# Demonstration of Wake Steering Through Yaw Control in a Wind Plant Field Experiment

## Cooperative Research and Development Final Report

## CRADA Number: CRD-16-00629

NREL Technical Contacts: Paula Doubrawa and Patrick Moriarty

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Contract No. DE-AC36-08GO28308

**Technical Report**
NREL/TP-5000-80492
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# Cooperative Research and Development Final Report

**Report Date:** July 6, 2021

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

**Parties to the Agreement:** NextEra Energy Resources, LLC; Ystrategies Corp.

**CRADA Number:** CRD-16-00629

**CRADA Title:** Demonstration of Wake Steering Through Yaw Control in a Wind Plant Field Experiment

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**Sponsoring DOE Program Office:**

Office of Energy Efficiency and Renewable Energy (EERE), Wind Energy Technologies Office

**Joint Work Statement Funding Table showing DOE commitment:**

| Estimated Costs | NREL Shared Resources a/k/a Government In-Kind |
|---|---|
| Year 1 | $250,000.00 |
| Year 3, Modification #5 | $15,250.00 |
| Year 3, Modification #6 | $521,889.00 |
| Year 4, Modification #7 | $20,938.00 |
| TOTALS | $808,077.00 |

**Executive Summary of CRADA Work:**

Over the last few decades, wind energy has evolved into a large international industry involving major players in the manufacturing, construction, and utility sectors. Coinciding with the industry's growth, significant innovation in the technology has resulted in larger turbines with lower associated costs of energy and more complex designs in all subsystems. However, as the deployment of the technology has grown and its role within the electricity sector become more prominent, so have the expectations of the technology in terms of performance, reliability, and cost. The industry currently partitions its efforts into separate paths for turbine design, plant design and development, finance, grid interaction and operation, mitigation of adverse community and environmental impacts, and other areas.

One prominent area where this partition is evident is in wind turbine control. Traditionally, each wind turbine in a wind plant has been controlled separately – via its own internal controller using only its own sensors. However, wind turbines in a plant interact with each other through the plant-level fluid dynamics. Wake losses (due to upstream turbines extracting energy from the winds and "waking" downstream turbines) can be up to 10% or even 20% of the gross energy production (if each turbine experienced the free stream wind inflow to the plant). A series of studies and experiments have demonstrated that there is potential for improving energy output at existing plants through plant control methods which seek to optimize total wind plant energy production over the current "greedy" approach where each turbine maximizes its own production. Wake steering induced by yaw offsets (turning the turbine to be out of the plane perpendicular to wind inflow) for upstream turbines has shown significant promise in simulations and wind tunnel experiments. In simulation studies, annual energy production has been shown to increase by 2% or more depending on the particular aspects of the wind plant (turbine spacing, meteorological conditions, etc). This project seeks to demonstrate the potential of plant-level controls via wake steering at a commercial wind plant. This is an important step towards commercialization and industry adoption of this plant-level modeling and analysis capability.

**Summary of Research Results:**

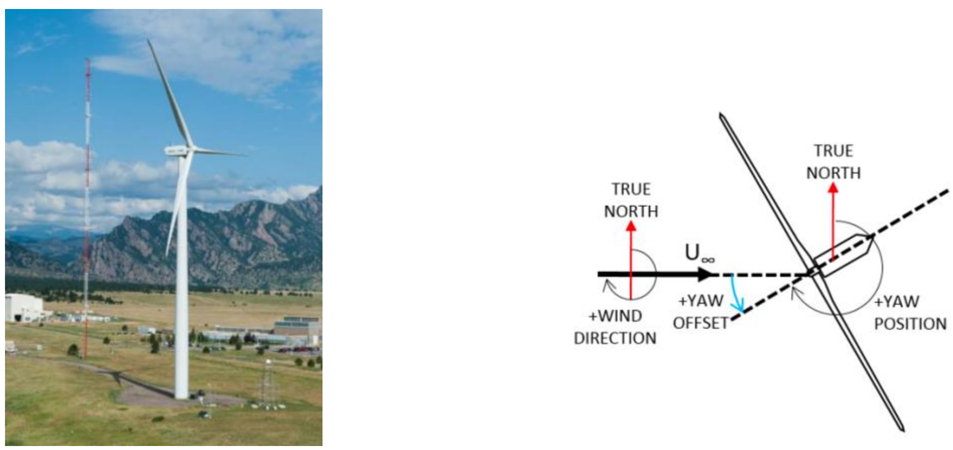
This section summarizes the data collected, research conducted, and conclusions obtained within each task originally outlined in the joint work statement of the agreement.

**Phase I of Joint Work Agreement**

"DOE-owned GE 1.5sle at the NREL NWTC: loads analysis with yaw misalignment"

**Phase I, Task #0: Define plan for yaw misalignment test implementation, instrumentation and analysis**

The first step in this project was to test yaw misalignment implementation at a site owned by DOE, with easy access to expertise and materials and at a relatively low cost. The test turbine was the GE1.5 SLE ESS turbine owned by DOE located at NREL's Flatirons Campus (Figure 1a). The wind turbine has a rated power of 1.5 MW, hub height of 80 m, rotor diameter of 77 m, and rated wind speed of 14 m/s. The measurement and data processing were planned according to the International Electrotechnical Commission (IEC) standard 61400-13: Measurements of Mechanical Loads (International Electrotechnical Commission, 2015). The planned yaw misalignment setpoints were: -25°, -18°, -12.5°, 0° (i.e., aligned operation), +12.5°, +18°, +25°. These values follow the coordinate system definition in Figure 1b, and imply that with positive yaw offset the hub center is to the right of the tower centerline when looking downwind.




