Comparison of yaw angle selection strategies for wake steering control of wind farms using FLORIS

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***Abstract*—Research over the past decade has explored the area of yaw angle optimization or "wake steering" as a control strategy to maximize the power output of a wind farm. There is broad agreement in the literature that the optimal control strategy involves yawing the upstream turbine by the largest misalignment angle and decreasing the yaw offset for each downstream turbine. However, current wind farm yaw control capabilities do not always allow for independent offset control at the turbine level [1].**

This project uses the FLOw Redirection and Induction in Steady State (FLORIS) modeling tool developed by NREL to evaluate two different control strategies for wake steering operation through parametric wake modeling simulation [2]. In one strategy, all turbines except the final one are misaligned by the same yaw angle, as tested in [1, 3]. In the other, yaw angle offsets decrease linearly from the most-upstream turbine to the penultimate one while the last turbine is not misaligned [2, 3]. The performance of these control algorithms is characterized for a variety of different input wind conditions.

Keywords—wake steering, FLORIS, yaw angle optimization, wake management, wake modeling

I. Introduction

Wake losses severely decrease the power output of wind turbines and can reduce the array efficiency of a wind farm by up to 40% when turbines are aligned in the streamwise direction [5]. Wake steering has been explored as a method to reduce wake losses by redirecting the wakes of upstream turbines away from downstream turbines. Researchers agree that the optimal method of yaw control involves a yaw offset that decreases for turbines that are further downstream in an array. However, not all wind farms have control systems that allow for yaw misalignment control at the turbine level; as such, another strategy involves a farm-wide offset that is the same for all misaligned turbines in an array. This paper compares these two control strategies for a variety of different input wind conditions using parametric wake modeling. From a practical standpoint, the results of this comparison would help wind farm developers and operators evaluate whether the expected efficiency improvements of the optimal strategy are significant enough to warrant the additional complexity in control design.

II. Review

Several evaluations of wake steering control have been completed by researchers in recent years, though most focus on characterizing the performance of a single control strategy across various wind conditions. One notable study which compares multiple control strategies is a thorough series of wind tunnel experiments by Bastankhah and Porté-Agel [3] in 2019 which found that the "decreasing offset" strategy resulted in more power gains than the "fixed offset" strategy. That study compared these strategies for one fixed wind speed (8 m/s) and one fixed inter-turbine spacing (5D, or 5 rotor diameters). Additionally, the turbines used in that study were physical models scaled down in size – while they had C_P and C_T values tuned to be representative of larger utility scale machines, the Reynolds number corresponding to the flow in the wind tunnel is different from what would be experienced for a utility scale wind farm.

Field studies involving wake steering campaigns, such as in [1] and [6], provide useful real-world data but are limited by practical constraints such as array layout and controller complexity that limit their ability to effectively compare control strategies. Similarly, simulation studies using high- and medium-fidelity LES- or RANS-based solvers are limited by the computational complexity and number of grid points that these simulations require. To the author's knowledge, a parametric study that directly compares the effectiveness of the aforementioned control strategies has not been published.

Researchers have also examined the effect of wake steering control on turbine loads. Readers interested in this topic are referred to Houck [5] and Kanev [4, 6] as a starting point. Notably, Kanev's work has found that fatigue loads are decreased by wake steering control because they reduce the turbulence in the wind at downstream turbines [6] and increase the overall lifetime and lifetime power production of wind farms. Other studies, such as by Fleming [7] in 2017, restrict the yaw misalignment of the most-upstream turbine to a maximum deviation from the angle of incoming wind in order to reduce loads on the most-upstream turbine. However, Kanev [6] argues that for large wind farms where the direction of the wind changes, the upstream-most turbine for a given wind direction is the downstream-most turbine for wind flowing in the opposite direction and that the reduced fatigue loads in the latter case more than make up for the potentially increased fatigue loads in the former. Site-specific wind data is needed to evaluate the need for any safety constraints based on loading and this analysis is not part of this research.

