A Numerical Study on the Effect of Wind Turbine Wake Meandering on the Power Production of Hywind Tampen

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Abstract. The purpose of the study is to show the importance of wake meandering effect with regard to power production, in terms of annual energy production (AEP), and velocity deficit for wind turbines affected by wake meandering. A simplified economical and environmental analysis is also presented. A replica of Equinor’s layout for Hywind Tampen wind farm, referred to as the original layout, is made and used as a basis for comparison. An alternative configuration is produced through a pragmatical optimization process, applying the SIMA-DIWA software, which reduces the effect of wake meandering on the downstream wind turbines, when the wind approaches from the most frequent direction. To show the aerodynamic effects of applying greater spacing between turbines, an enhanced version of Hywind Tampen is also presented. The main findings of the project correlate greater wake effect meandering for wind turbine configurations spread over a smaller area. The estimated annual energy production for the three configurations is 488.5 GWh for the original, 497.6 GWh for the up-scaled and 486.2 GWh for the alternative configuration, respectively. Furthermore, the optimization process revealed that a reduction in turbine distance can contribute to reduced wake effect in particular cases.

1. Introduction
To ensure feasibility of floating wind farms projects, it is important to understand the wake behavior behind wind turbines to a full extent. Downstream turbines located in a wake-affected area, will experience a drop in power production due to lower average inflow velocity, and adverse aeroelastic loading resulting in fatigue loads, due to high turbulence in the wake (1). An important phenomena that has been observed is wake meandering. Wake meandering is described as large-scale oscillations of the wake, in the lateral and vertical direction. Two hypotheses for wake meandering have been proposed. The first states that large-scale eddies in the atmospheric boundary layer (ABL) affect the wake into a meandering motion, and is proposed by Keck et al. (1). The second hypothesis proposes that wake meandering originates from the unstable nature of the wake, described by periodic vortex shedding downwind of the turbine, as described by Eliassen et al. (2).
Previous studies indicate that wake effects decrease the AEP for a typical modern wind farm by 5-20\%, and increases the fatigue loads by 20-80\%, dependent on the considered component (1). The latter can be explained since the damage due to fatigue loads is defined as the number of stress cycles divided by the number of cycles to failure (3), hence enhanced by the wake as it sweeps in and out of the rotor plane of downstream turbines, and will vary at different sections of the rotor (4). In addition, floating offshore wind turbines (FOWTs) may experience stability complications originating from the meandering effect. Onshore facilities are often located in areas that are topographically advantageous in regards to wake effects. All wake effects including meandering will therefore be more prominent in offshore installations.

Previous wake models disregard the presence of meandering in the wake (2). This implies that initial aerodynamic simulations performed on Hywind Tampen wind farm are lacking the important aspect of wake meandering, and its effect on all turbines from a 360° perspective. The effect of meandering on AEP, wake velocities, levelized cost of energy (LCOE) and CO\textsubscript{2} emissions is presented in the present paper. To conduct this, three different layouts of Hywind Tampen wind farm are considered; a replica of Equinor’s layout, referred as original; an alternative layout aerodynamically optimized, but keeping the original area dimension; and an enhanced area with the original configuration. All the optimizations and analyses presented here include wake meandering, and the effect of wake meandering can be interpreted through the performance of each layout.

2. Methodology

The 1-year wind data measured at Tampen, represented by the wind rose in Figure 1, are used as input for the analysis. West is indicated as 0°, and increasing angles anti-clockwise (south is 90°), and the wind speed distribution is divided in sectors of 30°. All simulations were done with constant ambient wind speed and turbulence intensity (TI), set to 10 m/s and 10\% respectively. A wind speed of 10 m/s is a good approximation to the average wind speed measured at Tampen. The information on the distribution of the wind direction given by the wind rose, illustrated in Figure 1, was used for the calculation of AEP, LCOE and CO\textsubscript{2} emissions. Average power retrieved from simulations is compiled with an estimated duration for each wind direction, to calculate AEP, as shown in equation 1. The calculation is repeated for each configuration. A capacity factor of 66\% is later applied, to achieve a more realistic value of AEP.