(a) (b)

**Figure 1: DOE GE1.5 SLE wind turbine and meteorological tower (a) and schematic showing coordinate system used when referring to turbine yaw angles (b).**

To implement these yaw misalignments, the turbine nacelle's wind vane signal was planned to be modified using a frequency modulation device with a dedicated user interface for programming yaw-offset schedules of discrete offset values and durations. In no other way was the turbine or its controller to be manipulated.

The atmospheric inflow to the turbine was planned to be measured by the meteorological tower located at the same site, 161 m upwind of the wind turbine (approximately 2 rotor diameters) along the predominant wind direction at the site. The meteorological data collection was focused on a wind direction sector of 260° to 360° and 0° to 25° relative to true north to avoid conditions in which the tower is waked by the turbine.

An original GE aeroelastic model was modified to be used with NREL's aero-hydroservo-elastic tool for wind turbine design (FAST) version 8 (FASTv8) (Jonkman et al., 2015). FAST is a widely used industry and academic tool for load estimation. Since this work was conducted, FAST has been superseded by OpenFAST, an open-source set of codes for detailed wind turbine analyses.

**Phase I, Task #1: Instrument DOE 1.5 wind turbine and meteorological tower at the NWTC to assess overall yaw loads over range of wind conditions**

To assess the structural response of the DOE turbine to aligned and misaligned operation, it is first necessary to instrument the rotor and tower with strain sensors. (Task 1.1) The wind turbine was instrumented for loads measurements following the IEC 61400-13: Measurements of Mechanical Loads guidelines (International Electrotechnical Commission, 2015). The following loads of interest were measured during this experiment:

- Blade flap (all blades)
- Blade edge (all blades)
- Main shaft bending
- Main shaft torque
- Tower top torque
- Tower top acceleration
- Tower top bending (fore-aft and side-to-side)
- Tower base torque
- Tower base bending (fore-aft and side-to-side)

In addition to the loads instrumentation, encoders were used to measure yaw position, blade pitch, and rotor azimuth. The turbine was also instrumented for independent power measurements. All signals were collected with a time-synchronous deterministic EtherCAT protocol and stored at a sample rate of 50 Hz.

The meteorological tower was instrumented in accordance with IEC standard 61400-12-1: Power Performance Measurements of Electricity Producing Wind Turbines (International Electrotechnical Commission, 2017).

**Phase I, Task #2: Induce yaw misalignment on DOE 1.5 machine and collect data**

Once the required instrumentation was installed, the turbine was operated in aligned and intentionally misaligned conditions. During this time, the meteorological tower measurement signals were time-synchronously recorded with the turbine loads signals. The data collection period was between August 4th, 2016 and September 12th, 2018. The amount of data collected at the various yaw offsets is summarized in Figure 2.

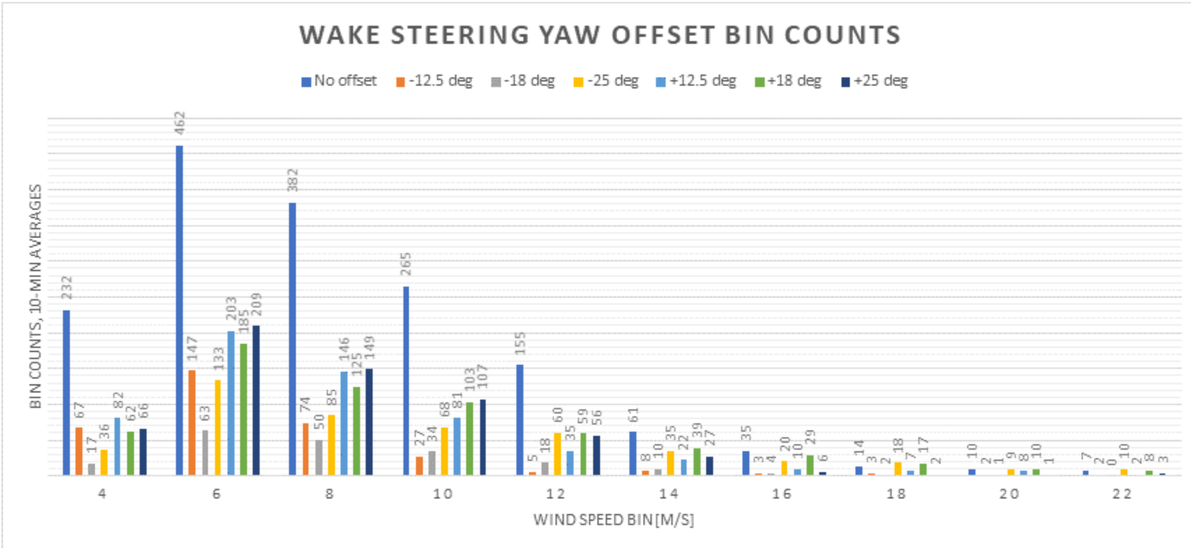



**Figure 2: Number of 10-minute periods for which data were collected at the various planned yaw offsets. Data are given as a function of hub-height wind speed.**

### Phase I, Task #3: Analysis of loads and meteorological data from yaw offset measurements and presentation of findings

Once sufficient data were collected, the loads and inflow data were analyzed (Task 3.1) to characterize the structural response and power changes of the turbine when intentional misalignment was prescribed. The measurements were quality controlled, processed in accordance with IEC guidelines, and statistically summarized for comparison with aeroelastic simulations (Task 3.2 -3.3). The analysis considered fatigue loads and ultimate loads. The results from this analysis were published in Damiani et al., 2018. Here, we provide an example of the analysis conducted and results obtained. For a more detailed discussion, the reader is referred to the journal publication. (Task 3.4) The results were presented to the partner (including Figure 3 below).

