THE OPENWIND DEEP-ARRAY WAKE MODEL

Development and Validation

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INTRODUCTION

In the past several years, researchers have become aware that the current generation of wake models may underestimate wake losses in large wind projects with multiple rows of wind turbines. The crux of the problem is that the leading wake models – including the Park, Modified Park, and Eddy Viscosity (EV) models – ignore two-way interactions between the atmosphere and the turbines.[1] Each turbine extracts energy from the wind passing through its rotor plane, creating a zone of reduced speed extending some distance downstream. Upstream and outside this zone of influence, it is assumed the ambient wind is unaffected.

Both theory and experiments suggest that, for large arrays of wind turbines, this assumption does not hold. The presence of numerous large wind turbines in a limited area can alter the wind profile in the planetary boundary layer outside the zone of direct wake effect, both within and around the array, thereby reducing the amount of energy available to the turbines for power production. Experimental data supporting this hypothesis comes mainly from offshore wind projects, where the contrast between the drag induced by the turbines and the relatively low roughness of the ocean surface makes the so-called deep-array effect especially pronounced. Onshore, the effect is attenuated, but theory suggests it may nonetheless be significant in projects involving hundreds to thousands of wind turbines.

It has become clear that new models are required that can simulate deep-array wake effects with reasonable accuracy. Predicting the overall impact of a large wind turbine array is a complex problem involving dynamic interactions between the turbines and various properties of the atmosphere, including vertical and horizontal gradients of temperature, pressure, and speed, as well as turbulence. This problem can be solved completely only through sophisticated numerical modeling requiring very large computer resources. However, it may be hoped that simplified approaches will work well enough for the purpose of designing and estimating the energy production of the next generation of wind energy projects.

This paper describes a deep-array wake model (DAWM) developed by AWS Truepower and implemented in the openWind plant design and optimization program. The paper discusses the theoretical background of the approach, its specific application in DAWM, and validation of the model at two power plants, one offshore and one onshore, where operational turbine output data are available.

THEORETICAL BACKGROUND

The approach we have taken is based on a theory advanced by Sten Frandsen,[2] in which an infinite array of wind turbines is represented as a region of uniform high surface roughness. The roughness imposes drag on the atmosphere, causing a downstream change in the structure of the planetary boundary layer (PBL) and, in particular, a reduction in the free-stream wind speed at the turbine hub height. According to this theory, the wind-farm equivalent roughness z_{00} is given by

$$z_{00} = h_H \exp\left(- \frac{\kappa}{\sqrt{c_t + \left(\kappa / \ln\left(h_H / z_0 \right) \right)^2}} \right)$$

In this equation, h_H is the hub height, κ is the von Karman constant (about 0.4), z_0 is the ambient roughness between turbines, and c_t is the distributed thrust coefficient,

[1] Frandsen, S.T., Barthelmie, R.J., Pryor, S.C., Rathmann, O., Larsen, S. Højstrup, J. and Thøgersen, M. 2006: Analytical Modeling of Wind Speed Deficit in Large Offshore Wind Farms. *Wind Energy*, 9, 39-53.

[2] Sten Tronæs Frandsen, *Turbulence and Turbulence-Generated Structural Loading in Wind Turbine Clusters*, Risø-R-1188(EN), Risø National Laboratory (January 2007).

$$c_t = \frac{\pi}{8 s_d s_c} C_T \,,$$

where C_T is the turbine thrust coefficient and s_d and s_c are the mean downwind and crosswind spacings in rotor diameters (RD). The chart on the left in Figure 1 shows z_{00} for a range of C_T and mean array spacings $(s_d s_c)^{0.5}$. The roughness is strongly dependent on the spacing, much less so on the background or ambient roughness (here assumed to be 0.001 m for offshore arrays and 0.03 m for onshore arrays).

