

# Wind turbine wake control strategies: A review and concept proposal

Ryan Nash, Reza Nouri<sup>\*</sup>, Ahmad Vassel-Be-Hagh

Fluid Mechanics Research Laboratory, Tennessee Technological University, USA

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## ABSTRACT

A wind farm's overall power production is significantly less than its nominal power, defined as the sum of the wind turbines' rated outputs. The primary cause for this significant loss is the exposure of downstream wind turbines to the aerodynamic wake of their upstream counterparts. Wind farm layout optimization aims at minimizing such adverse effects by finding optimal wind turbine positions that are less exposed to the upstream wake. Over the past few years, researchers have extended their fight against adverse wake effects beyond the layout optimization, i.e., the design process, onto the control and operation process. Several active wake control strategies have been proposed and studied to decrease the power loss of downstream wind turbines by steering or weakening the upstream wakes. First, the article reviews these strategies, including yaw control, pitch control, torque control, tilt control, and finally, cone angle control. Then, it proposes a novel wake steering technique where passive stationary vanes redirect the upstream wake. The authors conducted scaled wind tunnel experiments to investigate the performance of the proposed concept. Using a 3D-printed wake deflector between two in-line turbines increased the downstream turbine's power production by more than 15%, which is significant compared to the existing wake control strategies. The article concludes by comparing the proposed technology's effectiveness against existing wake control techniques.

## 1. Introduction

Wind energy has had various applications for a very long time, dating back to nearly 1,500 years ago [1]. However, wind power harvesting for electricity production is still one of the most modern and fastest-growing energy production fields globally. One of the main motives behind all ongoing efforts to develop wind power is that it is an entirely renewable energy source, which can solve many global energy problems [2]. Wind energy is a very low-polluting power source [3] with the industry being focused on addressing the noise pollution [4] and bird/bat collision issues [5]. It reduces nations' dependence on the global oil market and foreign developments, as wind is a domestic power source [6]. It creates new jobs, particularly in rural areas where the windiest sites for developing new plants exist. Wind turbines can be built on-site within mobile fabrication facilities to reduce the transportation expenses and complications [7]. The on-site production further benefits the economy in rural areas. Despite all of these positives for wind energy, some critical issues remain that keep this field from being the primary energy source for the entire world. All of the wind turbines currently installed worldwide provide only 5% of the global electricity demand [8]. This low contribution of wind energy to the global market is due to its low power

production density, defined as power produced per unit surface area [9]. Although the power density of wind ( $\sim 1 \text{ W/m}^2$ ) is more than that of biomass and some types of hydro plants, it is lower than the power density of several other sources, including natural gas, nuclear, oil, coal, solar, and geothermal [10]. Below the two reasons that mainly cause the low power density of wind plants are discussed.

First, despite all recent progress, the rated power of horizontal axis wind turbines is still low as the Vestas V164, with a rotor diameter of 164 meters and rated power output of 10 MW, and Siemens-Gamesa 8.0-167 DD, with a rotor diameter of 167 meters and rated power output of 8 MW, are the largest available wind turbines. This topic is not within the scope of the present article.

Second, the aerodynamic interactions between a wind farm's wind turbines cause a drastic reduction in the power production of the inner wind turbines [11]. The front-row wind turbines receive the unaltered wind and produce much more power than their downstream counterparts [12]. To put this into perspective, a second-row turbine located 7D downstream of the front row, where D is the rotor diameter, produces 44% less power [13]. The wind coming out of an upstream turbine is very turbulent with a very low velocity as most of its energy is already extracted. This low-speed, highly turbulent wind is called "wake". The

<sup>\*</sup> Corresponding author.

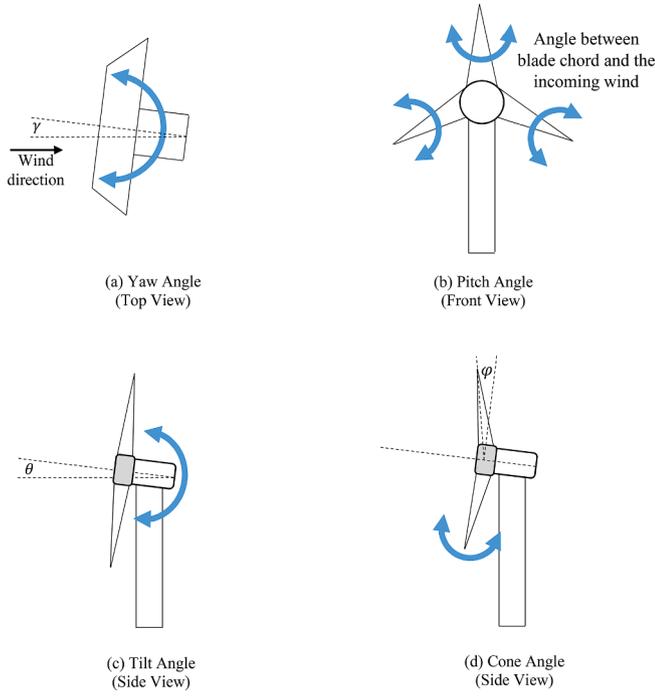
E-mail address: [reza.nouri@live.com](mailto:reza.nouri@live.com) (R. Nouri).

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**Fig. 1.** The four degrees of freedom of wind turbines: (a) yaw, (b) pitch, (c) tilt, and (d) cone. Tilt and cone angles are fixed in most commercial wind turbines.

downstream turbines exposed to upstream wakes experience a much lower inlet velocity, leading to a lower power production [14]. Research community have proposed various strategies to minimize the wake effect, including manipulating the direction of rotation of the blades [15] and optimizing the design of the wind farm [16]. This article, however, will focus on active control techniques that have been proposed and researched to minimize this issue.

One immediate solution that comes to mind to address the wake effect is increasing the space between wind turbines to let the wake recover back to undisturbed free-stream conditions. Some sources have reported 20D as the required recovery length [17]. As wind turbines' diameters (D) are now approaching 200 m, such large spacing (20D) is not practical for utility-scale wind plants. Such large spacing requires a vast leasing area and very long transmission lines, making the maintenance and security patrolling very complicated and costly [18]. Moreover, this colossal spacing further complicates the permitting process as conflicts between the wind farm and other neighboring activities significantly increase for such large areas. Offshore wind farms can cope with this issue easier as the spacing can be much larger than onshore farms since there are not too many other structures around [19]. The wake problem gets more complicated for onshore wind farms with the existing background wakes created by trees, trains, buildings, or other large-scale structures [20].

Wind farm developers use optimization algorithms to optimize a wide range of characteristics to minimize the negative impact of upstream wake on the performance of downwind turbines [21]. The list includes finding the optimal number of turbines [22], simultaneous optimization of the number of turbines and position of each turbine within the selected area [23], turbine type optimization [24], turbine hub height optimization [25], simultaneously optimizing turbine type and hub height [26], optimizing rotor diameter [27], and most importantly, identifying the optimal position of each turbine within the selected area [28]. While these algorithms are all utilized to achieve the most optimized design for future wind plants [29], researchers have been working persistently to develop active techniques to further reduce the negative wake effect for existing wind plants [30]. An effective way to increase the annual energy production (AEP) of existing wind farms is

active wake control which can be carried out by lessening the strength of the upstream wakes (referred to as an axial-induction-based control strategy) [31], accelerating the wake recovery by inducing increased mixing [32], and redirecting the upstream wakes away from the downstream wind turbines [33]. Many studies have investigated the effectiveness of each strategy. This article will review those studies while proposing a novel wake control approach.

Controlling the blade's pitch [34] and the generator torque [35] are two main strategies to reduce the strength of the wake. Pitch angle control can also induce increased mixing in the wake, which leads to accelerated recovery [36]. Other strategies focus on steering the wake away from downstream turbines. Steering the wake via imposing intentional yaw misalignment has emerged as a promising strategy [37]. This strategy has matured to higher technology readiness levels via utility-scale field tests, such as the work done by Astolfi et al. [38] and Bromm et al. [39]. Controlling the tilt and cone angles of the turbine are two other concepts for steering the wake [40]. Fig. 1 introduces all these angles.

The wind community is so focused on managing the wake using the turbine's degrees of freedom. Unfortunately, despite all the success, that has not led to a *significant* improvement in the production of wind plants. The authors believe the wind energy community needs to start thinking outside the box to address the wake loss problem. To provide an example, the authors propose steering the wake using external wake deflectors. Unlike other wake control strategies, this strategy is independent of turbines and does not require manipulating the wind turbines' control system. The incredible performance of this new concept is demonstrated experimentally, while acknowledging that it requires a comprehensive feasibility study. The authors also recognize that implementing the proposed concept is challenging. However, it can be a good lead for the research community to start thinking beyond the turbine's capabilities to control the direction and strength of the wake.

This paper first explores the yaw misalignment concept (Section 3). Section 4 explains controlling the blade's pitch to help the wake recover quicker and increase power production. Section 5 reviews the existing research on using variable generated torques to control the wake intensity. Sections 6 and 7 cover controlling the turbine's tilt and cone angles. Section 8 proposes the concept of wake redirection using a stationary vane. Finally, Section 9 compares each method's outcome to determine their effectiveness and reach practical recommendations.

## 2. Evaluating wake deflection

This section addresses how to calculate the local wake position downwind of a turbine using a known velocity field. It introduces two general methods and a specialized technique proposed by Gebraad et al. [41] which can be applied only to yawed turbines.

