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Wind farms with counter-rotating wind turbines

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ABSTRACT

The objective of this study is to assess the effects of using counter-rotating wind turbines on the performance of a wind farm. Large eddy simulations, coupled with the actuator line model, were conducted to investigate flow through a test wind farm with 48 large-scale wind turbines with the same layout as Lillgrund in Sweden. Two counter-rotating cases were tested; first, an alternate-row wind farm in which each turbine has one rotor, rotating either clockwise or counter-clockwise, with alternating rows of clockwise and counter-clockwise turbines throughout the farm; and second, a wind farm with dual-rotor wind turbines in which each turbine has two rotors, with the first rotor rotating counter-clockwise and the second rotor rotating clockwise. It was found that both counter-rotating configurations were more efficient in power generation than the control case in which all turbines have one clockwise rotor; the alternate-row case was found to produce 1.4% more power and the dual-rotor case was found to produce 22.6% more power than the control wind farm. The wakes of the counter-rotating cases, particularly the wind farm with dual-rotor wind turbines, exhibit different characteristics from those in the control case. These differences are discussed through wind speed distribution, thrust coefficient, and power production of wind turbines.

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Introduction

Energy supplies are moving away from environmentally damaging, finite, and expensive fossil fuels to renewable energy resources, such as wind [1,2], solar [3], biomass [4,5], geothermal [6], and hydrogen [7], through technological innovations. Wind energy conversion is one of the most promising renewable energy technologies due to the extensive research that has been ongoing over the last decades to optimize aerodynamic performance of wind turbines [8–10], structural design of wind turbines [11,12], control strategies [13–15], site selection [16,17], and the layout of wind farms [18–21]. The focus of the investigations, however, has been mostly limited to single-rotor wind turbines with three blades as the most popular wind energy conversion technology, and there are only a few studies that have taken into consideration wind turbines with double rotors, either co-rotating or counter-rotating [22–33]. These studies are briefly reviewed here.

According to the Betz’s law, the power coefficient of an isolated single-rotor wind turbine cannot exceed \( C_{p,\text{max}} = 0.59 \). This maximum power coefficient \( C_{p,\text{max}} \) was deduced assuming that: the effects of fluid rotation were negligible, the flow was axial, there was no hub, the rotor had an infinite number of blades with no drag force exerted on them, there was no heat transfer, the flow was incompressible, and finally, the thrust force was distributed uniformly over the rotor. Any deviation from these ideal conditions causes a reduction in the power coefficient. Extending from the Betz’s law, and based on similar assumptions, Newman [22] proved that the maximum power coefficient of a dual-rotor wind turbine is \( C_{p,\text{max}} = 0.64 \). Hence, under the above mentioned ideal conditions, a single isolated dual-rotor wind turbine can produce approximately 13% more power in comparison with an isolated single-rotor wind turbine. Jung et al. [23] used the blade element theory to investigate the aerodynamic performance of a single small-scale dual-rotor wind turbine (30 kW). The effect of the wake of the upstream rotor on the downstream rotor was taken into account using the wind tunnel data obtained by Neff and Meroney [34]; the aerodynamic interference between the two rotors, however, was neglected. The best aerodynamic performance was achieved with an upstream rotor half the size of the downstream rotor, located at a distance equal to one-quarter of the diameter of the larger rotor.

Dual-rotor wind turbines have also been studied by researchers at Iowa State University. They conducted wind tunnel experiments under neutral stability conditions to investigate the aeromechanics and wake characteristics of a single isolated dual-rotor wind turbine for both co-rotating and counter-rotating cases [24]. The rotors were the same size and were located at a distance equal
gives the highest power coefficient optimal design for a single isolated dual-rotor wind turbine that Reynolds Averaged Navier–Stokes (RANS) equations to find an 4D, where the diameter of the main rotor. The mean power coefficient was found to be almost independent of the distance between the rotors in the studied range. The amplitude of the fluctuations of the instantaneous power coefficient, however, was found to significantly decrease with the distance between the rotors.

