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Prediction of wind farm energy yield using NWP considering within-cell wake losses

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Summary
Numerical Weather Prediction (NWP) models such as Weather Research and Forecasting (WRF) are widely used for prediction of wind resource at potential wind farm sites and, increasingly, for energy yield prediction. Such models solve a reduced form of the Navier-Stokes equations with typical resolution of 20-1000 m in the vertical axis and 1-2 km in the horizontal axes. Sub-grid models have previously been developed to represent wind farms including by modification of momentum sink and turbulence kinetic energy source terms within cells occupied by turbines. Here, semi-empirical wake models are employed to assess the extent of losses between turbines within a small group such as within a single WRF. Variation of thrust and power with wind speed and direction were obtained using the modified PARK and Eddy Viscosity methods in OpenWind. The influence of wake-losses on yield was evaluated through WRF simulations of resource only and with standard and modified turbine parameterizations. Annual energy yield of the Horns Rev wind farm was considered for reference with predictions obtained for annual data and a short duration subset of wind data with comparable occurrence. Predictions with an Eddy Viscosity model and ERA-Interim data for 2007 were approximately 13% higher than from WRF simulations and than measured yield, approximately 18%. Consideration of within cell losses reduced WRF predictions by approximately 2.5%. The subset of wind data used for WRF simulations was in close agreement with annual occurrence data but further assessment is required of yield over longer samples and directional dependence of losses.

1. Introduction
The accumulation of greenhouse gasses in the atmosphere due to the excessive use of fossil fuels has led many countries to introduce specific targets aimed at minimising the rate of emissions of gases that contribute to climate change. In this context, there is an onus on the power sector to transition from a carbon intensive portfolio to a broader portfolio of electricity generating technologies that would satisfy demand whilst also reducing carbon emissions. One of the most promising solutions is the rapidly evolving technology of wind turbines. The rated power of wind turbines has increased by almost a factor of eight over the past decade, reaching nominal values up to 8 MW. Wind farms are expanding throughout the world, both onshore and offshore, exceeding a total installed capacity of 300 GW worldwide by the end of 2013 [1]. To inform investment decisions and enable integration of the supply from large wind farms with the wider power network, accurate prediction of energy yield is required. This is a function of the operating conditions, turbine design and, of increasing importance as the scale of wind farms increases, on the interactions amongst turbines within an array.

Energy yield may be predicted to a degree of confidence via statistical and semi-empirical methods and this approach has been widely used historically. Currently there is increasing interest in implementing wind farm models within atmospheric flow models providing both energy yield prediction and improved understanding of the influence of large-scale energy extraction on the natural environment. The Weather Research and Forecasting (WRF) model [2], which is a Numerical Weather Prediction (NWP) model, is widely used for wind energy research as it provides the ability to conduct simulations with real data and to take into account a great range of variables, such as the complexity of the terrain and the meteorological dataset for initial and boundary conditions.

Various approaches are available for representing wind turbines within the WRF model. Singer et al. [3] developed an actuator disk model to represent wind turbines. This
was tested within the WRF model and demonstrated qualitative agreement with both Large Eddy Simulations and analysis of an operational wind farm. Blahak et al. [4] also developed a simple parameterization characterizing the drag forces induced by wind turbines within WRF. Their model involved reduction of the kinetic energy of the flow at cells containing wind turbines as well as proportional increase of turbulent kinetic energy over a vertical column of cells, which was divided into a set of horizontal sub-layers. Fitch et al. [5] further developed a turbine representation including a momentum sink and a source of Turbulent Kinetic Energy (TKE) based on the turbine performance characteristics. One of the major improvements of the model is the representation of TKE, which is designed to vary with the wind speed, based on the ratio of power to thrust. Furthermore, a grid cell may encompass more than one turbine and a turbine density factor $N_i^j$ is defined such that thrust per cell is by linear summation. As noted by [4], this formulation accounts for the interference between adjacent cells, but not the interference of the turbines contained within the same cell. In this study the influence of turbine number and configuration within a cell is studied to determine the variation of power and thrust for a cell from a linear summation and to evaluate the influence of such within-cell losses on yield.