The time-averaged center of the wake generated by the yawed turbine must be identified at different axial distances to evaluate whether a control strategy can redirect a wind turbine's wake. It is essential to use time-averaged data to relax the wake meandering effect [20]; otherwise, the identified wake center is instantaneous and not precisely representative of the wake center. Several approaches are available to identify the wake center. For instance, the wake center can be assumed as the barycenter of the momentum deficit [42]:

$$y_m = \frac{\int y(1 - U^*)ds}{\int (1 - U^*)ds} \quad (1)$$

$$z_m = \frac{\int z(1 - U^*)ds}{\int (1 - U^*)ds} \quad (2)$$

where  $y_m$  and  $z_m$  are the center of the wake in their respective direction,  $y$  and  $z$  are the positions of the wake,  $ds$  is a surface element over the area for which  $U^* < 1$ , and  $U^*$  is the normalized stream-wise velocity (velocity in the x-direction) defined as:

$$U^* = \frac{u}{U_\infty} \quad (3)$$

in which  $U_\infty$  is the undisturbed upstream wind speed. The integrals in Eqs. (1) and (2) are calculated over the area within which  $U^* < 1$ .

An alternative approach for locating the center of a wake is finding where the minimum wind speed occurs (i.e., maximum wind speed deficit) [43,44].

Another equation for the wake center position at any given point downstream of a yawed turbine is given by Gebraad et al. [41] using Computational Fluid Dynamics (CFD) data. This model consists of three parts. The first is finding the yaw induced components:

$$\delta_{yaw}(x) = \frac{\psi(15(\frac{2k_d(x-X)}{D} + 1)^4 + \psi^2)}{\frac{30k_d}{D}(\frac{2k_d(x-X)}{D} + 1)^5} - \frac{\psi D(15 + \psi^2)}{30k_d} \quad (4)$$

where  $\psi$  is the initial angle of the wake at the rotor,  $k_d$  is a model parameter that defines the wake deflection sensitivity to yaw,  $x$  is the distance downstream,  $X$  is the location of the turbine in the x-direction, and  $D$  is the rotor diameter. When looking from above toward the ground, the x-direction is the wind direction, and the y-direction is normal to the wind. The second required part is the rotation induced components:

$$\delta_{rotation}(x) = a_d + b_d(x - X) \quad (5)$$

in which  $a_d$  and  $b_d$  are both model parameters. The third part of the model uses both the yaw induced components and the rotation induced components to pinpoint the wake center position as:

$$y_{center} = Y + \delta_{yaw}(x) + \delta_{rotation}(x) \quad (6)$$

where  $Y$  is the location of the turbine in the y axis.

### 3. Yaw angle control

Controlling wind turbines' yaw angle can enhance a wind farm's performance. This section explains the logic behind this concept, reviews the existing models to predict wake when yaw misalignment is imposed, and presents the effectiveness of yaw angle optimization. It also touches on the impact of yaw misalignment on structural loads.

#### 3.1. Explanation of yaw misalignment

Applying an intentional yaw misalignment to a turbine can deflect its wake away from its downstream counterparts. A yaw misalignment is defined as the turbine's rotor axis not being parallel with the wind's direction (or wind not being normal to the rotor) [8]. The rotor must directly face the wind direction to maximize the wind intake amount and produce the most power. Therefore, if an upstream wind turbine of a given wind plant has a yaw offset applied to it, the power output of that

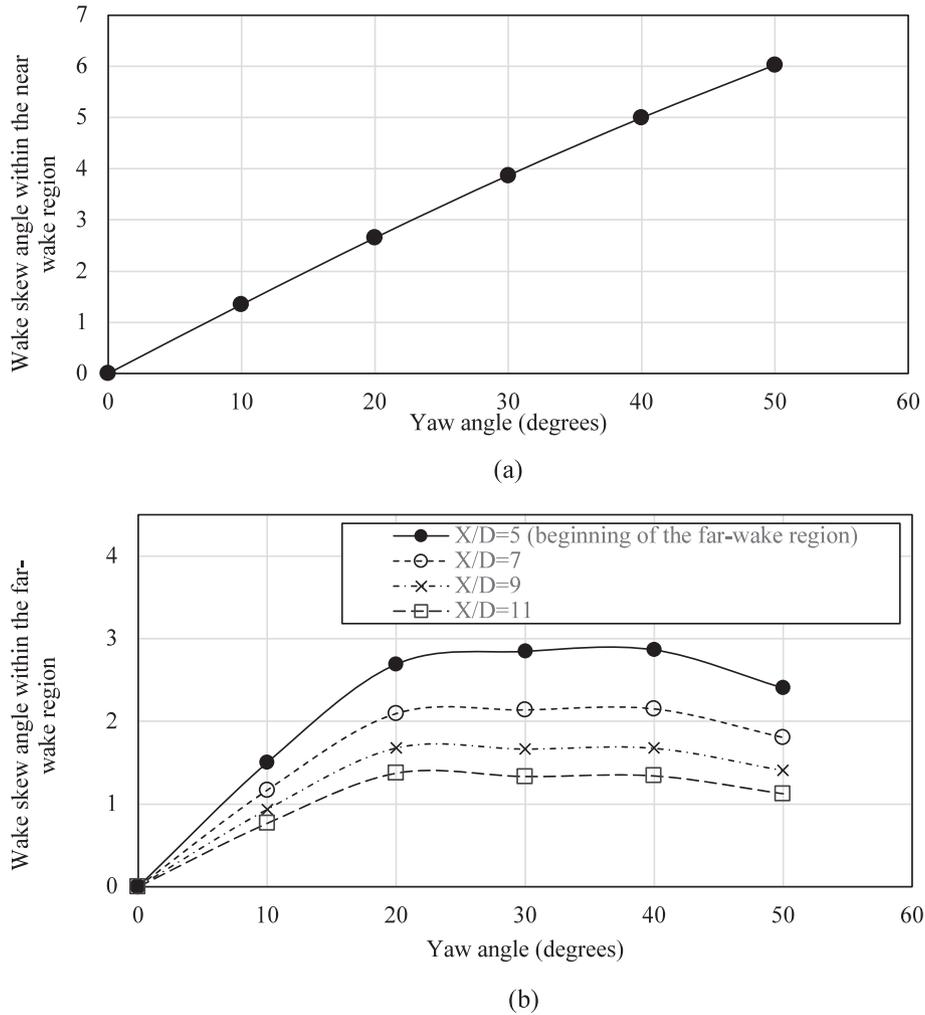


Fig. 2. The figure shows the wake skew angle versus rotor yaw misalignment within both (a) near-wake and (b) far-wake regions. In the near-wake region, based on Bastankhah & Porté-Agel's equation (Eq. (9)), the skew angle is only a function of yaw misalignment and does not change with the axial distance downstream of the rotor. In the far-wake model, i.e., Jiménez et al.'s equation (Eq. (7)), the skew angle is a function of both yaw misalignment and axial distance.

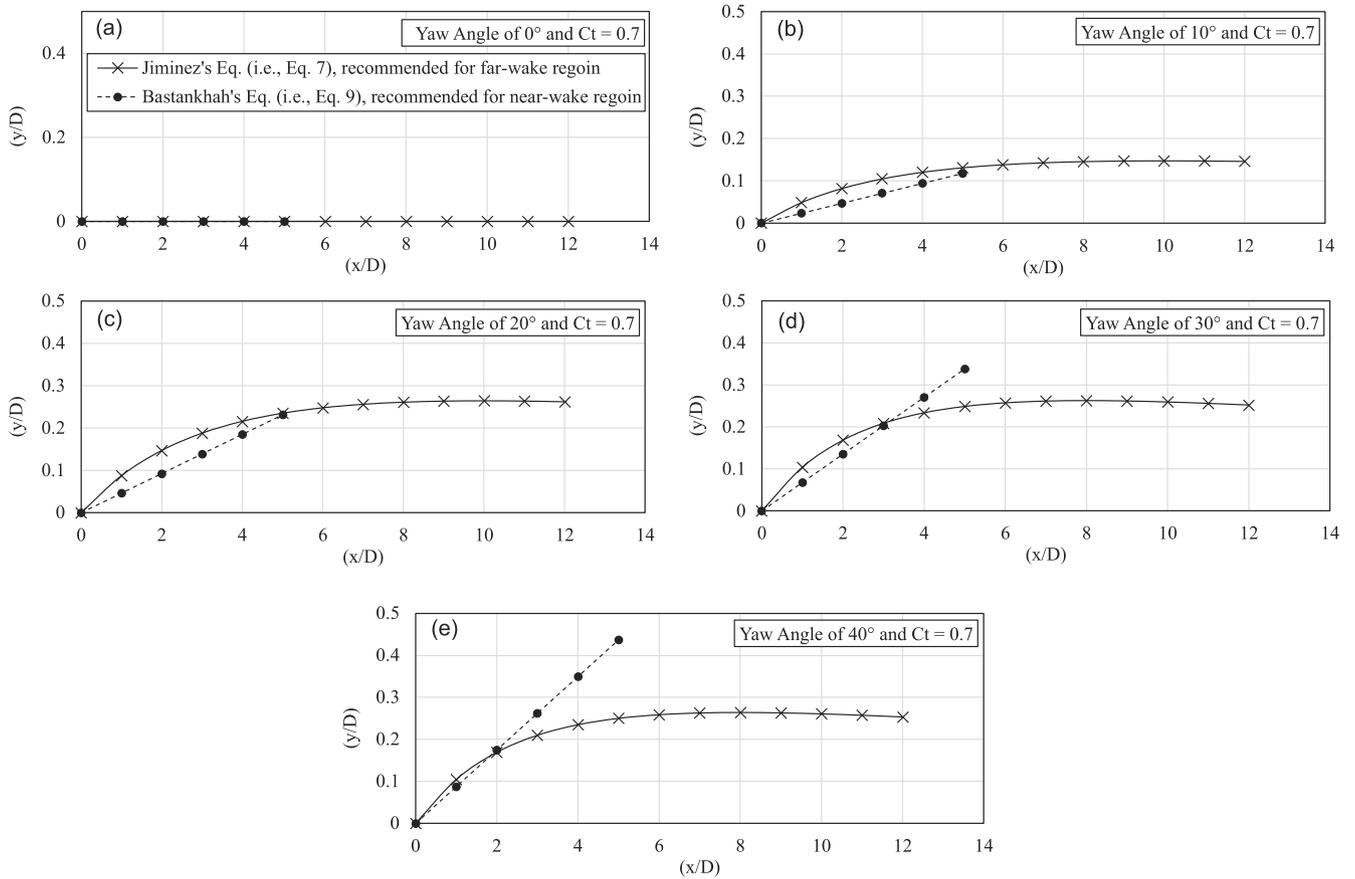


Fig. 3. Wake deflection versus downstream distance at different yaw angles: (a)  $\gamma = 0^\circ$ , (b)  $\gamma = 10^\circ$ , (c)  $\gamma = 20^\circ$ , (d)  $\gamma = 30^\circ$ , and (e)  $\gamma = 40^\circ$ . Data presented here is extracted from Jiménez's equation [56] (the line with crosses) and the Bastankhah's equation [57] (the line with circles) assuming  $C_t = 0.7$ .