III. Experiment Setup

A. Wake Modeling

The simulations for this experiment will be conducted using NREL's FLOw Redirection and Induction in Steady State (FLORIS) tool for parametric wake modeling and wake steering control. FLORIS is a controls-oriented framework that includes several models for velocity deficit, wake deflection, and secondary steering [2]. While parametric models do not solve flows in the same way that RANS-based or LES-based simulations do, they are instructive to illustrate trends and make comparisons between different control strategies for a given turbine layout.

In this paper, FLORIS's Gauss-curl hybrid (GCH) model is used to account for the effects of secondary steering. Secondary steering describes a phenomenon where nonzero lateral (i.e. spanwise) and vertical components of wind velocities in the wake of an upstream turbine cause deflection of the wakes of downstream turbines—this has been shown by many researchers, including Fleming [8] and Zong [9], to impact the output power and therefore the optimal offset angles of downstream turbines. The GCH model was developed by NREL [10] to account for this impact and modifies the more-commonly-used Gaussian velocity deficit model to account for the secondary steering effects. To validate the implementation in FLORIS, King [10] compared the GCH and Gaussian models to LES simulations and showed that the GCH model more closely agreed with LES simulation than the Gaussian model.

B. Parameters of Interest

Simulations for this experiment use NREL's 5-MW offshore reference turbine which has cut-in, rated, and cut-out wind speeds of 3 m/s, 11.3 m/s, and 25 m/s respectively [11]. The power (C_P) and thrust (C_T) coefficient curves for the turbine are chosen to be representative of industry-standard utility scale turbines. Turbines are restricted to yaw in the counterclockwise direction as there is broad agreement in the literature that wake losses are lower for counterclockwise yaws than for equivalent clockwise yaws [5].

Parameters of interest related to the flow are as follows:

- Array Depth: Rows of 2, 3, 4, 5, and 6 turbines are tested. The relative benefit of any wake steering control over the un-yawed case is expected to increase with increasing array depth per Bastankhah and Porté-Agel [3].
- Wind Speed: A control wind speed of 8 m/s is chosen to remain consistent with existing literature. This speed corresponds roughly to the steepest part of an offshore wind turbine's power curve. Speeds of 6 m/s and 10 m/s are also tested to examine the benefits of wake steering when the incident wind speed is closer to a turbine's cut-in speed or to its rated speed.
- Array Spacing: A spacing of 5 rotor diameters (5D) is chosen as the control. Array spacings of 3D and 7D are also tested. Larger array spacing results in greater wake recovery; as such, the relative benefit of wake steering over the un-yawed case is expected to decrease with increasing array spacing.
- Turbulence Intensity (TI): In addition to a control of 6% intensity, a TI of 10% is also tested. Greater turbulence intensity aids wake recovery; as such, the relative benefit of wake steering over the un-yawed case is expected to decrease with increasing turbulence intensity.

C. Control Strategies and Yaw Angle Optimization

Two control strategies will be used to optimize the power for the selected arrays. The total power output of the optimized wind farms will be compared to the reference case arrays where no turbines are misaligned.

- Fixed angle strategy: This strategy assumes the reduced control capabilities of some wind farms in operation, such as the one involved in Howland's field campaign [2] which has farm-level yaw misalignment control. In this method, all turbines except for the last turbine will have the same yaw misalignment, and the last turbine necessarily has no misalignment.
- Decreasing angle strategy: This strategy assumes a wind farm with control of yaw misalignments at the individual turbine level. In this method, the yaw misalignment decreases from the upstream turbine to the penultimate turbine. The last turbine is fixed at 0 degrees.

The optimal yaw angles for the fixed-yaw strategy are determined by sweeping the array's yaw angles clockwise in steps of one degree and calculating the farm's total output power. For the decreasing-yaw strategy, the first turbine's yaw angle is swept freely while the yaw angles for the remaining turbines are calculated by sweeping the size of the decreasing step. The step size is restricted so that no turbines can have a negative yaw angle. This research tests the decreasing-yaw strategy in two ways. In the first, the size of the decreasing step is constant so the difference between the yaw misalignments of any two consecutive turbines (except for the last pair) is the same; in the second, the size of the decreasing step is left variable with the restriction that the difference between the yaw misalignments of any downstream pair of consecutive turbines must be greater than or equal to the difference between misalignments of any pair of consecutive turbines further upstream. For the remainder of this paper, the former will be described as the "fixed-step decreasing offset strategy" while the latter will be described as the "variable-step decreasing offset strategy".