A summary comparison between predicted and measured short-term damage-equivalent loads (DELs) for the various channels of interest and for 10 m/s (below rated operation) and 14 m/s (at rated operation) are shown in Figure 3. These results show good agreement between predicted and measured data. The asymmetry in mean loading as a function of yaw offset is clearly visible in both datasets. The simulations slight underpredict blade loads, shaft torque, and tower top bending, while slightly overpredicting tower top torque and tower bottom bending. The results are consistent for both wind speeds.

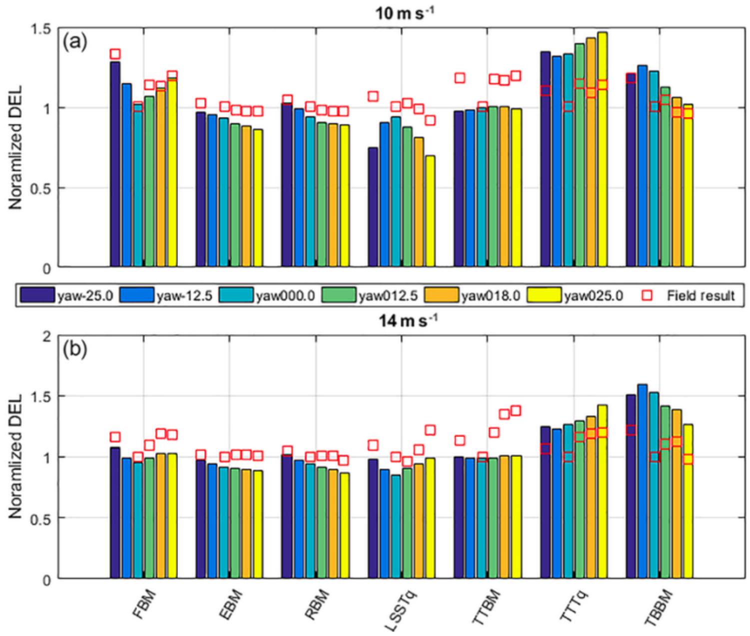


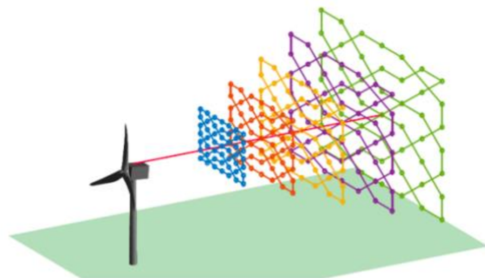

**Figure 3: Comparison between predicted (FAST, bars) and measured (field, square symbols) mean damage-equivalent loads (DEL) as a function of yaw offsets for mean hub-height wind speed of 10 m/s (a) and 14 m/s (b). The load values presented are normalized by their respective mean values at zero yaw offset as calculated from the field measurements for the respective wind-speed bins. The signals shown are: flapwise bending moment (FBM), edgewise bending moment (EBM), their resulting root bending moment (RBM), low-speed shaft torque (LSSTq), tower top bending moment (TTBM), tower top torque (TTTq), and tower bottom bending moment (TTBM). For more details, please see Damiani et al., 2018.**

### Phase I, Task #4: Measure wake location on DOE 1.5 under yaw misaligned operation

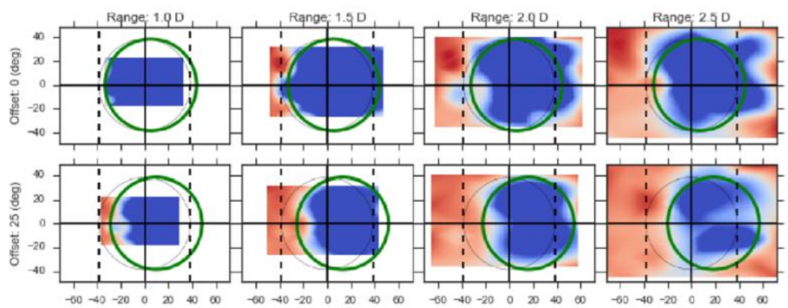
The objective of the intentional misalignment is to deflect the wind turbine wake. To verify whether this control technique was having the predicted effects, it was necessary to measure its wake. To measure the wake, the wind turbine was instrumented with a rear-facing lidar mounted at the nacelle (Figure 4, Task 4.1). The data was collected, analyzed, and summarized in Fleming et al., 2017. Here, we provide an example of the analysis and results obtained. For a more detailed discussion, the reader is referred to the full article.


