

Reviewer Response
April 24, 2019

We thank the reviewers for their helpful and constructive remarks. We have prepared a revised version of the paper including the suggestions of the reviewers, and below outline these changes in response to your recommendations.

Additionally, since the original submission, both the FLORIS model and the energy ratio method have been improved somewhat independently of this research, and these improvements are reflected somewhat in the final analysis. The energy ratio method is described in greater detail, and a link to the source code are now included.

Reviewer 1:

Page 2 line 17, spelling of "University"

This is fixed

Page 15, last sentence is not entirely clear and a bit confusing.

This sentence is removed

Table 1: the difference in wind conditions between baseline and controlled could also be explained more clearly.

More text was included to make these cases more clear:

The energy ratio calculation is repeated on several differently-defined FLORIS models of the site to provide a point of comparison. An "Aligned" case simulates every observed wind speed and direction in the Baseline field data with all turbines perfectly aligned to the flow, while a "Baseline" case uses the actual small offsets observed. An "Optimal" case, simulates all the wind speeds and direction in the Controlled field data using the exact offset requested by the control strategy, while "Controlled" applies the actual achieved offset. These four settings are summarized in Table~\ref{tab:floris}. For each of the FLORIS models, and for each 1-minute wind speed and direction observed in the field, a matching FLORIS simulation was run and the power of T3 and T4 tabulated and the energy ratio computed. When considering gains in energy, "FLORIS Optimal Gain" refers to the change from "Aligned" to "Optimal" whereas "FLORIS Controlled Gain" refers to the change from "Baseline" to "Controlled".

Reviewer 2:

Author list: depending on their contribution you might consider to move some persons to the acknowledgment section.

The test campaign was a large group undertaking and it was decided to share authorship among those who worked across aspects of the campaign

Abstract: You could consider to add the 3.7% of the aggregated analysis as well. Wake steering is a wind farm control method and thus the effect to the combined energy is also very important.

Good point, this value is now added

Figure 4: You could add some other wind speed as well to provide a better feeling for the 2 D lookup-table.

This figure is updated to include additional wind speeds and the caption updated to reflect

Text to Figure 5: You could provide the time constants of the low pass filter. It is partly visible from Fig. 9, but might help to better understand the issue with the time offset.

Each of the filters has a 30-s time constant this is now included in the description.

And why did you use a filter for the offset? Wouldn't it be enough to have the inputs filtered?

It was felt more cautious to filter the offset to smooth the step changes when the wind direction changes from 139-138, however, indeed this appears now unnecessary and is not used in phase 2

Equation 1 and 2: You could mention that u^* is the frictional velocity, and 0 means perturbations.

This is corrected

And isn't the unit m missing in $L < -1000$?

This is corrected

Figure 6 and 7c are without a box, all others have one.

Figure 7c was updated to include a box to match the other subplots in that figure, while figure 6 was left for now since it stands alone, however this can be added in the final version

Figure 7c: After some time, I figured out that the third color is due to the overlay of baseline and controlled case. Couldn't you simply have to column for each wind speed bin? And what are the lines?

Figure 7c is replaced by a dodged histogram to make the comparison more visually apparent

Figure 7d and 8: What does the shading here mean? The 95% confidence interval seems to be unlikely, since the mean is not centered.

The points are medians and the shadings are 95% confidence of the medians, descriptions are updated in the legends and text

Equation 3: You could consider to describe all components of the equation. It is pretty clear what A means, but just for the sake of completeness.

These descriptions are added

And couldn't you use the mean power curve from T4 outside of the controlled region to get the power from the sodar within the controlled region instead of the power coefficient to avoid issues with wind speeds near rated?

The complexity of the terrain as the wind moves to the west or east cause the relationship between sodar and turbine to be non-constant outside of the controlled region unfortunately

Equation 4-6: you could consider to write the subscripts in normal text mode (not math mode).

This change is made

Page 14, line 15: There is an additional)

Fixed

Figure 11-15: Is the shading the 95% confidence interval? If so, you could add this to the captions or in the text.

This is the 95% interval, and the description now included the caption of figure 11:

Figure 11. Energy ratio for T3 for field data and the Baseline and Controlled FLORIS cases (see Table 1). An energy ratio of 0.5 corresponds to a production of 50% of the total expected based on the measured inflow without considering wakes. The vertical magenta lines indicate the region where control is applied and a difference between the Baseline and Controlled is expected. Size of circles at each point indicate the number of points in the bin, while the bands indicate 95% confidence as computed by the bootstrapping.

Also, the placing is a bit strange. . . e.g. Figure 15 is on page 20 and the reference on page 17... but might be the usual latex mystery

This is indeed a latex mystery, but we hope that working with the journal editors, the placement of figures can be more reasonably situated in the final version,

Initial Results From a Field Campaign of Wake Steering Applied at a Commercial Wind Farm: Part 1

Paul Fleming¹, Jennifer King¹, Katherine Dykes¹, Eric Simley¹, Jason Roadman¹, Andrew Scholbrock¹, Patrick Murphy^{1,3}, Julie K. Lundquist^{1,3}, Patrick Moriarty¹, Katherine Fleming¹, Jeroen van Dam¹, Christopher Bay¹, Rafael Mudafort¹, Hector Lopez², Jason Skopek², Michael Scott², Brady Ryan², Charles Guernsey², and Dan Brake²

¹National Wind Technology Center, National Renewable Energy Laboratory, Golden, CO, 80401, USA

²NextEra Energy Resources, 700 Universe Blvd, Juno Beach, FL 33408

³Dept. Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, CO, 80303, USA

Correspondence to: Paul Fleming (paul.fleming@nrel.gov)

Abstract. Wake steering is a form of wind farm control in which turbines use yaw offsets to affect wakes in order to yield an increase in total energy production. In this first phase of a study of wake steering at a commercial wind farm, two turbines implement a schedule of offsets. Results exploring the observed performance of wake steering are presented, as well as some first lessons learned. For two closely spaced turbines, an approximate ~~13~~14% increase in energy was measured on the downstream turbine over a 10° sector. ~~Additionally, the increase of energy for,~~ with a 4% increase in energy production of the combined upstream/downstream ~~pair was found to be in-line with prior prediction~~turbine pair. Finally, the influence of atmospheric stability over the results is explored.

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1 Introduction

Wind farm control is a field of research in which the control actions of individual turbines are coordinated to improve the total performance of the wind farm as defined by the total power production of the wind farm as well as the loads experienced by

downwind turbines. Wake steering is a form of wind farm control wherein an upstream turbine intentionally offsets its yaw angle with respect to the wind direction to benefit downstream turbines. Wagenaar et al. (2012); Dahlberg and Medici (2003).

Wake steering has been studied through wind tunnel studies [e.g., Medici and Alfredsson (2006); Park et al. (2016); Schottler et al. (2017); Bartl et al. (2018)], and large-eddy simulation (LES) studies of wake steering have been undertaken to date [see, for example, Fleming et al. (2015); Vollmer et al. (2016); Howland et al. (2016)]. Coupled with theoretical derivations, the results of the previously mentioned studies have enabled the development of control-oriented engineering models of wakes and wake steering that can be used to design and analyze wake steering controllers for wind farms, as well as predict the performance benefit. Important examples include the Jensen wake model (Jensen (1984)) and the model of wake steering of Jiménez et al. (2010).

FLOW Redirection and Induction in Steady State (FLORIS), (NREL (2019)), is a software repository that provides an engineering model of wake steering that can be used in the design and analysis of wind farm control applications (Gebraad et al. (2016)). Originally based on Jensen (1984) and Jiménez et al. (2010), it now employs the wake recovery and redirection models of Bastankhah and Porté-Agel (2014, 2016); Niayifar and Porté-Agel (2015). Annoni et al. (2018) provide a detailed description of the current FLORIS model. The FLORIS model is open source and available for download and collaborative development (<https://github.com/nrel/FLORIS>). Development is ongoing, and future models will incorporate the advances proposed in Martínez-Tossas et al. (2018).

Critical to advancement, improvement, and eventual adoption of wake steering are field trials of wake steering in realistic environments. Wagenaar et al. (2012) attempted wake steering at a scaled wind farm. One important campaign took place at the National Wind Technology Center in Boulder, Colorado. In that study, a rear-facing scanning lidar from the University of Stuttgart was placed on top of the nacelle of a GE 1.5-MW turbine, which held various yaw offset positions for periods of one hour at a time (Fleming et al. (2017a)). The data from that campaign were used to investigate the accuracy of predictions made by FLORIS (Annoni et al. (2018)) as well as the impact on turbine loads caused by yaw offsets (Damiani et al. (2017)). A related campaign is being undertaken at the Scaled Wind Farm Technology facility in Lubbock, Texas. Similar to the National Wind Technology Center study, a rear-facing lidar (in this case the Technical University of Denmark spinner lidar) is used to scan the wake of a V27 experimental turbine. The resulting data are used to examine wake behavior (Herges et al. (2017)) as well as understand loading impacts (White et al. (2018)). Finally, a first published field trial at a commercial offshore wind farm is presented in Fleming et al. (2017b). In that study, a single turbine implements a yaw-offset control strategy to benefit three downstream turbines.

