Flow Control Leveraging Downwind Rotors for Improved Wind Power Plant Operation

Preprint

Christopher J. Bay,[1] Jennifer Annoni,[1]
Luis A. Martínez-Tossas,[1] Lucy Y. Pao,[2]
and Kathryn E. Johnson[1,3]

1 National Renewable Energy Laboratory
2 University of Colorado Boulder
3 Colorado School of Mines

Presented at IEEE American Control Conference
Philadelphia, Pennsylvania
July 10–12, 2019

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Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5000-73125
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Suggested Citation
Bay, Christopher J., Jennifer Annoni, Luis A. Martínez-Tossas, Lucy Y. Pao, Kathryn E. Johnson. 2019. *Flow Control Leveraging Downwind Rotors for Improved Wind Power Plant Operation: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5000-73125. https://www.nrel.gov/docs/fy19osti/73125.pdf.

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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This work was authored [in part] by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Flow Control Leveraging Downwind Rotors for Improved Wind Power Plant Operation

Christopher J. Bay[1], Jennifer Annoni[1], Luis A. Martínez-Tossas[1], Lucy Y. Pao[3], and Kathryn E. Johnson[1,2]

Abstract— **Controlling the air flow within wind power plants has the potential to improve plant performance and is an active area of research in the wind energy control community. In order to develop, test, and tune wind power plant controllers efficiently, an accurate engineering model of the turbine wake dynamics is required. Two elements of flow control are wake steering via yaw and tilt of a turbine. When a turbine is yawed or tilted away from the incoming wind field, the wake shape is changed. This is largely due to shed vortices that produce a curled wake. In this work, the well-known wake engineering model FLOw Redirection and Induction in Steady State (FLORIS) wake engineering model is enhanced to include these curled wake effects due to tilt. Since decay of these vortices has not been previously captured in an engineering model, the authors describe how vortices with decay have been added to FLORIS and how the updated model has been used to study the effects due to tilt in the wake. Results are demonstrated and compared to high-fidelity large-eddy simulations. Potential wind power plant performance gains due to flow control using tilt are investigated across different wind conditions and sites. Preliminary results show power gains by using tilt to implement flow control in a variety of wind distributions and tilt values.**

I. Introduction

As installed wind energy capacity continues to grow, wind power plant operators are increasingly interested in maximizing their plant production. Maximizing plant production can increase revenue and/or decrease the cost of wind energy. This, in turn, makes wind energy more competitive with traditional energy sources, furthering the progress toward many countries' renewable energy goals. Control plays a significant role in increasing plant production for both new and existing wind power plants.

Wind power plant control seeks to implement operational strategies at a plant level that will offer improved performance beyond the traditional mechanism of maximizing individual turbine operation. Turbines generate wakes, which are areas of turbulent wind structures and lower wind velocities. These wakes propagate downstream, decreasing the performance of turbines they overlap. As such, efforts to improve wind plant performance have focused on flow control, through axial induction control or wake redirection. Changing axial induction can increase the power available in the wake for downstream turbines; however, it is uncertain whether axial control can provide a net power gain for the wind plant [1]–[3]. Axial induction control has been used successfully to provide load reduction across wind power plants [4], as well as to perform active power control for grid services [5]–[7].

Wake steering and redirection has also been investigated as another method for improving wind plant performance. If a wind turbine is misaligned to the incoming wind field, the subsequent wake can be deflected away from its fully aligned location. This makes it possible to effectively steer wakes around downstream turbines. While the misaligned turbine will suffer some power loss, several studies have shown that the overall plant can experience a power gain [8]–[10].

Wake steering can leverage the same physics to induce vertical deflections with a tilted rotor turbine. To date, tilt has undergone only modest investigation, yet shows promise for improved plant performance, particularly for downwind turbines [8], [11], [12]. This is due to the fact that upwind turbines can only tilt the bottom of the rotor away from the tower, such that the rotor imparts an upward vertical deflection on the wake. While this upward deflection has been shown to result in a slight increase in power to downstream rotors [9], larger power gains are possible if the tilt is implemented in the opposite direction. If a downwind rotor's lower half is tilted away from the tower, an overall downward deflection is imparted on the wake, causing higher-speed winds from above the wind power plant to be entrained into the flow for downstream turbines (see Fig. 2). This entrainment and associated total power gain has been shown in high-fidelity simulations [8], [12], but only for small numbers of turbines in limited wind conditions.

