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Wind Turbine Wake Redirection via External Vanes

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Abstract
The aerodynamic interactions of wind turbines are a wind farm's most significant source of energy loss. Every wind turbine creates a low-speed, highly turbulent, plume-like airflow called a "wake." To minimize the said losses, one needs to reduce the overall exposure to upstream turbines' wakes. One can achieve this goal by optimizing the farm's layout and actively controlling the parameters that can either steer or weaken the wake, such as yaw or pitch angles. Both practices, i.e., layout optimization and active yaw control, are still insufficient, leaving the wind farms as one of the least power-dense forms of plants with a power density of 1-2 W/m^2. In this article, we propose the application of external vanes to steer the wake from downstream turbines in real time. While acknowledging that implementing this strategy with a current technology readiness level of 1 is not easy, this research only serves as a preliminary proof of concept demonstrating this idea's effectiveness. The study utilized large-eddy simulations and an inline, three-turbine configuration. It revealed that a sizeable external vane between the front- and the second-row turbines increased the production of the second and third turbines by approximately 45% and 42%, respectively, which is significant compared to all other studied active wake control strategies.

1. Introduction

What is the problem?

In 2021, wind-driven electricity generation expanded by approximately 17% (275 TWh), the most notable increase among renewables [1]. This expansion was driven by policy deadlines in the United States and China, forcing the developers to complete many projects late in the fourth quarter of 2020. Despite this significant progress, wind energy still amounts to less than 7% of the world's electricity generation. Energy losses caused by the aerodynamic interactions of wind turbines appear to be the central restriction preventing wind energy from soaring beyond 7%.

What are wake losses?

Suppose high-speed, undisturbed wind enters a wind farm's front-row wind turbine. The wind turbine's large rotating blades extract the wind's kinetic energy and induce severe turbulence. Hence, wind leaving the turbine becomes a low-speed, highly turbulent, expanding plume called a "wake" [2]. Downstream turbines that receive an upstream wake at their inlet produce much less power than their front-row counterparts [3]. To realize the significance of these wake losses, note that a second-row turbine can convert approximately 60% less energy than its upstream counterpart in wind directions aligned with the column of turbines [4-5].

What are the existing solutions to the wake loss issue?

The first step in addressing the wake loss issue is wind farm layout optimization (WFLO) [6]. By considering the wind direction and speed frequencies, a WFLO algorithm identifies every wind turbine's optimal position within the given perimeter to minimize their overall exposure to the upstream wakes [7-9]. Researchers have employed a wide variety of optimization algorithms for this application, including different versions of genetic algorithms [10-11], heuristic methods (such as Monte Carlo tree search [12] and Variable Neighborhood Search [13], among many), machine learning-based approaches [14], and gradient-based techniques [15].

Researchers have also considered layout optimization in the vertical plane by investigating the effectiveness of staggering the turbines in the vertical in reducing the exposure to the upstream wakes [16]. One can achieve this by optimizing the hub height [17-18].

Any WFLO algorithm would also require a model to compute the wind speed deficit. The most precise option is employing computational fluid dynamics (CFD) [19], particularly large-eddy simulations [20]. However, they require high computational power and are generally slow. An analytical wake model is a reasonable alternative to CFD models [21-23]. The literature includes a comprehensive review that compares the performance of six major analytical wake models for different kinds of wind farms [5].

The second step in dealing with the wake loss problem is to actively control some turbines' features to either redirect the wake away from downstream turbines or weaken the upstream wakes to lower their effect. So far, controlling the yaw, pitch, tilt, and cone angles have been proposed as potential strategies to control the wake. The idea is to impose