**Figure 4: Photo showing the lidar, wind vane, and cup anemometers mounted to the back of the wind turbine nacelle.**

The wake measurement strategy is shown in Figure 5a. The average wake measured by the lidar is shown in Figure 5b for four different distances downstream of the turbine (Task 4.3), at aligned operation (offset = 0) and the largest positive offset (offset = 25 deg). The model and test data show relatively good agreement (Task 4.2). Note, for example, that FLORIS (FlOw Redirection and Induction in Steady State) predicts nonzero deflection in the aligned case, which is observed in the lidar data. Both datasets also show that significant deflection has occurred by 1.5 rotor diameters (D) downstream. Note that at the 1D range, the lidar scan is largely within the wake. However, a difference in deflection between aligned and offset operation can still be observed on the left edge of wake.



**(a)**




**(b)**

**Figure 5: (a) Visualization of the lidar scan pattern that is used to measure the wake behind the wind turbine. The lidar is measuring with a sampling frequency of 1 Hz simultaneously in five distances from 1 to 2.8 times the rotor diameter (D). (b) Median scans of the wake at 8 m/s for aligned and yawed conditions between 1 D and 2.5 D. Blue (red) indicates lower (higher) wind speeds. The green circles indicate the position of the wake predicted by SOWFA and FLORIS. For more details, please see Fleming et al., 2017.**

### Phase I, Task #5: Make go/no-go decision for Phase II

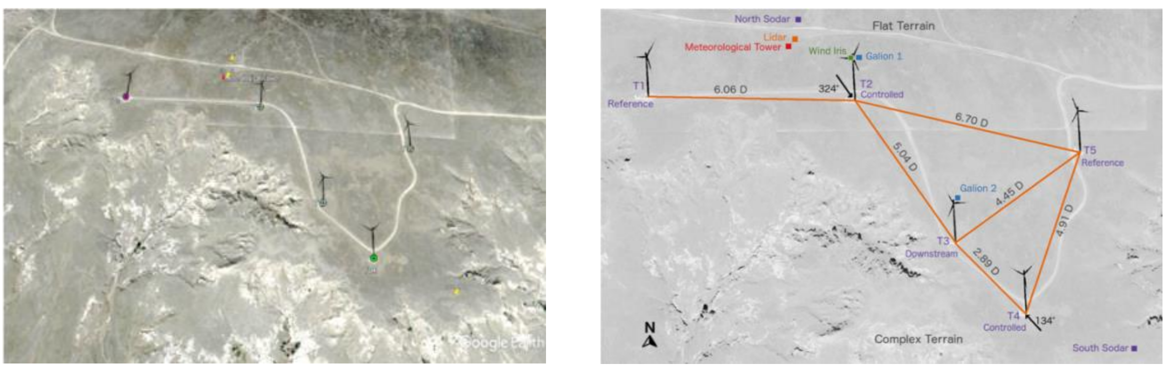
(Task 5.1 – 5.2) The ultimate objective of this initial experiment conducted at NREL was to determine whether model predictions for wind turbine response under yaw misalignment are robust. If so, a follow-on test at the partner's wind plant would follow. The work conducted between Tasks 1 and 4 produced sufficient data to answer these questions and make a decision towards the follow-up experiment. The inflow, turbine performance, turbine loads, and wake measurements confirmed the predictions obtained with modeling tools. Given the promising indication of wake steering as a method to increase wind plant performance, our proven ability to steer the wind turbine wake, and the minimal impact on loads for most wind speed and yaw offset combinations, it was decided to follow with Phase II of the joint work stated under this agreement.

**Phase II of Joint Work Agreement**

"Wake steering demonstration at utility-scale wind plant"

**Phase II, Task #0: NREL and partners will define the plan for overall wake steering test implementation, instrumentation, and analysis**

Once all parties agreed to proceed with the wind plant test, the next step was to draft the test plan (Task 0). The test plan was jointly defined by NREL and the partners to take place at a utility-scale wind farm in northern Colorado. A subset of five turbines within the farm was the focus of the experiment, as shown in Figure 6. The measurement plan was defined to have two reference turbines (T1 and T5), two controlled turbines (T2 and T4) and one waked turbine (T3). Depending on the wind direction, either T2 or T4 were to be controlled for wake steering and the effect of this control strategy was to be evaluated based on the response of T3. Therefore, two campaigns were conducted within the same field experiment: a south campaign, when the predominant wind direction was from the south; and a north campaign, for a predominant wind direction from the northern sector.




**(a)** **(b)**

**Figure 6: Satellite image of the cluster of five turbines that were the focus of the experiment (a) and schematic showing instrumentation used to measure atmospheric conditions and relative distances between all turbines (b).**

The objectives of the test were jointly defined to be:

- Validate the ability to improve power production through wake steering consider a pair of turbines
- Field-test the ability to steer wind turbine wakes in a commercial wind plant and a wide range of atmospheric conditions
- Validate multi-fidelity approaches to simulating wake steering for turbine pairs in a range of atmospheric conditions.

The inflow was to be measured by two sodars, one meteorological tower, and one lidar. In addition, lidars were to be mounted to the nacelle of the turbines of interest: a forward-facing Wind Iris lidar on T2, and two rear-facing scanning lidars on T2 and T3. The instrumentation location is shown in Figure 6b.

In addition to the independent instrumentation deployed in this campaign, the SCADA data for all five turbines (T1-T5) would also be collected. This data comes from each turbine's controller and is provided to NREL by the owners of the farm. Although researchers have less control over the signals, they play a vital role in the implementation of the wake steering controllers.