The significant impact of this vertical wake deflection was presented in [13], which calls for the effect of tilt to be factored into future wind power plant control design. The authors of [13] are shifting the wind plant control paradigm toward flow control, and changing how wind plant controllers are developed. Recent efforts have revealed that these wake deflections are driven by shed vortices [14],

This work was partially supported by ARPA-E award number DE-AR0000667 and a Palmer Endowed Chair at the Univ. of Colorado Boulder.

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

C. J. Bay (https://orcid.org/0000-0002-2658-5559) is a researcher at the National Renewable Energy Laboratory (e-mail: christopher.bay@nrel.gov). [1]National Renewable Energy Laboratory, Golden, CO 80401 USA. [2]Electrical Engineering Dept., Colorado School of Mines, Golden, CO 80401 USA. [3]Electrical, Computer, & Energy Engineering, University of Colorado, Boulder, CO 80309.

[15]. These vortices, which originate from the edges of a yawed/tilted turbine, move the wake and create a curled shape within the flow [13], [16]. This effect has been seen in large eddy simulation (LES) [14], [17] and experimental results [18], but was only recently captured in an engineering model [16]. This curled-wake model was implemented in FLOw Redirection and Induction in Steady State (FLORIS) and shown to give more accurate results for yawed rotors in two- and three-turbine arrays; however, some of the results incorrectly predicted greater performance gains from misaligning turbines when compared to LES data. The authors of [16] stated this is due to a lack of decay of the generated vortices within the model. Thus, further investigation of and improvement to this engineering model is needed for the development of effective controllers for wind power plants.

This paper aims to expand on the previous work of [12] and [16], looking specifically at opportunities for tilt-based wind plant optimization, control, and development of the associated modeling tools. Novel contributions include: 1) the addition of decaying vortices to the FLORIS engineering model presented in [16], 2) study of tilt performance on larger wind power plants, and 3) study of tilt performance across realistic wind conditions, accounting for variations in wind direction. These contributions to the open-source FLORIS provide opportunities for the broader control community to better understand and contribute to the wind plant control research and characterize opportunities for future tilt-based optimization and control.

The paper is organized as follows. The model used is described in detail in Section II. The model verification and simulation scenarios are outlined in Section III. Plant performance results are discussed in Section IV. Lastly, conclusions and plans for future efforts are given in Section V.

II. Engineering Model Of Flow In A Wind Power Plant

Some of the most accurate simulations of the complicated and turbulent flows across a wind plant are completed by solving numerically the three-dimensional, incompressible Navier-Stokes equations. For example, the high-fidelity, LES software known as Simulator fOr Wind Farm Applications (SOWFA) [19] solves such equations, along with equations for transport of potential temperature that account for the thermal buoyancy and Coriolis effects in the atmosphere due to the Earth's rotation, to model the flow within the wind power plant. While models such as SOWFA give fairly accurate results, the computation takes hours or days, even when using a supercomputer leveraging several hundred to thousands of cores [12]. This computation problem only grows with the size of the wind plant. As such, sufficiently accurate engineering models are needed for more efficient control development. FLORIS provides these capabilities and has seen increased use in recent research efforts [10], [20].

FLORIS is a steady-state flow simulator that offers several wake definitions and low computational cost. It can be used to perform real-time optimization on wind power plants and is designed to easily accept new wake models and/or augment existing wake models. Recently, a model that captures the curled-wake effects due to the yaw of misaligned turbines was implemented in FLORIS [16]. This model, based on a linearized version of the Reynolds-Averaged Navier-Stokes streamwise momentum equation for incompressible flow, accounts for the curling of the wake, wake rotation due to the turbine rotor rotation, contributions to the background flow from the atmospheric boundary layer (ABL), ABL turbulent viscosity, and ground effects on the shed vortices. One component lacking in this model is the decay of these vortices as they move downstream, which would significantly impact the predicted power production of downstream turbines. This work intends to expand on the curled-wake model given in [16] by including a decay model within FLORIS that is suitable for investigating tilt optimization and control.