IV. Results

FLORIS was used to simulate the performance of rows of wind turbines under a variety of conditions reflective of the range of input wind conditions and array configurations that can be expected at a typical offshore wind farm. For each condition, the baseline power output was first measured without manipulating the yaw angles of any turbines. Afterwards, the optimal yaw angles that maximized the farm output power were found using both the fixed offset strategy and the decreasing offset strategy. Table III in the Appendix describes the wind conditions and array parameters for each experiment as well as the optimal yaw angles and total output power of the array identified for the specified conditions.

A. Array Depth

The performance of both yaw optimization angle techniques was evaluated for rows of depth 2, 3, 4, 5, and 6 turbines. For arrays with depth 2, the fixed offset strategy and decreasing offset strategy are equivalent since the downstream-most turbine is not yawed. To provide additional data points for comparison, the optimal yaw angles for arrays with 3 or more turbines were calculated for a strategy that involved yawing only the turbine furthest upstream. For arrays with 4 or more turbines, both the fixed-step and variable-step decreasing offset strategies were used to optimize the offset angles of the array.

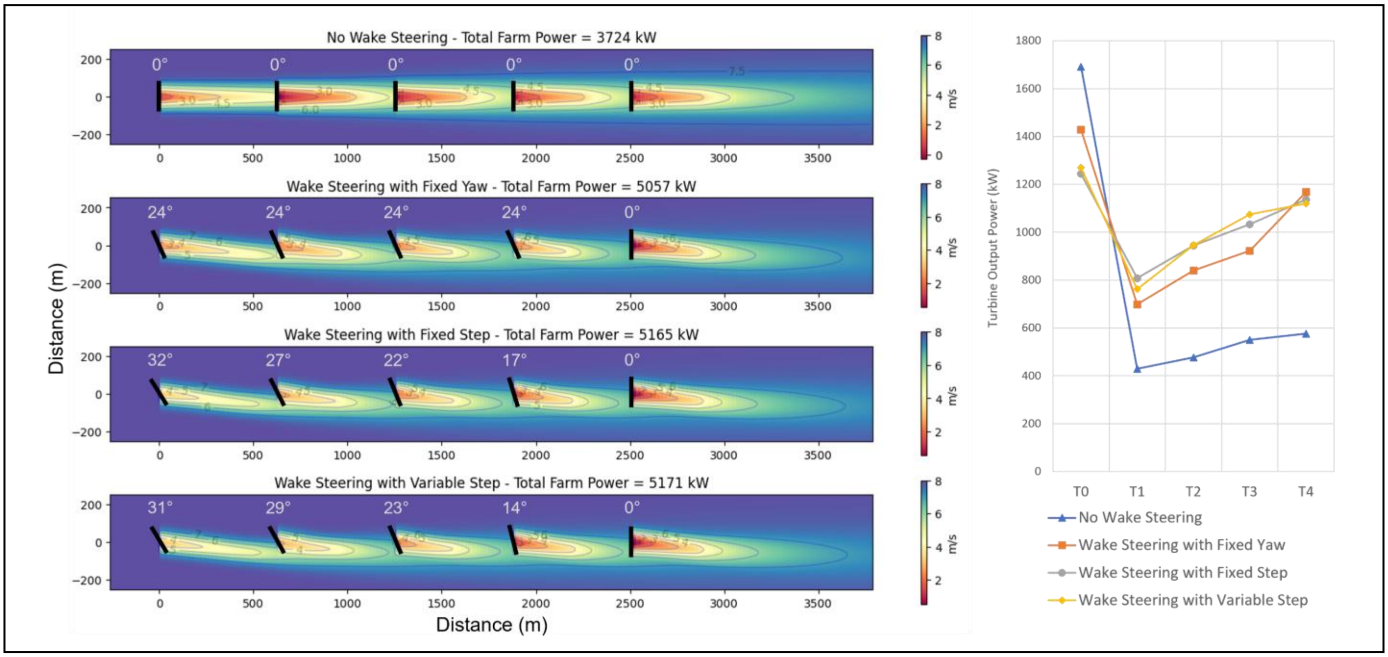

Fig. 1: Left: Wind speeds in a 5-turbine array measured at the turbine hub height of 90 meters. The spacing between turbines is 5 rotor diameters (630 meters). The initial wind speed is 8 m/s and the turbulence intensity is 6%. Right: Output power of individual turbines in kW. T0 represents the most upstream turbine.

Fig. 1 illustrates the wind speeds at turbine hub height as well as individual turbine output powers for a 5-turbine array with the turbine yaw offsets optimized using different control strategies. As upstream turbines are yawed further, their power output decreases because they capture less and less of the incident wind. However, the power output of downstream turbines increases because the velocity deficit due to upstream turbines is decreased.