turbine decreases [14]. The secondary effect of the yaw misalignment is steering the yawed turbine's wake; therefore, the downstream turbines are less affected by the upstream wake. The hope is that the amount of power gained by the downstream wind turbines will outweigh the power loss of the intentionally yawed turbine, leading to an increase in the farm's total power production as a whole [45].

One significant point that has been brought into attention within the literature is the difference between the impact of clockwise and counter-clockwise yaw misalignment angles (if the turbines are looked at from the top) [13]. A proper application of counter-clockwise yaw misalignment (i.e., positively yawed) in the northern hemisphere can positively impact the AEP of wind farms, while clockwise yaw misalignment (negatively yawed) causes a reduction in the AEP. While it has been acknowledged that this disparity between the impact of positive and negative yaw angles might not hold for specific layouts and certain wind directions (e.g., see [46]), two primary reasons have been proposed for it: (i) The clockwise rotation of wind turbines [47] and (ii) the Coriolis effect [48], both of which cause a background shift in the turbines' wake. Nouri et al. [49] found the Coriolis force contributes more to this background shift. A counter-clockwise yaw misalignment pushes the wake back to the center, which erases the background power gains and reduces the total power production.

### 3.2. Models for wake deflection caused by yaw misalignment

This section addresses the following:

1. What analytical models exist to predict local wake deflection downwind of a yawed turbine if the yaw angle is known?
2. How does the performance of these models compare?

### 3. Whether wake deflection keeps increasing with the yaw angle?

Applying the approaches explained in Section 2 to the velocity field of misaligned wind turbines captures the time-averaged wake traces downstream the yawed rotor. The input velocity fields are obtained either numerically [50–52], experimentally [53,54], or by conducting field studies via LIDAR [55]. Using these wake traces, a few models have been developed to correlate the wake skew angle  $\theta$  with the yaw angle of the misaligned wind turbine  $\gamma$ . Finding the wake skew angle as a function of yaw angle is essential as it provides a mathematical platform for adjusting the existing analytical wake-loss models to include non-zero yaw misalignment angles. This upgrade is critical for conducting layout optimization for wind farms that will implement a yaw control strategy.

One wake deflection model was constructed by Jiménez et al. [56] based on a simple top-hat model to formulate wake skew  $\theta$  as a function of yaw angle  $\gamma$  within the far-wake region. The authors will refer to this model as the far-wake model hereafter. This model formulates the wake skew angle at a distance  $x$  downstream of a misaligned rotor as:

$$\theta = \frac{\cos^2 \gamma \sin \gamma \frac{C_t}{2}}{(1 + \beta \frac{x}{D})^2} \quad (7)$$

where  $\gamma$  is the yaw misalignment,  $\beta$  indicates the wake's radial growth rate for the top-hat velocity deficit profile. Recommended values for  $\beta$  are  $\beta = 0.1$  for  $\gamma = 10^\circ$  and  $20^\circ$ , and  $\beta = 0.125$  for  $\gamma = 30^\circ, 40^\circ$ , and  $50^\circ$ . In Eq. (7),  $C_t$  is the local thrust coefficient given by:

$$C_t = \frac{T}{0.5 \rho (\frac{\pi}{4} D^2) u_h^2} \quad (8)$$

where  $T$  is the total force of the incoming wind on the turbine,  $\rho$  is the air density, and  $u_h$  is the velocity coming into the turbine at the hub height level [56].

Bastankhah & Porté-Agel also studied the wake skew angle associated with the yaw angle of the rotor. They used wind tunnel experiments to collect data at yaw angles of  $\gamma = 0^\circ, 10^\circ, 20^\circ$ , and  $30^\circ$ , and proposed the following model for the skew angle at the rotor [57]:

$$\theta = \frac{0.3\gamma}{\cos\gamma}(1 - \sqrt{1 - C_t \cos\gamma}). \tag{9}$$

Although Eq. (9) is an estimation for the skew angle at the rotor disk, it yields a reasonable estimate for the skew angle in the near-wake region up to 5D downstream. Hence, the authors will refer to this model as the near-wake model hereafter.

It is important to determine whether the wake is angled more with a higher yaw angle, and if so, whether it continues that trend when going into a substantial misalignment angle. Using the above-described near-wake and far-wake models, wake deflection based on skew angle is illustrated versus the yaw angle for  $C_t = 0.7$  (see Fig. 2) [58,56]. According to the near-wake model (Eq. (9)), the wake skew angle is only a function of yaw misalignment (Fig. 2a) and increases with the rotor yaw misalignment monotonically. The far-wake model (Eq. (7)), however, indicates that wake skew angle changes with both yaw misalignment and axial distance downstream of the turbine (Fig. 2b). This model predicts a reduction in wake skew angle when the yaw angle exceeds  $40^\circ$ . Wake skew angle stays approximately unchanged for yaw angles ranging between  $20$  to  $40^\circ$ .

A CFD-based study found that an almost linear lateral deflection occurs when the yaw angle is increased up to  $20^\circ$  but proceeds to diminish as the yaw angle increases more, which correlates very well with the far-wake model (Eq. (7)) [59]. This study also found that with a downstream distance of 5D and a yaw angle of  $40^\circ$ , the wake moves laterally about one-third of rotor diameter. This distance is between the predictions from far-wake and near-wake models (Eqs. (7) and (9)) which yield a lateral movement of  $0.25D$  and  $0.43D$ , respectively, at 5D and  $\gamma = 40^\circ$ . Another CFD simulation shows that with a yaw angle of  $30^\circ$  and a wind speed of  $11.4$  m/s, the lateral deflection located 7D downstream is about 0.4 of the rotor diameter [13]. This is in agreement with the near-wake and far-wake models' predictions, further verifying that Eqs. (7) and (9) are good models for the wake skew angle. Multiple other research studies used CFD-based packages such as the Simulator for Wind Farm Applications (SOWFA) [60] as well as analytical models such as the FLOW Redirection and Induction in Steady-state (FLORIS) to develop models of the wake and optimize the yaw angle based on the wake centerline [59].

Illustrating wake deflection based on the normalized lateral distance ( $y/D$ ) versus the normalized axial distance ( $x/D$ ) could reveal more details about the near-wake and the far-wake models (see Fig. 3). Evidently, the two models are pretty consistent within the near-wake region, while the near-wake model diverges sharply within the far-wake region. Note that the near-wake model predicts skew angle at the rotor; hence, one should not expect it to perform well within the far-wake area. The far-wake model, however, shows an acceptable performance even within the near-wake region.

More on the wake structure downwind of yawed wind turbines can be found in articles by Kleusberg et al. [61], and Liew et al. [62].

### 3.3. Yaw optimization for maximized power production

This section focuses on the impact of yaw misalignment on the power production of wind turbines. More specifically, it explains:

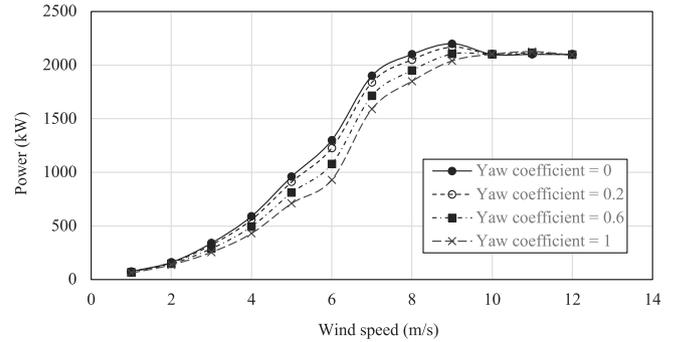
1. the sensitivity of a yawed turbine's power drop to wind speed
2. the overall impact of yaw control on power production of wind farms

The main reason for controlling the yaw angle of a turbine is to

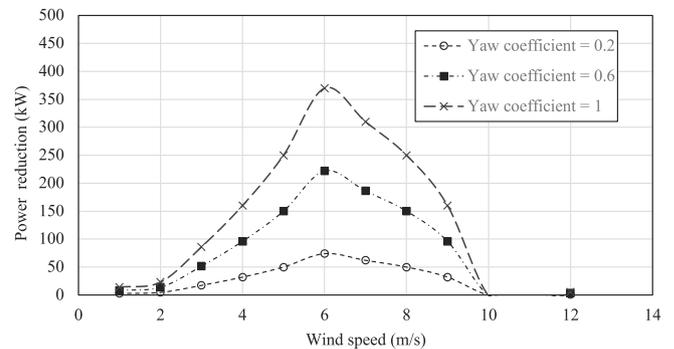
**Table 1**

Reduction of maximum power coefficient with yaw angle [58]. Data was measured at wind tunnel using a scaled, 3-bladed turbine with a diameter of 15 cm.