A. Addition of Vortices with Decay to FLORIS

The tilt and yaw effect are modeled by the inclusion of a collection of Lamb-Oseen vortices [16] (see Fig. 1). These vortices (known as shed vortices) are expected to decay due to turbulence added to the flow by the turbine's wake. This turbulence causes more mixing of the wakes, which in turn causes faster recovery to the free-stream wind velocity. The authors test a simplified decay model based on a Lamb-Oseen vortex with approximations. A Lamb-Oseen vortex is expected to behave as follows:

$$u_t = \frac{\Gamma}{2\pi r}\left[1 - \exp\left(-\frac{r^2}{4\nu_T t + r_0^2}\right)\right] \quad (1)$$

where u_t is the tangential component of the vortex velocity; Γ is the strength of the vortex; r is the radial position within the vortex; ν_T is the turbulence viscosity; t is time, which

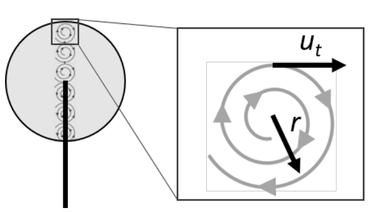


Fig. 1. An illustration of the elliptical vortices that are distributed across the rotor, where u_t is the tangential wind velocity and r is the radial distance within the vortex.

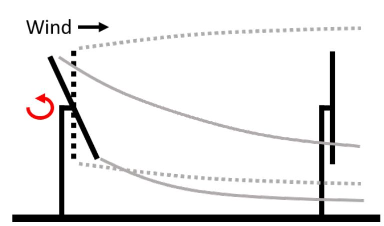


Fig. 2. Tilting a turbine rotor causes a vertical deflection in the wake, as shown by the solid gray curves. The red arrow indicates the positive direction of tilt.

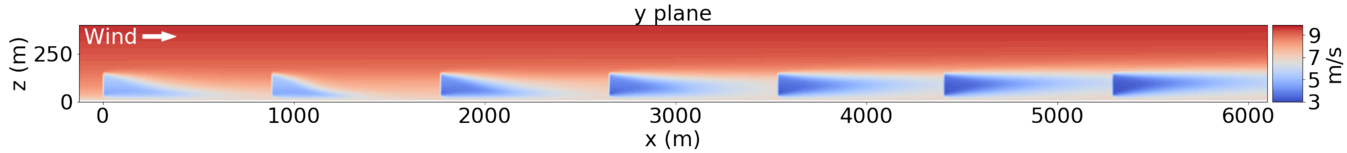


Fig. 3. LES Simulation of a seven-turbine array showing the y plane at the center of the turbines. The first turbine is tilted at 25 degrees and all other turbines are tilted at 0 degrees. The vertical wake deflection and entrainment of higher-velocity winds lasts beyond the second turbine due to the persistence of the shed vortices caused by the tilted lead turbine.

we express as the travel time for the flow ($t = x/U_\infty$ where x is downstream distance); and r_0 is the initial vortex core radius; which is assumed to be 20% of the rotor diameter.

The ratio of the velocity from the initial vortex to the vortex at some later time t is then expressed as

$$\frac{u_t(t)}{u_t(0)} = \frac{\left[1 - \exp\left(-\frac{r^2}{4\nu_T t + r_0^2}\right)\right]}{\left[1 - \exp\left(-\frac{r^2}{r_0^2}\right)\right]}. \quad (2)$$

As written, (2) would have to be recomputed for every downstream plane, because it has a radial dependency at every time. We are interested in minimizing the computational expense of the algorithm. Expressing the exponential using a Taylor series expansion and using only the first two terms in the series, (2) becomes

$$\frac{u_t(t)}{u_t(0)} = \frac{r_0^2}{4\nu_T x/U_\infty + r_0^2}. \quad (3)$$

This new formulation has no radial dependency, which means that the vortices need to be computed only once at the initial plane, and then they can be scaled by the downstream distance x in (3) for different downstream locations.

