang, U., and 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.

Sarlak, H., Nishino, T., Martinez-Tossas, L., Meneveau, C., and Sørensen, J.: 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.

Schepers, J. G., K. Boorsma, K., and Munduate, X.: Final Results from Mexnext-I: Analysis of detailed aerodynamic measurements on a 4.5 m diameter rotor placed in the large German Dutch Wind Tunnel DNW, Journal of Physics: Conference Series, 555, 012 089, doi:10.1088/1742-6596/555/1/012089, 2014.

Schottler, J., Hölling, A., Peinke, J., and Hölling, M.: Wind tunnel tests on controllable model wind turbines in yaw, AIAA 34th Wind Energy Symposium, p. 1523, doi:10.2514/6.2016-1523, 2016.

Schottler, J., Hölling, A., Peinke, J., and Hölling, M.: Brief communication: On the influence of vertical wind shear on the combined power output of two model wind turbines in yaw, Wind Energy Science, 2, 439–442, doi:10.5194/wes-2-439-2017, 2017.

Schottler, J., Bartl, J., Mühle, F., Sætran, L., Peinke, J., and Hölling, M.: Wind tunnel experiments on wind turbine wakes in yaw: redefining the wake width, Wind Energ. Sci., 3, 257–273, doi:10.5194/wes-3-257-2018, 2018.

Schreiber, J., Cacciola, S., Campagnolo, F., Petrovic, V., Mourembles, D., and Bottasso, C. L.: Wind shear estimation and wake detection by rotor loads - First wind tunnel verification, Journal of Physics: Conference Series, 753, 032 027, doi:10.1088/1742-6596/753/3/032027, 2016.

Sørensen, J., Shen, W., and Mikkelsen, R.: Wall correction model for wind tunnels with open test section, AIAA Journal, 44, 1890–1894, 2006.

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.

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, 1, 129–141, doi:10.5194/wes-1-129-2016, 2016.

Wheeler, A. J. and Ganji, A. R.: Introduction to engineering experimentation, Upper Saddle River, NJ, USA, Pearson/Prentice Hall, XI, third edition edn., 2004.

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).*

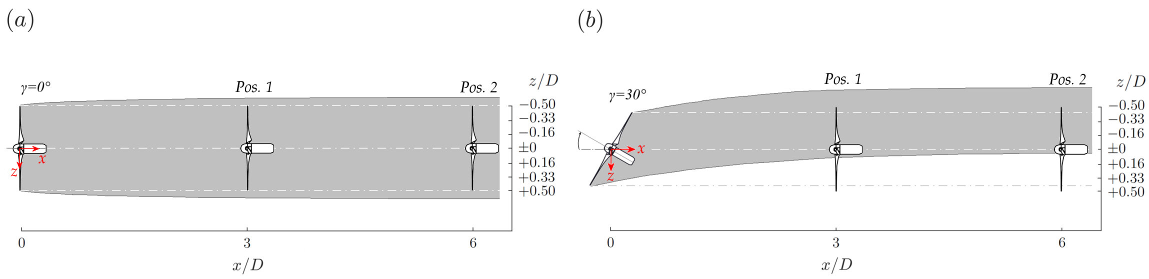

Figure 1: **Figure 2.** Topview of the aligned downstream turbine operated in the wake of an upstream turbine at the two different positions $x/D = 3$ and $x/D = 6$. The wake flow is indicated ~~by measured example cases~~ for **(a)** $\gamma_{T1} = 0°$ and **(b)** $\gamma_{T1} = 30°$.