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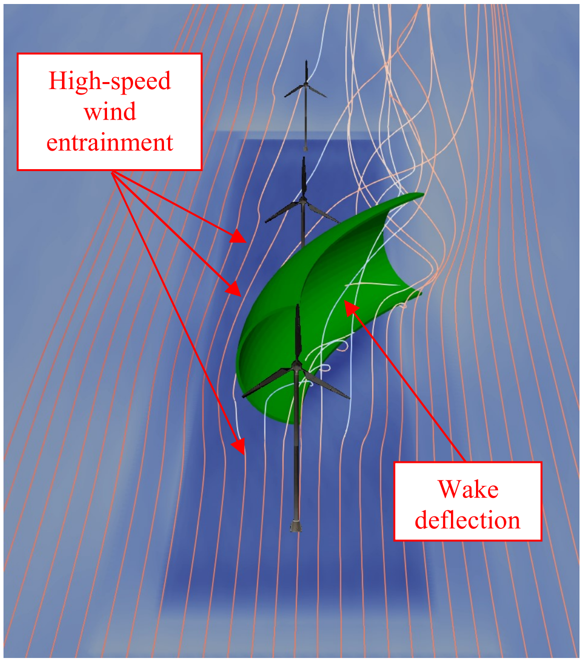
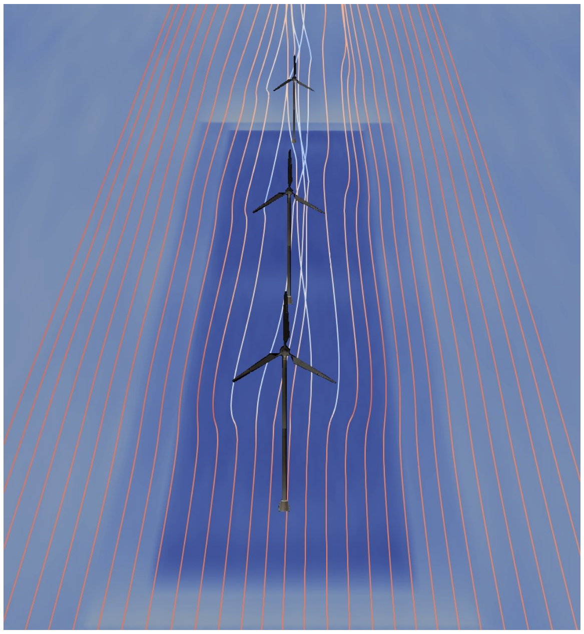
intentional misalignment to a turbine's yaw angle, for instance, to steer its wake away from its downstream counterparts [24]. The yawed turbine losses power since it is not normal to the wind direction anymore and hence receives less mechanical energy at the inlet; however, the downstream turbines' exposure to the yawed turbine's wake reduces, leading to an increase in their power production [25-26]. The literature suggests that the gain is larger than the loss; as a result, the overall farm's production increases. The same idea applies to tilt, pitch, and cone angle control. We recently reviewed the effectiveness of all these strategies [27].



(a)



(b)

Figure 1: An external wake-deflector can capture and redirect the wake to reduce its impact on the downstream turbines.

What is this article's proposed solution?
Given all the above-described efforts to address the wake loss issue, this major loss is still the most significant restriction to the wind farm's annual energy production. Hence, any viable solution to reduce it is of great value. This article proposes a rough concept of a potential solution that can address the wake loss issue to a great extent. This concept, sounding wild, requires extensive research and development beyond what this article presents before achieving a technology readiness level that allows for a full-scale field experiment.

2. Proposed Concept

2.1 The need for new solutions

The existing wake control strategies have a few common problems, demonstrating the necessity of developing more effective wake control strategies. Below we briefly discuss three of these problems.

First, they decrease the production of an upstream turbine to increase the production of a few downstream turbines. While the sum of the gains is more significant than the loss, the loss erases a great deal of the gains. Hence, they increase the farm's production by only a few percent. While this is significant, it is not large enough to push wind farms' power density beyond any of wind energy's competitors. Wind farms have a power density ranging between 1 and 2 W/m^2, behind Geothermal (2-3 W/m^2), solar (7-8 W/m^2), and every conventional power source, including natural gas, nuclear, oil, and coal [28].

Second, the existing strategies demand changes to the turbine and farm control system, hardware-wise or software-wise. Executing such changes makes it challenging and, in some cases, impossible to implement these strategies on the existing wind farms.
Third, these wake control techniques require all or a subset of turbines to operate under non-normal conditions. For example, a turbine is commonly not supposed to be yawed, but the yaw control technique requires yawing all or some of the turbines. Yawing a turbine increases the blades' mechanical loads, reducing their lifespan and inducing new costs. We do not know how these costs compare to profits made by the AEP increase caused by yaw control.

2.2 Redirecting the wake via external vanes

A turbine's wake is like a plume; hence, it can be captured and redirected to minimize its interaction with downstream turbines. A simple, stationary vane can achieve this wake deflection. Figure 1, produced via large-eddy simulations, illustrates this concept by showing the wake via streamlines. While one can imagine all kinds of geometries and dimensions for this wake-deflector, here, an elementary geometry similar to that of Figure 1 is investigated to understand if a stationary vane would really capture and deflect the turbine's wake and how effective this strategy appears to be before going after a geometry and layout optimization.