Yaw angle (degrees)	Maximum Power coefficient
0	0.35
10	0.34
20	0.29
30	0.22



**Fig. 4.** Variation of a wind turbine power curve with yaw misalignment. The yaw misalignment effect diminishes at wind speeds larger than rated speed. Maximum power drop occurs right between cut-in and cut-out wind speeds.



**Fig. 5.** Power reduction at the yawed turbine first increases with wind speed and then reduces to almost zero at rated wind speed and beyond.

minimize the negative wake effect on downstream turbines in order to increase the total power of any particular wind farm. As stated in Section 3.1, yawing a turbine decreases its power intake. Table 1 presents a laboratory experiment's results indicating that the maximum power coefficient decreases for a wind turbine as the yaw angle increases. The sensitivity of a turbine's power production to its yaw misalignment varies with wind speed. The power reduction of a yawed wind turbine at different wind speeds has been investigated using SCADA (Supervisory Control And Data Acquisition) data [8]. The studied wind turbine has a rated power of 2 MW and is located in South China. SCADA data are scattered clouds of points where each yaw coefficient value corresponds to multiple output power values. One can employ the least square fitting method to substitute the data cloud with a single line. Figs. 4 and 5 show power production and reduction in production versus wind speed for different yaw coefficients ( $\alpha$ ), defined as  $\alpha = \frac{\gamma}{\gamma_b}$ , where  $\gamma_b$  is the base yaw angle [8]. Power production is more sensitive to a yaw misalignment at wind speeds below the rated speed (Fig. 4). As wind speed increases from the cut-into the rated values, the power loss in the misaligned turbine initially increases, then reduces, and the yaw effect tapers off as the power goes back to normal (Fig. 5).

Although increasing the yaw misalignment of a turbine does

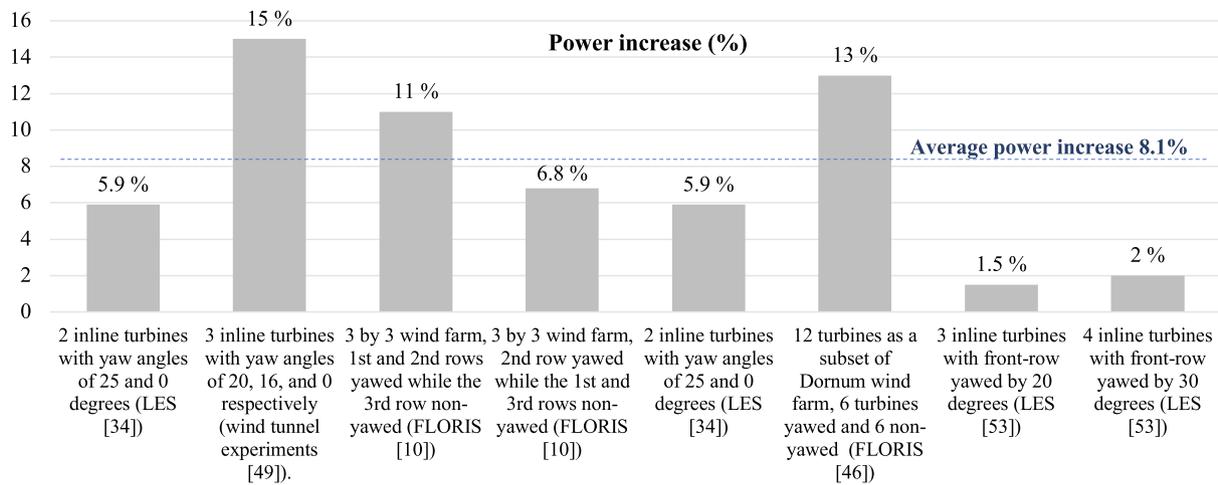


Fig. 6. Power production increase using yaw control.

decrease its power production, many studies have gone into determining if the downstream turbines have a power production increase due to the deflection of the upstream wake that offsets the power reduction at the misaligned turbine. Assessing whether or not the total power is increased has been done through experimentation [63], simulation [48], or a combination of experimentation and simulation [64].

Through an experimental investigation, Campagnolo et al. [63] studied the impact of yaw misalignment on power production for a setup of three inline turbines with a rotor diameter of 1.1 m in a wind tunnel. The study found that yawing the upstream turbine by 20° and the second-row turbine by 16° can increase the wind farm's total power production by as much as 15%.

Gebraad et al. [65] created a data-driven parametric wind plant model for predicting power (and energy) production of wind farms with yawed rotors. This model, called FLORIS, captures the yaw control's effects on the redirection of the wake behind the turbine and the wind speed deficit in the wake. The redirection effect is modeled using Eq. (7) and the deficit within the wake is captured via Jensen's (also called PARK) model [66]. Modified versions of this model were later proposed to make it compatible with gradient-based optimization [67] and incorporate atmospheric stability effects [65].

Quick et al. [68] also used FLORIS and an optimization technique, known as Optimization Under Uncertainty (OOU), to simulate the Princess Amalia Wind Farm with 60 2.0 MW wind turbines with a rotor diameter of 80 m. The results showed that optimizing the yaw angles using the OOU approach could increase the total power production by about 3.3%. Schreiber et al. [64] used FLORIS to model SCADA data collected for a whole year from Windpark Dornum in north-western Germany. They used only a cluster of six identical turbines (E-70, rotor diameter 71 m, hub height 64 m) for their study. This study focused on the output data from a cluster of 12 inner turbines and found that at low wind speeds, this cluster of wind turbines had a maximum power increase of 17% while the estimated yearly gain in energy production (AEP) was 1.7%.

Gebraad et al. [35] used large-eddy simulations to investigate the impact of yaw misalignment on power production of two inline wind turbines. The simulated turbines were the National Renewable Energy Laboratory (NREL) 5-MW baseline turbine, which has a rotor diameter  $D = 126$  m. The yaw offset was applied only on the front-row turbine. For yaw offsets between 0° and 40°, the production gain on the downstream turbine was higher than the loss of production on the front-row turbine. A 25° yaw angle led to a maximum power production increase of 5.9%. A RANS-based CFD simulation (RANS) considered two inline NREL 5-MW wind turbines to investigate the power increase by yawing and if the yaw angle sign affects power [13]. Applying positive yaw angles of 15° and 30° increased the total power by 15% and 17%

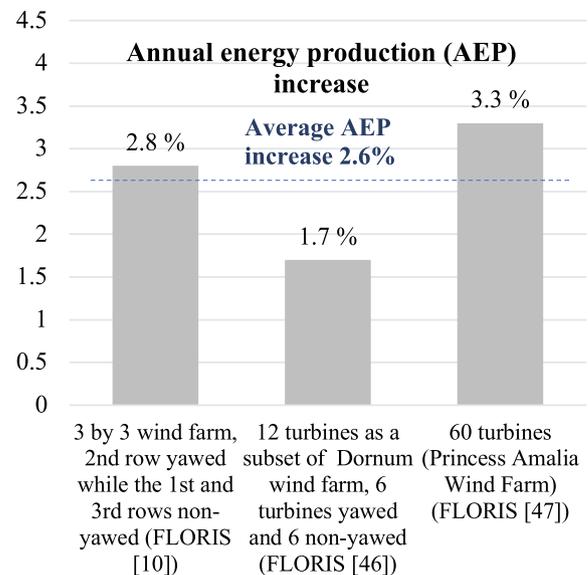


Fig. 7. Annual energy production increase using yaw control.

respectively, while negative yaw angles of 15° and 30° had an opposite effect and caused a reduction in power production by approximately 11%.

Archer and Vassel-Be-Hagh [48] used large-eddy simulations to investigate whether power production of a wind farm consisting of 28 turbines can be improved by yawing only a subset of wind turbines rather than optimizing the yaw angle for all turbines. Their study used Siemens 2.3 MW, 93 m diameter wind turbines. Four different cases were examined, including imposing a yaw misalignment to the front-row, mid-row, and deep-row turbines, in addition to changing the sign of the yaw misalignment. Imposing a yaw misalignment to the front- or deep-row turbines appeared as an effective strategy to increase the overall power production, while yawing mid-row turbines was not as effective. Small, positive yaw misalignment angles (e.g., 10°) were found as safe strategies for both front- and deep-row turbines because the losses associated with yawing were small. Although the gains associated with the non-yawed turbines were also small in absolute terms (kW), but relatively large when compared to the losses themselves (ratio of net gain over the loss). For the front-row, an intermediate yaw misalignment (e.g., 20°) was the most effective strategy, giving high net gains for a moderate loss in power at the yawed turbines (ratio of net gain over loss >37%). That study does not recommend large yaw offsets

(e.g.,  $30^\circ$ ) at the front-row as the ratio of net gain over loss is small (i.e.,  $<10\%$ ). For the deep-rows, the recommended strategy was to apply a slight misalignment (i.e.,  $10^\circ$ ) as the power losses caused by it at the yawed turbines are not significant; thus, it leads to the highest net gains.

Figs. 6 and 7 summarize the literature on the impact of yaw optimization on the power and annual energy production of wind farms. Fig. 6 compares the different types of studies conducted that looked at power increases, while Fig. 7 compares the studies that investigated the annual gain in energy production for each setup. Studies that focused on instantaneous power production of wind farms report an average of 8.1% power gain, while total energy production showed an average of 2.6% increase.

Note that the literature has mostly focused on investigating the performance of yaw control in a neutral atmosphere. Howland et al. [69], however, demonstrated that the power production of a yawed wind turbine depends on atmospheric stability. More on yaw optimization can be found in articles by Saenz-Aguirre et al. [70], Kuo et al. [71], Qian and Ishihara [72], Astolfi et al. [73], Liu et al. [74], Bernard et al. [75], and Dou et al. [76].