Fig. 2 shows the relationship between array depth and total farm output power for the various yaw control strategies tested. Power increases both as turbines are added to the array and as yaw angle optimization techniques are implemented. The percentage increase in power output over the reference case that is achieved by yawing only the first turbine increases as the array depth is increased from 2 to 3, showing that the yaw offset of a given turbine affects the power output for more turbines than the one immediately downstream. However, the improvement over the reference case remains relatively constant as the array depth is increased further.

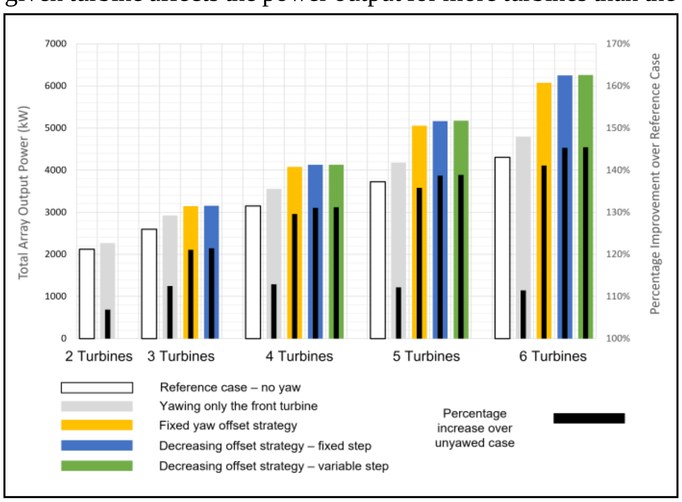

Fig. 2. Total farm power output vs array depth for several wake steering control strategies.

For an array of depth 3 turbines, there is not a significant difference in the maximum power output achieved by the fixed offset and decreasing offset strategies; as the depth is increased, the performances of both of the decreasing offset strategies improve at a greater rate.

Finally, the difference between maximum power output achieved via the fixed-step and variable-step decreasing offset strategies is negligible for all the array depths considered. As shown in Table I, the variable-step decreasing offset strategy yields the optimal offset angles for arrays of all depths considered, but the improvement in the array output power compared to an array of the same depth optimized by the fixed-step decreasing offset strategy is less than 7 kW for all depths considered. For computational simplicity, the variable-step decreasing offset strategy is ignored for the remainder of experiments.

TABLE I. OUTPUT POWER FOR DECREASING OFFSET STRATEGIES

Experiment Number	Number of Turbines	Decreasing Offset Yaw Strategy	Output Power (kW)	Percent of Reference Case Output Power
A7	4	fixed step	4125.70	131.06%
A8	4	variable step	4130.19	131.20%
A11	5	fixed step	5165.44	138.71%
A12	5	variable step	5171.89	138.88%
A15	6	fixed step	6253.35	145.29%
A16	6	variable step	6259.51	145.43%