These shed vortices have been seen to persist and impact several turbines downstream in LES simulations [13], as well as in simulations conducted for this study. Fig. 3 shows how the vertical wake deflection from a tilted lead turbine causes the wakes of nontilted downstream turbines to be vertically deflected as well. Due to this persistence, the benefits of tilting just the lead upstream turbine can potentially reach deep into the wind power plant. As such, the authors hypothesize there may be nontrivial power gains when only tilting the leading-edge (in relation to a dominant wind direction) or perimeter turbines of a wind plant.

B. Tuning the FLORIS Model

A handful of important parameters must be tuned so that the augmented FLORIS model matches the key performance characteristics of the SOWFA model. The first is the number of elliptic shed vortices that are distributed across the rotor to model the curled-wake effect. While fewer vortices can lower computational cost, too few vortices can result in an insufficient representation of the flow from the turbine and inaccurate results. The results presented use 100 vortices, anymore of which provide negligible change in power prediction (see [16] for more details).

The other set of parameters that must be decided upon are the grid resolutions for the wake. The wake has three relevant resolutions corresponding to three dimensions: 1) the x (streamwise) direction, 2) the y (horizontal spanwise) direction, and 3) the z (vertical spanwise) direction. As with the number of shed vortices, the higher the grid resolutions, the higher the computational cost. However, as detailed in [16], the grid resolutions have a lower limit where the solver will begin to experience instabilities.

Lastly, the model presented in [16] does not include the effects of turbulence added to the flow from the wakes of turbines. This turbulence causes more mixing of the flow to occur and the wakes to recover quicker than what was shown in simulation in [16]. To include this turbulence effect, the diffusion term in the momentum equation (Eqn. (16) in [16]) was scaled by a factor of approximately 10 to match the SOWFA simulations.

The turbine powers for a two- and three-turbine array of NREL 5-MW machines [21], with 7 rotor-diameter (7D) spacing between the turbines, were compared to previous SOWFA results [12]. The authors only had SOWFA data for these two- and three-turbine arrays on which to base tuning. In the two-turbine case, only the lead turbine was tilted to 25 degrees. In the three-turbine case, the first and second upstream turbines were tilted to 25 degrees. Overall results of tuning the model are shown in Table I. Additionally, deflections of the wake in the NREL 5-MW three-turbine array case are shown in Fig. 4 and Fig. 5.

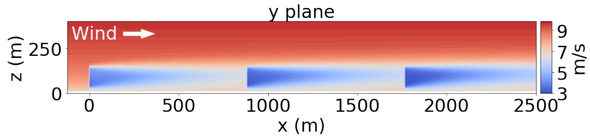
III. Simulation

Two turbines are investigated in these simulations: the NREL 5-MW turbine [21] and the Segmented Ultralight Morphing Rotor 13MW (SUMR-13) turbine [22], [23]. The NREL 5MW turbine is included as a baseline to verify the model against previous SOWFA results. The SUMR-13 turbine, developed in an Advanced Research Projects Agency - Energy (ARPA-E) funded research project that includes three of the authors [24], is chosen because its downwind

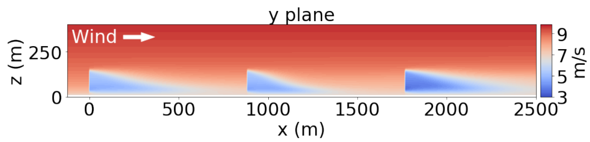
TABLE I. Power-Gain Results Over Nontilted Turbines of the Tuned Curl Model and SOWFA

Model	Curl w/ Decay	SOWFA
Two-turbine array power gain	5.1%	6.8%
Three-turbine array power gain	13.1%	13.0%
Run time	∼10 sec	2 days

*For the NREL 5-MW turbine for 8 m/s wind speed and 7D streamwise turbine spacing.