### Phase II, Task #1: Develop SOWFA and FLORIS models of subset of turbines at the wind plant

Before carrying out a field experiment, the partner shared SCADA data (Task 1.1) and simulations were performed (Tasks 1.3-1.4) to assess the expected response of the field turbines to the control strategies that would be implemented. Additional simulations of the wind farm were performed prior to the field experiment to support the choice of instrumentation location and to further refine the implementation of the various control strategies planned for the experiment (Task 1.2). These simulations were performed with FLORIS and SOWFA (Tasks 1.3-1.4). An example of a pre-experiment FLORIS simulation is shown in Figure 7. These simulations were performed for the entire wind farm and for various yaw offsets. The analysis of results was used to determine the maximum allowable yaw offset that could be pursued as a function of hub-height wind speed during the field experiment. Optimization studies performed with FLORIS led to a yaw-offset look-up table as a function of wind speed and direction for each of the two turbines that would be controlled: T4 for the southern experiment and T2 for the northern experiment.

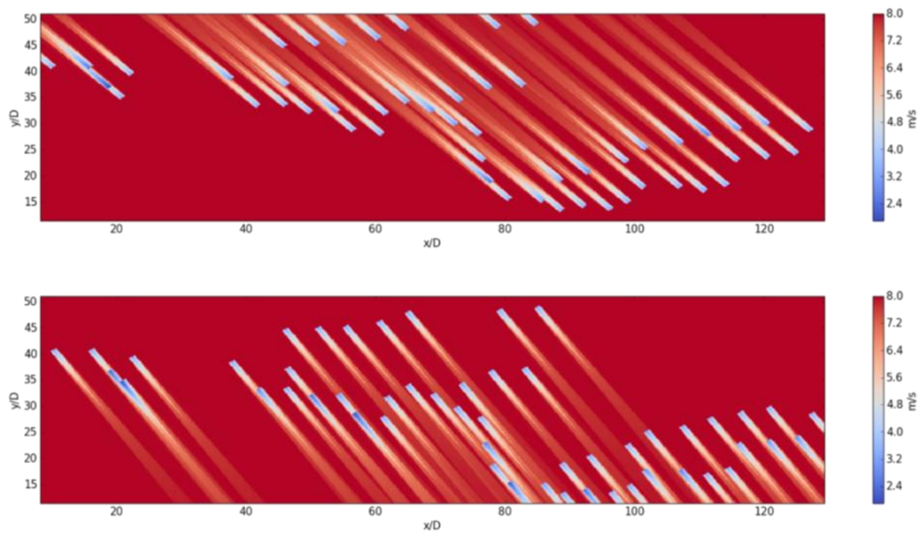



**Figure 7: FLORIS simulation of the wind farm for a southerly (135°) and northerly (325°) wind direction, for an inflow wind speed of 8 m/s at hub height. The five-turbine cluster considered in the experiment is on the left side of the field of view, centered at x/D~16 and y/D~38.**

Figure 8 shows a simulation of the field site performed with the large-eddy simulation (LES) tool SOWFA. The results were used to validate FLORIS and demonstrated a dependence of dynamic power output on the stability and wind speed of the inflow.

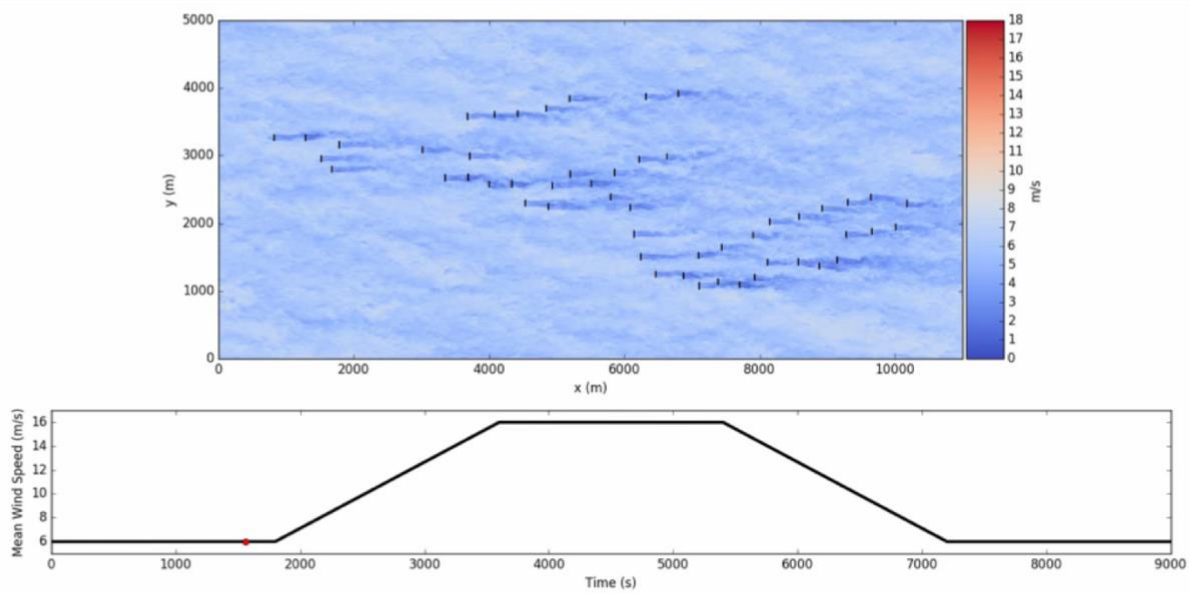
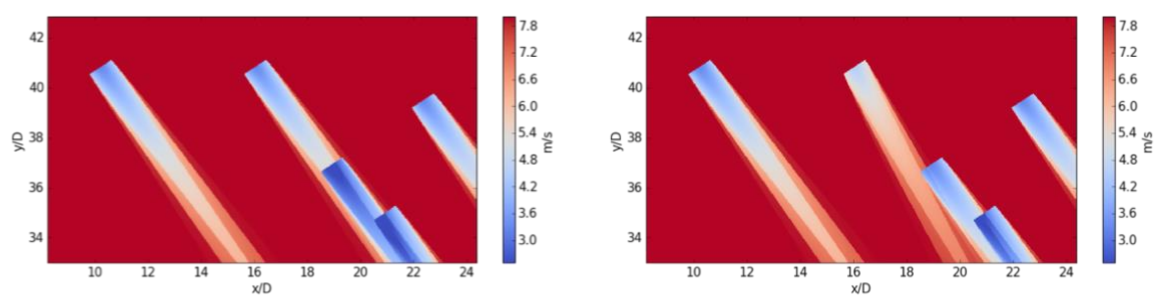