In addition to the aerodynamic performance, several other aspects of dual-rotor wind turbines, such as design, control and electrical concerns, have been taken into consideration. Farahani et al. [29] evaluated the fault-ride-through capability of dual-rotor wind turbines and single-rotor wind turbines under constant pitch angle and constant speed conditions, and realized that dual-rotor wind turbines introduce higher damping torque to the network in both constant speed and constant pitch angle modes. By using dual-rotor wind turbines, both steady state and transient performance of the wind farm would be enhanced. They also evaluated risk of subsynchronous resonance (SSR) for both single-rotor and dual-rotor wind turbines [30]. They introduced a genetic algorithm for optimizing the dual-rotor system design with the objec-

to one-quarter of the rotor diameter from each other. In addition to measuring power output and wind loads, they used particle image velocimetry to quantify the flow characteristics in the near-wake of turbines. Their measurements revealed that the power production performance of the dual-rotor wind turbines and the wind loads acting on them were much higher compared to those of a single-rotor wind turbine. Furthermore, the rotational direction of the rotors was found to have a significant effect on the aeromechanic performance of the dual-rotor wind turbines; the counter-rotating dual-rotor wind turbine was found to harvest more energy than the co-rotating dual-rotor wind turbine. They also studied a unit of two in-line wind turbines where the upstream one had two rotors and the downstream one had one rotor [25]. The secondary rotor of the dual-rotor wind turbine, located immediately upstream of the main rotor, was approximately half the size of the main rotor. The single-rotor wind turbine located downstream of the dual-rotor wind turbine was found to produce more power in comparison with the single-rotor wind turbine located downstream of another single-rotor wind turbine, provided that the distance between downstream and upstream turbines was larger than 4D, where D is the rotor diameter. In a different study, they solved Reynolds Averaged Navier–Stokes (RANS) equations to find an optimal design for a single isolated dual-rotor wind turbine that gives the highest power coefficient Cğ at one operating point [26]. Three optimization parameters were taken into account: the rotor diameter, the distance between the two rotors, and the tip-speed ratio. Two two-dimensional parametric sweeps were carried out. First, the secondary rotor size and tip-speed ratio were varied while the distance between two rotors was constant. An optimal diameter of D/4 was found for the secondary rotor, where D was the diameter of the main rotor. Then, the distance between the rotors and the tip-speed ratio of the secondary rotor were varied while holding the secondary rotor diameter at the optimum value (i.e. D/4). The best performance was obtained for a distance of 2D between the two rotors, where D was the diameter of the main rotor. The optimal tip-speed ratio was found to be 6. This optimal design caused the power coefficient of the wind turbine to increase by approximately 7%. They then conducted large eddy simulations under neutral and stable atmospheric conditions to study the effects of atmospheric stability conditions on the performance of the above mentioned optimal design [27].

Shen et al. [28] used the actuator line model along with the EllipSys3D code to simulate flow over a single isolated dual-rotor wind turbine. The EllipSys3D code, developed at the Technical University of Denmark in cooperation with the Department of Wind Energy at Risø National Laboratory, is a finite volume discretization of the incompressible Reynolds averaged Navier–Stokes (RANS) equations in general curvilinear coordinates. The dual-rotor wind turbine was assumed to have two rotors of the same size with a distance varying from 0.05D to 0.4D, where D is the rotor diameter. The mean power coefficient was found to be almost independent of the distance between the rotors in the studied range. The amplitude of the fluctuations of the instantaneous power coefficient, however, was found to significantly decrease with the distance between the rotors.
tive of reducing the SSR possibility to the same level of single-rotor wind turbines. No et al. [31] presented the blade pitch control scheme and a nonlinear simulation software for the performance prediction of a new design for dual-rotor wind turbines. The proposed dual-rotor wind turbine was treated as a constrained multi-body system and the equations of motion were obtained using the multi-body dynamics approach. Blade element and momentum theory along with a simple flow interaction model were used to calculate the aerodynamic forces and torques. The effectiveness of the proposed pitch control algorithm was examined by implementing it under three different operational modes: maximum aerodynamic torque mode, optimum tip-speed tracking mode, and rpm limitation mode. Inspired by the power transmission of motor vehicles, Kim [32] designed a new planetary-type power transmission for the dual-rotor wind turbines which depends on the torque ratio and not the gear ratio, as in common gear systems. The experimental results showed that the proposed planetary-type gear box caused fewer energy losses, and had a higher efficiency and lower manufacturing costs, making it suitable for commercial wind turbines. Habash et al. [33] engaged a new induction generator (TRIAS generator) in dual-rotor wind turbines that integrates a unique symmetry winding technology with a standard generator. Both standard induction and synchronous machines have one set of stator winding per phase, whereas the proposed generator has two stator windings per phase. The additional winding creates the reactive component that provides the means for maximum energy transfer and efficiency.