Still, there is a need for more conclusive field campaigns on the performance of wake steering, as well as evaluation of the latest models. For this reason, a new field campaign was initiated as a collaboration between the National Renewable Energy Laboratory (NREL) and NextEra Energy Resources. A portion of a commercial wind farm was selected as a test site, and significant additional sensing equipment is being deployed including a (ground-based) lidar, meteorological (met) tower, and two sodars. Additional nacelle-based lidars are being deployed for the upcoming second phase. Wake steering controls based on the latest version of FLORIS are implemented on two turbines. This paper presents the results of the first phase of this campaign focused on wake steering.

The main contribution of this paper is the initial results and analysis of a land-based, wake steering field-test campaign. The paper presents the controller as implemented in the present phase and proposes improvements based on these initial results. The performance of wake steering, in terms of increased energy production, is analyzed and compared with predictions from the FLORIS code. In addition, the wake steering performance is assessed with respect to atmospheric stability, which can be estimated using sensing available on the met mast. Finally, several practical lessons learned are discussed.

The paper is organized as follows. Section 2 provides an overview of the field campaign’s layout of turbines and sensors, as well as meteorological conditions. Section 3 discusses the implemented controller. Section 4 describes the data collected, in terms of total amount and characteristics. The performance of the controller, specifically in terms of achieving targeted offsets, is reviewed in Section 5. Challenges specific to this first phase are described in Section 6. Finally, Section 7 presents the results.

10 2 Field Campaign

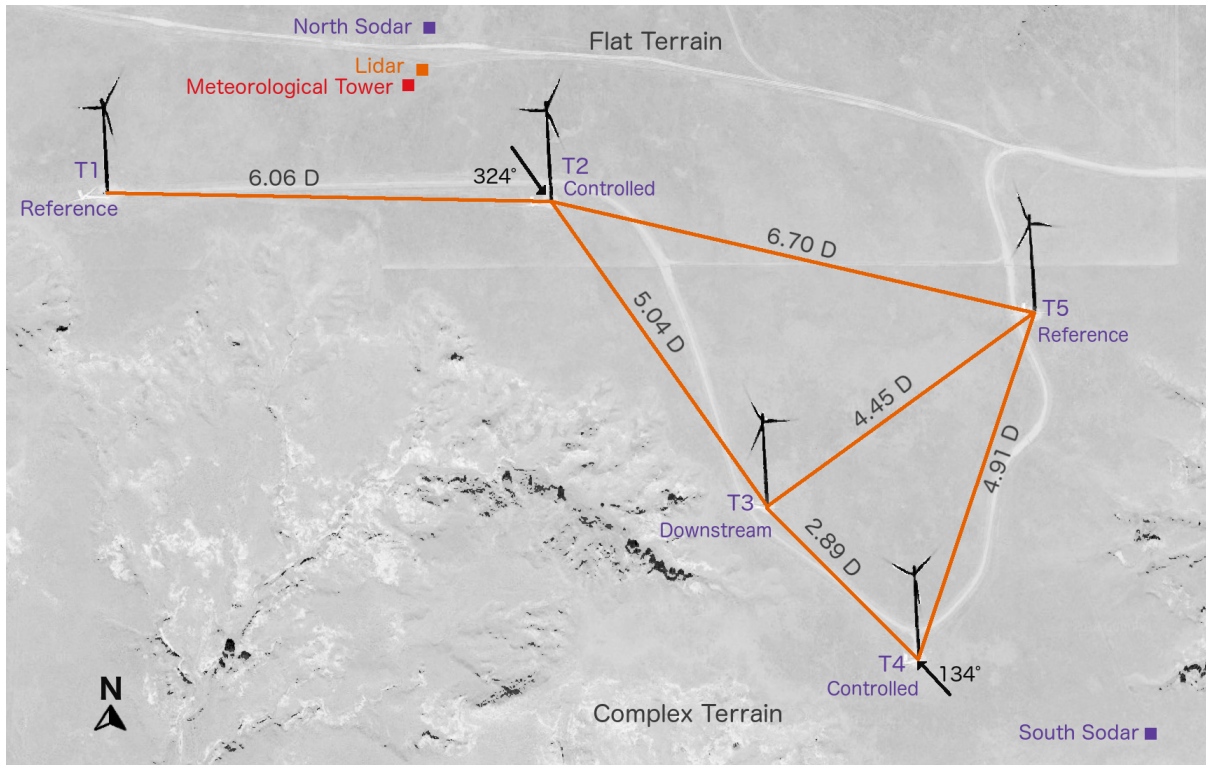


Figure 1. Layout of the experimental site. Turbines 2 (T2) and Turbine 4 (T4) have wake steering implemented to benefit Turbine 3 (T3), whereas Turbine 1 (T1) and Turbine 5 (T5) are reference turbines. The position of the installed meteorological equipment is also shown. Finally, the complexity of the terrain to the south and flat terrain to the north are indicated.

A subsection of a commercial wind farm was selected as the test site for the wake steering campaign. The site was chosen to include a set of turbines where the main wind directions that generate strong waking conditions would occur relatively frequently and the turbines were close enough for wake steering effects to be discernible. The selected wind farm subsection is shown in Fig. 1.

- 5 Five turbines (Fig. 1) are located in one corner of the overall farm. Note there are no turbines to the north or south, making these wind directions effectively freestream. The five turbines are relatively closely spaced, especially the three turbines labeled T2, T3, and T4. T2 and T4 were controlled turbines, and T3 was selected as the downstream turbine to be evaluated based on wake impacts of T2 and T4. The wind directions that T2 (324°) or T4 (134°) directly wake T3 are indicated in Fig. 1. T1 and T5 serve as reference turbines, uncontrolled and unaffected by the control turbines during wind conditions during which
- 10 controls would be applied. Fig. 2 illustrates the directional conventions for steering applied to the T4 and T3 turbine pair.

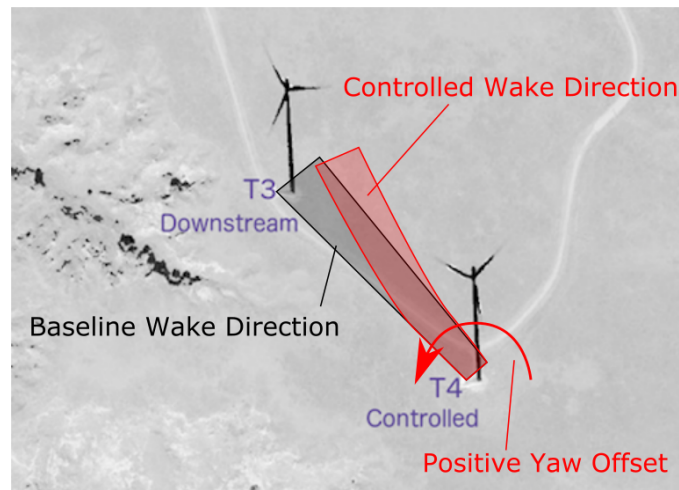


Figure 2. Illustration of wake steering showing that a positive yaw offset is meant to indicate a counter-clockwise rotation of the controlled turbine.

The terrain of the site is also illustrated in Fig. 1. Generally, the terrain to the north is flat, whereas the terrain to the south is complex (some escarpments can be seen in the southwest Fig. 1 and these extend to the south of T4). The campaign is divided into the “north” campaign, where flows from the north arrive over flat terrain, and T2 is the controlled turbine, and the “south” campaign, where flows from the south arrive over complex terrain and are expected to be more turbulent.

- 15 The locations of the meteorological equipment are indicated in Fig. 1. Based on the simpler terrain and overall wind rose, the equipment is placed to prioritize the north campaign. A Leosphere Windcube v2 profiling lidar (shown in Fig. 1) provides profiles of wind speed and wind direction calculated nominally every second but averaged to 1-min intervals. This lidar (similar to that used in Lundquist et al. (2017)) samples line-of-sight velocities in four cardinal directions along a nominally 28° azimuth from vertical, followed by a fifth vertically pointed beam. Range gates were centered every 20 meters from 40 m up to 180 m.

The sodars used in the campaign are Vaisala Triton Wind Profilers. The sodars provide measurements of wind speed and wind direction every 20 m up to 200 m.