### 3.4. Impact of yaw misalignment on structural loads and moments

One of the inevitable effects of a yaw misalignment is its adverse impact on the structural load. The yaw angle should normally be limited to  $\pm 30^\circ$  as the load on the turbine increases with yaw misalignment [64]. Applying a yaw angle greater than  $30^\circ$  drastically reduces the lifetime of the turbine. Note that this  $30^\circ$  limit on the yaw angle does not reduce yaw control's effectiveness since, as explained in Section 3.2, applying a yaw misalignment larger than  $40^\circ$  does not add any benefits from an energy point of view anyway [64].

Studies such as that of Dijk et al. [14] have been done to optimize the yaw angle to increase the total power production and minimize the structural load that a turbine experiences. Van Dijk et al. [14] used FLORIS to maximize the power production and minimize differential blade loads of a 3-column, 3-row wind farm with yaw misalignments applied. They used the NREL 5 MW baseline turbine. For one specific wind direction, which was aligned with columns of the turbines, the power optimizer yawed both the first and the second rows of turbines to increase the power production by +11%, while both mean differential flap-wise and edge-wise moments also increased by approximately 95% and 59%, respectively. However, the combined optimizer did not yaw the first row as it would significantly increase the loads. The combined optimizer reduced the mean differential flap-wise and edge-wise moments by 34% and 40%, respectively. Nonetheless, the power production due to the second row's optimized settings was still higher than the baseline by +6.8%. Applying the yaw misalignment found by the combined optimization for all wind directions caused the total mean omnidirectional power to increase by 2.8% and the mean differential flap-wise and edge-wise loads to decrease by 8.2% and 12.5%, respectively. Optimal yaw angles assigned to the turbines were not given for any of these optimal settings. One could conclude that while optimizing the yaw angle of the first-row turbines significantly increases the farm's power production as a whole, it considerably increases the loads and moments acting on the blades.

Lin and Porté-Agel [77] also conducted a multi-objective parametric optimization for a column of three miniature wind turbines with a diameter of 15 cm to identify the optimal yaw angles that lead to a maximized power and minimized fatigue load. Large-eddy simulations were used to calculate the mean power and the yaw-moment damage equivalent load (DEL) for different yaw angles imposed on the first two turbines. They found that using a small yaw angle for the first wind turbine is inefficient as it leads to a significant increase in fatigue while achieving small power gains. Their study suggested moderate yaw misalignment ( $\sim 15^\circ$ ) for the best outcome.

Ke et al. [78,79], Ennis et al. [80], and Rahimi et al. [81] have also discussed the impact of yaw offset on wind turbine loads with further

details.

## 4. Pitch control

This section presents blade pitching, the concept of using blade pitching to control a wind turbine's wake, and its effectiveness.

### 4.1. Explanation of blade pitching

The pitch control system includes a device installed at each blade's root to rotate it longitudinally to the desired angle [82]. The pitching system can operate as either *collective blade pitching* or *individual blade pitching*. Collective blade pitching changes all of the blades to the same pitch angle at the same time. Individual blade pitching changes each blade's pitch angle separately to meet their individual needs [83]. While some studies have employed individual blade pitching [31], most studies that focus on blade pitching for wake control purposes focus mainly on collective blade pitching [34].

Manufacturers install pitch controllers on wind turbines for reasons other than controlling the aerodynamic wake. These controllers' intended use is to regulate the blades' rotational speed to maintain an optimal tip speed ratio (TSR) to maximize the power production and minimize structural loads [83]. The TSR, also shown by  $\lambda$ , is the ratio of the linear speed of the tip of the blade ( $R\omega$ ) to the average incoming wind speed into the rotor ( $u_\infty$ ) [84]. Pitch controllers also assist the emergency shutdown procedure [85]. In emergencies, the pitch angle can approach almost  $90^\circ$  to create a considerable drag against the blades' rotation to slow down the turbine quickly [86]. Recently, researchers have investigated the possibility of using the pitch control system in reducing wake losses. This system can contribute to active wake control strategies in two ways.

First, it can be used simultaneously with other wake control strategies as a load-reducing tool to offset the loads induced by the primary wake control technique. For instance, Wang et al. [87] found pitch adjustment an effective way to alleviate excess loads and moments induced by imposing intentional yaw misalignment.

Second, pitch control systems can play the primary role in controlling the wake [34]. It does that by steering the wake away from the downwind turbines [88] and causing increased mixing in the wake, which leads to accelerated recovery of the wind [36].

### 4.2. Wake control using pitch angle

Multiple experimental and numerical studies have evaluated the effect that certain pitch angles might have on the turbine's wake recovery and redirection. Three major studies devoted to this concept are those by Fleming et al. [31], Wang et al. [89], and Dilip & Porté-Agel [88]. Fleming et al. [31] and Wang et al. [89] focused on the possibility of redirecting the wake via the pitch control system, while Dilip & Porté-Agel [88] investigated the impact of imposing intentional pitch angles to the blades on wake recovery speed. Fleming et al. [31] studied individual pitch control, and Wang et al. [89] considered collective pitch control.

Large-eddy simulations indicate individual pitch control could steer the wake on the same magnitude as of yaw misalignment but at the cost of significantly greater loads on the blades [31]. Hence, the strategy does not seem very practical. Wind tunnel experiments using a two-turbine setup equipped with a collective pitch control system did not indicate any significant lateral move in the wake at a pitch angle of  $7^\circ$  [89]. A generic wind turbine with a 2-m diameter was used for this study. A swirl, however, was introduced into the wake. The experiment was followed up by a series of numerical simulations with the pitch angles ranging from  $-10^\circ$  to  $+10^\circ$ . Results were very similar to the experimental case of  $7^\circ$ . The results did show a linear increase in the deflection of the wake between  $0^\circ$  and  $-3^\circ$ , but the investigators dismissed this observation as they found it misleading based on the way the data was

post-processed [89]. The plot used to interpret the data employed the wake center as the tracking system of the deflection, but this can be misleading since the wake has a swirl introduced to it.

Large-eddy simulations of a two-turbine setup using Vestas 2MW V80 model were also used to investigate pitch control's effect on the spatial length required for the wake to recover [88]. The wake recovered faster when a higher magnitude of negative pitch angle was applied. Frederik et al. [32] reiterated this finding by proposing that one can manipulate the pitch control system to cause the wake to further interact with the adjacent higher speed winds. Hence, the wake can recover some of the energy extracted by the upstream turbine, leading to higher input wind speeds for the downstream turbines. Although the literature does not find the pitch angle capable of making the wake laterally deflect, findings on the recovery speed imply that pitch control is still feasible to minimize the wake effect.

#### 4.3. Power production increase based on pitch angle control

This section discusses the existing knowledge on how manipulating upstream pitch angles can impact downstream turbines' power production.

Gebraad et al. [35] and Wang et al. [89] studied the impact of pitch angle on the power production of a two-turbine setup using large-eddy simulations using the NREL 5-MW turbine and a 2-m diameter turbine, respectively. They discussed the power production change between the front and rear turbines. Wang et al. found a slight power increase for different pitch angles. They explained that this small power gain is a trade-off for the significant increase in the loading experienced by the front-row wind turbine [89]. Gebraad et al. [35], however, found that applying pitch angles from  $-8^\circ$  to  $+12^\circ$  resulted in a loss in total power production and a significant increase in loading. A wind tunnel study by Bartl and Sætran [90] also investigated a case of two in-line turbines with a diameter of 0.9 m; however, the axial distance between the two turbines was 3D, which is not realistic. Their results were very similar to those of Wang et al. [89] and Gebraad et al. [35] when comparing the total power production. The power gained by the downstream turbine was essentially equal to the power lost by the upstream turbine. Hence, controlling the upstream pitch did not appear to improve the total power production.

Based on what was learned from yaw control, the authors believe it takes more than one turbine (at least two) downwind of a pitched turbine to observe the actual benefits of wake control via pitch angle. This idea is supported by the study conducted by Lee et al. [34], where they found somewhat different outcomes than each of the previous studies. The study looked at two different wind farms in Denmark: Horn Rev wind farm with Vestas 2.0MW, 80-m diameter turbines and Nysted wind farm with Siemens 2.3 MW, 93-m diameter turbines. They examined data for ten wind turbines positioned in a line. Pitch angles of each turbine were then optimized. The pitch angles were kept between  $-5^\circ$  and  $+5^\circ$  to avoid excessive loads. After optimizing all ten turbines' pitch angles, the farm's total power increased by 4.5% [34]. Another study by Dilip and Porté-Agel [88] using Vestas 2MW V80 turbines also shows promise for the field of pitch control. They had four separate cases, each of which showed an increase in the total power produced between the two turbines. The case that showed the most remarkable improvement in total power was at a turbulence intensity of 4.3% and 7D downstream. At a pitch angle of  $-2^\circ$ , they found a total power increase of 2.8%. A more recent study indicating promising results for pitch control presents CFD-based analyses of two 5MW NREL turbines in an inline configuration [91]. In this work, Cacciola et al. [91] reported enhancements of up to 20%. They found that pitch control was more effective at lower wind speeds and larger axial spacing. Such satisfying enhancements, which are at odds with some other research results, demonstrate the urge for deeper investigations on the potential impact of pitch optimization on the energy production of utility-scale wind farms.

## 5. Torque control

Similar to pitch control, torque control affects the wake's strength rather than its direction. This section explains this concept and discusses its success in improving wind farm's production.