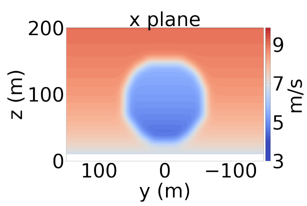


(a) Non-tilted turbines

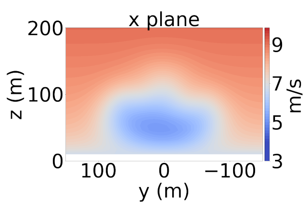


(b) Tilted turbines

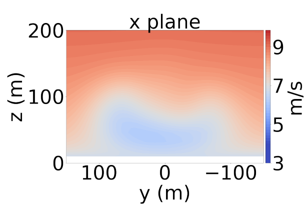
Fig. 4. Looking at the y plane at the center of the turbines for both NREL 5-MW nontilted and tilted cases. The two upstream turbines in (b) are tilted at 25 degrees.



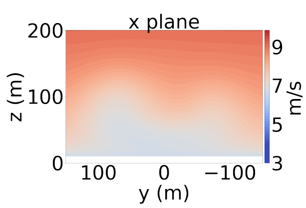
(a) 0D downstream



(b) 2D downstream



(c) 4D downstream



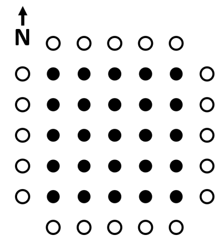
(d) 6D downstream

Fig. 5. The streamwise velocity downstream behind the lead NREL 5-MW turbine tilted at 25 degrees. The wake shapes and velocities closely match those of the SOWFA simulations [12] (not shown in this paper due to space constraints).

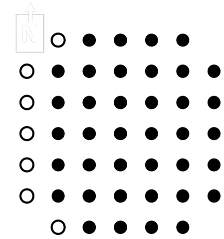
configuration makes it ideal for tilt-based optimization. The SUMR-13 is a significantly larger rotor (diameter of 296 m) compared to the NREL 5-MW (diameter of 126 m), a characteristic that enables substantially increased annual energy production and therefore reduced levelized cost of energy [25]. This objective is balanced with that of operating the rotor at a lower axial induction factor to minimize loads.

A. Wind Power Plant Layout

One wind plant layout was simulated. The plant consists of 45 turbines on a 7-by-7 grid, with the four corner grid positions remaining empty (Fig. 6). The turbines were spaced 7D apart in both the streamwise and spanwise directions. This layout was adopted due to the significant number of turbines and offshore wind power plants that are commonly built in grid formations. As displayed in Fig. 3, the shed vortices have been seen to persist beyond the first turbine downwind of a tilted turbine. Thus it has been proposed that



(a) Perimeter Tilt Layout



(b) Edge Tilt Layout

Fig. 6. The plant layout used for the simulations, with tilted turbines shown as unfilled circles.

tilting only the most upstream turbine can produce increased power production for multiple downstream turbines, leading to an overall gain in the wind plant production.

Two tilt configurations were investigated, as shown in Fig. 6. One layout (the "perimeter-tilt" case) has all of the perimeter turbines tilted, whereas the second layout (the "edge-tilt" case) has just one edge (seven turbines) tilted. In the edge-tilt case, the set of turbines selected for tilting are the ones most upstream according to the dominant wind direction. In an effort to characterize a range of opportunities for future tilt-based optimization and control, the simulations were performed at four different tilt settings: 25 degrees, 17.3 degrees, 12.5 degrees, and 7.5 degrees.

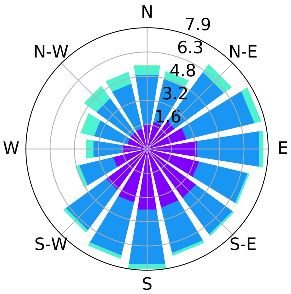
B. Wind Roses

Three different wind roses were used in the simulations, as shown in Fig. 7. Wind roses are commonly used to display relative frequencies of wind speed and direction, with the radial axis representing windspeed and frequency and the angle equaling degrees on a compass. These wind distributions were gathered for [26] at three sites found off the East Coast of the United States at water depths ranging from 20-23 m. The specific station numbers for the three wind data sets are: (a) ST63428, (b) ST63330, and (c) ST63150. ST63428 was chosen due to its semiregular distribution. ST63330 was chosen due to its bias along the N-E/S-W axis. ST63150 was chosen as a distribution that is somewhere in the middle of ST63330 and ST63428.