2.3 Some immediate advantages and challenges

The proposed concept addressed all three challenges discussed in Section 2.1. The wake-deflector does not need modification or manipulation of the turbines' hardware and software. It does not interfere with the upstream turbine's production unless it is installed too close to it so that its stagnation pressure slows down the wind approaching the upstream turbine. More importantly, using a wake-deflector appears to significantly enhance the farm's production. Section 4 shows a farm-averaged increase of approximately 20% for the investigated three-turbine farm. This is considerably more than any other existing wake deflection strategy.

However, fabricating, installing, and moving such a large structure is undoubtedly challenging. We recommend fabricating the wake deflector using sailboat fabric to keep it light and flexible. The authors believe optimizing the wake deflector's geometry might allow for substituting the large wake deflector studied here with a couple of smaller deflectors that are small enough to be installed on a single tower and be rotated in the horizontal plane and translated in the vertical as wind direction changes. This would make the implementation of the proposed concept much simpler.

2.4 The scope of the current article

We have already released some scaled wind tunnel results supporting the effectiveness of this concept [27]. The current article evaluates this concept's performance within a utility-scale wind farm of three inline wind turbines. The article only considers one vane and tests it for only one wind direction and speed. This article's scope does not cover optimizing the geometry of the vane nor identifying how often, to what extent, and in what direction one must move the vane as the wind direction changes. This article assumes the wake deflector is a rigid vane to avoid dealing with vortex-induced vibrations.

3. Methodology

3.1 Numerical Solution

The performed large-eddy simulations had three steps. The first step was performing a neutral atmospheric boundary layer simulation for 20,000 seconds of flow time to achieve a quasi-equilibrium flow field in the wind farm without considering the turbines. Then, a sampling function was added to the solver to keep the record of the incoming velocity profile at the western boundary, and the simulation continued from 20,000 s to 22,000 s to generate 2,000 s of precursor data. The third step was carrying out a wind plant simulation for 2,000 s (from 20,000 to 22,000) by considering the turbines in action and applying the precursor data. The actuator line model proposed by Sørensen and Shen [29] was used to simulate turbine blades. The governing equations of large-eddy simulations and actuator line model solved for this study can be found in Vasel-Be-Hagh and Archer [30]. Simulator fOr Wind Farm Applications, widely known as SOWFA, a CFD solver developed by the United States National Renewable Energy Laboratory [31] based on the OpenFOAM toolbox [32], was used to solve the equations.

3.2 Setup

Two large-eddy simulations were conducted to investigate the effectiveness of an external wake deflector. The wind farm consisted of three SWT-2.3-MW-93-m wind turbines placed in an inline configuration with an axial spacing of 6D, with D=93 m being the diameter of the rotor. The wind farm was at a latitude of 41.3 degrees in the northern hemisphere. The sole difference between the first case (base case) and the second case (vane case) was the presence of only one wake deflector in the second case. The wake deflector was positioned concentrically behind the first-row turbine at an axial distance of D, as shown in Figure 2. The wind direction was westerly, aligned with the column of wind turbines. The wind speed was 8 m/s at the hub height. The computational domain was 3348 m long, 558 m wide, and 1000 m high. The computational grid was developed following the recommendations made by Luis A. Martínez-Tossas et al. [33]. Using the blockMesh utility supplied by OpenFOAM, a coarse mesh with approximately 2,500,000 hexahedral cells was first created. Then, the grid resolution was enhanced by refining the mesh near the turbines and deflector twice. The final mesh ended up having 7,300,000 cells. Figure 2 illustrates the wind farm's dimension and the deflector's location. The deflector fits in a box with length, width, and height of 333 m, 158 m, and 98 m, respectively. Figure 1 also shows an elevated view of the deflector for better demonstration.

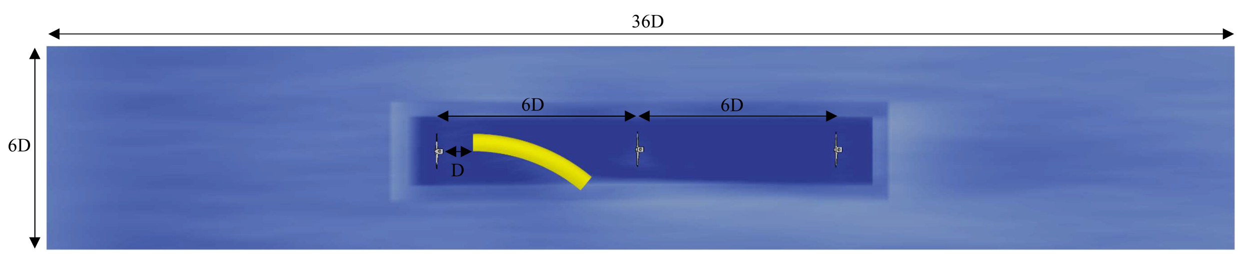


Figure 2: Computational domain.