\[
AEP = 0.66 \cdot \sum_{i=1}^{N} P_{tot}(\text{winddirection}) \cdot \text{hours}(\text{winddirection})
\]

An example of how AEP is calculated for a specific wind direction can be shown from the 90° interval, where the wind distribution is measured at 14.5\% (1270 hours). The resulting simulated power for the original layout at wind speed 10 m/s is 89.89 MW, hence the fraction of AEP is 102.7 GWh.
LCOE was calculated by dividing the sum of costs over lifetime, based on simple estimations, with the sum of electricity produced over lifetime. The following simplified equation 2 can be used to describe LCOE

\[
LCOE = \frac{\sum_{t=1}^{n} \left( \frac{M_t}{(1+r_d)^t} \right) + I_c}{\sum_{t=1}^{n} \left( \frac{E_t}{(1+r_d)^t} \right)}
\]

where \( I_c \) is the initial investment cost, \( M_t \) is annual operational and maintenance (O&M) cost, \( E_t \) is AEP and \( r_d \) is the discount rate. Annual O&M cost for modern wind turbines can be estimated at around 1.5% of the original investment cost (5). With the Hywind Tampen project Equinor estimates a reduction in CO\(_2\) of 200 000 ton/year (6). The annual CO\(_2\) reduction is calculated with the ratio between estimated AEP for the three different layout and the Hywind Tampen, by assuming a linear relation between AEP and reduction in CO\(_2\) emission.

Three diverse layouts are conducted and tested with the SIMA-DIWA software, represented in Figures 2, 3 and 4, which also show the numbering given to the wind turbines and orientation. Since the characteristics of the 8 MW wind turbines of Hywind Tampen wind farm are
confidential, the the 10-MW reference wind turbine developed by DTU is used to re-construct the park layouts for the simulations. The original layout of Hywind Tampen includes 11 wind turbines covering a total area of 11 km². The three configurations have been reproduced as follow. For the original layout the number of turbines is 11, same as for Equinor’s park, with similar spacing. The rotor diameter of the reference turbine is only about 3% bigger than the ones used in the park (7), so the difference can be considered negligible. The alternative layout is the result of an iterated process of optimization of AEP and LCOE, based on the wind data measurements at Tampen. For the enhanced layout the wind turbines are distributed over an up-scaled area of 15 km², while keeping the same configuration as the original, resulting in an increment of distance between the turbines of about 36%.

The intention behind the alternative layout configuration was to apply theory and broadening the understanding of wake evolution in a park set-up. Based on the wind rose, wind distribution was taken into account and weighted respectively after the most frequent wind directions. This ensures the setting of an attentive preliminary configuration. The process involved changing coordinates within the opted area of 11 km², then simulating for every direction to identify weaknesses and trying to adjust the location for responsible turbines, simultaneously without affecting the overall performance.

Each simulation with SIMA-DIWA produces power, thrust and velocity plots for every turbine in the park. The calculations are based on the Dynamic Wake Meandering (DWM) model. A simplified sketch in Figure 5 indicates how the model superimposes the meandering behaviour to the steady wake in a time averaged series.
There are several steps implemented in the current DWM model, although the DWM can be represented by three monitor components, as shown in Figure 6. The first submodel calculates the wake velocity deficit, and is based on the N-S equation with TSL approximation. The second estimate stochastic meandering due to large-scale atmospheric turbulent fluctuations of the wake center. The third submodel computes small-scale mechanically generated turbulence and wake shear. Additionally, DWM is implemented with Blade Element Momentum (BEM), which calculates local forces on the blade, including tip and hub losses. (8; 9; 10)

Figure 6. Schematic representation of the three major submodels implemented in the DWM model.

2.1. Software limitations
The simulations with SIMA-DIWA implicates some assumptions. The inflow field is considered uniform, hence neglecting vertical wind shear, which will accumulate deviations in turbulence level compared to actual values. The wind turbines structure is considered stiff so that the aeroelastic loading cannot be calculated. The software calculates meandering in the lateral and vertical direction, which are mainly governed by large-scale ambient fluctuations, while the effect in the longitudinal direction is not considered. All simulations presented were run at neutral stability. Yaw control is not implemented in the current version of the software, hence the wind turbines’ rotor plane is always perpendicular to the wind direction. The above-mentioned simplified inflow conditions allow to isolate on the effect of wake meandering. It is foreseen a development of the SIMA-DIWA software which will allow to include more variables in the inflow conditions.