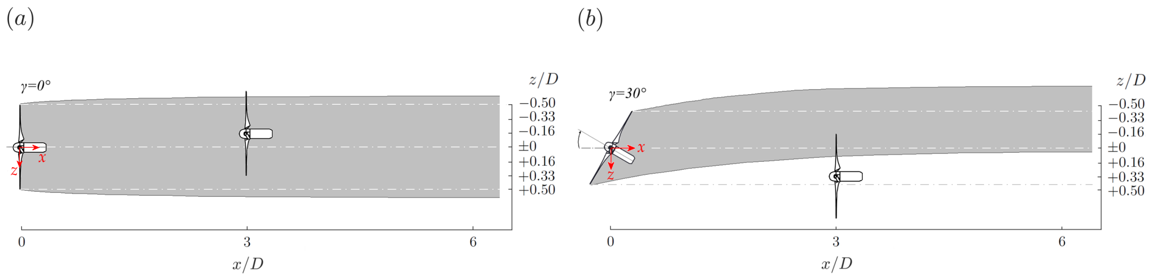

Figure 2: **Figure 6.** Topview of two lateral offset positions ((**a**) $z/D = -0.16$ and (**b**) $z/D = +0.33$) of the downstream turbine while operated in the wake of an upstream turbine at $x/D = 3$. The upstream turbine is operated at **(a)** $\gamma_{T1} = 0°$ and **(b)** $\gamma_{T1} = 30°$.

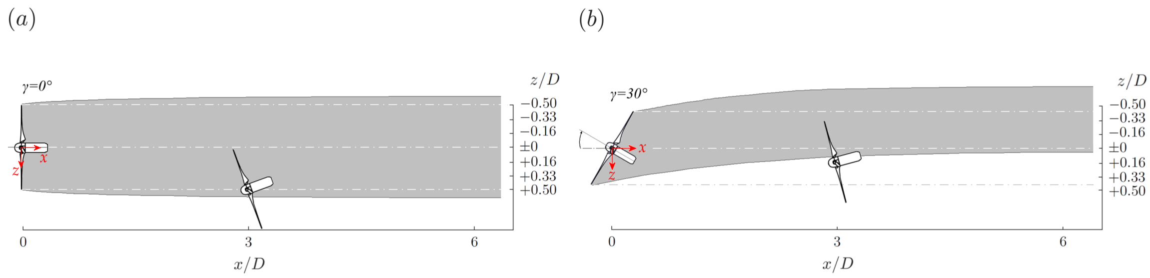

Figure 3: **Figure 10. (a)** Topview of the downstream turbine T2 operated at a lateral offset position $z/D = +0.50$ and a yaw angle of $\gamma_{T2} = -20°$ in the wake of an upstream turbine T1 operated at $\gamma_{T1} = 0°$. **(b)** Topview of the downstream turbine T2 operated at a lateral offset 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 $\pm30°$ 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.

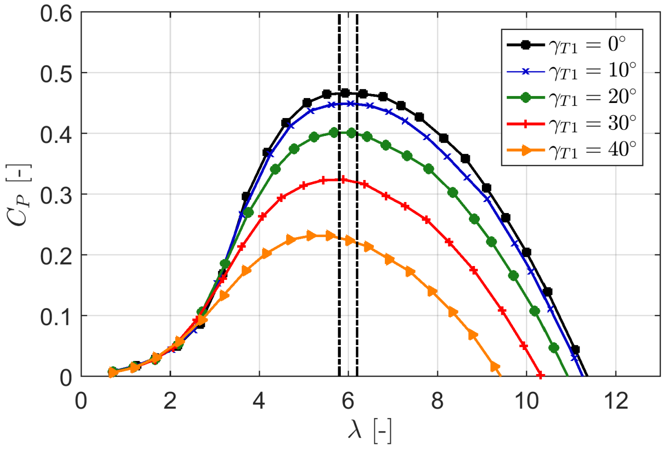

Figure 4: Tip-speed-ratio-dependent operating characteristics of the upstream turbine T1 operated at yaw angles from $\gamma_{T1} = 0°$ to $+40°$ at inflow B.

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 $\pm30°$. A slight shift towards a lower optimum tip speed ratio of $\lambda_{T1} = 5.5$ is measured for $\gamma_{T1} = \pm40°$ (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~~ $\cancel{u/u_{ref} = 1.10}$ 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

[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] Damiani, R., Dana, S., Annoni, J., Fleming, P., Roadman, J., van Dam, J., and Dykes, K.: Assessment of Wind Turbine Component Loads Under Yaw-Offset Conditions, Wind Energ. Sci., 3, 173–189, doi:10.5194/wes-3-173-2018, 2018.