Our review on counter-rotating wind turbines indicates that the existing literature is focused on single isolated wind turbines, and there is a dearth of published research exploring the performance of counter-rotating wind turbines in commercial-sized wind farms. The present study aims at filling this gap by examining the performance of contour-rotating wind turbines in a wind farm consisting of 48 wind turbines with rotor diameter and hub height of 93 m and 63 m respectively. To this aim, three large eddy simulations were conducted under neutral atmospheric conditions in the prevailing wind direction (southwest). The wind farm configuration, including base locations of the wind turbines and their rotational direction are presented in the next section, followed by a description of the computational methodology used in the present study. Results of the large eddy simulations will then be presented and discussed in three parts: the first on the aerodynamic loads acting on the wind turbines, the second on the power production performance of the wind farm, and the third on the wake characteristics.

Wind farm configurations

A wind farm with 48 wind turbines with the same layout as Lillgrund in Sweden was chosen as the test case. Wind turbines were assumed to be SWT-2.3-93 model manufactured by Siemens AG with a rated power 2.3 MW, rotor diameter of 93 m, cut-in wind speed $u_{cutin} = 4$ m/s, rated speed $u_{rated} = 15$ m/s, and cut-out wind speed $u_{cutout} = 25$ m/s. Large eddy simulations were conducted to examine three configurations illustrated in Fig. 1 in the prevailing wind direction from the south-west (i.e. 225° from the north using meteorological convention).

The first was the control case, illustrated in Fig. 1a, in which all turbines were assumed to have a single three-blade rotor rotating clockwise. In the second case, illustrated in Fig. 1b, an alternate-row configuration (ALTR) was investigated in which each turbine has one single three-blade rotor, rotating either clockwise or counter-clockwise, with alternating rows of clockwise and counter-clockwise turbines throughout the farm. Turbines in the odd rows, including the front row, were rotating clockwise, while turbines located in the even rows were rotating counter-clockwise. In the third case, illustrated in Fig. 1c, each turbine had two three-blade rotors, with the first rotor rotating clockwise and the second rotor, located immediately upstream of the first one, rotating counter-clockwise. A schematic side view of each dual-rotor wind turbine (DRWT) is depicted in Fig. 1d.

Computational methodology

The model formulation and numerical strategies employed throughout the present study are detailed in this section.

Large eddy simulations (LES)

Large eddy simulations treat the dynamics of large eddies by removing those with scales smaller than a filter width from the unsteady Navier–Stokes equations and parameterizing their effects via subgrid scale models. The filter width is defined as $\Delta = \sqrt{AXYZ}$ where $AX$, $AY$, and $AZ$ are the cell size in $X$, $Y$ and $Z$ directions respectively. The incompressible formulations of the filtered continuity and momentum equations are as follows:

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial \tilde{u}_i \tilde{u}_j}{\partial x_j} = -\frac{\partial \tilde{p}}{\partial x_i} + \frac{1}{\rho_0} \frac{\partial \tilde{p}_0(x,y)}{\partial x_i} + F_{ext},$$

where the bar denotes spatially resolved components; $i$, $j$, and $k$ are the indices of the three spatial components $x$, $y$ and $z$; $u$ is the wind speed; $t$ is time; $p$ is the modified pressure defined as $\tilde{p}(x,y,z,t)/\rho_0 - \tilde{p}_0(x,y)/\rho_0 + \rho_0 g z/\rho_0 + (\tau_{ext})/3$; $p_0$ are the static and mean pressure; $\rho_0$ is the reference air density; $\tau_{ext}^p$ is the traceless part of the wind stress tensor; and $F_{ext}$ stands for the external forces applied to the wind, including those induced by the wind turbines. According to the Boussinesq eddy viscosity assumption, the traceless stress tensor $\tau_{ij}^p$ given in Eq. (2) is defined as:

$$\tau_{ij}^p = -2\nu_v S_{ij},$$

where the kinematic eddy viscosity $\nu_v$ is defined using the subgrid scale model proposed by Smagorinsky [35] as:

$$\nu_v = (c_s A|^S|),$$

in which $c_s = 0.168$ is the Smagorinsky constant, $S = (\partial \tilde{u}_i/\partial x_i + \partial \tilde{u}_i/\partial x_i)/2$ is the filtered strain rate tensor, and $|S| = \sqrt{2S^2}$ is the norm of the filtered strain rate tensor. The external force $F_{ext}$ term in Eq. (2) includes the Coriolis force, the buoyancy force, and the force exerted by turbine blades that is calculated using the actuator line model presented in the next section. Accordingly, the external force $F_{ext}$ can be expressed as:

$$F_{ext} = \frac{1}{\rho_0} F_i + g \left( \frac{\tilde{\theta} - \theta_0}{\tilde{\theta}_0} \right) \delta_{k} - e_{\theta_k} \delta_{\theta_k},$$

where $F_i$ is the force generated by the actuator line model, $e_{\theta_k}$ is the alternating unit tensor, $g$ stands for the gravitational acceleration, $\theta$ is the potential temperature, $\tilde{\theta}_0 = 300$ K is the reference temperature, $\delta_{k}$ is the Kronecker delta, and $f$ is the Coriolis parameter, defined as $f = 2\cos \phi \nu_0$, where $\phi$ is the Earth rotational speed ($\sim 2.95 \times 10^{-5}$ rad/s), and $\nu_0$ is the site latitude. The following potential temperature equation needs to be solved coupled with Eqs. 1 and 2 to obtain the potential temperature needed to calculate the buoyancy term in Eq. 5:

$$\frac{\partial \tilde{\theta}}{\partial t} + \frac{\partial (\tilde{\theta} \tilde{u}_i)}{\partial x_i} = \frac{\partial q_i}{\partial x_i},$$

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where \( q_j \) represents the temperature flux defined as:

\[
q_j = - \frac{v_j}{Pr_t} \frac{\partial T}{\partial x_j}
\]

and \( Pr_t \) is the subgrid turbulent Prandtl number defined as [36]:

\[
Pr_t = \frac{1}{1 + \frac{2}{\lambda}}
\]

in which,

\[
l = \begin{cases} 
\min \left( 7.6 \sqrt{\frac{5}{2}} (s^{-2}), \Delta \right) & \text{if } s > 0 \\
\Delta & \text{if } s \leq 0
\end{cases}
\]

and

\[
s = \frac{g \theta}{h}
\]

Usually \( l = \Delta \), and hence, \( Pr_t = \frac{1}{\lambda} \).

**Wind turbine modelling**

The actuator line model, proposed by Sørensen and Shen [37], was employed along with LES to model the wind turbines. In this model, the turbine blades are represented by three rotating lines that are discretized into blade elements with centers located at \( (x_j, y_j, z_j) \). Using airfoil lookup tables, the aerodynamic forces are calculated for each blade element \( f_{a}^{j}(x_j, y_j, z_j, t) \). Summation of the aerodynamic forces of blade elements corrected via a regularization kernel yields the body force exerted by the blades onto the flow field,

\[
F_i = \sum_{j=1}^{40} f_{a}^{j}(x_j, y_j, z_j, t) \exp \left[ -\frac{(r_j)^2}{\pi l^{1/2} a^3} \right],
\]

where \( f_{a}^{j}(x_j, y_j, z_j, t) \) denotes the aerodynamic forces at 40 equally spaced blade elements with centers located at \( (x_j, y_j, z_j) \). \( F_i \) is the force field projected as a body force onto the CFD grid, \( r_j \) is the...
distance between the cell center and the blade element, and $\varepsilon$ is used to control the Gaussian width so that it spans from the leading edge to the trailing edge of the blade elements. In the present work, $\varepsilon$ was set to be $c/4.3$, where $c$ indicates the chord length of the blade elements, so at both trailing and leading edges (i.e. $r_j = c/2$) the exponential term was reduced to approximately 1% of its maximum [38]. The power calculations are based on the aerodynamic torque that is exerted on the blades. Multiplying the aerodynamic torque by the rotational speed of the rotor yields the power output.

**Numerical solution**

The governing equations described in two previous sections were solved using Simulator for Wind Farm Applications (SOWFA), which is a CFD solver developed by the United States National Renewable Energy Laboratory [39] and is based on the OpenFOAM toolbox [40]. The equations were discretized using a finite volume formulation. A second order central differencing scheme was used to conduct the spatial discretization as large eddy simulations are too sensitive to false numerical diffusion.
and the central differencing scheme significantly reduces the numerical diffusion in comparison with the upwind scheme. The Pressure Implicit with Split Operator (PISO) algorithm was used for the pressure–velocity coupling [41]. Comparing to other pressure–velocity coupling methods, such as SIMPLE [42] and SIMPLEC (SIMPLE-Consistent) [43], the PISO algorithm requires more CPU time per solver iteration; however, it significantly helps to maintain a stable calculation with larger time steps, and hence, decreases the number of iterations.