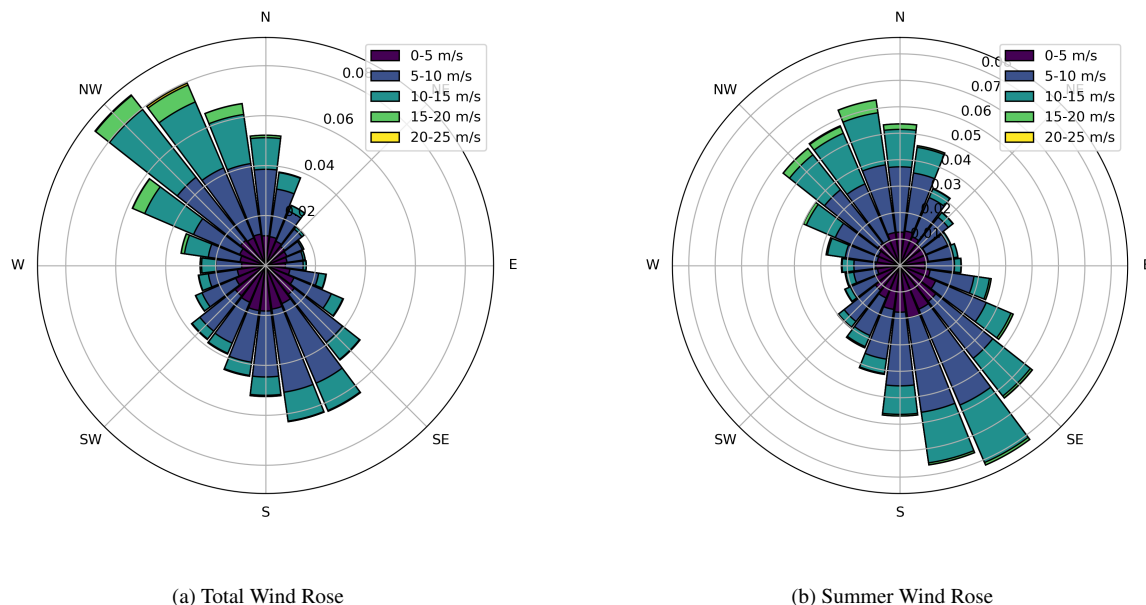


Figure 3. Total wind rose for the site and for the particular months encompassing the test, based on data collected from <https://www.nrel.gov/grid/wind-toolkit.html>

Phase 1 of the field campaign uses an initial deployment of the wake steering controller, and initial collection of data over the summer of 2018 (from May 4 through July 11, 2018). The wind resource is seasonal: in the summer, southern winds are more probable than northern winds. Fig. 3 shows two wind roses for the site, the data for which were obtained using NREL's

5 Wind Integration National Dataset toolkit and are for 100 m height. Fig. 3a shows the annual wind rose, with winds coming dominantly from the north-northwest and south-southeast. Fig. 3b shows the expected wind rose for the months during which the campaign was run has more frequent south-southeasterly winds.

Controllers were implemented and running on both T2 and T4. Because the south-southeasterly winds are more prominent

10 in this season, phase 1 focuses on the south campaign as most of the collected data correspond to this direction. The final study will consider the north experiment as well. Because of this focus on the south campaign, the most relevant components of Fig. 1 are T4 (controlled turbine), T3 (downstream turbine), and the “south sodar,” to measure inflow.

3 Controller

The controller implemented onto T4 was designed by optimizing a FLORIS model of the site based on wind direction and wind

15 speed. This resulted in a look-up table, which provides a desired yaw offset for T4 as a function of wind speed and direction.

Fig. 4 shows this target offset function, as a function of wind direction for ~~the case of 8 m/s winds~~ several wind speeds. The magenta lines indicate the approximate boundary of control and will be reused in upcoming figures to distinguish controlled and uncontrolled wind directions. The offset is largest around the peak wake loss direction near 134° and decreases as the wind rotates southerly.

- 5 These offset tables were constrained to be below load impact limitations determined by Damiani et al. (2017). A safe load envelope was determined to be yaw offset angles no larger than 20° during wind speeds of 12 m/s and less. Finally, offsets were restricted to be in the counterclockwise direction with respect to the wind (when viewed from above).

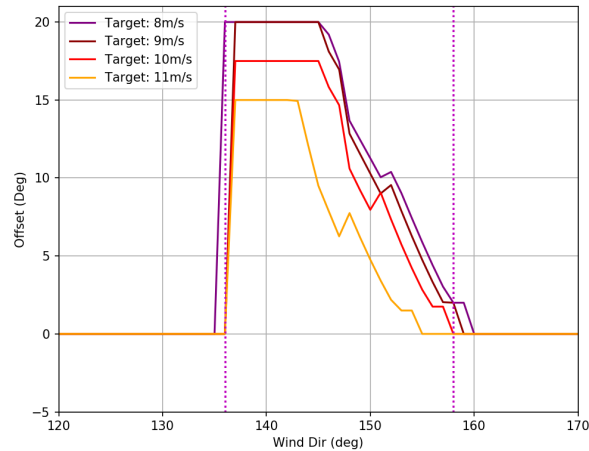


Figure 4. Target offset for 8, 9, 10 and 11 m/s. The red line-lines indicates the target offset by wind direction. The magenta vertical lines indicate the approximate boundaries of the experiment (these vary slightly by wind speed, but the overall shape is the same).

The yaw controllers of the controlled turbines were then modified to implement this yaw offset strategy. Specifically, the nacelle vane signal fed into the controller was modified by the specified yaw offset amount in the look-up table to induce the yaw controller to track an offset. An external wake steering controller was implemented to determine the offset to apply at a given moment. The specific setup is shown in Fig. 5.

The controller in Fig. 5 computes a wind speed and wind direction from sensors available on each turbine. It then filters both of these signals to remove high-frequency changes. The signals are fed into a look-up table, which is also filtered, and then the modified offset vane signal is sent to the turbine yaw controller.

- 15 The offset function is toggled on and off every hour, as indicated in the diagram. This toggling enables the performance of the wake steering controller to be compared to a baseline control data set that includes a similar composition of wind speeds. The decision to toggle every hour was a balance between accounting for the slowness of most yaw controllers and the variation of wind conditions. The optimal toggling period should be studied in more detail in the future to optimize the usefulness of the data collected.

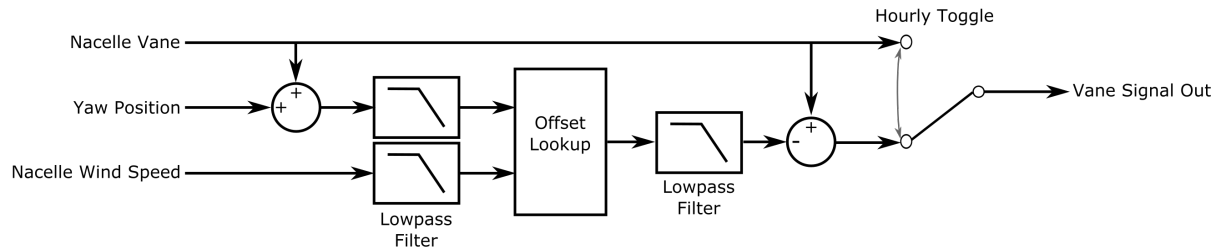


Figure 5. Block diagram of wake steering controller implementation. Inputs are provided by a typical turbine sensor, and the output is a modified vane signal to supply the turbine yaw controller for wake steering. Note this output is toggled on/off hourly. [All low-pass filters have a 30 second time constant.](#)

4 Data Collection

The phase 1 campaign lasted for approximately 3 months during which the wake steering offset controller on T4 was toggled on and off hourly. This section describes the inflow conditions during this period.

The inflow conditions are described from the south sodar data. Wind speed and wind direction are computed by a weighted average of the sodar measurements at heights that are within the rotor area of the turbine similar to the rotor-equivalent wind speed (Wagner et al. (2014)). Turbulence intensity (TI) is estimated at hub height by the sodar as the 10-minute standard deviation of the wind speed divided by the mean wind speed. Finally, stability is quantified via the Obukhov lengths (Stull (2012)). For this case Obukhov length L is computed via:

$$L = \frac{-u_*^3 \overline{\theta_v}}{Kg w' \theta'_v} \quad (1)$$

$$u_* = |\overline{u'w'^2} + \overline{v'w'^2}|^{1/4} \quad (2)$$

where K is the von Kármán constant assumed to be 0.4, [\$u_*\$ is the frictional velocity](#), g is gravity, θ_v is virtual potential temperature calculated with the met tower pressure at 2.5 m, and u, v , and w are meteorological coordinates of wind speed components in the west-east, south-north, and vertical planes [and the ' indicates perturbations](#). Fluxes were calculated using a Reynolds decomposition based on a 30-minute average. Using the classification scheme of Wharton and Lundquist (2012), the data were divided into stable, neutral, and unstable conditions. This division is simplified here so that “stable” is defined as $L < -1000$ [and all other data are categorized as “not stable.”](#)

The total amount of data collected is summarized in Fig. 6. The amount of data collected between the “Baseline” set, i.e., controller off, and “Controlled,” i.e., controller on, is comparable. The data are broken into “stable” and “not-stable” atmospheric conditions to show that toggling ensures both sets are similarly composed of atmospheric conditions.