[3] 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, 19, 95–114, doi:10.1002/we.1822, 2016.

[4] Schottler, J., Hölling, A., Peinke, J., and Hölling, M.: Wind tunnel tests on controllable model wind turbines in yaw, AIAA 34thWind Energy Symposium, 1523, doi:10.2514/6.2016-1523, 2015.

[5] Schottler, J., Hölling, A., Peinke, J., and Hölling, M.: Brief communication: On the influence of vertical wind shear on the combined power output of two model wind turbines in yaw, Wind Energy Science, 2, 439–442, doi: 10.5194/wes-2-439-2017, 2017a.

[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.

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

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.

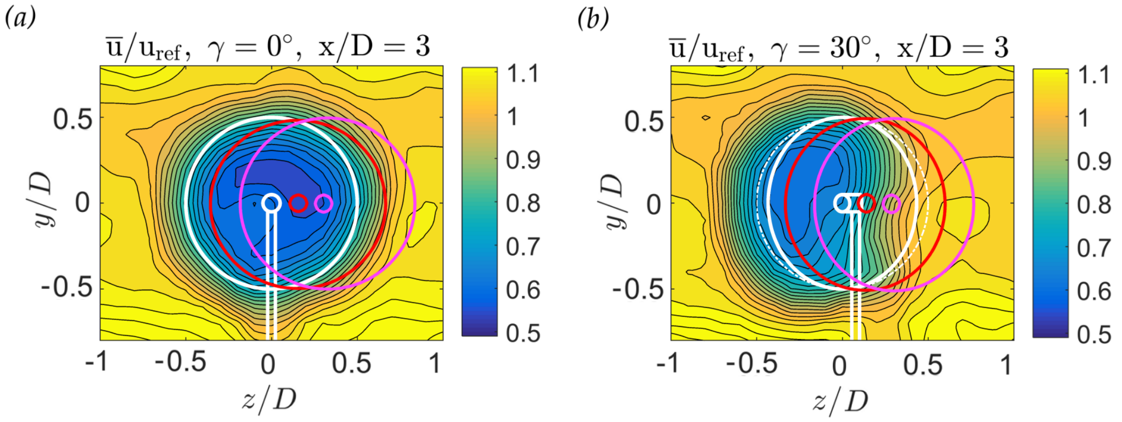

Figure 1: Mean streamwise velocity $\overline{u}/u_{ref}$ in a cross-sectional cut at $x/D = 3$ through the wake flow behind a single turbine for **(a)** $\gamma_{T1} = 0°$ and **(b)** $\gamma_{T1} = 30°$. The red and pink circles indicate the locations of an imaginary downstream turbine operated at 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.

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 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 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 α 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.

Authors' response to Referee #3:

We thank the referee for reviewing this manuscript and appreciate the constructive feedback and the improving comments. At this stage, we answer to referee #3's comments and propose 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

Comment (1)

Page 5, Line 14-15: The sentence should be rewritten as follows: "The total uncertainties in power and thrust coefficient are 0.006 (2.5% of the absolute 15 CP -value) and 0.007 (0.9% of the absolute CT-value), respectively."

Thank you for the hint. We will change the sentence 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.

Comment (2)

Page 8, line 2-3: "The asymmetric wake deflection is considered to be the main reason for the asymmetric distribution of T2's yaw moments.". It is quite clear that yawing the upstream wind turbine in two different direction leads to different power gain on the downstream one. The authors trace back this behavior to not-well specified asymmetric wake deflection. It would be interesting, for the readers, if the authors could provide a deeper insight into this topic, considering that the authors (previously cited publication) already measured the wake shed by the upstream WT for two different yaw misalignment. Is the observed asymmetry due to asymmetric wake displacement or wake recovery?