The paper presents the methodology employed in Section 2, an assessment of the aggregate power and thrust of a group of turbines employing an Eddy Viscosity wake model in Section 3 and an evaluation of the sensitivity of yield prediction to the source of resource data and of farm power and thrust curve in Section 4.

2. Methodology

The study has the following aims.

1. To determine the accuracy of energy yield predictions using standard semi-empirical wake models and data from NWP models at a range of spatial resolutions.
2. To assess the variation of momentum extraction and power output with arrangement of a sub-set of turbines within a farm representing a group of turbines within a cell.
3. To represent sub-groups of turbines, with and without wake losses, in WRF and to assess energy yield for a typical range of operating conditions, to assess sensitivity of yield to within-cell losses.

These aims are addressed by analysis of the variation of power and thrust due to simplified wake models for a range of turbine configurations using Openwind [6] and by evaluation of yield for a case study location using WRF. The existing Horns Rev offshore wind farm is employed as a basis for the case study of energy yield. Existing semi-empirical wake models provide the sensitivity of the power and thrust curves of groups of turbines with the inter-turbine distance and the number of turbines in a group. Aggregated power and thrust curves are employed to represent a group of turbines within a single WRF cell via the available scheme of Fitch et al. [5].

2.1 Horns Rev Background

The Horns Rev offshore wind farm is located outside Denmark in the East North Sea. It consists of 80 Vestas V80-2.0 MW with a rotor diameter of 80 m and a hub height of 70 m. The centre of the wind farm can be found at 55.486° N (Latitude) and 7.840° E (Longitude). The 80 turbines are arranged in an 8×10 rectangle (Figure 1). Turbines are aligned along bearings of 090 and 355 and inter-turbine spacing is approximately 7D in these directions. The diagonal spacing is in the 9.3 – 10.4D. This offshore wind farm has been the subject of numerous scientific studies as according to Barthelmie et al. [7], “the offshore wind farm at Horns Rev is characterized by low turbulence (<8%) and many hours in near-neutral stability”, thus making it ideal for studying.

2.2 Energy Yield

The energy yield from a group of turbines over a specific time interval was calculated by combining wind data with an aggregated power curve derived using semi-empirical wake models via Eq. 2.1.

$$E = \sum_{i=1}^{N_i} P_h(u_i, \theta_i) = \sum_{i=1}^{N_i} \sum_{j=1}^{N_i} H(u_i, \theta_i) \cdot P_i(u_i, \theta_i)$$  (2.1)

Where:

- $P_h$ is the power output of the group during time increment $h < N_i$, as derived via either Modified PARK or Eddy Viscosity wake models.
- $H(u_i, \theta_i)$ is the total number of hours that a wind speed in the range $u_i \pm du/2$ m/s and direction in the range $\theta_i \pm d\theta/2$ occurs. Direction is measured clockwise from
North. Herein $du = 1 \text{ m/s}$ and $d\theta = 5^\circ$ were employed with $N_u = 25/du$ and $N_\theta = 360/d\theta$.

The wind speed time-history describes the wind resource at the centre of the group. The method used to obtain the aggregated power curve for a group of turbines and the source of resource data for these yield calculations is described in Sections 2.3 and 2.4 respectively.

2.3 Power Curve for Farm and Subgroup

OpenWind [6] was used to calculate the power and thrust variation of a group of turbines. Both the Modified PARK and Eddy Viscosity models were employed to represent the flow behind each rotor. The first utilizes the momentum theory and assumes a linear expansion of the wake radius downstream whereas the second one is based on a thin shear layer model, observing the conservation of mass and momentum in the wake. The aggregated, wake affected, power output of a turbine group was calculated by summation of the power output of the individual turbines for each wind speed and direction, in accordance to the following equation.

$$P_k(u_i, \theta_j) = \sum_{m=1}^{M} P_m(u_i, \theta_j)$$

(2.2)

Where $P_k(u_i, \theta_j)$ is the wake affected power output of the $k^{th}$ wind turbine for a wind speed of $u_i \text{ m/s}$ and direction of $\theta_j^\circ$, given in the centre of the farm. This approach was also used for thrust. This method was employed for the entire Horns Rev farm configuration (for which $M = 80$) and to characterise subgroups of turbines as described in Section 3.