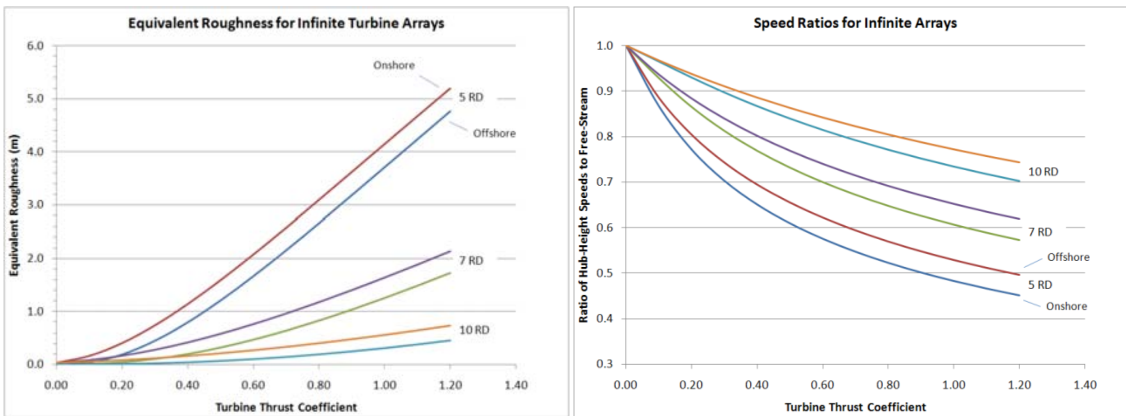

Figure 1. *Left*: Wind farm equivalent roughness z_{00} for an infinite turbine array as a function of thrust coefficient and array spacing in rotor diameters (RD), for both offshore (ambient z_0=0.001 m) and onshore (ambient z_0=0.03 m) projects. *Right:* Asymptotic hub-height wind speed as a fraction of the free-stream speed for the same cases. Based on Frandsen (2007).

Once the equivalent roughness is defined, the impact on the hub-height wind speed deep within the array (i.e., where the PBL has reached equilibrium with the array roughness) is estimated from meteorological theory under the assumption of a constant geostrophic wind speed *G* and a neutral logarithmic profile throughout the PBL. The result is approximated by the following equation.

$$\frac{v_H'}{v_H} = \left(\frac{z_{00}}{z_0}\right)^{0.07} \frac{\ln\left(h_H / z_{00}\right)}{\ln\left(h_H / z_0\right)}$$

Here, v'_H and v_H are the hub-height speeds deep within the array and far upstream, respectively. The results are plotted in the right-hand chart in Figure 1.

IMPLEMENTATION IN OPENWIND

An important issue with the Frandsen theory is that it does not address the wake effects of individual turbines. Instead, it treats the array as an infinite sea of undifferentiated surface drag. This means that the predicted wind resource at a particular location does not depend on whether there are any turbines immediately upwind or not, which is unrealistic. Furthermore, the roughness depends on the array density, which implies that it would have to be recalculated every time the layout is modified. Thus, to be useful for wind project design and optimization, the Frandsen theory must either be modified or combined in some way with other methods.

In the course of this research we developed and tested a number of different methods of addressing these two issues. The methods fall into two categories – one based on numerical mesoscale weather modeling, the other on empirical equations describing the growth of internal boundary layers (IBLs) at roughness changes.

Mesoscale Modeling

This approach relies on a mesoscale numerical weather prediction model to simulate the roughness effect. We hypothesized that this might produce superior results because the model is capable of simulating the impact of roughness changes under a range of atmospheric conditions, most notably thermal stability. The MASS model (Mesoscale Atmospheric Simulation System) was run at a relatively high resolution of 300 m for a representative sample of 72 days. Each grid cell coinciding with a turbine was assigned an increased surface roughness value. The results of the simulations were then used to produce a wind resource grid (WRG) file. Finally, this file was loaded into openWind for energy production calculations.