### 5.1. Torque controllers

Like pitch control systems, torque controllers' primary purposes are other than controlling the wake. The original use of torque controllers is to maintain the optimal TSR by controlling the generated torque of a turbine. This task is mainly essential in the second region of the power curve (between cut-in and rated wind speeds) because once the power curve enters the third region (wind speeds larger than the rated speed), the nominal rotor speed cannot be controlled strictly by the generated torque [85].

The torque is controlled by

$$T = k_g \Omega^2 \quad (10)$$

where  $\Omega$  is the speed of the generator and  $k_g$  is the optimal constant leading to the optimal TSR defined as [83]

$$k_g = 0.5 \rho \pi R^5 \frac{C_{p,max}}{\lambda^3} \quad (11)$$

in which  $\rho$  is the air density,  $R$  is the rotor's radius,  $C_{p,max}$  is the maximum power coefficient found for the turbine, and  $\lambda$  is the optimal TSR that leads to the  $C_{p,max}$ . Tip speed ratio can be used as another parameter in experiments to evaluate how the output power can be changed by strictly varying the rotor speed without varying the wind speed. This can happen by controlling the torque via brakes, for instance.

Torque controllers can control the strength of the wake of a turbine. This idea aims to reduce the induction factor of the upstream turbines to increase the amount of kinetic energy available in the wake of the downstream turbines to extract [90]. Adjusting the induction factor is done by adjusting the TSR, which can be achieved by changing the blades' pitch, explained earlier, or the generated torque. When the TSR is altered, the respective wake's strength (or wind speed deficit) will change. Like the yaw and pitch control strategies, the hope is that the power gained by the downstream turbines is more than the loss in the power production of the upstream turbine, which is intentionally subjected to additional torque and operates at a non-optimal TSR.

### 5.2. Power production increase via torque control

According to the literature, torque control is not an effective active wake control strategy. It is essential to note that the strategy has not been tested on large clusters of wind turbines yet, neither numerically nor experimentally.

A study conducted by Gebraad et al. [35] used torque controllers to control the TSR and, therefore, the wind speed deficit within the wake of NREL 5-MW wind turbines. They studied two inline wind turbines, with the wind aligned with the column of the turbines. In their CFD-based investigation, Gebraad et al. applied a scaling factor to the torque to have a range of TSRs between 7.3 and 10. Increasing the torque on the first turbine caused the downstream turbine to have a higher inflow velocity and power production. However, considering the turbines as a pair, the second turbine's power was not enough to cope with the first turbine's power loss and resulted in a total power production drop. Bartl and Sætran [90] also used a setup of two scaled inline wind turbines with a diameter of 0.9 m to investigate the effectiveness of torque control. As opposed to Gebraad et al.'s work, this was an experimental effort. Decreasing the TSR of the upstream wind turbine from 6 to 5 caused the downstream turbine's power production to increase by 2%. Further decrease of the front-row turbine's TSR to 4 pushed up the

downstream turbine's power production by approximately 20%. Comparing the power gained by the downstream turbine against the power lost by the upstream turbine revealed that the total power generation for the pair was about even for TSR ranging from 4.5 to 6.5.

The authors believe that the studies mentioned above did not find torque control as an effective strategy for enhancing the total power production because they looked into an inline combination of only two wind turbines. Similar to the yaw and pitch control strategies, perhaps there needs to be more than one turbine downwind of the controlled turbine to benefit from the redirected/weakened wake.

Torque control has appeared more promising when combined with other wake control strategies, in particular with pitch control. Another

study by Zhu et al. [84] investigated four different scenarios where (i) the rotor speed was kept constant, (ii) the TSR was kept constant, (iii) the rotor speed was set as the maximum rotor speed, and (iv) the thrust coefficient was kept at a minimum. They also used the NREL 5 MW wind turbine. All these were made possible via torque and pitch control. They observed two facts. The first is that minimizing the thrust coefficient was the best approach for increasing the downstream turbine's power. The second observation showed that these strategies to control the wake were more effective in lower wind speeds. Also, in the Ph.D. dissertation of Gionfra [92] and a subsequent publication [93], the author has shown that a deloaded control strategy based on torque and pitch control allows optimizing the global production of a wind farm. Their simulations

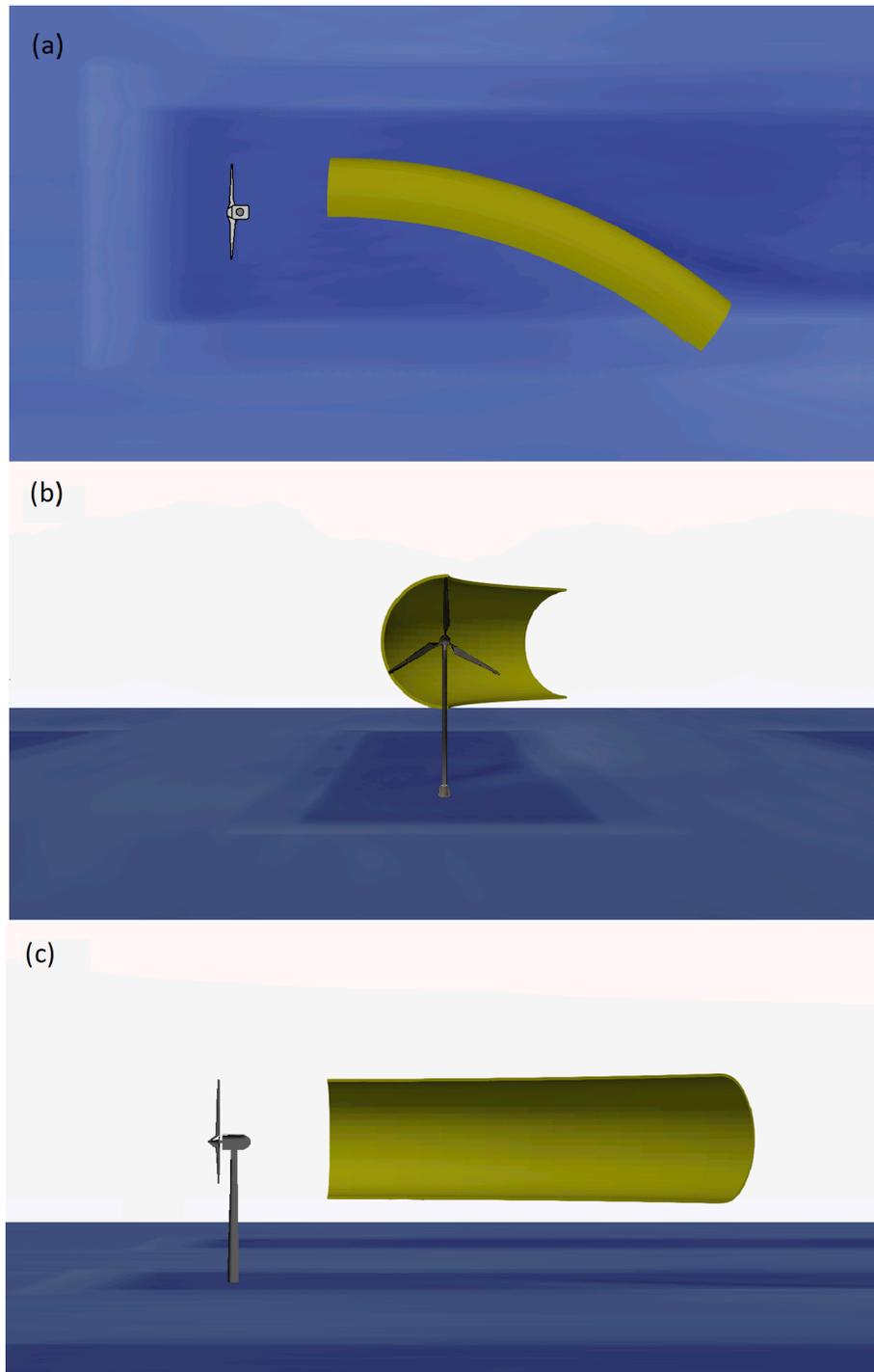


Fig. 8. Stationary deflector concept: (a) top view, (b) front view, and (c) side view.

were carried out based on a wind farm with 600 kW turbines.

## 6. Tilt angle control

This section clarifies the effect of tilting a rotor on the wake's properties and a wind farm's power production.

### 6.1. Impact of tilt angle on the wake characteristics

Controlling the tilt angle is considered as another potential strategy for wake redirection. The angle between the horizontal axis and the rotor shaft is changed to tilt a turbine (see Fig. 1c). Note that only the positive tilt angles can be considered. Negative tilt angles would result in a collision with the wind turbine tower [13]. Moreover, note that many of the existing turbines do not provide active tilt control [31]. This is one of the primary reasons that tilting an upstream turbine to redirect the wake has not been excessively studied. There have, however, been some studies on this subject.

Tilting the turbine results in a redirection of the wake downstream similar to the lateral deflection found when applying a yaw misalignment. Weipao et al. [13] studied the wake deflection caused by a yaw misalignment and a tilt angle at a wind speed of 11.4 m/s. Applying a tilt angle of 15° caused the wake to deflect approximately 0.8D laterally at an axial distance of 7D downstream. Applying a yaw angle of -30° led to a similar wake deflection. Fleming et al.'s study [31], however, somewhat contradicts these findings. Fleming et al. used the same turbine model as Weipao et al. [13] but wind speed averaging 8 m/s. They found a lateral deflection of about 0.11D when a tilt angle of 15° was applied. This is significantly smaller than the deflection identified by [13], while wakes are generally more sensitive to the rotor misalignment at smaller velocities.