Thank you for this very constructive comment. This is indeed one of the most important observations in this publication, and we agree that the underlying reasons for the asymmetry require a more detailed explanation. A previous publication by Bartl et al. (2018) discussed the asymmetries in wake displacement in detail, but we consider it to be important to revive the main reason for the asymmetric wake deflection here. For clarification, the following changes are suggested for the manuscript:

p.8, l.2 f:

The asymmetric wake deflection for positive and negative yaw angles is considered to be the main reason for the asymmetric distribution of T2's yaw moments. As discussed in an analysis of the wake flow behind a yawed turbine by Bartl et al. (2018), the overall wake displacement for positive and negative yaw angles was observed to be slightly asymmetric. The interaction of the rotor wake with the turbine tower was identified to be the main contributor for the asymmetric wake flow. This finding is supported by a previous study on the non-yawed wake by Pierella and Sætran (2017), in which they attributed a significant displacement of the wake center to the interaction with the turbine tower.

Comment (3)

Page 9, line 4-5: "Moreover, the downstream turbine's power output at low inflow turbulence (inflow A) is observed to be more asymmetric with respect to T1 than at high inflow turbulence (B)." This is quite surprising since one would expect that as more homogenous the flow is, as higher the symmetry of the phenomena is. It would be interesting if the authors could argue more about the reasons behind the observed data.

This is a very good comment, that also needs some more detailed explanation in the text. As the downstream turbine is operated in the partial wake of the upstream turbine, the inflow to the downstream turbine is no longer homogeneous. As shown in the analysis of the wake flow in Bartl et al. (2018), the deflection of the wake for positive and negative yaw angles is more asymmetric for an inflow of low turbulence (Inflow A). This can be qualitatively observed in the comparison of the mean wake flow at $x/D = 6$ presented in Figure 1 below. For a quantification of the shape and deflection of the mean wake flow for different inflow conditions, it is referred to Figure 7 and Figure 9 in Bartl et al. (2018). In order to make a clearer connection to the asymmetries in the incoming wake flow, the following modifications in the text are suggested:

p.9, l.4 ff:
Moreover, the downstream turbine's power output at low inflow turbulence (inflow A) is observed to be more asymmetric with respect to than at high inflow turbulence (inflow B). Especially for $x/D = 6$, the downstream turbine power $C_{P,T2}$ is strongly asymmetric for inflow A. This observation corresponds well with the asymmetry in the mean streamwise wake flow measured for positive and negative yaw angles reported in Bartl et al. (2018). Therein, the wake flow behind a positively and negatively yawed turbine exposed to inflow A was observed to feature a higher degree of asymmetry than for the same turbine exposed to inflow B.