After testing at two sites (one offshore, one onshore), we concluded that the mesoscale modeling approach offers no substantial improvement over the IBL-growth approach at two sites. Furthermore, it would be impractical to implement it for layout optimization because each new layout would require a new set of mesoscale runs. For these reasons it was decided not to implement this approach for the time being. Continuing research with mesoscale models at AWS Truepower is focused on simulating turbines as elevated momentum sinks and turbulence sources rather than surface roughness elements.

IBL Growth

The second approach is implemented entirely in openWind and relies on equations describing the downstream effects of roughness changes on wind speed.[3] Each turbine is assumed to occupy a discrete area of increased surface roughness. As the wind reaches a turbine, an IBL is created by the increased roughness. Within this IBL, the wind profile, or shear, is defined by the turbine roughness rather than by the ambient roughness, with the constraint that the speed at the top of the IBL must match the speed immediately above it. After the wind has passed the turbine, a second IBL is created representing the transition back to ambient surface conditions. Both IBLs grow with distance downstream according to the equation,[4]

$$h_{ibl}\left[\ln\left(h_{ibl}/z_0\right)-1\right]=\left(x/z_0-1\right)z_0,$$

where x is the distance from where the IBL is created, and z_0 is the downstream roughness (for the first IBL, the turbine roughness, and for the second, the ambient roughness). Subsequent turbines create their own IBL pairs underneath the previous ones.

Considering just the first turbine's IBL pair, and assuming both IBLs have grown to exceed the hub height (H), the equation for the ratio of the adjusted speed to the free-stream speed at hub height is as follows:

$$\frac{v_H'}{v_H}=\frac{\ln\left(h_1/z_0\right)}{\ln\left(h_2/z_0\right)}\frac{\ln\left(h_2/z_{00}\right)}{\ln\left(h_1/z_{00}\right)}$$

Here, h_1 and h_2 are the heights of the first and second IBLs, respectively, and z_0 and z_{00} are the turbine and ambient (background) roughness, respectively. This formula is easily generalized to IBL pairs from multiple turbines. It is assumed that any IBL that has not attained hub height has no impact on the hub-height speed, and any IBL that exceeds the height of a previous IBL supersedes the previous IBL.

After some experimentation, it was decided that the first IBL for each turbine would be initialized at the height of the top of the turbine rotor, while the second would be initialized at the bottom of the rotor. This is physically reasonable considering that turbines act not at the surface but across the rotor plane. Effectively it gives the IBLs a head start and allows the large-array effect to develop more rapidly. (The height settings can be varied; those described are the defaults.)

[3] This approach is conceptually similar to the approach taken by Garrad Hassan in its large-array wake model, part of the WindFarmer software package. However, the methods differ in many details.

[4] J.R. Garratt, *The Atmospheric Boundary Layer*, Cambridge University Press (1992), p. 111.

In previous versions of DAWM, the background roughness was set to a constant value (typically 0.001 m for offshore sites, and 0.03 m for onshore sites). In the latest version, the background roughness is replaced by a roughness map derived from a land cover data set.

Blending with the EV Model

The IBL-growth approach has the important advantage that it runs fast and, therefore, can be applied easily in an array-optimization procedure. It also varies the wake impact depending on the locations of upstream turbines. Thus it represents something of a cross between a conventional wake model and Frandsen's theoretical approach.

Still, because its effect depends on the gradual growth of the IBL, the method underestimates the immediate downstream wake impact of individual turbines. For this reason, it must be combined in some way with another wake model to provide a complete picture of the wake effects throughout the array.

Two methods of solving this problem were developed and tested. In the first, the IBL equations modify the free-stream wind speeds that are input to the EV model. In the second, the net output of each turbine is estimated separately (i) with the EV model alone (roughness effect switched off), and (ii) with the roughness effect alone (EV model switched off). The two results are then compared and the one predicting the largest wake deficit is retained. This approach implicitly divides the array into two parts, a "shallow zone" where the conventional wake model applies, and a "deep" zone where the roughness effects become dominant. In tests, the dividing line between zones typically occurs about three rows into a wind project.