**Figure 8: SOWFA simulation of the wind farm for a westerly (270°) wind direction, for an inflow wind speed that ramps from 6 m/s to 16 m/s and back down to 6 m/s over a period of 2.5 hours. The five-turbine cluster considered in the experiment is on the left side of the field of view, centered at x~1000 m and y~3000 m.**

**Phase II, Task #2: Wake steering analysis and prediction of performance impacts**

One important part of the pre-experiment simulations is to assess how the plant performance is expected to change when turbines are operated to follow wake steering control strategies. To do so, a suite of FLORIS simulations was performed for a range of wind speeds, wind directions, and yaw offsets (Task 2.1). An example of these simulations is shown in Figure 9.




**(a)** **(b)**

**Figure 9: FLORIS simulation of the five-turbine cluster without wake steering (a) and with wake steering via yaw misalignment of 25° (b). Hub-height wind speed is 8 m/s, and direction is 325°.**

The load envelope of the turbine was also simulated (Task 2.2). It was found that the impact on loads was negligible for wind speeds in Region 2 and offsets below 20°. Based on the results from FLORIS, the NREL recommendation for the field test was to limit the wake steering to positive yaw angles and stay below +20°. The target yaw offsets as a function of wind direction are shown in Figure 10 for several wind speeds. A test plan for the campaign was crafted based on the simulation results (Task 2.3) and a report presented to the partners in July 2017 (Task 2.4).

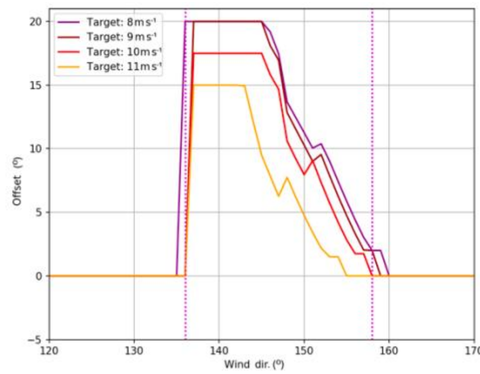



**Figure 10: Target offset for 8-11 m/s as a function of wind direction. The magenta vertical lines indicate the approximate boundaries of the experiment (these vary slightly by wind speed, but the overall shape is the same).**

### Phase II, Task #3: Partner will make go/no-go decision for Phase II tasks 4 and 5

The work performed up to this point provided strong evidence that the model predictions are robust in terms of power performance and structural response of the wind turbines when operating under yaw misalignment. Furthermore, the predicted response envelope was acceptable to the partner and, upon evaluating the collective results to this point, the partner decided to proceed with the field experiment at their wind farm.

### Phase II, Task #4: Run experimental campaign on selected subset of wind plant turbine pairs

This task represents the culmination of the work outlined under this agreement. After a preliminary field experiment carried out at a DOE-owned wind turbine at a NREL site, and extensive simulations of the GE wind turbines located at the partner's wind farm, a field campaign was run at the wind plant. The field campaign was carried out between May 2018 and February 2020. The partners instrumented the turbines with controller modifications and encoders to ensure low uncertainty data retrievals (Task 4.1). Both partners collected extensive data, which were analyzed and published as follows (Task 4.2). Detailed results from the southern campaign can be found in Fleming et al. (2019) and from the northern campaign in Fleming et al. (2020). Here, we provide an example of the results obtained for each campaign. For a more detailed discussion, the reader is referred to the full articles. In addition to these two seminal papers, data obtained during this experiment led to valuable model validation studies and scientific results which can be found in the following publications: Simley et al. (2020), Brugger et al. (2020), Murphy et al. (2020), Shaler et al. (2020), Debnath et al. (2020).

The wake steering controller is shown by the schematic in Figure 11. The controller computes an offset vane signal to send to the (unmodified) turbine yaw controller—illustrated in the figure. More details on the development of this controller can be found in Simley et al. (2020).