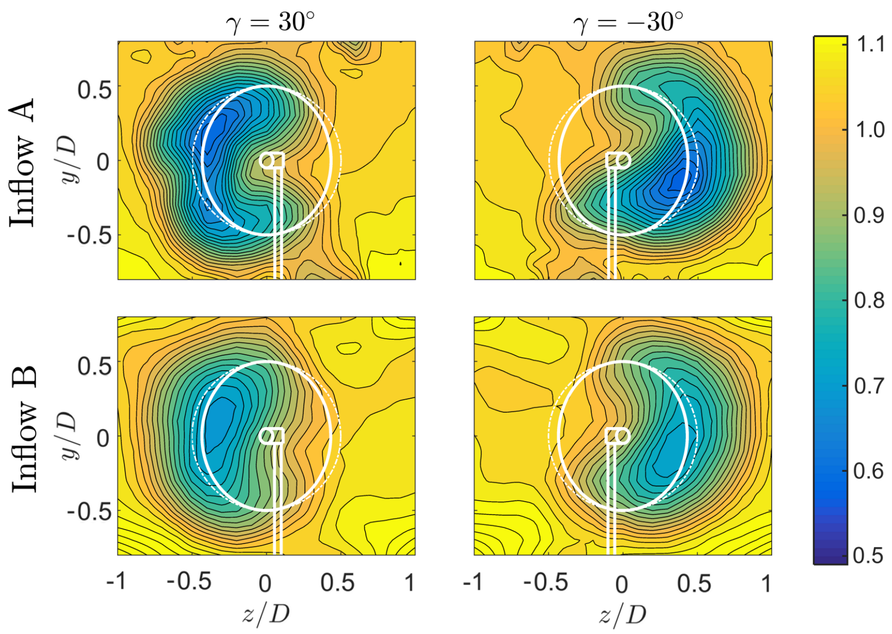

Figure 1: Mean streamwise velocity $\overline{u}/u_{ref}$ in cross-sectional cuts at $x/D = 6$ through the wake flow behind a single turbine for $\gamma_{T1} = 30°$ and $\gamma_{T1} = -30°$ for inflow conditions A (upper row) and B (lower row). The plots are adapted from Bartl et al. (2018) and were measured behind the same model turbine under the same boundary conditions.

Comment (4)

Page 10. In a previous sentence, the authors reported that quite substantial wake blockage was observed, leading to an increase of 10% of the speed outside the wake of the upstream model. How much is the blockage affecting the results presented in Figure 5? Moreover, the rotor speed of the upstream model was kept constant even for a very high yaw misalignment, which implies that the upstream model is operating at sub-optimal conditions. Indeed, when yawing a wind turbine it would have been better to keep constant the effective TSR, i.e. the TSR computed by using the component of the wind speed orthogonal to the rotor disk. How much power is lost, on the upstream model, due to the fact the model itself is operating, while yawed, at sub-optimal conditions? How this affects the results presented in figure 5?

Answer to first part of the question (how much blockage affects results): This is a very good comment, which points to one of the main weaknesses of the present study. In general, it is very difficult to quantify, how much the blockage of the wind tunnel walls affects the combined power results. For this study, we have not tried to use any kind of blockage correction models on our results.

It would be possible to correct the power and thrust of a single turbine operated in a wind tunnel. Different models have been proposed by, amongst others, Sørensen et al. (2006) and Ryi et al. (2015). However, wind tunnel blockage possibly also affects the deflection and expansion of the wake flow, which is more difficult to correct. A dedicated study on the effects of blockage on the wake development 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%. The third and most difficult component of an assessment of the effects of blockage on the performance of a turbine array would be the performance of the downstream turbine operated in a (partial) wake of an upstream turbine. To our knowledge, there are currently no correction models available for this rather complex case. A comparative computational study of our setup in a domain, which includes and also omits the wind tunnel boundaries could be performed to shed light on this problem.
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.

Answer to second part of the question (how much additional upstream turbine TSR-control would affect results): Also this second part of the question is a very good comment. A similar comment was given by reviewer #1. 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 2 for positive yaw angles only (note that negative yaw angles have an insignificantly higher magnitude, but 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°. In conclusion, we think that only the results for the extreme yaw angles of $\pm 40°$ could slightly be affected by a non-optimum TSR control of the upstream turbine (ref. Figure 5 of the manuscript). Fore all other yaw angles, the upstream turbine was operated very close to its optimum.

Nevertheless, we suggest to add some additional lines of text to the manuscript discussing the TSR-dependency.

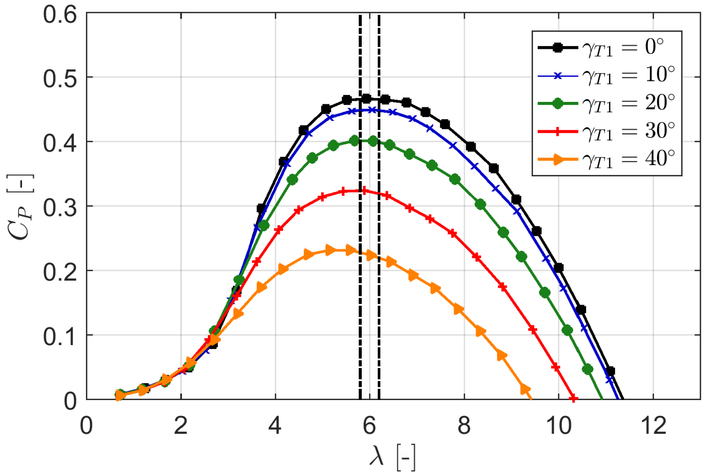

Figure 2: Tip-speed-ratio-dependent operating characteristics of the upstream turbine T1 operated at yaw angles from $\gamma_{T1} = 0°$ to $+40°$ at inflow B.