### 6.2. Impact of tilt angle on power production

Adjusting the upstream turbine's tilt angle can increase the total power production of a two-turbine setup with an axial spacing of 7D [13]. Applying tilt angles of 10° and 15° to the upstream turbine increases the total power by 6.9% and 12.0%, respectively [13]. These numbers, found using the NREL 5 MW turbine, are very promising as studies on pitch and torque control strategies indicate that the total power production of a pair of two wind turbines does not increase by pitching the front-row turbine or by applying a greater torque to it. The literature suggests that such significant increase in power of a turbine located downwind of a tilted turbine would occur if the axial distance is not beyond 8D. This effective distance decreases by wind speed, so that at wind speeds of approximately 15 m/s, the second turbine can only have this type of increase in power up to 4D downstream [40]. It is important to mention that tilting did not appear to add much loading to the turbine, although it does add more bending to the blades when having a positive tilt angle [31].

The tilt control's promising results have encouraged the research community to find creative ways to address the wind turbine's lack of the degree of freedom to adjust the tilt angle actively. One proposed approach is applying water ballast control systems to offshore floating wind turbines. This concept does not need introducing additional mechanisms as some of the floating concepts already incorporate such systems to modify the attitude of the floating platform [94]. Numerical and experimental investigations into this concept indicate that redirection of the wake towards the sea surface positively affects the cluster's power production, while deflecting the wake towards the sky decreases the overall power [95].

## 7. Cone angle control

Controlling the cone angle is defined as changing the angle between the rotor plane and the blade axis (Fig. 1d). Literature provides little

guidance on the impact of cone angle on the wake direction. A study on controlling the cone angle of the NREL 5-MW turbine reports that increasing the cone angle does not affect the wake direction and makes the wake wider and more turbulent, leading to a decrease in the power production between an upstream and downstream turbine pair [13]. Applying a 5° cone angle to the front row of a two-turbine setup decreased the total power production by approximately 10 %. This reduction in power production became worse with increasing the cone angle. For instance, the total power production decreased by approximately 15% at a cone angle of 7.5°.

## 8. Introducing a new wake control concept

This section proposed a new wake control concept and evaluates its energy performance via laboratory experiments.

### 8.1. Steering the wake via an external wake deflector

The wake control strategies discussed in previous sections have some common shortcomings:

1. They sacrifice an upstream turbines' performance to steer or weaken wakes that are adversely affecting the downstream turbines. The hope is that the downstream gains outweigh the upstream losses. This tradeoff generally leads to gains that are not very significant.
2. They generally add to the structural loads, which can lead to premature failures.
3. They all demand changes to the turbines' control algorithms, requiring the turbine manufacturers' involvement. The involvement of more parties adds to the complexity of implementing these advanced strategies. For instance, a wind turbine's standard yaw control algorithm always keeps the turbine normal to the incoming wind. Hence, imposing the optimal yaw misalignments to every wind turbine in every wind direction requires manipulating the yaw control system somehow.

Here a new wake control concept that does not suffer from any of these issues is proposed, although it introduces a new implementation challenge. The authors are currently working on addressing this challenge and will communicate their solutions in future publications. Here the focus is on the energy performance of this concept rather than how one can implement it. The proposed concept is illustrated in Fig. 8. As was mentioned in earlier sections, wind turbines' wakes are plume-like volumes characterized by lower wind speeds and higher turbulent kinetic energy than the undisturbed free stream wind. Static vanes can redirect these volumes. By steering the wake away from the downstream turbine, undisturbed flow from the surrounding wind corridors between the column of interest and the adjacent columns rushes into fill the void, exposing the downstream turbine to higher kinetic energy levels. The vane itself creates a new wake; however, the wake of a static vane is much less severe than that of rotating turbine blades. Note that a geometry optimization was not conducted for this specific problem. However, the geometry used here to prove this concept is inspired by the work of Maddison Dittner [96], in which she used Genetic Algorithm and Computational Fluid Dynamics to identify the optimal geometry of a bladeless wind turbine. That research aimed to find the optimal funnel geometry that captures and redirects wind without causing a backflow while having the largest area ratio between the inlet and the outlet.

Steering the wake via external wake deflectors does not decrease the production of the upstream turbines; hence, it leads to significant gains in the overall power production. It does not add to structural loads as the turbines will operate in their normal operating conditions without any form of misalignment. It is entirely independent of the turbine operation and works as some add-on to the farm, which does not require any turbine manufacturers' involvement. The performance of this concept was evaluated via wind tunnel experiments. The following two sections

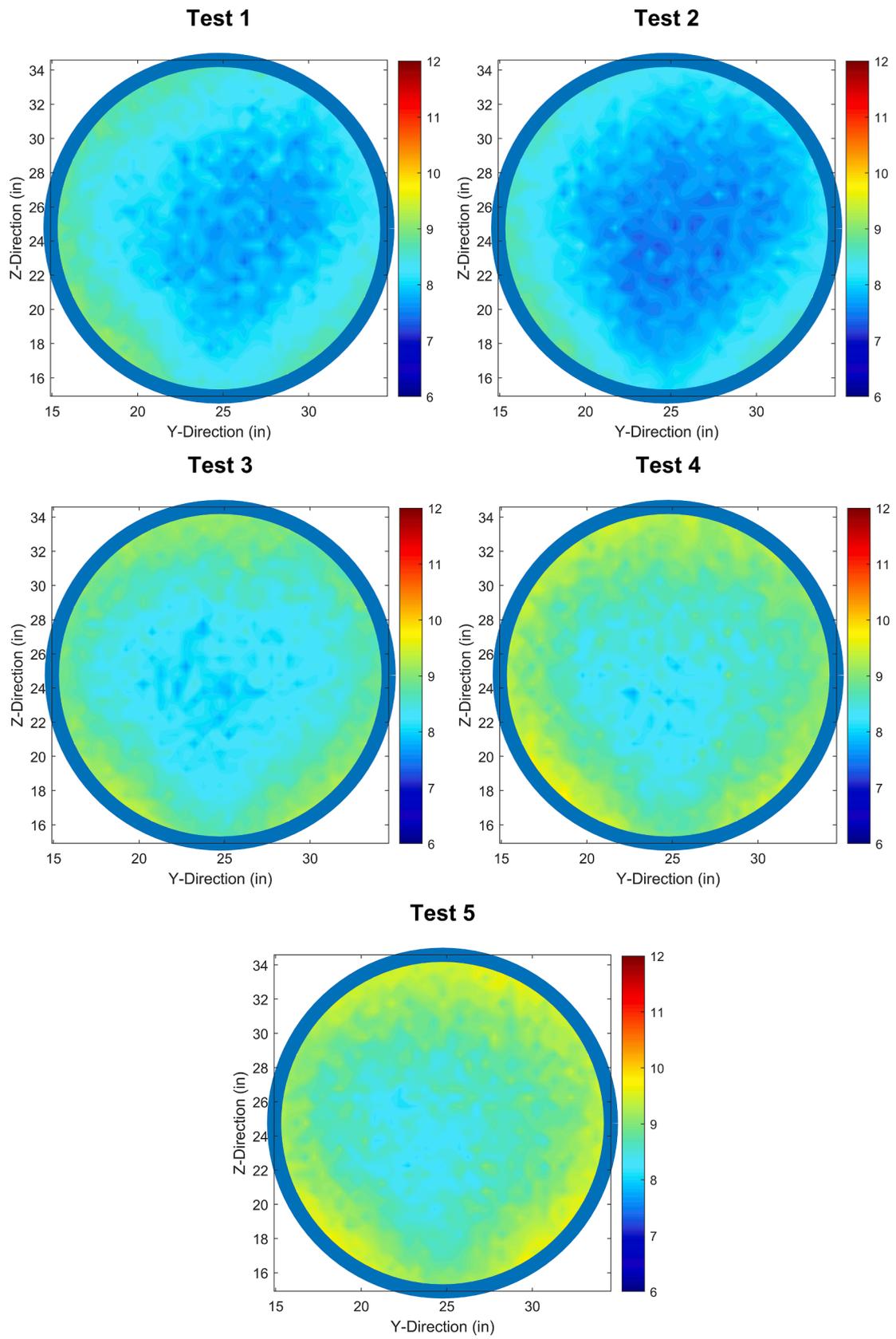


Fig. 9. Velocity profile in m/s of the inlet of the downstream turbine found 5D downstream of the front row wind turbine.