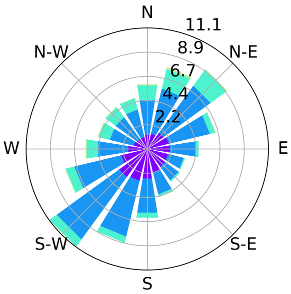
As the buoys used to take these wind measurements sample the wind at ˜10 m, the wind speeds were scaled up to hub height for the two different turbines using a shear factor [16] of 0.1. Weibull curves were fit to the data and used to produce wind-speed probabilities in 1-m/s increments from 1–25 m/s for the simulations. The relative frequency information was used from the cut-in wind speed to cut-out wind speed for each turbine (3–25 m/s for the NREL 5-MW and 5–25 m/s for the SUMR-13). These frequencies were normalized across the wind directions and applied to the power produced at each wind speed and direction.

IV. Results

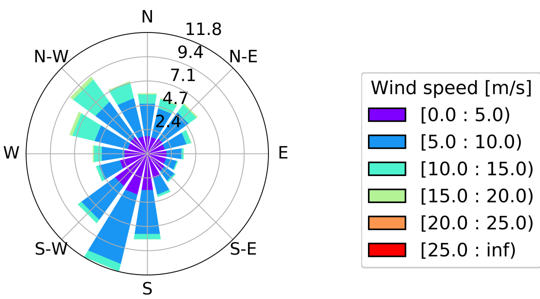
The results of the simulations are shown in Fig. 8. The cases in the four subplots of Fig. 8 correspond to NREL 5-



(a) ST63428 - Semiregular



(b) ST63330 - Biased



(c) ST63150 - Hybrid

Fig. 7. Three different wind distributions that were used in the simulations.

MW vs. SUMR-13 and perimeter vs. edge tilt. The simulations show improvement in annual energy production (AEP) for some of the tilt setpoints, suggesting opportunities for tilt-based optimization. Specifically, for the NREL 5-MW turbine with a perimeter-tilt configuration, 12.5 degree of rotor tilt showed the greatest improvement in AEP compared to the other tilt values. The SUMR-13 perimeter-tilt configuration performance differed from that of the NREL 5-MW in that a lower rotor tilt setting of 7.5 degrees showed the highest gain in AEP out of the four tilt settings. This supports the idea that optimal tilt angles differ from rotor to rotor, and further confirms the need for including these tilt effects in future control design, as stated in [13].

The perimeter-tilt case results in larger AEP deviations in comparison to the edge-tilt case. This makes sense, as it can provide additional entrainment from all wind directions, but also results in power losses at more turbines due to tilt. The results suggest that using perimeter tilt at a well-selected setpoint has the most potential to increase total wind power plant AEP. Additionally, across all cases, the tilted turbines gave the greatest increase in power production for the semiregular wind rose ST63428, compared to the biased and hybrid wind roses, balancing power production/loss across the wind directions.

When looking at the tilt setting previously investigated in high-fidelity simulations [12], the larger value of 25 degrees of tilt resulted in power increases for the two- and three-turbine arrays. These increases were shown for one wind speed in fully waked conditions (one wind direction). However, when considering a tilt of 25 degrees across entire wind roses, all the simulations showed a decrease in wind power plant AEP, indicating additional complexity for larger wind plants. This further illuminates the need for engineering models such as the one described in this paper, since computational fluid dynamics and LES solvers are impractical to run for many wind cases and tilt settings across large wind power plants. More investigation of lower tilt settings as well as active tilt control is required.