**Simulation setup**

The computational area was a rectangular cuboid with width, depth and height of 4000 m, 4000 m, and 1000 m respectively. At first, a coarse mesh with approximately 5,900,000 hexahedral cells was created using the blockMesh utility supplied with OpenFOAM. This mesh was then refined locally around the wind turbines leading to approximately 42,000,000 cells. The simulations were conducted in two steps. First, a precursor simulation was

Fig. 3. Standard deviation of the thrust coefficient of single-rotor wind turbines of the Control Case (see Fig. 1a) and the rotors of dual-rotor wind turbines of the DRWTs Case (see Fig. 1c).
carried out to develop the flow field through the computational domain without taking into account the wind turbines for 12,000 s and then a wind plant simulation was performed for 2000 s by adding the wind turbines into the developed flow field. Conducting the wind plant simulation over the above-described computational domain requires approximately 60,000 CPU-hours using a 2.4 GHz processor of a high-performance computing cluster. The present study was conducted using 192 parallel processors.

A horizontally-averaged wind speed of 9 m/s was specified at the height of 90 m in the south-west direction, i.e. 225° clockwise from the north using the meteorological convention. Wind speed at other heights was initialized using the log law under the neutral stability condition. The wind speed boundary conditions were set as slip at the top and bottom boundaries, outlet at the north and east boundaries, and inlet with time-varying mapped fixed values at the west and south boundaries. The buoyant pressure boundary condition was used at all six boundaries of the domain to define the pressure boundary field. The temperature boundary field was set as fixed gradient with a uniform value of 0.003 K m/s at the top boundary, zero gradient at the bottom, east, and north boundaries, and time-varying mapped fixed values at the south and west boundaries. Finally, the surface roughness was set to be 0.016 m.

Results and discussions

Aerodynamic loads

The thrust, or axial force, acting on the rotor of a wind turbine can be expressed as the mass flow rate of the wind flow through the rotor multiplied by the change in velocity in the axial direction. Hence, the reduction in wind speed, or, in other words, the momentum extracted from the wind, is directly related to the thrust coefficient of the rotor. Fig. 2 compares the thrust coefficient \( C_T \) of the rotor of single-rotor wind turbines of the control case with the thrust coefficient of the rotors of dual-rotor wind turbines of the DRWTs case along every column of the wind farm. Thrust coefficients presented in this figure were calculated using the undisturbed freestream velocity of wind upstream of the front row turbine of each column, which was 8.81, 8.4, 8.87, 8.83, 8.76, 8.59, 8.66, and 8.54 m/s for columns 1 to 8 respectively. The thrust coefficients of the upstream and downstream rotors of dual-rotor wind turbines are approximately equal for all turbines in all columns indicating that both rotors extract almost equal amount of momentum from wind. It is also observed that the thrust coefficient of the rotor of single-rotor wind turbines is larger than the thrust coefficient of each rotor of dual-rotor wind turbines for all turbines in all columns. However, the total thrust coefficient of dual-rotor wind turbines, defined as the sum of the thrust coefficients of upstream and downstream rotors, is larger than the thrust coefficient of the rotor of the single-rotor wind turbines. Hence, the rotor of single-rotor wind turbines delivers better aerodynamic performance in comparison with each individual rotor of dual-rotor wind turbines, but the overall performance of dual-rotor wind turbines is better than the overall performance of single-rotor wind turbines. As is seen in Fig. 2, the total thrust coefficient of dual-rotor wind turbines that are located in the front row of each column is slightly beyond 1, whereas according to the Betz’s law, the thrust coefficient of a single-rotor wind turbine can never exceed \( C_{T,max} = 1 \) even under ideal conditions. The variation trend of the thrust coefficient of single-rotor turbines of the alternate-row case (not shown) was similar to that of the control wind farm. The thrust coefficients of both single-rotor and dual-rotor wind turbines suffer a significant drop as wind moves from the front row to the second row of the wind farm. In the control case, the thrust coefficient of single-rotor wind turbines continues to drop as wind moves from the second row to the third row, while in the wind farm with dual-rotor wind turbines the thrust coefficients of the third-row wind turbines are larger than the thrust coefficients of the second-row wind turbines, indicating that wind flow recovers faster downstream of the second-row dual-rotor wind turbines than the second-row single-rotor wind turbines. It should be mentioned that the jump in the thrust coefficient of the forth turbine of column 4 and the third turbine of column 5 is due to the “hole” inside the Lillgrund wind farm, shown in Fig. 1. There is a relatively larger distance between these turbines and their upstream turbines so the velocity deficit in the upstream wake is more eroded and wind gains more momentum before reaching these turbines.