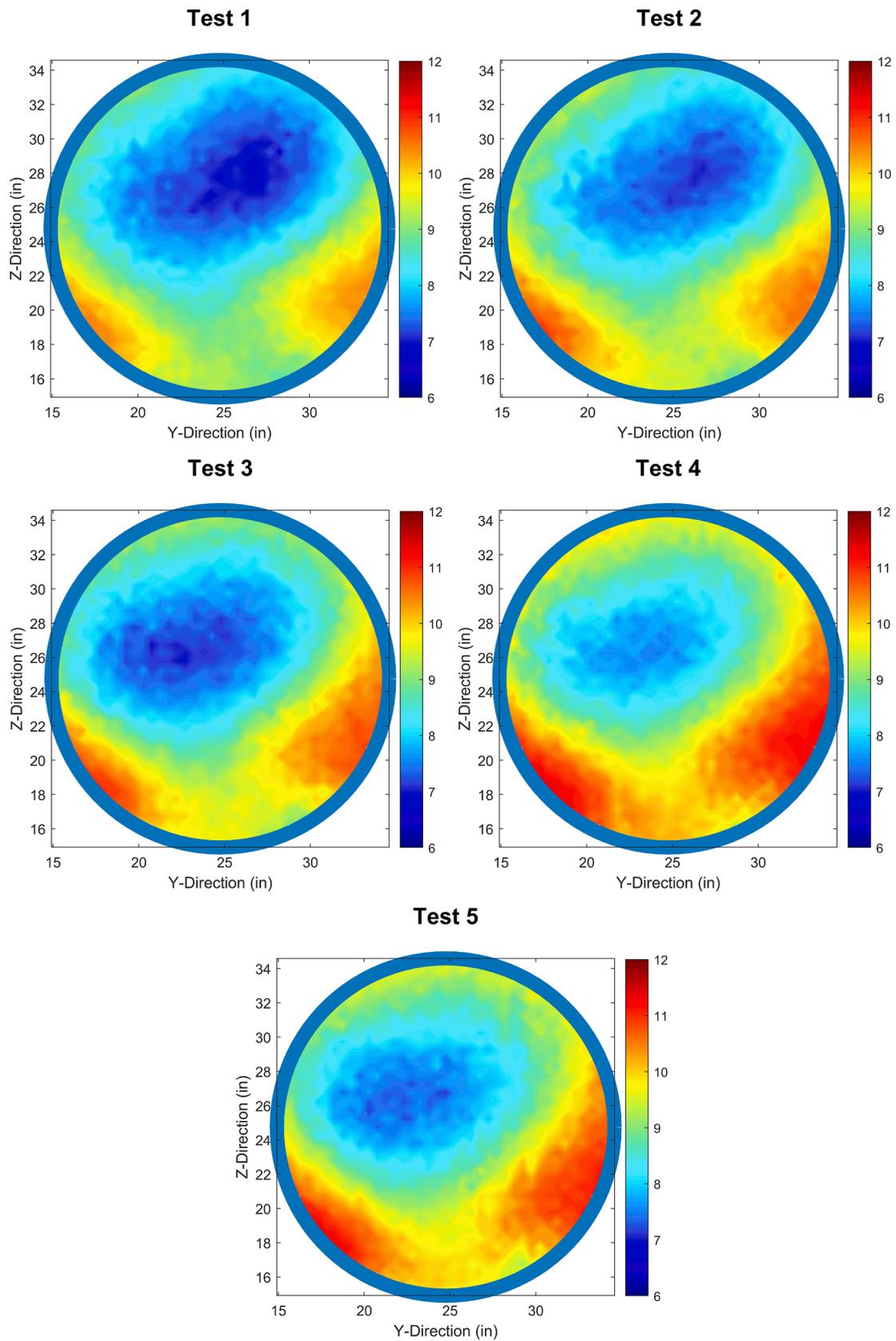


Fig. 10. Velocity profile in m/s of the inlet of the downstream turbine with the vane implemented found 5D downstream of the front row wind turbine.

focus on reporting these experimental and numerical studies.

### 8.2. Testing a scaled prototype in wind tunnel

The performance of this concept was tested in an open-loop wind tunnel at 10 m/s. A 3D-printed wake deflector vane was installed in the wake of a scaled turbine with a diameter of 0.5 m. Using Constant Temperature Anemometry (CTA) probe, velocity over a downstream rotor was measured at an axial distance of 5D. The downstream turbine did not need to be present in this test as what this research cared about was the velocity that the rotor of this turbine would experience if it were present. The velocity was measured via a 1D hot wire probe traversed using a robot within a grid with a resolution of 1.27 cm (0.5 inches). These tests were repeated five times on five different days to ensure repeatability.

### 8.3. Results and discussion of laboratory experiments

Figs. 9 and 10 illustrate the results without and with the wake deflector, respectively. Adding the wake-deflector vane led to the setting cut the wind speed deficit by 33%. Power production of a turbine can be calculated via  $P_{out} = \frac{1}{2}C_p\rho V^3A$ . Hence, the relative increase in power production induced by the wake deflector equals to  $\Delta P/P = (V_{w/deflector}/V_{w/o deflector})^3 - 1$ . Power production of the downstream turbine increased by more than 15%. This power production gain is larger than any gain reported in the literature for any of the existing wake control strategies.

## 9. Conclusions and applications

This review explains six potential wake control techniques: yaw control, pitch control, torque control, tilt control, cone control, and use of external wake deflectors. Each of these methods has its strengths and weaknesses. Some show promise in being implemented into the field to provide real-time wake control to improve the performance of wind farms as a whole, while others do not appear to have the potential for such a purpose. This section cross compares these wake control strategies.

The first comparison is the ease of use and implementation. It appears that it is more straightforward to implement the yaw, pitch, and torque control strategies than applying a tilt or cone angle. Ways to control the tilt and cone angles do not exist in many turbines already operating in the field. Implementing an external wake deflector is also very challenging as at least the one presented here is huge in dimensions. As wind direction changes, the operator must have the ability to relocate the wake deflector to a new optimal position to avoid blocking the airflow into specific downstream turbines to maintain its effectiveness. Using sailcloth instead of rigid materials can address this to a great extent. Sailcloth is light and can move easily and quickly. The authors are also researching other possible designs based on the same concept presented here to address the implementation challenges.

The most needed comparison of these six wake control strategies discussed here is to compare the power boost each of them yields. One crucial fact to note is that the layout of the turbines, meteorological conditions, and other impactful settings are not identical across various studies that have researched each of these methods' performance. Hence, the overall performance comparison provided in this section might not be exact; however, it provides a general instrumental insight into the effectiveness of each wake control strategy.

Among all six wake control strategies reviewed here, the cone angle control is the least effective method for increasing the total power output as the existing literature unanimously concludes that cone control leads to an overall power loss. However, one must note that there is a dearth of any published research investigating the effectiveness of cone angle control for a utility-scale wind farm, and the existing studies

**Table 2**  
A summary of existing wake control strategies

Control Strategy	Advantages	Disadvantages
Yaw	<ul style="list-style-type: none"> <li>– The most researched strategy</li> <li>– The only strategy tested in a wind farm</li> <li>– Existence of analytical models to predict wake deflection caused by yaw misalignment</li> <li>– Increases the overall production of the farm</li> <li>– Literature suggests that yaw control is effective even in the case of only two inline turbines.</li> </ul>	<ul style="list-style-type: none"> <li>– Adversely affects the structural loads</li> </ul>
Pitch	<ul style="list-style-type: none"> <li>– Leads to a faster wake recovery rather than changing wake direction</li> <li>– If there are more than two turbines in the column of interest, pitch angle control increases overall production</li> </ul>	<ul style="list-style-type: none"> <li>– Causes a more significant spike in structural loads compared to yaw misalignment</li> <li>– The literature mostly believes pitch control does not add to the production of a pair of two turbines (unless axial distancing is very large and wind speed is low).</li> </ul>
Torque	<ul style="list-style-type: none"> <li>– Does not lead to a significant increase in structural loads</li> <li>– Lessons learned from pitch control signal that torque control can likely lead to an overall increase in production if more than one turbine is in the wake of a controlled turbine. It is yet to be studied and proven, though.</li> <li>– It performs better if mixed with other strategies, particularly with pitch control</li> </ul>	<ul style="list-style-type: none"> <li>– Has not been tested on large clusters of wind turbines, neither numerically nor experimentally</li> <li>– Does not appear to increase power production of a pair of two turbines</li> </ul>
Tilt	<ul style="list-style-type: none"> <li>– Redirects the wake</li> <li>– Does not induces large structural forces</li> <li>– Increases power production, even in the case of only two inline turbines</li> </ul>	<ul style="list-style-type: none"> <li>– Many of the existing turbines do not provide active tilt control</li> </ul>
Cone	<ul style="list-style-type: none"> <li>– No significant advantage was noted.</li> </ul>	<ul style="list-style-type: none"> <li>– Many turbines cannot perform a real-time cone control</li> <li>– Does not enhance the wake properties, and hence, does not lead to a production increase</li> </ul>
External vanes	<ul style="list-style-type: none"> <li>– It leads to very high gains in production. It is an add-on to the farm that does not require any turbine modification and does not interfere with the turbines</li> </ul>	<ul style="list-style-type: none"> <li>– Challenging implementation</li> <li>– Lack of any feasibility study</li> </ul>

focus on a set of two inline wind turbines. The torque control method seems to keep an even power output, again, for a set of two wind turbines. This observation might change if more turbines are present in the column.

The literature is divided over the impact of pitch control. Some studies, mainly those focused on two inline turbines, suggest pitch control keeps an even power output, with upstream losses wiping out the downstream gains. Other studies, primarily those considering larger wind plants, claim pitch control can lead to overall gains. This observation makes the authors believe there must be more than one wind turbine downwind of the controlled turbine to benefit from the upstream wake's redirection. Otherwise, it is not worth losing so much power in the upstream turbine to steer the wake away from one single turbine downwind.

Controlling the tilt angle appeared to be very promising, even in the case of two-turbine setups, particularly at lower wind speeds. As was mentioned before, many installed turbines cannot control the tilt actively. The research community explores ways to go around this issue,

for instance, applying water ballast control systems to tilt offshore floating wind turbines. Controlling the yaw angle is the most researched and advanced concept among all, although many studies have advised against yawing turbines in the negative direction.

While yaw and tilt controls have appeared viable solutions in response to substantial wake losses that keep wind energy from becoming the front-runner of the power industry, the authors believe wakes can be captured and redirected via external deflectors, such as static vanes. Here, the experimental results were presented for a simple scaled case. The outcome appears to be very promising. While the authors have not done any geometry or layout optimization, the presented vane appeared to boost the overall power production of a pair of two turbines by approximately 15%, which is very significant.

Table 2 summarizes some major points about the reviewed wake control strategies.

## 10. Note

Any intellectual property (IP) in this paper is protected to the satisfaction of the Office of Research at Tennessee Technological University (TN, USA). In June of 2020, Tennessee Technological University filed a provisional application (# 63034218) in the US patent office to protect IP developed here.

## CRediT authorship contribution statement

**Ryan Nash:** Methodology, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Reza Nouri:** Methodology, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Ahmad Vassel-Be-Hagh:** Conceptualization, Software, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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