Tests indicated that the maximum-deficit method appears to have an edge in both accuracy and ease of implementation. Therefore, this approach was adopted in DAWM.

TEST METHOD

Turbine production data and wind speed and direction data were acquired for five wind projects: three onshore and two offshore. With minor variations, the same method was applied to all five to compare the accuracy of DAWM with the EV model. The main measure of model accuracy is the root-mean-square error (RMSE) calculated over all turbines for which data are available. The error is defined as the predicted output minus observed output as a percentage of the observed output. Both the predicted and the observed output are normalized to the mean from un-waked turbines. The aim of this procedure is to reduce discrepancies that might arise because of differences between the actual and theoretical power curves and between the predicted and actual free-stream speeds.

OFFSHORE TEST SITE 1: HORNS REV 1

The first offshore test case is Horns Rev 1, a plant located 14 km off the coast of western Denmark, which is owned by Vattenfall and DONG Energy. The experimental data set is described in detail elsewhere.[5,6] In brief, the project consists of 80 modified V80 1800 KW turbines in a regular trapezoidal array with a constant spacing of 7x7 RD (Figure 2). For the UpWind project, plant output and meteorological data were collected and made available to researchers for twenty-one different cases, each comprising one of three speeds (6, 8, and 10 m/s) and one of seven directions. The speed bins are 1 m/s wide and the direction bins are 5 degrees wide. The central direction was chosen so that turbines would be aligned one behind the other along the principle wind direction. The other six directions are in five-degree increments on either side of the central direction.

We downloaded the data set from the UpWind web site and set up openWind to run on a flat omni-directional WRG. Using openWind's binning and scripting capability, we ran each case with the EV model and DAWM. For the latter, we first tuned the turbine roughness parameter to provide the best fit for each case independently, and then we found the single roughness value that provided the best fit (zero mean error) across all cases. In the model's first incarnation, the IBLs were allowed to propagate only within the angle of the direction step being

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[5] Kurt S. Hansen, Project UpWind, Deliverable D8.1: Wake measurements used in the model evaluation, June 2008.

[6] Barthelmie, R. J., et al., 2010: Quantifying the Impact of Wind Turbine Wakes on Power Output at Offshore Wind Farms. *J. Atmos. Oceanic Technol.*, **27**, 1302–1317.

evaluated. Subsequently the effect of varying the wake angle was investigated, and a consensus wake width of 7.5 degrees was adopted and applied to all test sites.

Table 1 summarizes the results for the EV model, and Table 2 for DAWM for the best-fit turbine roughness of 1.12 m. The EV model performs relatively well for wind directions within 5 degrees of directly in line with the turbines (labeled ER-5, ER, and ER+5 in Figure 2), with the RMSE ranging from 5.2% to 10.9%. The error increases substantially at greater angles, however, and the average RMSE over all directions ranges from 12.8% to 15.1%. DAWM does not perform as well as the EV model when the wind is directly in line with the turbines; however, averaged over all directions the DAWM RMSE is substantially smaller than the EV RMSE, from 5.8% to 7.2%.

The seven pairs of charts in Figure 3 show results for the seven directions shown in Figure 2, all at 10m/s. The charts on the left show the performance of the best-fit DAWM configuration while the charts on the right show the performance of the EV model. When the wind direction is directly down the row, the EV model does quite well and even tends to over-estimate the wake losses for the first few columns of turbines. However, for the directions to either side, the EV model underestimates wake losses, and does progressively worse deeper in the array. In each case, the turbine output is normalized to the front "row," i.e., those turbines first encountered by the wind.

In most – though not all – cases the EV model significantly overestimates the production and underestimates the wake loss beginning at about the third turbine string from the front. With the tuned roughness, DAWM largely eliminates this problem.