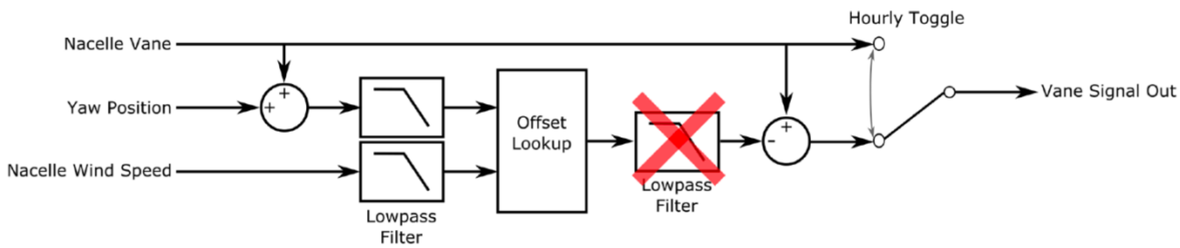



**Figure 11: Wake steering controller developed for this experiment.**

Figure 12 shows the number of hours of data collected between May 2018 and October 2019. Despite the shorter duration of northerly data collection, a similar amount of data were obtained for both direction sectors (~400 hours).

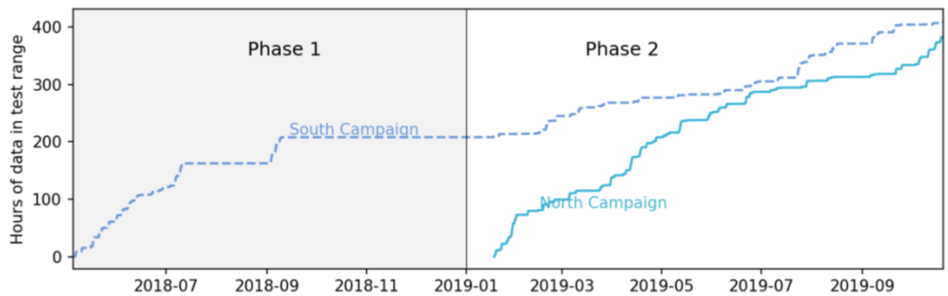
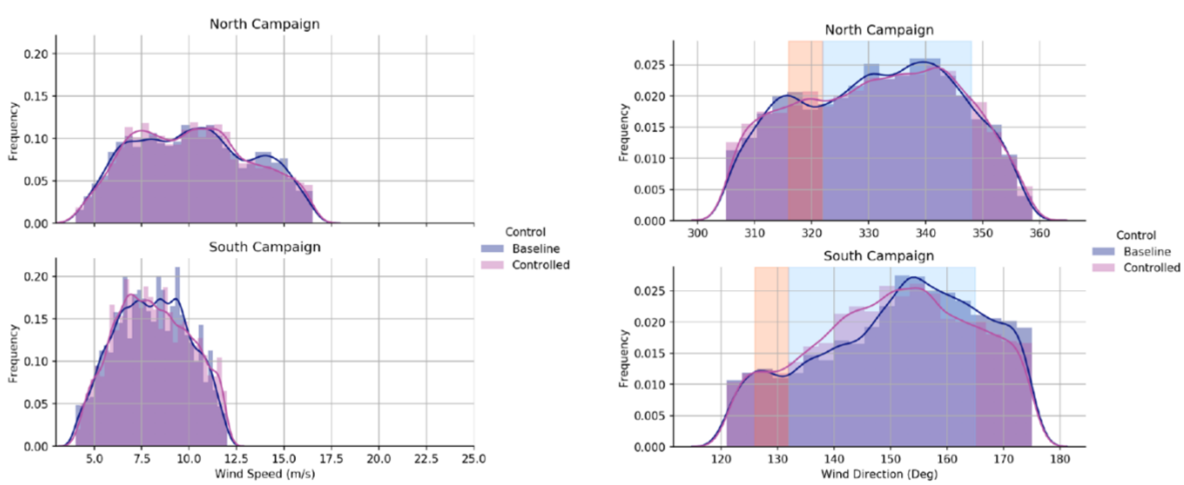



**Figure 12: Data accumulation for both phases of the field campaign. For both north and south, we consider only data that are in the range of wind directions where the control turbine would be activated. The data included in this count are usable in that they contain no faults or issues with any sensor used in control or analysis.**




(a) Wind Speed

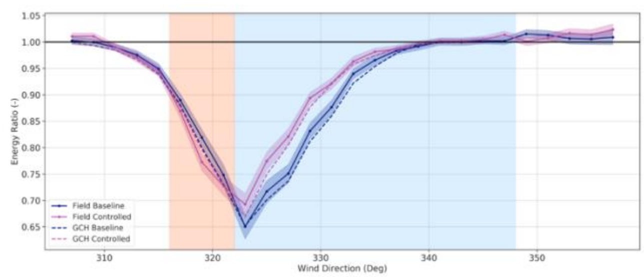
(b) Wind Direction

**Figure 13: Wind speed and wind direction histograms showing amount of data that was collected for north (top) and south (bottom) campaigns for aligned (i.e., baseline) and yawed (i.e., controlled) operation. Wind direction histograms show the range of desired vs. non-desired yaw offsets to illustrate the controlled region.**

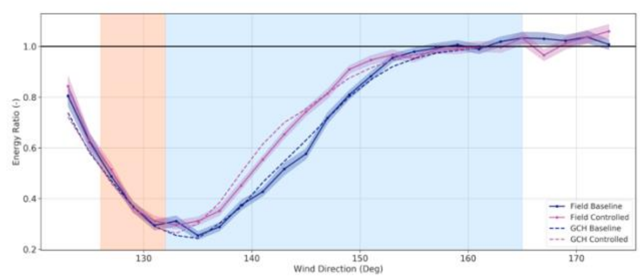
The field campaign results shown in Figure 13 reveal a wide range of wind speed and wind direction distributions for both campaigns, highlighting the benefits of conducting long-term measurements spanning more than one seasons. More field measurement results are shown in the next section, in comparison to simulation data. The key results from the findings were presented to the partner in meetings (Task 4.3).