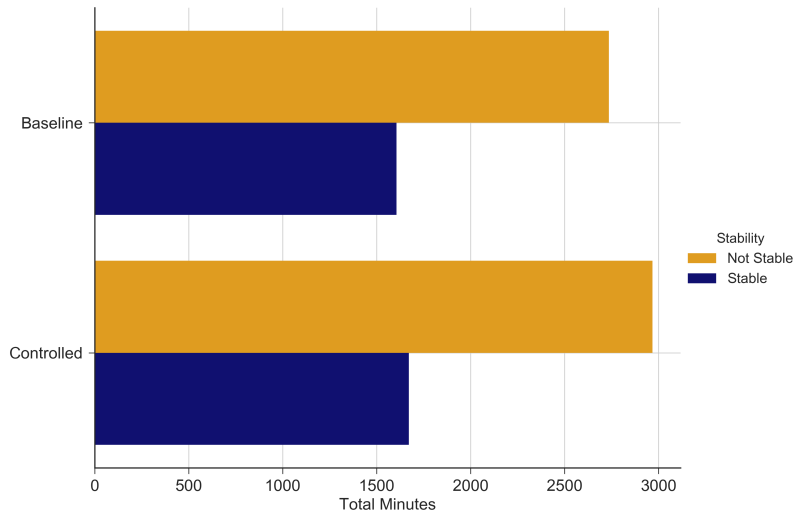
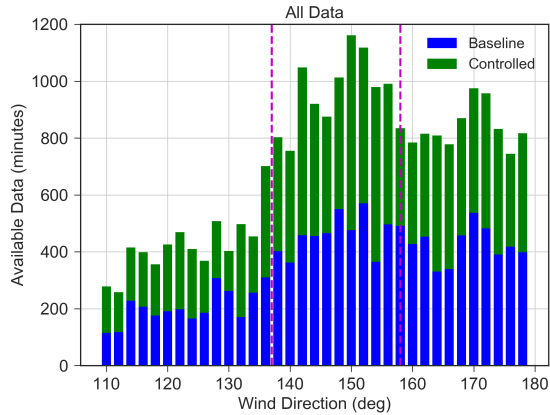


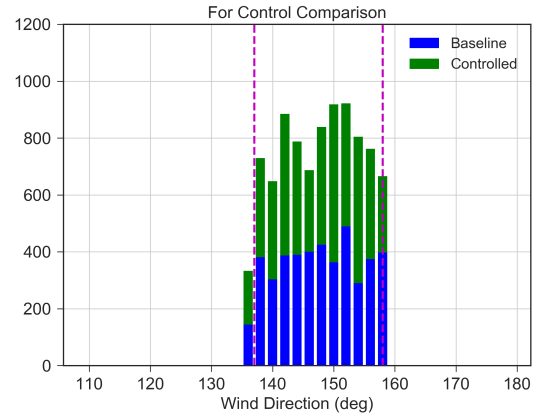
Figure 6. Total data collection. The yellow bars indicate the data from “not-stable” conditions and the blue bars indicate the data from “stable” conditions. The data were collected for both “Baseline” and “Controlled” cases.

Atmospheric conditions are described in Fig. 7. In Fig. 7a, the wind directions observed over the course of the campaign (as measured by the south sodar at hub height) are illustrated. If data are restricted to those points occurring in the range where the experimental controller is active (in terms of wind speed and direction), and further limited by removal of fault-coded data or faulty sensing, the data reduce to Fig. 7b. The distribution of wind speeds making up Fig. 7b are then shown in Fig. 7c.

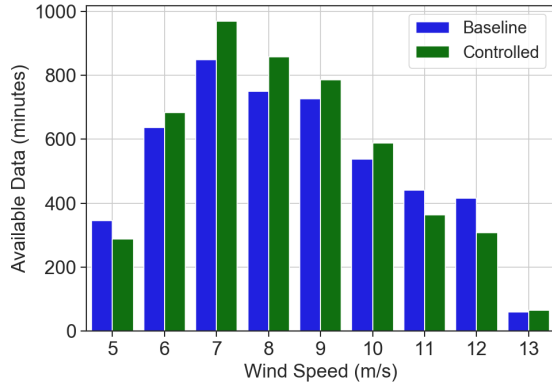
5 Finally, Fig. 7d illustrates the recorded TI within the data set remaining in Fig. 7b. The box sizes in Fig. 7d indicate the amount of data, and the data are subdivided into stable and not-stable categories to show that lower wind speeds are more likely to be higher-turbulence, unstable conditions, whereas higher wind speeds tend to be low-turbulence stable conditions. The black line of Fig. 7d will be used to describe the typical TI in the FLORIS model and will be discussed again later.



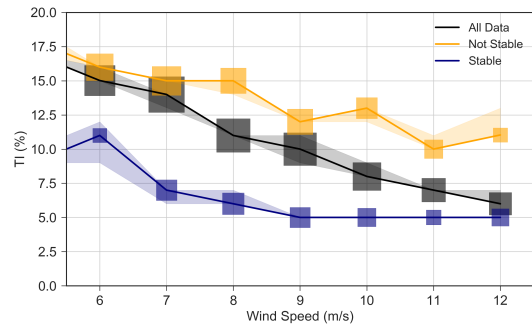
(a) Wind direction distribution



(b) Wind direction distribution of the controlled region and all signals passing quality control



(c) Wind speed distribution



(d) Turbulence intensity by wind speed and stability/ The points indicate medians, size of box indicates number of points while shading is 95% confidence interval of median

Figure 7. Atmospheric conditions observed by the sodar at hub-height over the duration of the test campaign.

5 Controller Assessment

We first analyze the phase 1 data by considering the performance of the controller in terms of its ability to produce a specific offset by wind speed and wind direction. The exact function of the turbine yaw controller is not known. Therefore, it was difficult to know in advance how effective the method shown in Fig. 5 would be in delivering the desired offsets.

5 Fig. 8 assesses the performance of this offset controller. Binned by wind speed, the figure shows the median maintained offset. The offset here is computed by comparing the nacelle position of T4 with the measurement of wind direction recorded by the south sodar. Generally, the offsets are reasonably well achieved; however, there is a tendency toward undershoot. The undershoot could be an artifact of temporal averaging over periods with and without offset, which biases computed offsets toward zero. However, we suspect that the undershoot is actually occurring because of the fact that the actual controller is
10 tracking an offset that is zero for most directions, except for a small band about the main waking direction. As the wind speed and direction drift in and out of controlled areas, the averaging effect biases the offset toward zero. This bias could be accounted for in future controller design.

In addition to a steady bias toward smaller-than-targeted offsets, we also noticed a dynamic issue in the controller design. [Dynamic design of wind farm controllers is a field of active research.](#) [Bossanyi \(2018\)](#). In the initial design phase, it was
15 assumed that, to avoid excessive yawing behaviors, we should both low-pass filter the wind speed and wind direction inputs to the look-up table, as well as the resultant offset sent to the yaw controller. We did not account for the fact that the yaw controller itself acts as a lag filter between changes in wind direction and changes in nacelle yaw position, and so the yaw offset control system as a whole is probably too slow and a general tendency toward overlapping changes in wind direction was observed. This is illustrated in Fig. 9. At approximately 2 minutes, the wind direction crosses into the region in which a
20 20-degree offset would be dictated by the static optimal look-up table. The low-pass filtering, however, causes the offset target to lag until the third minute to reach 20°. Then, the filtering of the offset achieves 20° around the fourth minute. Further, the turbine is observed to begin yawing around the fourth minute, and completes this action in the fifth minute, 3 minutes after the offset could have been optimally applied. Some lag is unavoidable, and potentially desirable to avoid adding too much additional yaw activity to the turbine, but based on this result, the controllers used in the upcoming phase 2 will be designed
25 dynamically, and the filter constants adjusted to account for this.

6 Challenges in This Campaign

This phase 1 campaign revealed several challenges that could inform future campaigns, including our future phases. Despite these challenges, the wake steering controller did produce the desired result of increasing power at the downstream turbine.