The resultant aggregated power curves for the Horns Rev farm are given in Figure 2 with the percentage reduction relative to the idealised case of negligible wake losses shown in Figure 3. The losses are considerable for wind speeds between 4 m/s and 13 m/s, being proportionally maximum at 4 m/s. The wakes have a significant impact for the wind directions where adjacent turbines are in line with the wind flow ($90^\circ, 175^\circ, 270^\circ, 355^\circ$). The maximum power deficit, which occurs at 11 m/s for easterly ($90^\circ$) and westerly ($270^\circ$) winds, is 50 MW (2.5% rated) by the Modified PARK wake model and 40 MW (2 % rated) by the Eddy Viscosity Wake model.

2.4 Resource Data and Yield

The wind resource data input to Equation 2.1 was obtained either direct from the ERA-Interim dataset or from WRF with input defined by the GFS dataset. Energy yield was calculated for a full year to reference to data available for the year 2007 [8]. Subsequently sensitivity of yield to the turbine representation in WRF was evaluated using a subset of wind resource data as described in Section 2.4.2.

![Figure 2. Horns Rev power output in MW, derived using (a) Modified PARK and (b) Eddy Viscosity. Wind direction is given in degrees, clockwise from North.](image-url)
2.4.1 Annual resource and yield

Annual data for 2007 was obtained from the ERA-Interim dataset. Both components ($U_x$, $U_y$) of wind speed at a 0.75 by 0.75 degrees resolution from ERA-interim datasets were extrapolated to a hub height, based on the DNV-OS-J101 Standard [9]. Wind speed and direction at the farm centre was obtained by bi-linear interpolation. Table 1 summarises the yield predicted via Equation 2.2 with wind speed at the farm centre from the ERA-Interim dataset and the aggregated power curves of 80 turbines in the Horns Rev configuration as illustrated in Figure 2 for both the Modified PARK and Eddy Viscosity methods.

Table 1. Horns Rev energy yield for 2007 calculated via Eq 2.2 with wind speed data from ERA-Interim dataset.

<table>
<thead>
<tr>
<th>Horns Rev energy yield (GWh) for 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>LORC [8]</td>
</tr>
<tr>
<td>Modified PARK</td>
</tr>
<tr>
<td>Eddy-Viscosity</td>
</tr>
</tbody>
</table>

Yield is overpredicted by between 15 to 18% compared to a published value for this year.

2.4.2 Resource representing 2007

A subset of time-varying wind data was selected on the basis of similarity to the Weibull distribution that describes the 2007 wind speed probability density function. This approach reduced the computational cost of the WRF simulation requirements whilst allowing sensitivity of yield to numerical method to be compared and referenced to the annual data. A wind speed histogram and corresponding Weibull shape and scale parameters were obtained for each single-week and 2-week interval of the years 2007-2013 obtained from hub height and farm-centered values of wind speed from the ERA-Interim dataset. An example of the variation of single-week average wind speed is shown in Figure 4.

Figure 4. Weekly averaged annual wind speed time series for 2007 at the centre of the Horns Rev site (ERA-Interim dataset).

Non-overlapping intervals were combined to minimise the root mean square error (RMSE) between both the histogram of wind speeds during 2007 and the histogram of wind speeds from the subset and between the Weibull parameters. The subset considered herein is the aggregate of three intervals of net duration five weeks (Figure 5) for which the RMS errors for histogram and Weibull parameters were 1.03% and 0.12% respectively.

Data from the Global Forecast System (GFS) was acquired for the intervals selected and applied as boundary and initial conditions for the WRF simulations (Section 4). These input data were compared statistically against the data extracted from the ERA-Interim dataset at the same height.
Figure 5. Comparison of Weibull PDF and Histogram for aggregated period.