In addition to the aerodynamic performance, comparing the thrust coefficient of single-rotor and dual-rotor wind turbines provides insights into their length of the near-wake region and the level of turbulence that is induced by them. According to Fig. 2, as the dual-rotor wind turbines have higher combined thrust coefficient than single-rotor wind turbines, the length of the near-wake region downstream of the dual-rotor wind turbines is longer than the length of near-wake region downstream of the single-rotor wind turbines, and dual-rotor wind turbines introduce larger levels of turbulence into the flow.

![Fig. 4. Time history of the mean power production of the wind farms.](image)

![Fig. 5. Time-averaged values of the mean power production of the wind farms.](image)

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The thrust force acting on the rotor of a wind turbine is a dynamic load that is directly transmitted to the tower on which the rotor is mounted. Hence, the standard deviation of the thrust coefficient, which is a measure of its dynamic nature, can be used as a parameter to assess the fatigue loads acting on the wind turbine. In the front row of all columns, the standard deviation of the thrust coefficient of each individual rotor of dual-rotor wind turbines is greater than the standard deviation of the thrust coefficient of the rotor of the corresponding single-rotor wind turbine (Fig. 3), meaning that, in the front row of each column, dual-rotor wind turbines are subjected to significantly greater dynamic loads in comparison with single-rotor wind turbines. As wind goes down to the next rows of the wind farm, the standard deviation of the thrust coefficient of single-rotor wind turbines goes beyond the standard deviation of the thrust coefficient of each individual rotor of dual-rotor wind turbines.

### Power production

The time history of the mean power production of the wind farm for the three cases (control, ALTR, and DRWT) is illustrated over 1000 s of flow-time in Fig. 4. The mean power is defined as the sum of the power production of all wind turbines of the wind farm divided by the total number of turbines. The amplitude of the

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**Fig. 6.** Panels (a1) to (h1): comparison between the time-averaged power production of single-rotor and dual-rotor wind turbines in the three cases considered (control, ALTR, and DRWT). Panels (a2) to (h2): gain in power production of each wind turbine in DRWT and ALTR cases with respect to corresponding single-rotor wind turbine in the control case.
fluctuations of the mean power production of the wind farm with
dual-rotor wind turbines is significantly larger than that of the
alternate-row and control cases. Looking at the time-averaged val-
ues of the time history of mean power production of each wind
farm (Fig. 5), it appears that alternating the rotational direction
of wind turbines along a column improves the power production
performance of the wind farm by 1.4%. To put this into perspective,
assuming that the studied wind farm always operates under the
conditions considered here, alternating the rotational direction
of the wind turbines would increase revenue by more than $2 million
over the lifespan of the wind farm. Employing dual-rotor wind
turbines, however, is more effective and can boost the total power
production of the wind farm up to 22.6%, although the costs of
installing twice as many blades and generators would need to be
considered too.

Fig. 6 draws a comparison between the time-averaged power
production of single-rotor and dual-rotor wind turbines along all
columns of the wind farm. Adding a secondary rotor to the wind
turbines brings a considerable increase in the productivity of the
wind turbines. The gain in power production of the wind turbines
varies from 5% to 40% depending on their location inside the wind
farm; the highest gain was observed in the front row, and the
lowest gain was observed in the second row and in rows deep
downstream of the wind farm (seventh and eighth rows). Consid-
ering the higher fatigue loads that dual-rotor wind turbines are
subjected to, one may argue that it is not worth it to employ

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dual-rotor wind turbines in the second row and in deep rows of a wind farm.

As is observed in Fig. 6, in the ALTR case, some of the wind turbines produce more power in comparison with their corresponding turbines in the control wind farm, while there are some other wind turbines that produce less power than their corresponding turbines in the control case. The overall impact of employing alternate rows of clockwise and counter-clockwise turbines, however, is positive and the mean power production of the alternate-row configuration is greater than that of the control case (Fig. 5).