V. Conclusions And Future Work

This study added vortices with decay to the FLORIS curl model [16] in order to improve its capability as a control-oriented model for wind plant optimization. The authors then used the updated FLORIS model to investigate potential gains in wind power plant performance by modifying the tilt angle of turbine rotors. With tuning, the turbine power performance of the vortices with a decay model was shown to closely match that of higher-fidelity SOWFA simulations. Simulations of multiple tilt configurations for a 45-turbine wind power plant were completed, considering two wind turbine designs (NREL 5-MW and SUMR-13). The results of these simulations showed that plant level AEP gains are possible by tilting rotors. In particular, differing turbines have different optimal tilt settings. This fact further confirms the need to include the effects of tilted rotors in future wind power plant control development.

As future work, the authors plan to further develop this model so that turbulence added by the wakes of wind turbines is included through physical relationships and not solely through a tuned parameters. Additionally, the authors will further improve the computation time of the curled wake model with a whole-farm solver. With a faster model, the authors also plan to perform a full optimization of tilt settings across the wind power plant to gain further insight into the effect of tilt on plant performance. Since FLORIS is available to the broader community [27], opportunities exist to make models available to a wide variety of experts to improve wind power plant performance.

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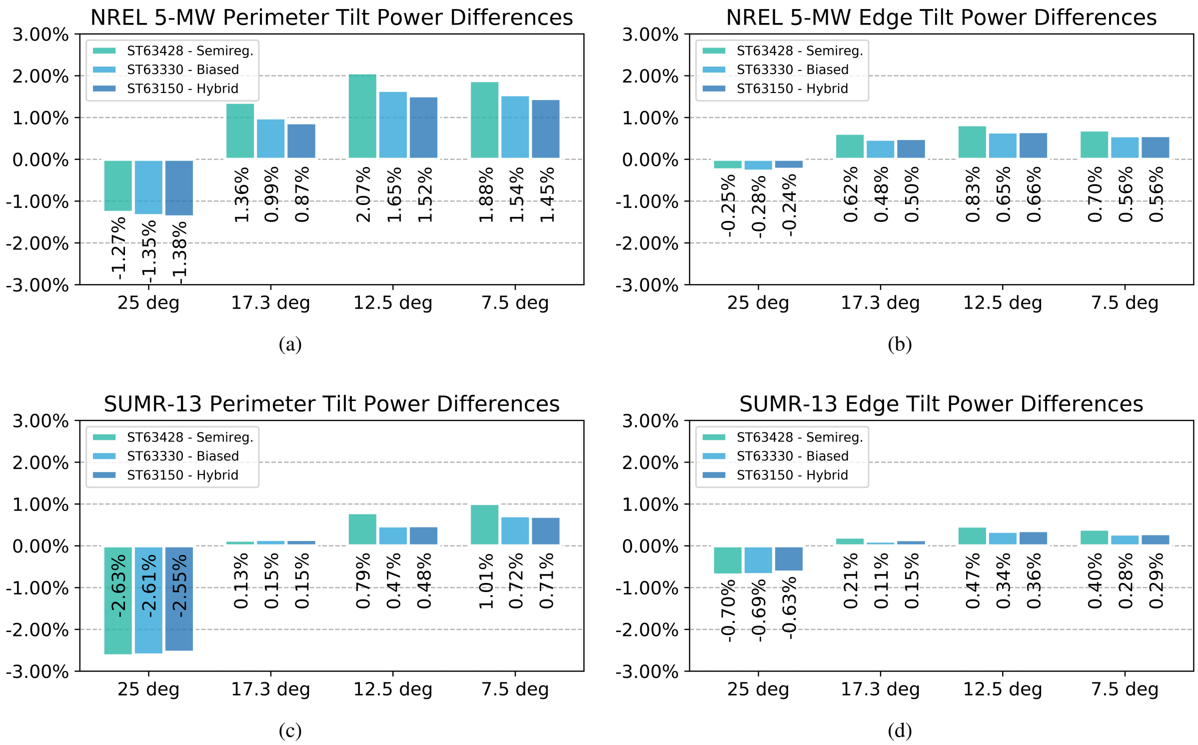

Fig. 8. Changes in AEP relative to nontilted baselines for each of the turbine types (NREL 5-MW or SUMR-13), wind roses, and tilt strategies (perimeter or edge).

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