3. Results
The result section is divided into two parts. The first section compares AEP, LCOE and CO\textsubscript{2} reduction for the three different layouts. The second section considers the worst-case scenarios, in terms of effect of meandering on the downstream turbines, for both the original and alternative layouts. The velocity deficits on downstream turbines are shown and the effect on both power production and fatigue loads is considered.

3.1. Annual Energy Production, LCOE and CO\textsubscript{2} analysis
Table 1 compares AEP for the three different configurations, and Figure 7 illustrates how AEP varies for different wind directions.
Table 1. AEP for the different layouts.

| AEP Original | AEP Alternative | AEP Enhanced |
|--------------|----------------|--------------|
| 488.5 GWh    | 486.2 GWh      | 497.6 GWh    |

Figure 7. AEP for different wind directions.

The results from Table 1 show that alternative configuration produces about 0.5% less than the original layout. Considering a lifetime of 20 years, this would accumulate to approximately 46 GWh less for the entire production period. Despite that it could be noticed from Figure 7 that, for the main wind direction of 90°, the alternative layout produces about 8% more than the original. That confirms the achievement in optimizing the alternative configuration for the most likely wind direction. Whether the reduction of wake effects for the alternative layout weighs up for the 0.5% cut in AEP, should be analyzed further with consideration of material fatigue, maintenance costs etc. Table 1 shows that the enhanced configuration produces 2% more than the original. Over 20 years, this would result in 182 GWh more. It is a good representation of how decreasing the wake effect by enhancing the area, contributes to better overall production. Changing the wind direction sections amplitude might affect the calculated AEP.

An economic evaluation is done for different configurations. Table 2 illustrates a simplified LCOE and the annual reduction in CO₂ emission for the three different layouts. An increase in AEP will directly influence the LCOE and reduction in CO₂ emission. Calculations on LCOE vary solely with AEP, as all other costs were presumed constant independent on park configuration. Accordingly, the enhanced configuration gives the lowest cost per energy unit at 1.034 NOK/kWh when production time is set to 20 years. Oppose to 1.053 and 1.058 NOK/kWh for the original and alternative layout respectively. Evaluating LCOE gives a good indication of investment profitability, however, it is usually applied to compare different concepts (e.g solar versus wind). The similarity in LCOE derives from constant rated power and costs for all solu-
Table 2. Economic and environmental results for different layouts.

| Layout     | LCOE [NOK/kWh] | Annual CO₂ reduction [ton/year] |
|------------|----------------|-------------------------------|
| Original   | 1.053          | 254 400                       |
| Alternative| 1.058          | 253 200                       |
| Enhanced   | 1.034          | 259 100                       |

tions. In reality, it is expected further variable costs due to fatigue on components, which are not considered in this analysis.

Despite the fact that overall AEP is better for the original layout, does not mean it is superior in every way possible. Seen from an aeroelastic perspective, it can be considered beneficial to reduce the AEP - for some directions - in favor of less influence of wake effect meandering and turbulent inflow conditions. However, overall power production is strongly correlated with wake influence together with ambient conditions, as they are the only phenomena contributing to lower power outputs. For that reason, it could be expedient to construct wind farms that are less influenced by wakes for the most frequent part of wind distributions. As most of these sectors often hold higher velocities, which in theory aggravates fatigue loads. Although, it will result in a lower total AEP. This will again be a matter of compromise, whether it will be economically advantageous to slightly lower the AEP and consequently minimize the maintenance cost, versus the opposite scenario.

3.2. Wake Meandering Effect for Worst-Case Scenarios

Worst-case scenarios simulations are shown for the original and alternative configurations. The effect of wake meandering is analysed by considering the velocity standard deviation of the inflow condition for the wind turbines. For the original layout, the worst-case occurs at near-southern wind-direction at approximately 100°, where average wind speed at each turbine is 8.27 m/s. A graphical representation of the flow field and a velocity plot for all turbines are shown in Figures 8 and 9.