4. Results and Discussion

The authors calculated each turbine's relative power generation with and without using the wake deflector to evaluate the wake deflector's performance. A wind turbine's relative power is the ratio of its power to the power production of the column's front-row turbine. For instance, if a turbine has a relative power of 0.4, it means its power production is 40% of the power production of its front-row turbine. Figure 3 shows the results. Power production of the two turbines downwind of the wake deflector increased by approximately 42% and 45%, respectively, while the front-row turbine lost only 4.21% of its generation due to increased local pressure as a direct result of the deflector being too close to the turbine. Increasing the distance between the deflector and the upstream turbine could potentially alleviate this loss. However, we have not investigated this yet. Overall, the average power gain through the column is 20%, with the total relative power increasing from 2.0 to 2.4. This increase in production is very significant.

Figure 4 illustrates the velocity contours at the hub height for both cases. The third contour on the bottom shows iso-velocity contours with black lines representing the no-vane and yellow lines showing the vane cases. The background contour belongs to the case with the wake deflector. The deflector captures the plume-like wake wind behind the front-row turbine and discharges it to the corridor on the right (with respect to the incoming westerly wind). As a result, the high-velocity wind shifts into the downstream turbines. The third turbine's production is boosted due to this high-speed wind entrainment and because the vane steers the wake of the second turbine, as illustrated in Figure 4. Also, note Figure 1 again as it depicts a bird view of this column showing time-averaged velocity streamlines to picture the above-described developments better.

There are a few essential items that one needs to consider.

First, the logic behind applying a right-hand deflector (i.e., deflecting the wake to the right of the incoming wind) originated from the fact that in the northern hemisphere, the Coriolis force redirects the wind to the right [24]. As a result, the Coriolis force favors what a right-hand deflector tries to achieve by pushing the wake further to the right side of the incoming wind, which decreases the downstream turbine's exposure to the upstream wake and increases the effectiveness of the wake deflector.

Second, note that the 20% production increase was achieved by adding only one deflector to a three-turbine wind farm. Adding more deflectors to larger wind farms with more turbines would lead to more significant power gains. Also, note that this deflector was tested only in one wind direction, i.e., westerly wind. In a real scenario, with more turbines and more deflectors, and with the wind direction changing in real time, the deflectors require to rotate and possibly move vertically to get out of the wind's way. Hence, one must optimize the number of wake deflectors, their dimension, and their vertical and horizontal locations for every given wind farm and their specific layout and wind data.

Third, several future steps are due before applying this concept to any utility-scale farm. The most crucial is geometry optimization to identify the least bulky external vane that can effectively control upstream wakes. It is essential to substitute the large wake-deflector tested in this study with several smaller vanes that can sit on one tower and easily rotate around and move in the z-direction. Then, several CFD simulations are due to generate the database required to develop a new or modify one of the existing wake loss algorithms to account for the wake of the wake deflector and the turbine's wake. This analytical model can then be used within an optimization algorithm to identify the optimal number and the location of the vanes for a given wind farm.

Fourth, after the deflector is optimized, one must engage manufacturing experts to identify the optimal process for the vane's fabrication and installation in a wind farm.

5. Conclusion

This article explains why there is a need for more effective active wake control strategies. It then proposes using external vanes to capture and deflect upstream wakes to minimize their impact on downstream wind turbines. The article evaluates the effectiveness of such a strategy using a straightforward setting: three inline turbines, one wind direction aligned with the column of turbines, and one vane with a simple geometry located between the first and the second turbine. The presence of the vane increased the power production of the second and the third turbines by 42 and 45%. It enhanced farm-averaged production by 20%. This article serves as a proof of concept. The authors will release more detailed and comprehensive data investigating the possibility of using small wake deflectors and optimizing their placement within a farm.