30 A first set of challenges corresponds to the site conditions for the south campaign. The topography is complex, but the version of FLORIS used in the design and analysis has no terrain modeling capabilities. This mismatch between the modeling assumptions and reality imparts a degree of uncertainty. Second, T4 and T3 are spaced such that T3 is in the near-wake region of T4. The version of FLORIS used does not contain a well-tuned near-wake model. Finally, as shown in Fig. 6, the collected

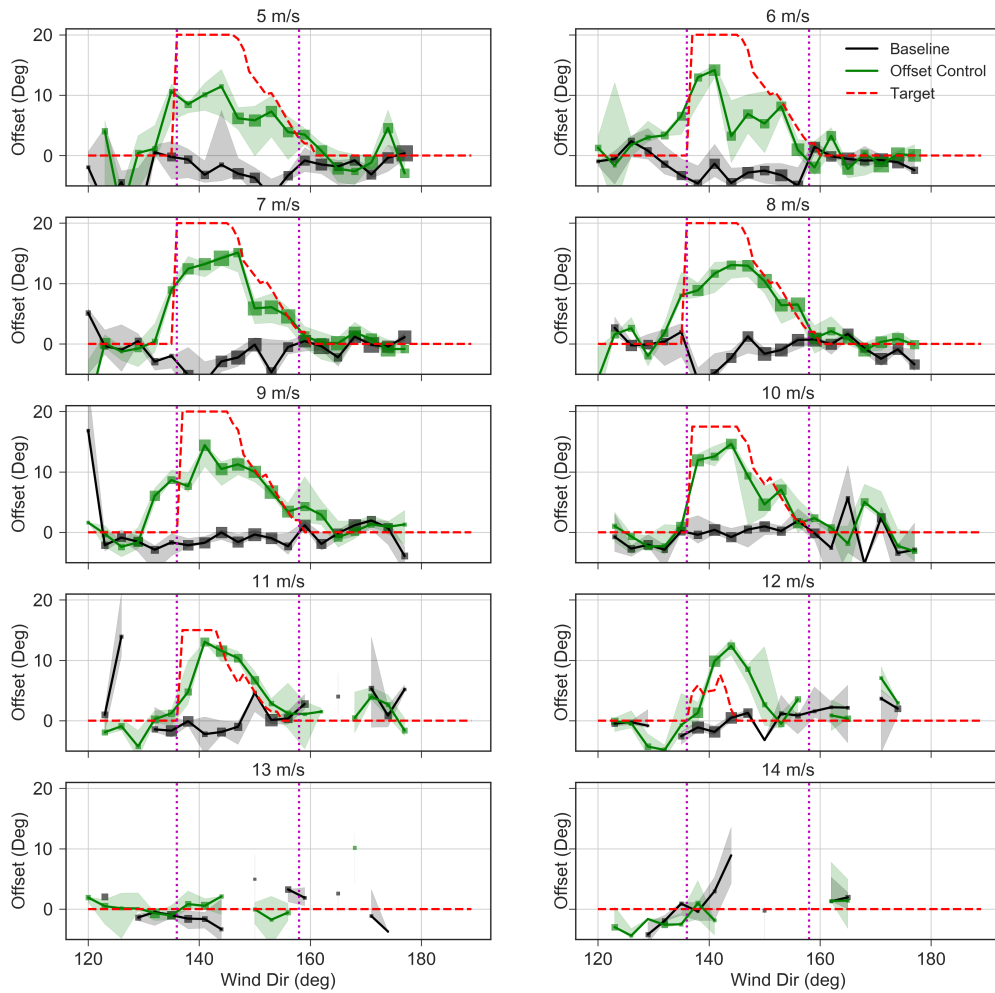


Figure 8. Comparison of observed yaw offset (green line) versus target (dashed red line) segregated by wind speeds. Note the achieved offset is computed as the difference between the sodar-measured wind direction and the turbine nacelle heading. Points indicate median offset, with size of box indicating number of points in bin, and bands indicating 95% confidence interval of median

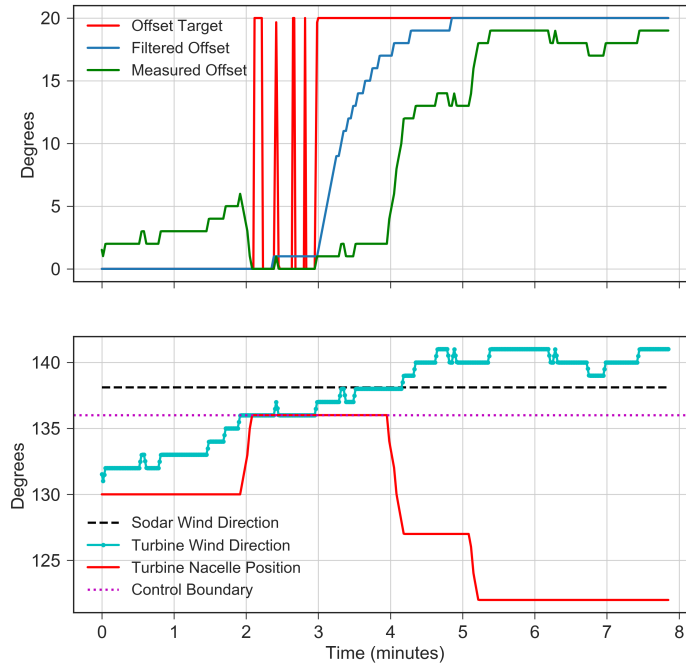


Figure 9. Time series data of T4 operation showing the sources of lag in yaw offset control. The figure shows that following the wind direction entering the range at which a 20° offset would be optimal at the 2-minute mark, the offset is not actually achieved until 3 minutes later.

data are only about one-third composed of stable atmospheric conditions because of the summer season and longer days. Stable, low-turbulence conditions would be more favorable to wake steering and may occur more frequently in the winter season.

A second set of challenges arise from more practical considerations. Specifically, the only sensor that could be used for the south experiment to measure the inflow is the south sodar, as it is the only one to the south of T4. The south sodar, in comparison to other instruments, was shown to measure the inflow well; however, it delivers data only once every 10 minutes, and this frequency is too coarse for the data analysis, because 10 minutes will include a diverse mix of wind directions and offsets. The turbine data are delivered at a frequency of 1 Hz, and through trial and error, a compromise of down-sampling the turbine data to 1 minute periods, while up-sampling the sodar data was selected (this up-sampling is done through a “zero-order hold,” wherein the data for each minute bin is assigned the 10-minute average). However, in the upcoming north campaign, more frequent data are available from the lidar and can be used.

Finally, the controller design, wherein we influence the yaw controller without fully understanding its behavior, is a major challenge. If the yaw controller could be directly modified, the delays shown in Fig. 9 could be reduced and performance improved.

7 Results

- 5 The first step in performing the analysis was selecting a reference for comparing the power of T3 and T4. In previous work, e.g., Fleming et al. (2017b), a reference uncontrolled turbine was preferred as it would provide a reference power that includes the effects not only of wind speed, but also shear, veer, and TI. For this reason, both T1 and T5 were considered, but a significant amount of noise/noncorrelation was observed likely because both turbines are far and downstream from T4. Ideally, the reference would be parallel to the upstream turbine on a line perpendicular to the controlled wind directions. In addition, the complex terrain varies from T1 to T5.

For this reason, a synthetic reference turbine power was used, based on the measurements of the south sodar. The wind speeds at heights corresponding to the turbine rotor were collected and applied to a weighted average, called U_{sodar} , wherein the weights were proportional to the sector of rotor area the heights correspond with, similar to a rotor-effective wind speed calculation (Wagner et al. (2014)). The hypothetical power of a reference turbine could then be computed using:

$$15 \quad P_{sodar} = 0.5\rho AC_p U_{sodar}^3 \quad (3)$$

where C_p is derived from the C_p look-up table included in FLORIS and ρ is the average observed density, A is the rotor area. This estimated sodar power was then compared with the measured power of T4, when the turbine is not intentionally operating in the offset condition (Fig. 10). The plot shows that correspondence is very close except for near rated.

- To analyze the effect of the wake steering implementation on the control and downstream turbine, the following method of analysis is used. First, the data are limited to include only periods in which both turbines were operating normally, and the quality of the sodar estimate was above a certain threshold, using quality flags reported by the sodar at each range. Next, all the data, including the power of T3 and the sodar reference power, are binned into wind direction bins every 2° (with 1° of overlap between adjacent bins as this was found useful in clarifying trends in the available data) and according to whether the wake steering controller was toggled on or off (Controlled) or off (Baseline).