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.*

Comment (5)

Page 11, line 1: the authors claim that the lack of symmetry, in the power output, for a downstream model placed on the right or left side of the upstream one, is due to "not perfectly axis-symmetric velocity deficit at x/D = 3". Since the authors measured the wake shed by the upstream wind turbine, it would be beneficial to add also a quantitative comparison: could the measured not perfectly axis-symmetric velocity deficit quantitatively explain the observed difference of power output?

This is a very good comment. Until now, the statement was only based on a qualitative assessment of the kinetic energy available in the wake. As observed in Figure 3, the left part (negative z/D) of the wake at $x/D = 3$ seems to contain slightly more kinetic energy than the right part (positive z/D).
As we are also able to calculate the available kinetic power contained in the wake (see

"available power method" described in Bartl et al. (2018)), we can quantify the power contained in circular areas at different positions in the wake. If we now laterally traverse an imaginary downstream turbine (red circle) from $z/D = -0.5$ to $z/D = +0.5$ through the wake and integrate over all measured and interpolated velocity points, we can assess the theoretical power contained in the wake for all lateral offset positions. The results for the calculated available power for 50 offset positions is shown in the red triangles in Figure 4. This curve is compared to the actually measured power of the downstream turbine in the wake (7 positions, 7 red circular dots) in Figure 4. Although the curves do not perfectly match (due to simplifications in the calculation of the power; the kinetic energy is not converted by a "real" rotor), the general trends of both curves confirm the initial assumption that more kinetic energy is available in the left part of the wake (negative z/D) than in the right part (positive z/D). Aside from the measured $C_{P,T2}$ values, also the calculated Available power values from the wake measurements confirm higher power contained for negative z/D-values.
We will add some lines to the passage in the text to support this statement, but suggest not to include further plots at this stage.

p.11, l.8 ff:
T2's power coefficient is observed not to be entirely symmetric with respect to its lateral position in the wake. Slightly higher power coefficients are measured for negative offset positions. 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). An analysis of the available kinetic energy contained in the wake at $x/D = 3$ behind a non-yawed upstream turbine confirmed a higher kinetic energy over an imaginary rotor swept area for negative lateral offsets z/D than for positive offsets.

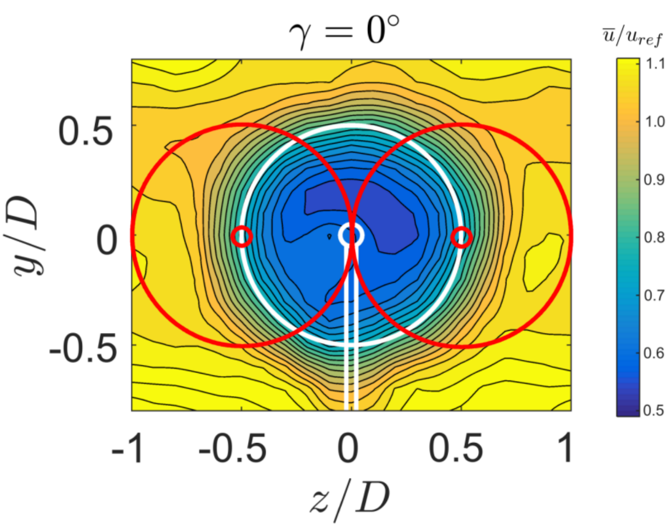

Figure 3: Mean streamwise velocity $\overline{u}/u_{ref}$ in a cross-sectional cut at $x/D = 3$ through the wake flow behind a single turbine for $\gamma_{T1} = 0°$ exposed to inflow conditions B. The plot is adapted from Bartl et al. (2018) and was measured behind the same model turbine under the same boundary conditions.