**Phase II, Task #5: Validation of SOWFA and FLORIS wake steering simulation and control**

As a final task of this agreement, the data collected between 2018 and 2020 was used to validate the same wake modeling tools that were used in the initial tasks to predict turbine behavior under wake steering. These tools are the controls-oriented, engineering model FLORIS and the large-eddy simulation tool SOWFA (Task 5.1). Figure 14 shows power ratio as a function of wind direction for the north and south campaigns for measurements (solid lines) and FLORIS simulations using the Gauss-Curl Hybrid wake model (dashed line). These results, which were presented to the partner internally (Task 5.2), reveal substantial and consistent power gains when the upstream wind turbine is wake controlled (magenta curve) to maximize power production. The gains are seen for both campaigns and are well predicted by FLORIS.




(a) North Campaign

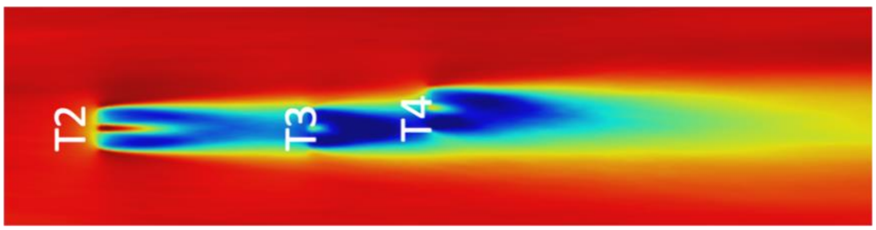



(b) South Campaign

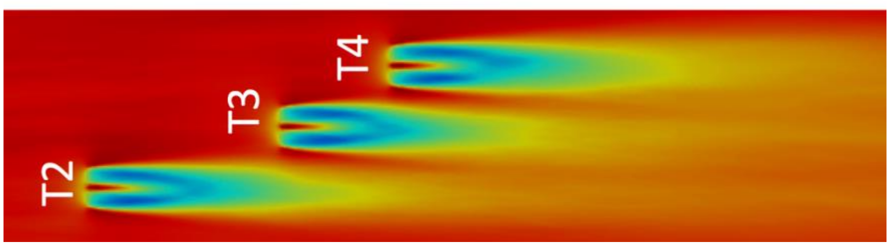
**Figure 14: Energy ratio of T3 (waked turbine) for the north and south campaigns. For both campaigns, this represents the ratio of energy produced by T3 with respect to unwaked reference turbines. The banded region is the same as in Figure 13, and indicates regions of yaw offset activity, either intended (blue) or unintended (orange).**

The entire wind plant was simulated using FLORIS. (Task 5.3) Three inflow turbulence intensity values were used (6%, 8% and 10%) and the wind speeds and directions were prescribed based on the wind rose at the site. The simulated wind turbines were allowed up to 25° of yaw steering. For one of the turbulence scenarios, wind direction uncertainty was also included to model limitations of the current controller implementation. Results revealed that the largest gains in plant performance were for easterly and westerly wind directions because of close turbine spacing (note that the greatest energy production occurs at north-northwest and south-southeast wind directions). At 8% TI, a 1.1% AEP gain from wake steering is estimated, representing a wake loss reduction of 17.4%. When the wind direction uncertainty is accounted for, this gain drops to 0.6%. By investigating different turbulence values, a reasonable range of AEP gains that could be expected from wake steering with more advanced control strategies for this wind plant is 0.7-1.6%.

Figure 15 shows mean wakes for three turbines at the wind farm as simulated by SOWFA under neutral atmospheric stratification. The inflow wind speed is 8 m/s at 80 m height. The turbines are facing two slightly different wind directions. For the 324-deg scenario, T2 and T3 are perfectly aligned. For a wind that is coming from a slightly different direction—only 16 degrees further north—the wake from T2 goes to the side of T3. These small differences can have direct consequences on the power production of the farm. The validation efforts and loads analysis were summarized into several articles [5,6,9] (Task 5.4).




**(a) Wind direction = 324 deg (NNW)**




**(b) Wind direction = 340 deg (NNW)**

**Figure 15: Mean wakes from three turbines at the wind farm as simulated with SOWFA for two wind directions: 324 deg (a) and 340 deg (b). Note that the coordinate system is rotated so that the flow is aligned left-to-right for both wind directions.**

Table I provides a comparison between simulation and measurements for a wind direction of 340 deg. The values given are power ratios: the power generated by T3 and T4 is normalized by the power of an unobstructed, upstream turbine. The values reveal that.

**Table I: Ratio of power between turbines T3 and T4 relative to an unobstructed, upstream turbine. Given for SOWFA simulation and measurements for a wind direction of 340 deg.**

| Power Ratio | SOWFA Simulation | Measurements |
|---|---|---|
| T3 | 1.049 | 1.045 |
| T4 | 1.071 | 1.069 |

All of the tasks from the original executed CRADA agreed upon by both parties were successfully completed. Any additional agreement modifications may have added either time or funding; however, no additional tasks were defined after the original agreement, which have all been explained above.

**Subject Inventions Listing:**

None

**ROI#:**

None

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