- 25 Then for each bin, an energy ratio is computed, which involves summing a weighted summation of all the power measurements P_i^{Test} of the test turbine (the determination of the weights w will be detailed later), i.e., T3, and the reference turbine, i.e., sodar estimate P_i^{Ref} , and then taking a ratio of the two.

$$R_{Energy} = \frac{\sum_{i=1}^N P_i^{Test} \sum_{i=1}^N w_i P_i^{Test}}{\sum_{i=1}^N P_i^{Ref} \sum_{i=1}^N w_i P_i^{Ref}} \quad (4)$$

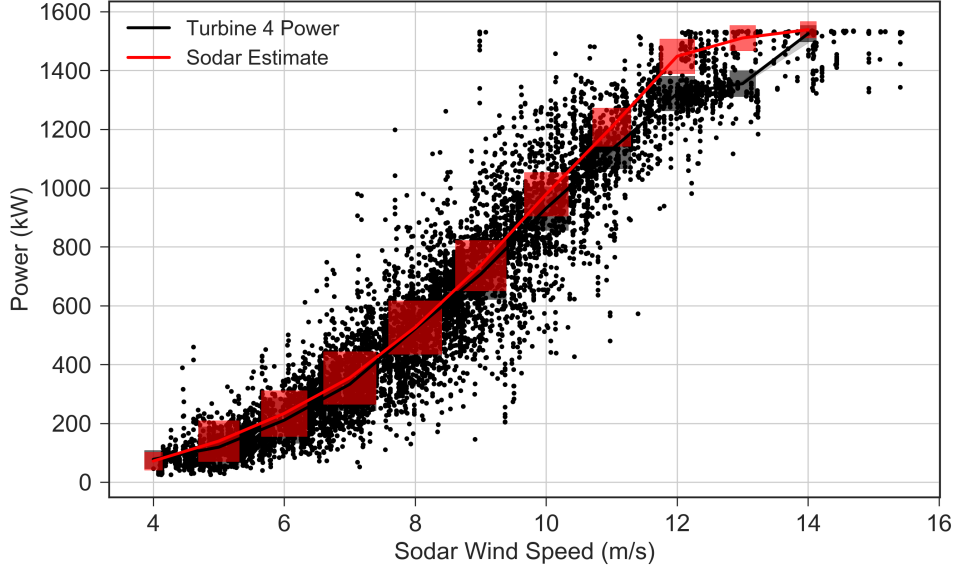


Figure 10. Sodar available power fit. The data from T4 are shown in black and the sodar estimate is shown in red. The red boxes refer to the wind speed bins and the size refers to the amount of data in each bin.

Note that this method is different from a power ratio method in which a power ratio is computed for each set of points and then averaged.

$$R_{\text{PowerPower}} = \frac{1}{N} \sum_{i=1}^N \left(\frac{P_i^{\text{Test}}}{P_i^{\text{Ref}}} \frac{P_i^{\text{Test}}}{P_i^{\text{Ref}}} \right) \quad (5)$$

It is also different than the slope method used in Fleming et al. (2017b).

$$R_{\text{SlopeSlope}} : \min_{R_{\text{SlopeSlope}}} \| \mathbf{P}_{\text{Test}} - R_{\text{SlopeSlope}} \mathbf{P}_{\text{Ref}} \|_2 \quad (6)$$

where $R_{[\dots]}$ is the ratio computed through the different methods, \mathbf{P}_{Test} and \mathbf{P}_{Ref} are vectors of all observed powers for the reference and test turbines, P_i^{Ref} is a single-minute average, and N is the total number of points in a given wind direction bin.

The energy ratio (4) is used for a few reasons. First, changes in relative energy production are more directly related to changes in revenue. Second, the power ratio is an average of ratios instead of the ratio of averages proposed in the energy ratio (5). The power ratio is more sensitive to small changes in power at low wind speeds, which do not contribute meaningfully to changes in energy production, which is the ultimate goal. The slope method (6) of Fleming et al. (2017b) was able to achieve a weighting of higher wind speeds through slope fitting. However, the energy ratio was finally thought to be more directly

related to annual energy production, the overall quantity of interest. The energy ratio represents the increase or decrease in energy produced for a specific wind direction bin.

In computing the energy ratio, a wind-speed-based weighting strategy helps to more quickly converge the analysis and reduce changes in energy ratios due to variations of the compositions of wind speeds for the two controllers within each wind direction bin with respect to differences owed to changes in controller. The main idea is that for each wind direction, the power values collected are binned according to wind speed (as measured by the sodar) and the total energy for the baseline and controlled cases are the weighted sum of the powers, where the weight is the number of points the other control setting has in this wind speed bin, out of the total. For example, if there are 10 samples of Baseline taken at 13 m/s, and 5 of Controlled, the baseline points are weighted by 1/3, and the controlled by 2/3, so the final energy ratios to be compared are more approximately even in terms of wind speed distributions represented. If the bins are perfectly balanced, there are an equivalent number of Baseline and Controlled points at each wind speed, the weights have no effect.

In addition to computing a single energy ratio for each bin, the process is boot-strapped, in which the data are randomly sampled with replacement and the energy ratio recomputed 1000 times or more depending on the amount of data. The results of these bootstrap iterations are then used to compute 95% confidence intervals. ~~The process is repeated within~~, and these are indicated in the plots of energy ratio as semi-transparent bands.

The method of computing energy ratios is now included within the open-source FLORIS model <https://floris.readthedocs.io>.

Note that all wind speeds are used in this calculation, including those (greater than 12 m/s) in which the 0° offset is actually targeted, even in the controller on mode. With the 10-min sodar rate, and the lag of the controller, it is difficult to draw an exact line in which the controller stops impacting the individual turbine yaw controller. Including all wind speeds also corresponds to the final change in energy.

The energy ratio calculation is repeated on several differently-defined FLORIS models of the site to provide a point of comparison. ~~The specific set of wind speeds observed within each bin are simulated in four separate FLORIS models (see An~~ “Aligned” case simulates every observed wind speed and direction in the Baseline field data with all turbines perfectly aligned to the flow, while a “Baseline” case uses the actual small offsets observed. An “Optimal” case, simulates all the wind speeds and direction in the Controlled field data using the exact offset requested by the control strategy, while “Controlled” applies the actual achieved offset. These four settings are summarized in Table 1). For each of the FLORIS models, and for each 1-minute wind speed and direction observed in the field, a matching FLORIS simulation was run and the power of T3 and T4 tabulated. ~~Note the input TI for FLORIS is set according to the average behavior observed in Fig. 7d. and the energy ratio computed.~~ When considering gains in energy, “FLORIS Optimal Gain” refers to the change from “Aligned” to “Optimal” whereas “FLORIS Controlled Gain” refers to the change from “Baseline” to “Controlled”.

The energy ratios can be computed from these FLORIS models. The comparison of the aligned and optimal case should present an upper bound on performance if exact offsets and alignments held, whereas the Baseline and Controlled cases show what we expect from this data set.

Table 1. FLORIS MODEL DEFINITIONS FOR COMPARISON. Columns yaw 4 and yaw 3 determine what sets the yaw angle for each turbine (aligned being 0° always), optimal being the true optimal, and “From Baseline” means applying the observed yaw angles from the baseline data of the field campaign. Wind conditions are similarly defined.

Model	Yaw 4	Yaw 3	Wind Conditions
Aligned	Aligned	Aligned	From Baseline Data
Baseline	From Baseline	From Baseline	From Baseline Data
Optimal	Optimal	Aligned	From Controlled Data
Controlled	From Controlled	From Controlled	From Controlled Data

~~Note that all wind speeds are used in this calculation, including those (greater than 12 m/s) in which the 0° offset is actually targeted, even in the controller on mode. With the 10-min sodar rate, and the lag of the controller, it is difficult to draw an exact line in which the controller stops impacting the individual turbine yaw controller. Including all wind speeds also corresponds to the final change in energy. All wind speeds are applied in FLORIS, so their effects are accounted for.~~

5 7.1 Turbine 3 Analysis

Fig. 11 shows the energy ratios by wind direction for T3. The wake loss is deeper than FLORIS expects (T3 is producing less than 40% of the energy of the reference at nadir); however, as mentioned, this is a difficulty of current near-wake models and the subject of active research. Still, the gain in energy production in the wind direction where the controller is active is observed.

~~It is useful to note the places in Fig. 11 where the FLORIS model results are somewhat jagged. Fig. 7a shows limited data below 138°. Even without any yaw offsets being applied, as would be the case in this range, the energy ratios can still vary based on the composition of wind speeds (e.g., very high wind speeds have high power ratios, whereas the lowest power ratios occur in the middle of region. Note that as described earlier, to clarify trends, the wind direction bins are every 2° near 8 m/s.) Given enough data, these effects should wash out, but we can see FLORIS shows a dip in the controlled case at 125° that is indeed observed in the field data. Fortunately, in the controlled band between 136° and 158°, the FLORIS results show less variability, which suggests adequate data collection. ° but are 3° wide (overlapping with adjacent) to increase the points available per bin.~~

The difference between the Baseline and Controlled cases for both the field data and FLORIS quantifies the impact of yaw control on power production (Fig. 12). In the 10-degree sector between 140° and 150° the average gain in energy is 13.14.6%. Compared to FLORIS’ predictions, ~~field results show slightly less increased production of energy than the optimal case for the deepest wake region closer to 140°; however, accounting for the undershoot in yaw offsets achieved seems to explain most of that discrepancy. In the right half of the controlled region, however, we note a tendency to exceed both the controlled and optimal FLORIS predictions for energy gain. The underperformance on the left of the control region in Fig. 12 near 140° could~~