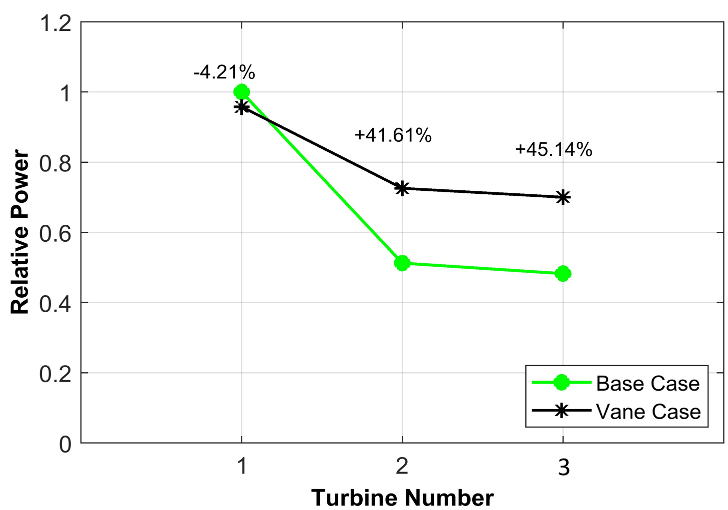


Figure 3: Comparing relative power production with and without the presence of the wake deflector.

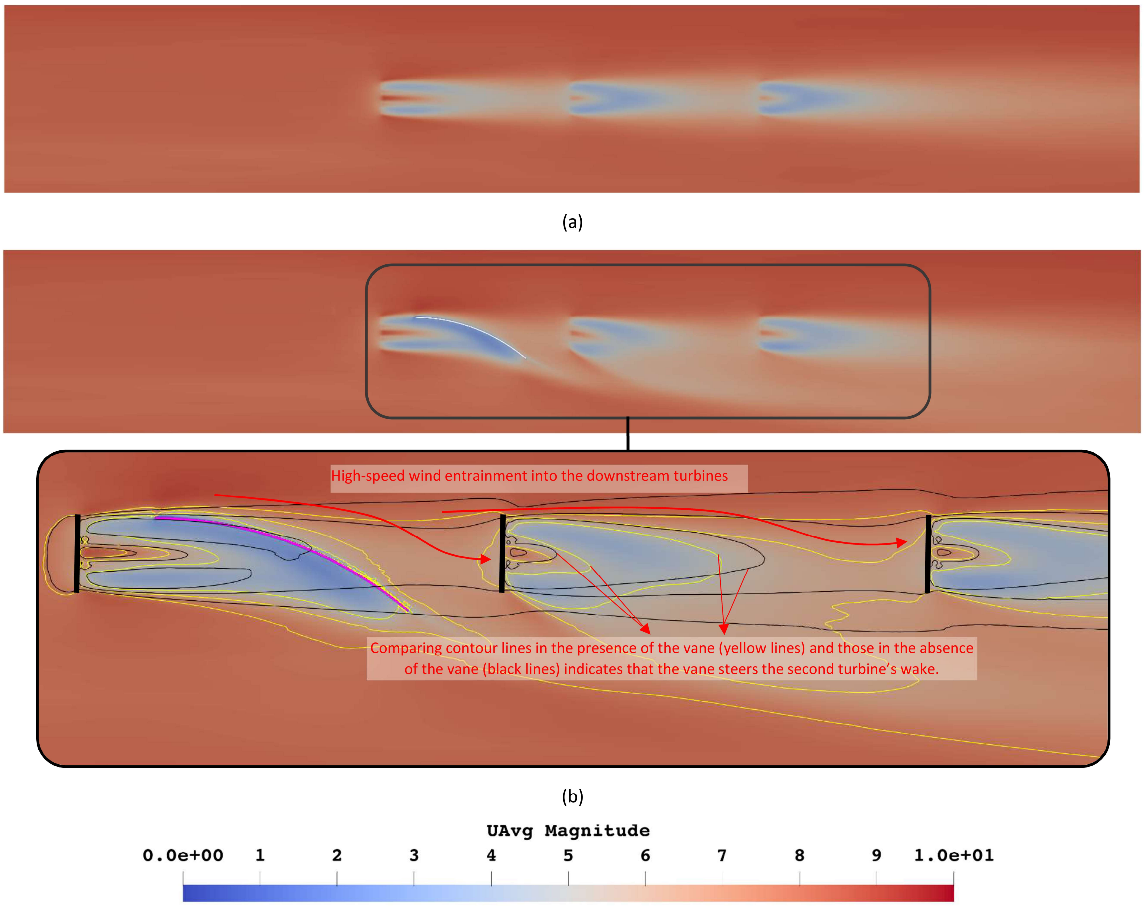


Figure 4: Time-averaged wind speed (m/s) at the hub height (a) with wake deflector and (b) without wake deflector.

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