Figure 6 presents both histograms and Weibull PDF’s, where it can be noted that the datasets have the same trend for the period analysed. To compare both dataset, the RMS error between the histogram and Weibull distribution of each dataset was calculated, obtaining respective values of 1.79% and 1.67%.

Figure 6. Comparison of Weibull PDF and Histogram for aggregated period from both ERA and GFS datasets.

2.5 WRF Mesh and Parameterization

Three types of WRF simulations were conducted using the input data defined in the previous section for:

A) resource only, neglecting wind turbines
B) wind turbines represented using the scheme of Fitch et al. [5], and
C) with modification of the wind turbine thrust and power curve to represent within cell losses (see Section 3).

The following WRF parameterizations were employed: single moment 3-class simple ice scheme to describe the microphysics; the longwave and shortwave radiation were represented with the Rapid Radiative Transfer Model and the Dudhia schemes, respectively. Cumulus physics were described using the Kain-Fritsch (new Eta) scheme applied only on the three coarser domains. To represent the phenomena at the land surface, the Rapid Update Cycle land surface model was selected; while for the surface layer, the Revised MM5 Monin-Obukhov [10] was chosen. Finally, to model the planetary boundary layer, a TKE closure scheme which is consistent with the wind turbine parameterization scheme [5] was selected, being this the Mellor Yamada Nakanishi and Niino (MYNN) level 2.5 PBL model [11].

Figure 7. Extent of four nested domains employed for WRF analysis.

All simulations were conducted with two-way coupling over four nested domains with resolutions of 30,240 m, 10,080 m, 3,360 m and 1,120 m with a computational size of 78 by 78 at each resolution (Figure 7). The topographic data was obtained from the ASTER Global Digital Elevation Map [12] at resolutions of 10, 5 2-arc-minute and 30-arc-second resolutions for domain from 4 to 1, respectively. 45 vertical levels were used including twelve vertical levels in the first 200 m. The centre of all domains was defined as the centre of the wind farm. For all the simulations a spin up period of 12 hours and hourly output interval were used.

Turbines were represented using the Fitch et al. [5] scheme, which applies a momentum sink as a function of thrust coefficient, and a TKE source as a function of the power and thrust coefficient. Since these are defined in terms of the turbine performance coefficients they vary with wind speed. It has been shown that this approach provides results congruent to real wind farm wakes [13].

A simplified symmetric 8×10 rectangular layout was considered (Figure 8) for this part of the study. This small amendment to the arrangement facilitated implementation within WRF. The farm was divided into smaller subgroups, each containing the same number of turbines, and the same
arrangement mapped to the WRF grid cells. The resolution of the inner domain was defined as 1,120 m such that each cell of the farm contained four turbines. The variation of both thrust and power coefficient for each subgroup of 4 turbines was examined using OpenWind [6] as described in the next section.

![Figure 8. Example arrangement of 80 wind turbines within domain of 1,120 m resolution. Markers indicate cell centres (solid) and wind turbine locations (open).](image)

3. Thrust Variation for Subgroup (Cell)

In this section, the sensitivity of the power and thrust curve to the inter-turbine distance and the number of turbines contained within a cell were investigated. The Eddy Viscosity model available in OpenWind [6] was employed. For all cases, a rectilinear arrangement of turbines was considered with equal spacing parallel to the x- and y- axes of the cell occupied. For a 2 x 2 arrangement, power is reduced by up to 50% and by more than 5% for wind speeds in the range 3 – 13.5 m/s (Figure 9a) at headings close to multiples of 90±10° and for a slightly reduced range of speeds and of headings close to multiples of 45°. As would be expected the range of wind speeds and headings over which power is reduced decreases as the inter-turbine spacing is increased (Figure 9a, spacings of 5D to 9D) due to the greater distance available for wake recovery. The same principles apply to the thrust curve (Figure 9b) for which reductions of up to 45% were observed and of more than 5% occur over the speed range 3 m/s to 12 m/s Approx.