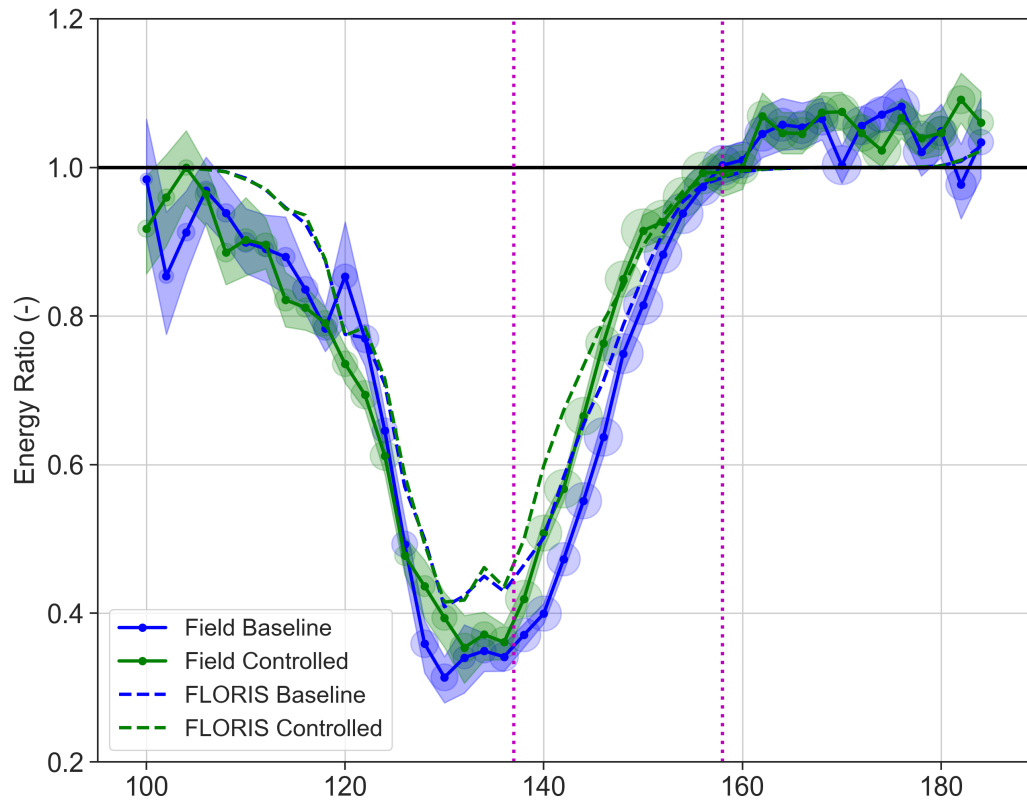


Figure 11. Energy ratio for T3 for field data and the Baseline and Controlled FLORIS cases (see Table 1). An energy ratio of 0.5 corresponds to a production of 50% of the total expected based on the measured inflow without considering wakes. The vertical magenta lines indicate the region where control is applied and a difference between the Baseline and Controlled is expected. [Size of circles at each point indicate the number of points in the bin, while the bands indicate 95% confidence as computed by the bootstrapping.](#)

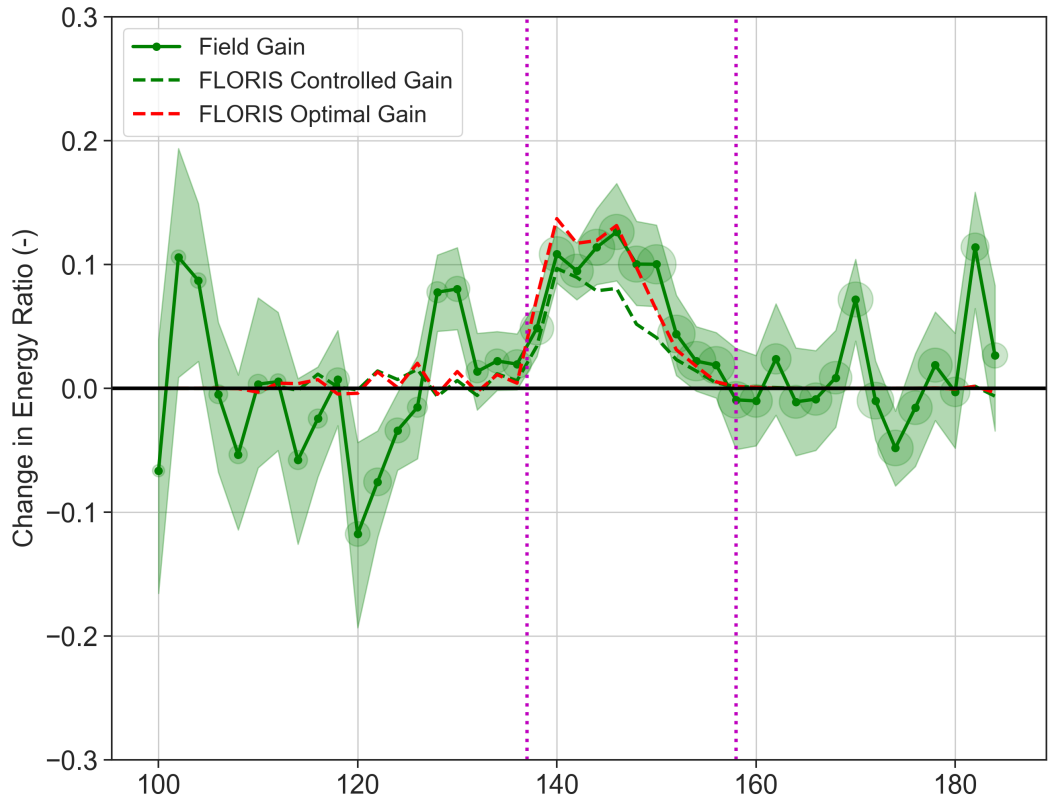


Figure 12. Change in the energy ratio of T3 from field data. Expectations from FLORIS using the actually achieved controlled offsets (Controlled - Baseline) and optimal (Optimal - Aligned) are shown to indicate comparison with expectations given control values, and what is optimally expected.

be the problem of yaw offset undershoot, and therefore a focus of controller design in future work. The overperformance on the right side may indicate the need for better modeling of wake steering partial wake and could be improved upon using newer vortex-based curl models in FLORIS, such as identified in Fleming et al. (2018) and Martínez-Tossas et al. (2015). On the other hand, another possibility is that uncertainty in wind direction lowers the performance on the left and raises it on the right through averaging. Finally, the field results compare favorably to the estimations from FLORIS. The data outside of the control bands, while noisy, indicate an average around 0, underlying the significance of the non-zero apparent average in the control region.

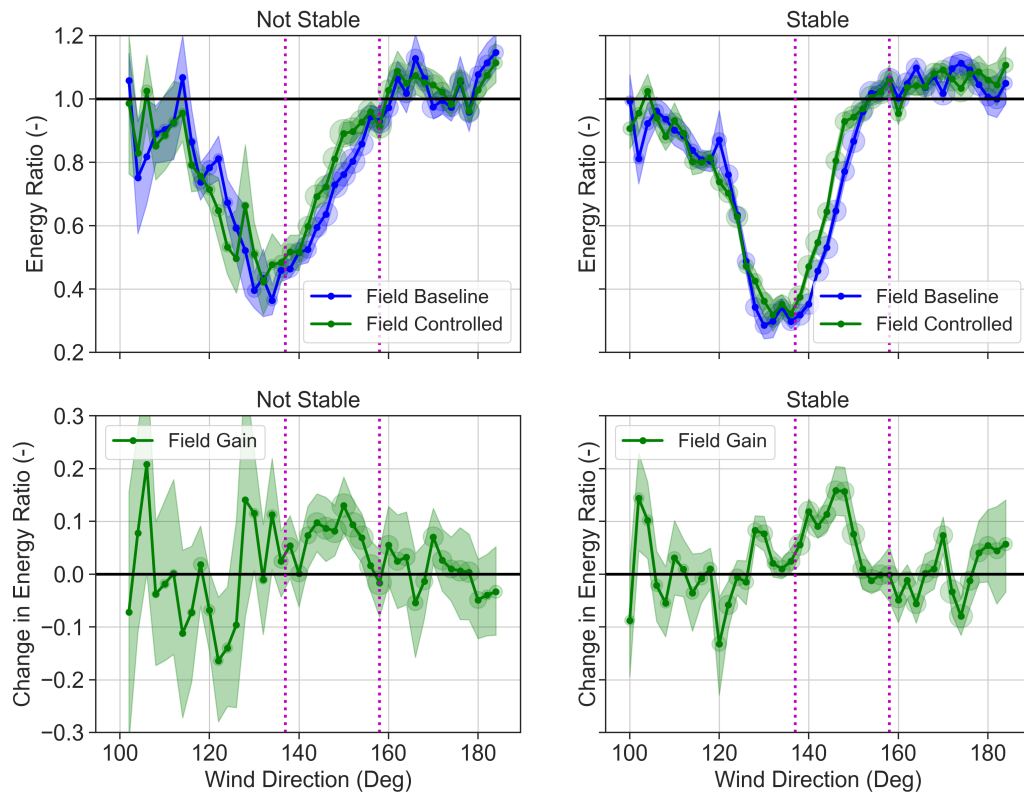


Figure 13. Energy ratio of T3, as in Fig. 11, divided into stable and not-stable conditions.