![Figure 8.](image1.png)  
**Figure 8.** Worst-case for the original layout. Wind from 100°

![Figure 9.](image2.png)  
**Figure 9.** Worst-case for the original layout represented by velocity deficit on downstream turbines. Each turbine is represented through a specific color.
The alternative layout endures a worst-case scenario at western wind-direction at approximately 0°, where average wind speed at each turbine is 9.47 m/s. A graphical representation of the flow field and velocity plots for all turbines are represented in Figures 10 and 11. Large-scale fluctuations in velocity are directly related to wake effect meandering.

Figure 10. Worst-case for the alternative layout. Wind from 0°

Figure 11. Worst-case for the alternative layout represented by velocity deficit on downstream turbines.

The effect of wake meandering is visible in Figures 9 and 11 for the original and alternative layout respectively. It is conspicuous that the original layout endures larger wake effects when studying velocity plots. As mentioned, the mean velocity is considerably lower, but meandering also contributes to bigger amplitudes in fluctuations. The maximum average deviation in wind for the alternative layout is 0.7813 m/s as oppose to 1.093 m/s for the original configuration.

Overlapping of multiple wakes will create turbulent inflow conditions for downstream turbines. Its effect on average wind velocity at each turbine with subsequent fluctuations is apparent in Figures 9 and 11. The original layout encounters a worst-case when inflow wind approaches from 100° and the mirrored equivalent from 280°. Only two turbines are located in the free-stream, and the average inflow velocity for the entire park is affected accordingly. The alternative layout is designed to withstand potential worst-case scenarios in a different way. The alignment of more than three turbines is eliminated for any wind direction in this layout, leading to a reduction in the amount of overlapping wakes. Even though estimated AEP is slightly lower for the alternative configuration, potential worst-case scenarios should be considered in the overall evaluation of wind farms. Regular occurrences of incoming wind from 100° (and 280°) will have a severe impact on power production and fatigue loads for the original configuration. According to the wind rose in Figure 1, 100° is one of the most frequent inflow angles, making it an unfavorable worst-case.

The meandering effect has utmost prominence in worst-case scenarios. Reduced wind speed and increasing turbulence affect overall production for the park. Average power derives from average inflow velocity and hinge primarily on deficit propagation of upstream wakes and ambient conditions. Wake meandering leads to deviations from mean production with maxima and minima, and is undesirable for a power-producing unit. The dynamic wake movement will especially aggravate fatigue loads. Downstream turbines will experience increased turbulence due to the influence of partial wakes on different components.
4. Conclusions and Further Work

AEP was accentuated as the most important parameter in this analysis with a direct influence on LCOE and a reduction in CO₂ emission. The enhanced layout gave the best estimation of AEP at 497.6 GWh, 2% more than the original. Boost in AEP directly correlated to an expansion in area and propagated to 182 GWh throughout the expected lifetime. However, expanding the farm size may increase costs. The alternative configuration, optimized based on wind direction, gives a slightly smaller total AEP but the best AEP for the most likely wind direction from the south.

Wakes meander and expand in the axial direction, consequently occupying larger areas downstream. As a result, the layout optimization process revealed that a reduction in turbine spacing can increase total power production for the most frequent wind speed direction, which is the south. This became evident by analyzing the southern inflow scenario for the alternative layout.

It was discovered in worst-case simulations that the alignment of more wind turbines aggravated power losses. The original layout experienced a significant loss in average velocity at downstream turbines, along with amplified fluctuations. Similarly, the alternative layout endured diverse wake effects, although with a more satisfying outcome due to fewer aligned turbines. Wake meandering was most prominent at downstream turbines located close to the worst-case area, which consequently relates to magnified fatigue loads and decreasing power production.

There are limitations related to the process of analyzing the three diverse cases. The choice of the size of the sections representing the wind directions might affect the calculation for AEP. The assumption of constant wind speed and TI leads to deviations from realistic atmospheric conditions. The assumption of stiff structures and no wind turbine control might affect the results. Future applications of SIMA-DIWA as an optimization tool should compile with an advanced algorithm including wind turbine control, costs related to O&M, cabling, transport, commissioning, etc.

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