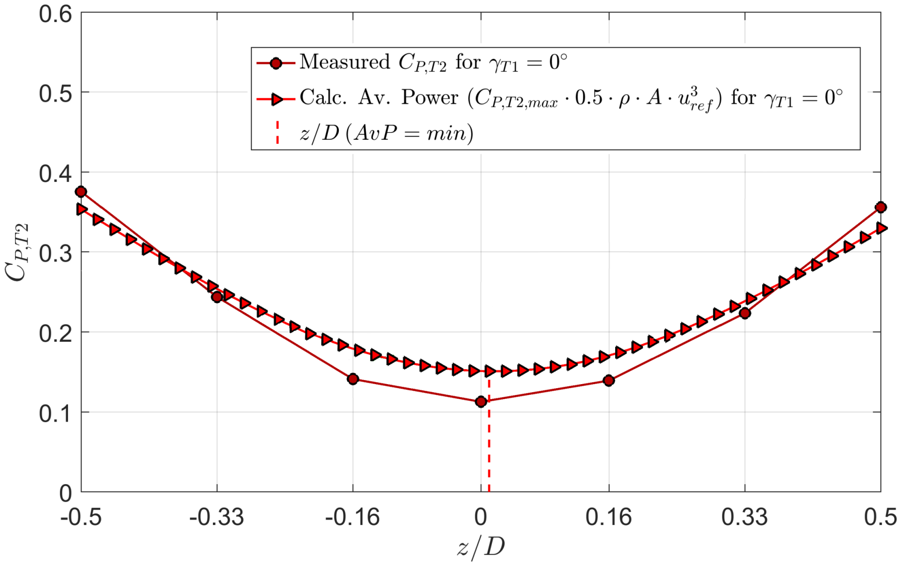

Figure 4: Comparison of the actually measured power of a downstream turbine and calculated kinetic power from wake flow measurements of an imaginary downstream turbine for different lateral offset positions z/D = [-0.5, ..., +0.5]

Comment (6)

Page 12: which is the effect of wake blockage on the data reported in Figure 8? As the authors properly write, the high Cp, measured on the downstream turbine experiencing partial-wake conditions, is due to blockage. How would the plots in figure 8 look like if the effects of blockage were compensated?

This comment is following up on the issue of wind tunnel blockage already discussed in Comment (4). As already mentioned in the answer to Comment (4), it is not possible to compensate for blockage effects on the power output of the downstream turbine operated in a partial wake with simple correction models. Advanced CFD techniques could simulate the flow around the turbine array with and without wind tunnel walls, but that would be a rather expensive study on its own.
One can use rough estimates for the power of the downstream turbine for cases, in which the wake is almost entirely deflected away from the downstream rotor, e.g. for $\gamma_{TI} = 30°$ and $z/D = +0.5$ (blue point furthest to the right in Figure 8 (a) of the manuscript). Instead of a power coefficient of $C_{P,T2;uncorr.} = 0.52$ one would obtain a blockage-corrected power coefficient of $C_{P,T2,corr.} = 0.39$, assuming that the downstream rotor is mostly exposed to undisturbed but blocked freestream flow ($C_{P,T2,corr.} = C_{P,T2;uncorr.}/(u_{wake}/u_{ref})^3 = 0.52/1.10^3 = 0.39$). For smaller lateral offsets, however, the situation is unfortunately more complex, as the downstream rotor is impinged by a partial wake.
For clarification, we suggest also to add a sentence in this passage of the manuscript:

p.12, l.22 f:
A power coefficient of $C_{P,T2} > 0.50$ *can be explained by increased freestream velocity lev-*

els of u/u_{ref} = 1.10 (Bartl et al., 2018) caused by wind tunnel blockage. Unfortunately, it is not possible to correct for blockage effects on the downstream turbine power, thrust and yaw moments with simple correction models. The influence of wind tunnel blockage on the highly complex inflow to the downstream turbine operated in a partial wake would have to be quantified by dedicated experiments or high-fidelity simulations.