The difference in energy production is more clearly realized in stable conditions as shown in Fig. 13, which segregates stable conditions from not-stable conditions and repeats the analysis of Fig. 11 and Fig. 12. The gain in stable conditions is more consistently realized (as indicated by the bands) and the peak gain is higher, than in not stable conditions. This distinct improvement in stable conditions could be because wake steering is more effective in stable conditions. Additionally, in stable conditions, atmospheric inflow is more homogeneous and therefore easier to measure. Upcoming winter measurements from

the north for phase 2 will consist of more stable measurements due to the longer nights and may shed more light on the role of atmospheric stability in wake steering.

7.2 Aggregate Analysis

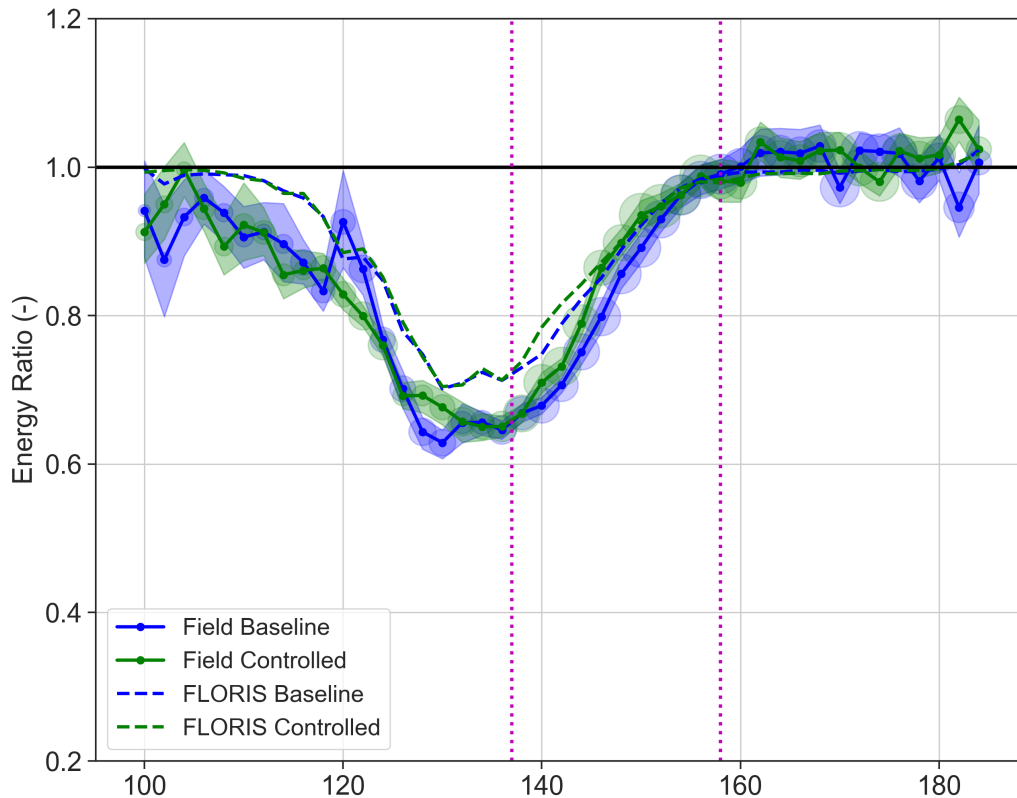


Figure 14. Energy ratio of the summed energy of T3 and T4.

Finally, the previously mentioned analysis is repeated, but using the aggregated power of T4 and T3, so that the losses in energy coming from offsetting the yaw of T4 are deducted from the gains made downstream (Fig. 14 showing the energy ratios and Fig. 15 shows the difference between-between them). Again, we gain less energy than FLORIS expects in the left half and more than expected on the right half. Intriguingly, but perhaps coincidentally, if we compute the energy gain over the band of direction for which the controller is active, both optimal FLORIS and the field data yield a 3.7% increase in energy, in which case the under and overperformance balance each other out. The aggregated energy gains appear to be somewhat more than the

current version of FLORIS expects (a net gain of 4.1% over the same 10° region from 140° to 150°) but this could again be connected to difficulty measuring the near wake.

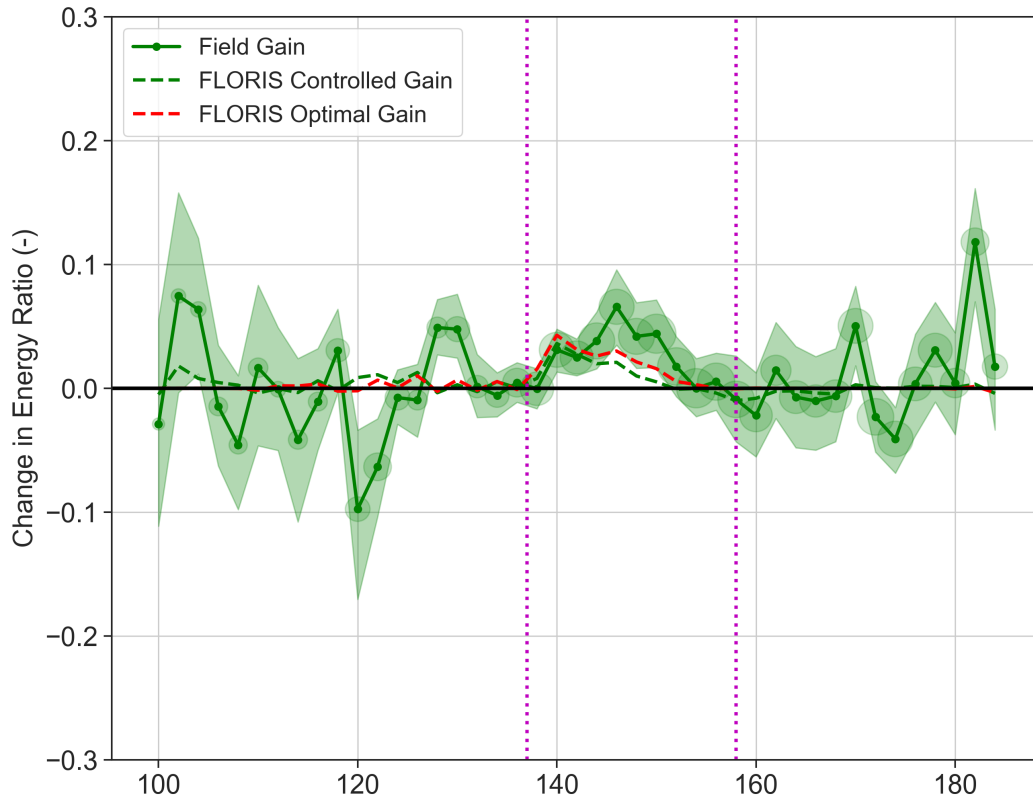


Figure 15. Combined change in energy ratio for T3 and T4.

8 Conclusions

We present the initial results from a first phase of a field campaign evaluating wake steering at a commercial wind farm. For two
5 closely spaced turbines, an approximate ~~13~~14% increase in energy was measured on the downstream turbine over a 10° sector
with 4% increase in energy when accounting for losses of the upstream turbine. The gains in energy were compared to predic-
tions made using the FLORIS model used to design the applied controllers. The overall gains were consistent with predictions
from FLORIS; ~~however, this agreement was due to less-than-expected gains in full-wake conditions, and more-than-expected
gains in partial wakes.~~

This initial stage of the wake steering campaign identified several areas for improvement in future work, such as aspects of dynamic controller design, time filtering, and uncertainty quantification. Difficulties with this particular south campaign, including complex terrain and summer atmospheric conditions, were identified as possible sources of improvement as the campaign moves to northern winter conditions. Additionally, near-wake modeling presented a challenge in accurately modeling the wake losses, and therefore may have realized a less-than-optimal controller. Still, the overall gains in energy were in line with prior expectations from FLORIS.

All together, the authors hope that the results presented might therefore represent a baseline for possibility of gains from wake steering. Better modeling and controls, simpler site conditions, and the exploitation of vortex modeling and larger arrays of turbines all present hopeful avenues for continued improvements. An upcoming companion paper on the second phase of the experiment will review results including opportunities for improvement identified in this paper.

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