Wake characteristics

No significant trend was observed by comparing the velocity fields through the control wind farm and through the wind farm with alternate rows of clockwise and counter-clockwise turbines (Fig. 7). By employing the alternate-row configuration, some of the turbines were subjected to higher wind speeds and some of them experienced lower wind speeds; the overall effect, however, was positive as the mean power production of the wind farm was enhanced by approximately 1.4%. The wakes in the ALTR case were not significantly different from those in the control case (Fig. 7b vs. Fig. 7a). The wind speed distribution through the wind farm with dual-rotor wind turbines, however, was found to be considerably different than the control case. As is seen in Fig. 7c, the velocity deficit downstream of dual-rotor wind turbines is larger than the velocity deficit downstream of the single-rotor wind turbines. It is also observed that length and width of the wake of dual-rotor wind turbines are significantly greater than those of single-rotor wind turbines. To provide further clarification, the difference between the mean velocity magnitude through the wind farm with dual-rotor wind turbines and the control wind farm, i.e. panels (c) and (a) of Fig. 7, is illustrated in Fig. 8. Although wind speed in the wind farm with dual-rotor wind turbines and the wind farm with

![Image](image-url)
single-rotor wind turbines are approximately equal over most of the area (white in Fig. 8), the velocity deficit downstream of the dual-rotor wind turbines is up to 3.5 m/s larger in comparison to the velocity deficit downstream of the single-rotor wind turbines. It is also observed that turbines located in the second row of the wind farm with dual-rotor wind turbines are subjected to a significantly weaker wind comparing to the second-row wind turbines of the control wind farm. This explains the trend observed in panels (a2) to (h2) of Fig. 6. Similarly, turbines located in the seventh and eighth rows of columns 2 and 3 of the wind farm with dual-rotor wind turbines experience lower wind speeds than their corresponding wind turbines in the control wind farm, while dual-rotor wind turbines located in the third, fourth, fifth and sixth rows of the wind farm are subjected to approximately similar wind speeds as their corresponding wind turbines in the control wind farm. This wind speed distribution supports the trend observed in the thrust coefficient and power production of the wind farm with dual-rotor wind turbines and suggests that adding a secondary rotor to the front-row and middle-row turbines is more effective than adding it to second-row and deep-row wind turbines, provided that the spacing between the rows of the wind farm is uniform. The effectiveness of adding the secondary rotor to the second-row and deep-row wind turbines can be enhanced by increasing the spacing between these rows and their upstream rows.

Conclusions

The effect of employing counter-rotating wind turbines on power production of a wind farm was investigated using large eddy simulations. Three configurations of a wind farm with 48 large-scale wind turbines with a layout similar to Lillgrund offshore wind farm in Sweden were studied: (I) all wind turbines were assumed to have one clockwise rotor, (II) an alternate-row configuration in which each turbine has one rotor, rotating either clockwise or counter-clockwise, with alternating rows of clockwise and counter-clockwise turbines throughout the farm, and (III) all turbines were assumed to have two rotors with the first rotor rotating clockwise and the second rotor rotating counter-clockwise. This study suggests that the rotational direction of the rotor (clockwise vs. counter-clockwise) could be an additional optimization parameter in wind farm layout studies.

Some notable observations from the studied conditions are summarized as follows:

1. The dual-rotor and the alternate-row configurations were found to produce approximately 22.6 % and 1.4% more power than the control case.
2. The amplitude of the fluctuations of the mean power production in the wind farm with dual-rotor wind turbines was approximately twice that of the control and the alternate-row configurations.
3. The performance of each single-rotor wind turbine of the control wind farm was better than the performance of each individual rotor of its corresponding wind turbine in the wind farm with dual-rotor wind turbines. The total performance of each dual-rotor wind turbine, however, was significantly greater than the performance of its corresponding single-rotor wind turbine in the control wind farm (5% to 40% more power production).
4. Adding a secondary rotor causes the fatigue loading acting on the tower to increase.
5. Adding the secondary rotor to the wind turbines was most effective in the front and middle rows of the wind farm. The performance of turbines in the second row and deep rows (i.e. seventh and eighth rows) of the wind farm was negatively affected by the stronger upstream wakes. Hence, it is recommended to increase the distance between these rows and their upstream rows to reduce the effect of strong wakes that are generated by the front-row and middle-row wind turbines.

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References