Comment (7)

Page 13, Figure 8. The caption reports: "The upstream turbine yaw angle is kept constant at gamma = 0". It should be "The downstream turbine yaw angle is kept constant at gamma = 0"

Thank you for pointing at this mistake. It is indeed the downstream turbine yaw angle, which is referred to.

p.13, caption of Figure 8:
The ~~upstream~~ downstream turbine yaw angle is kept constant at $\cancel{\gamma_{T1} = 0^\circ}$ $\gamma_{T2} = 0^\circ$.

Comment (8)

Page 16: quite surprisingly, it is found that the downstream wind turbine should be yawed by 10-15 degrees (quite a lot!) in order to improve its power production. However, again the TSR of the second turbine was not changed while varying its misalignment angle. This could again lead to sub-optimal operating conditions. If the models were operated as full-scale wind turbines are (constant effective TSR) the conclusions could have been quite different. The authors should comment on this.

Thank you for this very good comment. In our experiment, we pursued the following sequence :
(1) we scanned all tip speed ratios λ_{T2} for the downstream turbine located at a certain offset position,
(2) we operated the downstream turbine at its optimum tip speed ratio $\lambda_{T2,opt}$ for this offset,
(3) we varied the downstream turbine yaw angle in steps of $\Delta\gamma_{T2} = 5^\circ$.
When exposed to undisturbed inflow conditions the downstream turbine T2 has exactly the same operating characteristics (λ, γ) as the upstream turbine T1. These are shown in Figure 2 in this "Answers document". It is observed that the optimum tip speed ratio is more or less constant ($\lambda = 6.0$ in undisturbed inflow) up to yaw angles of $\gamma = \pm 30^\circ$. Therefore, it can be assumed, that also the optimum tip speed ratio of the downstream turbine does not significantly change as soon as the downstream turbine is yawed in a partial wake. At this stage, we do not see any indication, why the downstream turbine should have been operated at sub-optimal conditions. However, we cannot be 100% sure about this, as we do not completely know the three-dimensional inflow field of the partial wake and if the turbine's operating conditions change in such

an environment. Assuming that it could be possible, that an additional adjustment of the tip speed ratio λ_{T2} would optimize the turbine's performance, this would have resulted in an even bigger power gain for the downstream turbine.
In any case, our intention was to show that downstream turbine yawing in a partial wake situation can benefit the power output (similar results were reported by McKay et al. (2013) in a full-scale test). In case additional TSR-control would have resulted in an additional power gain, our results would still be conservative. The general concept of power gains through downstream turbine yawing in a partial wake is therefore not in doubt.
Nevertheless, we agree that this concept requires further research, in order to completely understand the underlying physics. For this purpose, it would be helpful to have all three velocity components measured in the shear layer surrounding the wake to identify possible lateral flow components in this region. Also, additional TSR-variations of the yawed downstream turbine should be investigated.
We suggested to add some more lines to the manuscript:

p.16, l.7 f:
A maximum power gain of about 5% is measured for offset positions $z/D = 0$ *and* $+0.16$ *and a downstream turbine yaw angle between* $\gamma_{T1} = -10°$ *and* $-15°$. *Note that the downstream turbine's tip speed ratio* λ_{T2} *is kept constant when the downstream turbine is yawed. As no change in optimum tip speed ratio was measured for yaw angle variations up to* $\gamma = \pm 30°$ *in undisturbed inflow, it is at this stage assumed, that no further adjustments of the tip speed ratio in a partial wake are needed for an optimal downstream turbine power output.*

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] Pierella, F. and Sætran, L.: Wind tunnel investigation on the effect of the turbine tower on wind turbines wake symmetry, Wind Energy, 20, 1753-–1769, doi: 10.1002/we.2120, 2017.

[3] 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.

[4] 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.

[5] 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.

[6] 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.