The sensitivity of the power output to the number of turbines within a cell was examined for groups of 4, 20 and 40 turbines. Figures 10a and 10b demonstrate the range of wind speed and heading for which there is more than 5% reduction in the power and thrust profiles of each layout respectively, when compared to the ideal case, as derived by the Eddy Viscosity model. The two graphs indicate that as the number of turbines within a cell increases, the range of wind speeds and directions for which the power and thrust decrease by 5% expands. The same principle applies and for the contour lines that express larger percentages of power deficit. Therefore the number of turbines contained within a grid cell affects its modelling and thus its representation within WRF.

To parameterize a group of turbines for inclusion in the WRF model via the specification of a single turbine input to the Fitch et al [5] scheme an inter-turbine spacing of 7D was considered, equal to the along-row and along-column spacing of Horns Rev (Section 2.1). Modified power and thrust profiles were developed for a cell containing a 2 x 2 arrangement of turbines. The fine grid resolution of 1,120 m maintains the same spacing between turbines in the same-cell and adjacent cells and this leads to reasonable computational cost. The influence of the location of the cell, in relation to the wind farm, on the cell’s power and thrust profiles is shown in Figure 11. The power output of a 2 x 2 group located in the centre of the 80 turbine farm, is lower than from the same sized group either at a corner of the farm or in isolation, for specific wind directions (Figures 11a and 11b).
Figure 9. 5% Reduction in (a) power and (b) thrust applied on a 2×2 cell for different inter-turbine distances, derived using the Eddy Viscosity wake model. For wind directions of 180° to 360°, symmetry applies about wind direction of 180°.

Figure 10: 5% Reduction in (a) power output and (b) thrust applied on a cell due to wakes for different layout sizes, for the Eddy Viscosity wake model.

As expected, the power output of the cell is greater when examined in isolation as it is not affected by the wakes of any other adjacent cells. The greatest power difference between the two is 1.22 MW according to Eddy Viscosity. As far as the thrust is concerned, at 12 m/s, the force applied on the cell is by 83.4 kN greater for the group when examined individually whereas at 13 m/s is 164.6 kN lower.

Figure 11. Reduction in (a) power and (b) thrust due to wakes, when a 2×2 sub-cell of the idealised layout is considered individually and within the centre of the farm, expressed as a percentage over the case where no wake losses are assumed.
Figure 12a illustrates the power and thrust curves averaged over wind direction and used as definition for a turbine within a cell for these two cases. The turbine group at the farm centre is subject to greatest losses and the turbine at the farm edge experiences greater losses than an isolated 2x2 group due to the large number of turbines upwind for some wind directions. The use of one of the above three modified parameterizations, rather than the use of the manufacturer provided curves, takes into consideration the within-cell wake losses. The discrepancy between these curves is due to wind speed reduction from upwind turbines (and groups) and so would be represented as between-cell wind speed reduction in a WRF simulation. On this basis the power and thrust curves for the isolated group of turbines was used in the WRF to represent each of four turbines within a cell (Figures 12a and 12b).

4 WRF Resource and Yield Prediction

WRF was employed to predict yield based on resource only (A), using standard (B) and modified (C) wind turbine thrust and power curves as input to the Fitch et al. [5] model. These three cases and the configuration of the WRF model were as summarised in Section 2.5 and the modified turbine model representing four turbines within a cell was as described in Section 3. This section summarises the resource and yield prediction.

4.1 WRF prediction: wind speed

Figure 13 compares the time series of the ERA data and the WRF results for the aggregated period mentioned. Results provide an accurate description of the wind resource; however, WRF results underpredict the low values of the ERA datasets, but they reach most of the peak values. Additionally, main differences can be appreciated from hours 192 to 228 and from 420 to 492, the last due to the end of the 14 days simulation.
4.2 WRF prediction: Energy yield

For each WRF simulation energy yield was obtained as the sum of yield from twenty subgroups (cells) of four turbines where the yield of each subgroup of four is from the wind speed distribution at the cell centre combined with an aggregate power curve for the sub-group only as Section 3. For all simulations this yield was within 0.1% of the value calculated from the wind speed distribution at the farm centre combined with an aggregate power curve for all turbines in the group only. As such the yields obtained from WRF simulations were scaled by the ratio of sample duration to one year to directly with the predictions of Table 1.