TABLE II. OPTIMAL YAW ANGLES FOR VARIOUS WIND SPEEDS

Experiment Number	Parameter		Optimal Yaw Angles (degrees)					Total Output Power (kW)
	Wind Speed	*Yaw Optimization Strategy*	*T0*	*T1*	*T2*	*T3*	*T4*	
V1	6 m/s	Fixed angle	24	24	24	24	0	2023.65
V2	6 m/s	Decreasing offset, fixed-step	33	27	21	15	0	2071.54
A10	8 m/s	Fixed angle	24	24	24	24	0	5057.13
A11	8 m/s	Decreasing offset, fixed-step	32	27	22	17	0	5165.44
V3	10 m/s	Fixed angle	24	24	24	24	0	9920.69
V4	10 m/s	Decreasing offset, fixed-step	32	27	22	17	0	10097.92
V5	6 m/s	Use optimized angles from A11, V4	32	27	22	17	0	2071.50

B. Wind Speed

Fig. 3 shows the relationship between wind speed and the farm output power improvements offered by different wake steering control strategies. This graph shows that variation in the site wind speed has a far greater impact on the farm output power than yaw control of the turbines through wake steering.

For all wind speeds, the decreasing offset strategy performs better than the fixed offset strategy. The percentage difference between the two strategies is higher at lower wind speeds due to the fact that the farm output power for the unyawed reference case is lower at those speeds. However, the difference in actual power output is greater at higher wind speeds because wake losses are higher at higher wind speeds so the effect of wake steering control is more pronounced.

Table II shows that the optimal yaw angles for all wind speeds considered are not significantly different. For all wind speeds considered, the optimal offset angle for the fixed offset strategy was determined to be 24 degrees. The optimal misalignments determined by the decreasing offset strategy were the same for wind speeds of 8 m/s and 10 m/s. When these misalignment angles were tested with a wind speed of 6 m/s, the total array output power was within 50 W (0.002%) of the array output power achieved when the array misalignment angles were optimized for the speed of 6 m/s. Though real-world wind speed varies in time, this result means that time-varying wind speeds from a fixed direction are not likely to cause excessive yawing of the turbine. For wind speeds significantly higher than the rated wind speed of 11.3 m/s, turbines would be operating at their rated power, rendering wake steering control unnecessary and irrelevant.

C. Array Spacing

Fig. 4 shows the performance of the selected wake steering control strategies for arrays with different inter-turbine spacing. For smaller distances, the velocity deficit due to the wake effect is greater and the overall farm output is decreased; as the spacing between turbines increases, wake recovery is increased and the power output of the farm increases as a result. At the distances tested, applying wake steering control had more of an effect on farm output than simply increasing the spacing by three rotor diameters. Wake steering has a greater effect in tighter spaces because redirecting turbine wakes reduces the average wind

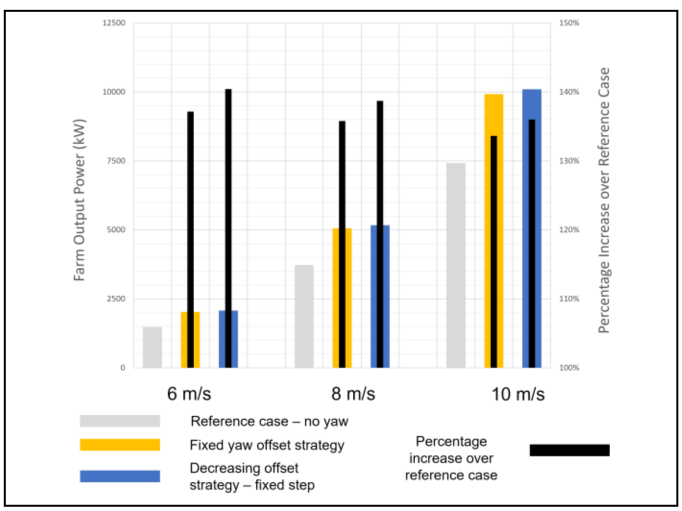

Fig. 3. Total farm power output as a function of wind speed for several wake steering control strategies.

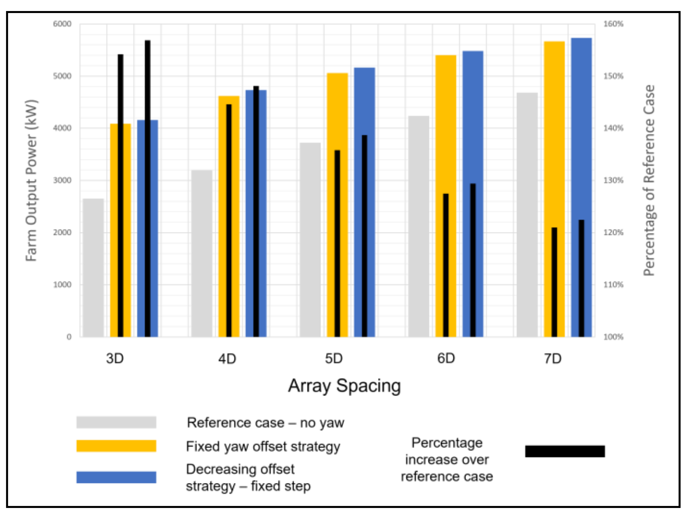

Fig. 4. Total farm power output as a function of the spacing between consecutive turbines for several wake steering control strategies.

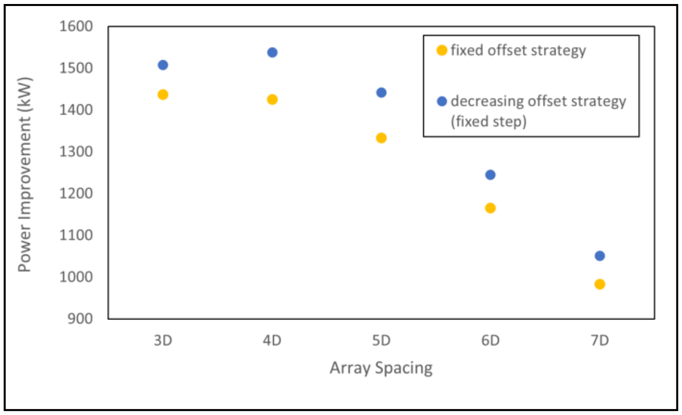

Fig. 5. Power improvement over the reference (unyawed) case as a function of the spacing between consecutive turbines for different wake steering strategies.

velocity deficit experienced by downstream turbines and this is reflected in the trend observed in the improvements that both wake steering strategies offered over the reference cases for the array spacings tested. For the inter-turbine spacings tested, the percentage improvement of the decreasing yaw strategy relative to the reference unyawed case is highest for a spacing of 3D and decreases as the spacing is increased.

As the spacing is increased, the actual power improvement of the decreasing offset strategy relative to the reference case first increases, then decreases, reaching a maximum value of 1537 kW for spacings of 4D as shown in Fig. 5. This trend suggests the existence of a "sweet spot" where a marginal increase in array spacing results in both a marginal improvement in wake loss recovery as well as marginally increased space for intentional wake deflection caused by wake steering control. In other words, the average wind speed across the swept area of a downstream turbine is increased not only because the wind has more room to recover from wake losses but also because there is more room to steer the wake away by intentionally yawing upstream turbines.

D. *Turbulence Intensity*

Fig. 5 shows the effect of turbulence intensity (TI) on the effectiveness of wake steering control. We note that increasing the turbulence intensity from an average value of 6% to a higher value of 10% significantly improves the performance of the reference unyawed case - the output power in scenario R8 is more than 1 MW greater than in scenario R3. At the same time, the total farm output power in the "steered" cases only improves marginally. Since turbulence aids wake recovery and reduces wake losses, the effectiveness of wake steering decreases significantly at higher turbulence intensities. The output power improvement offered by the decreasing offset strategy over the fixed offset strategy also decreases as the turbulence intensity increases.