Table 2. Horns Rev energy yield (GWh) for 2007 calculated from ERA-Interim data for three week interval representing wind speed occurrence of 2007 and using three types of WRF simulation.

<table>
<thead>
<tr>
<th>Horns Rev energy yield (GWh) predictions</th>
<th>For duration of 2007 (as Table 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LORC [8]</td>
</tr>
<tr>
<td></td>
<td>659.52</td>
</tr>
<tr>
<td></td>
<td>Eddy-Viscosity</td>
</tr>
<tr>
<td></td>
<td>778.56</td>
</tr>
<tr>
<td>Interval of wind speed, Eddy-Viscosity model</td>
<td></td>
</tr>
<tr>
<td>ERA-Interim</td>
<td>781.13</td>
</tr>
<tr>
<td>WRF: Wind only</td>
<td>687.27</td>
</tr>
<tr>
<td>WRF with Fitch et al. [5] model</td>
<td></td>
</tr>
<tr>
<td>Standard turbines</td>
<td>685.84</td>
</tr>
<tr>
<td>Modified turbines</td>
<td>671.02</td>
</tr>
</tbody>
</table>

The standard WRF methods provide a lower yield than the ERA-Interim resource data with Eddy Viscosity model for 80 turbines. If resource data is used as input to the farm power curve the over-prediction is reduced by nearly 14% (to within 4.2%) and if Fitch et al. [5] Standard model is used the over-prediction is reduced marginally further (to within 4%). Use of a modified power and thrust curve to represent a group of four turbines via the Fitch et al. [5] scheme leads to the lowest of the predictions; approximately 2.3% lower than the standard Fitch et al. [5] model. These estimates of annual yield are based on a relatively small sample of wind speed data but provide an indication of the extent to which within cell losses influence yield predictions and of the accuracy with which the yield during a typical year may be predicted.

5. Conclusions

Alternative methods for predicting the energy yield from an array of wind turbines have been evaluated. Evaluation is against a reference case of the yield during 2007 predicted using ERA-Interim and Modified Eddy viscosity model applied to 80 turbines. This approach overpredicts available data for the yield from Horns Rev over the same period by 18%

A subset of resource data of net duration three weeks was identified as a suitable interval for preliminary WRF simulations. For this aggregate interval of three week duration the RMS error between the histogram of wind speed data and the wind data for 2007 was less than 1%. This data combined with the aggregate power curve for the farm provided yield to within 0.5% of the prediction using the same power curve but the wind speed data for the duration of 2007. Use of such a subset significantly reduced computational time required for the WRF simulations. However, further analysis is currently in progress for longer intervals for a more complete assessment of the sensitivity and accuracy of energy yield predictions.

The OpenWind [6] software has been used to quantify the variation of power and thrust with wind-speed and direction and the resultant reduction of power and thrust coefficient have been used to modify the representation of a group of turbines within a single cell of the WRF model using the Fitch scheme. For an arrangement of 2x2 turbines at 7D spacing in each axis, thrust and power are reduced by up to 45% and 50% respectively and by more than 5% over a wide range of wind speeds and a narrow range of headings. Losses have been averaged across all directions to define a turbine in WRF on the basis of the variation of performance with wind speed only. This does not fully account for losses,
particularly when the wind direction is parallel with aligned turbines.

Predictions of energy yield of the Horns Rev farm to within 4% and 2% of yield data available from 2007 have been obtained by standard application of WRF and through use of a modified turbine model implemented in WRF using the Fitch et al. [5] scheme and selected to represent wake interactions between four turbines within a cell. The resource data used for this evaluation provides a close approximation to the annual wind speed statistics and the findings indicate the extent to which yield may be affected by the resolution of the resource data, the wake model employed and the turbine configuration within a cell. However, only a short interval has been considered to-date and so the trends observed may only be considered indicative. Further analysis is required, and ongoing, to evaluate prediction accuracy for longer-term datasets.

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