V. Discussion and Conclusion

In this paper, two different wake steering control strategies were evaluated over different array configurations and input wind conditions. The fixed yaw offset strategy represents a "global" approach to wind turbine yaw angle control—yaw

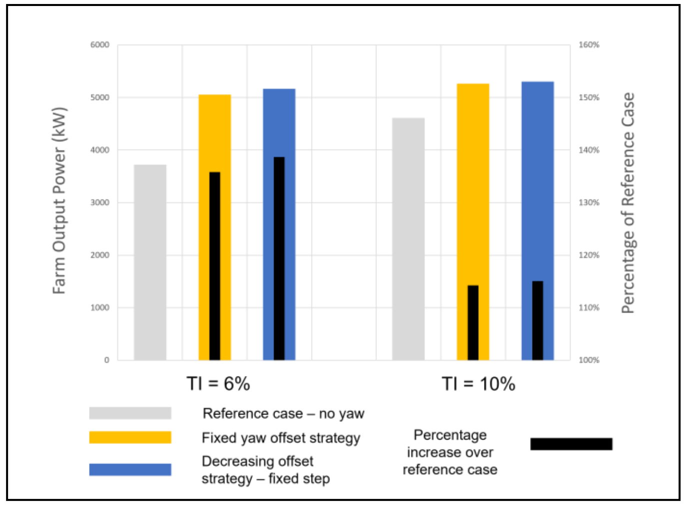

Fig. 6. Total farm power output as a function of the turbulence intensity of the wind resource for several wake steering control strategies.

control can be enabled or disabled for individual turbines but all turbines for which the controller is enabled must yaw to the same misalignment angle. The optimal performance under this strategy is achieved when yaw control for the downstream-most turbine is disabled while all the upstream turbines misalign to the selected yaw angle.

The decreasing yaw offset strategies represent a "local" approach as the yaw angle for individual turbines can be independently selected. There is broad consensus in the literature that this optimization strategy, which involves decreasing the misalignment for successive turbines in an array and fixing the downstream-most turbine to not yaw, yields the optimal yaw misalignments to maximize the power output of the array. The experiments performed as part of this research were designed to characterize the trends in the relative difference between the two strategies for conditions that vary from site to site in wind farms.

The simulations conducted confirmed that the decreasing offset strategy increases the total array power output by between 0% and 3% compared to the fixed offset strategy for all the conditions tested. The difference between the two strategies is significantly reduced when the array depth is low or the turbulence intensity is high. As the spacing between turbines is increased, the power benefit of the decreasing offset strategy relative to the fixed offset strategy first increases, then decreases. Finally, variation in wind speed affects power output significantly more than wake steering control using either yaw strategy. Though the relative power benefit of the decreasing offset control over the fixed offset control increases with increasing wind speed, this effect is expected to plateau past the rated wind speed of a given turbine. As a general rule, conditions that are favorable to wake steering control will increase the relative difference between the fixed offset and decreasing offset strategies.

Future research could compare the performance of these strategies for varying wind directions. This research also does not explore the how the different strategies impact the mechanical loads on the turbine towers and blades. Since the differences in power output between the two control strategies is at most a few percent, a 2-3% difference in turbine lifetime due to mechanical loads could be a significant enough reason to select one strategy over the other.

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APPENDIX

TABLE III. PARAMETRIC SWEEP RESULTS

Experiment Number	Parameter					Optimal Yaw Angles (degrees)						Total Output Power (kW)
	Number of Turbines	*Wind Speed*	*Array Spacing*	*Turbulence Intensity*	*Yaw Strategy*	*T0*	*T1*	*T2*	*T3*	*T4*	*T5*	
R1	2	8 m/s	5D	6%	No yaw	0	0	n/a	n/a	n/a	n/a	2120.77
R2	3	8 m/s	5D	6%	No yaw	0	0	0	n/a	n/a	n/a	2597.96
R3	4	8 m/s	5D	6%	No yaw	0	0	0	0	n/a	n/a	3147.99
R4	5	8 m/s	5D	6%	No yaw	0	0	0	0	0	n/a	3724.02
R5	6	8 m/s	5D	6%	No yaw	0	0	0	0	0	0	4304.12
R6	5	6 m/s	5D	6%	No yaw	0	0	0	0	0	n/a	1475.93
R7	5	10 m/s	5D	6%	No yaw	0	0	0	0	0	n/a	7424.31
R8	5	8 m/s	3D	6%	No yaw	0	0	0	0	0	n/a	2650.82
R9	5	8 m/s	4D	6%	No yaw	0	0	0	0	0	n/a	3195.72
R10	5	8 m/s	6D	6%	No yaw	0	0	0	0	0	n/a	4237.66
R11	5	8 m/s	7D	6%	No yaw	0	0	0	0	0	n/a	4683.52
R12	5	8 m/s	5D	10%	No yaw	0	0	0	0	0	n/a	4609.46
A1	2	8 m/s	5D	6%	Yaw front only	26	0	n/a	n/a	n/a	n/a	2266.85
A2	3	8 m/s	5D	6%	Yaw front only	29	0	0	n/a	n/a	n/a	2922.82
A3	3	8 m/s	5D	6%	Fixed angle	28	28	0	n/a	n/a	n/a	3145.22
A4	3	8 m/s	5D	6%	Fixed step	29	24	0	n/a	n/a	n/a	3154.85
A5	4	8 m/s	5D	6%	Yaw front only	30	0	0	0	n/a	n/a	3553.38
A6	4	8 m/s	5D	6%	Fixed angle	27	27	27	0	n/a	n/a	4079.40
A7	4	8 m/s	5D	6%	Fixed step	31	25	19	0	n/a	n/a	4125.70
A8	4	8 m/s	5D	6%	Variable step	31	27	18	0	n/a	n/a	4130.19
A9	5	8 m/s	5D	6%	Yaw front only	30	0	0	0	0	n/a	4177.75
A10	5	8 m/s	5D	6%	Fixed angle	24	24	24	24	0	n/a	5057.13
A11	5	8 m/s	5D	6%	Fixed step	32	27	22	17	0	n/a	5165.44
A12	5	8 m/s	5D	6%	Variable step	31	29	23	14	0	n/a	5171.89
A13	6	8 m/s	5D	6%	Yaw front only	30	0	0	0	0	0	4795.79
A14	6	8 m/s	5D	6%	Fixed angle	24	24	24	24	24	0	6073.32
A15	6	8 m/s	5D	6%	Fixed step	32	27	22	17	12	0	6253.35
A16	6	8 m/s	5D	6%	Variable step	31	29	23	17	10	0	6259.51
V1	5	6 m/s	5D	6%	Fixed angle	24	24	24	24	0	n/a	2023.65
V2	5	6 m/s	5D	6%	Fixed step	33	27	21	15	0	n/a	2071.54
V3	5	10 m/s	5D	6%	Fixed angle	24	24	24	24	0	n/a	9920.69
V4	5	10 m/s	5D	6%	Fixed step	32	27	22	17	0	n/a	10097.92
V5	5	6 m/s	5D	6%	Copy A11, V4	32	27	22	17	0	n/a	2071.50
S1	5	8 m/s	3D	6%	Fixed angle	28	28	28	28	0	n/a	4087.47
S2	5	8 m/s	3D	6%	Fixed step	34	29	24	19	0	n/a	4158.58
S3	5	8 m/s	4D	6%	Fixed angle	27	27	27	27	0	n/a	4620.81
S4	5	8 m/s	4D	6%	Fixed step	34	28	22	16	0	n/a	4733.21
S5	5	8 m/s	6D	6%	Fixed angle	24	24	24	24	0	n/a	5402.67
S6	5	8 m/s	6D	6%	Fixed step	31	26	21	16	0	n/a	5482.80
S7	5	8 m/s	7D	6%	Fixed angle	23	23	23	23	0	n/a	5666.41
S8	5	8 m/s	7D	6%	Fixed step	28	24	20	16	0	n/a	5734.08
I1	5	8 m/s	5D	10%	Fixed angle	22	22	22	22	0	n/a	5266.60
I2	5	8 m/s	5D	10%	Fixed step	28	24	20	16	0	n/a	5304.00