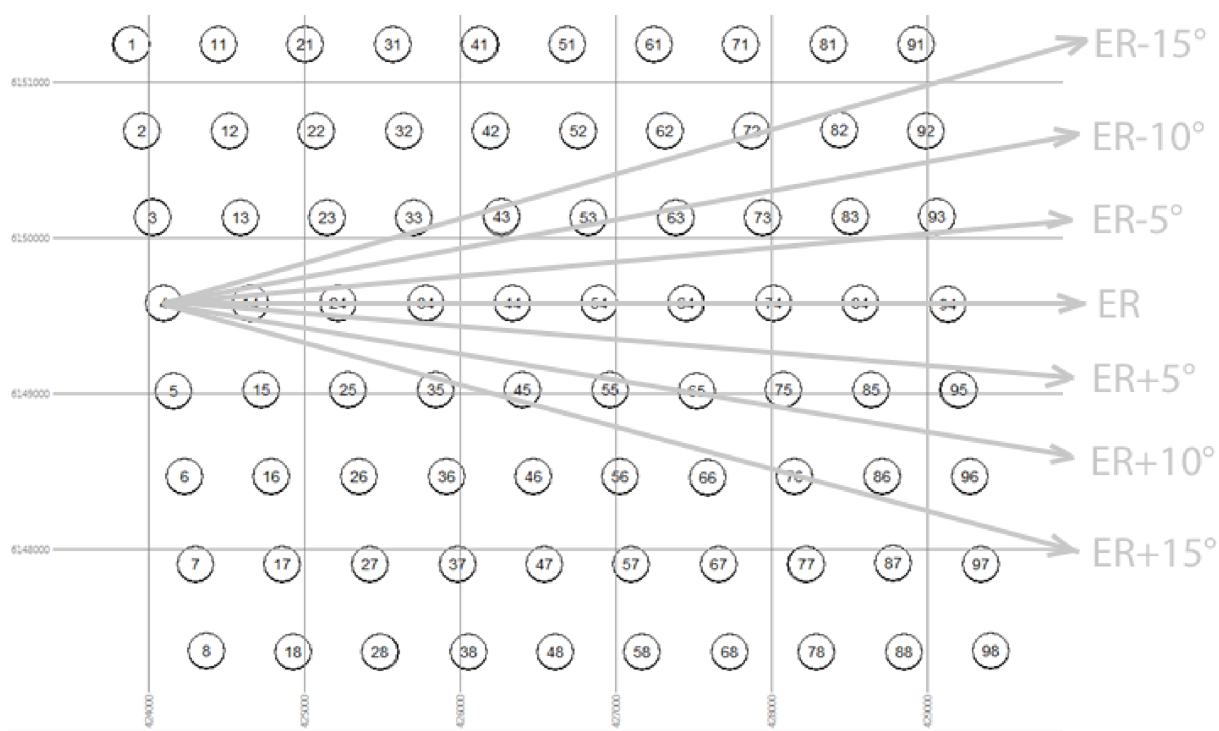

Figure 2. Horns Rev 1 layout with test case directions. ER is the case in which the turbines are directly in line, one behind the other. The numbers (e.g., ER+15) refer to positive and negative direction shifts, in degrees, from ER.

Table 1. RMSE at Horns Rev 1 for the openWind EV model for a range of wind directions.

Wind Speed [m/s]	RMS Error [%] By Direction							
	ER-15	ER-10	ER-5	ER	ER+5	ER+10	ER+15	Average
6	15.8	21.7	9.6	7.4	9.2	19.3	16.2	15.1
8	16.6	20.4	7.1	6.4	10.9	15.0	15.1	13.9
10	14.5	19.8	9.3	5.2	9.1	14.5	11.7	12.8

Table 2. RMSE at Horns Rev 1 for DAWM for a best-fit turbine roughness of 1.12 m.

Wind Speed [m/s]	RMS Error [%] By Direction							
	ER-15	ER-10	ER-5	ER	ER+5	ER+10	ER+15	Average
6	4.6	8.6	5.6	10.1	3.9	9.2	6.0	7.2
8	4.3	8.1	7.5	9.3	5.4	4.7	4.5	6.5
10	3.7	7.7	7.1	6.6	3.7	4.2	6.4	5.8

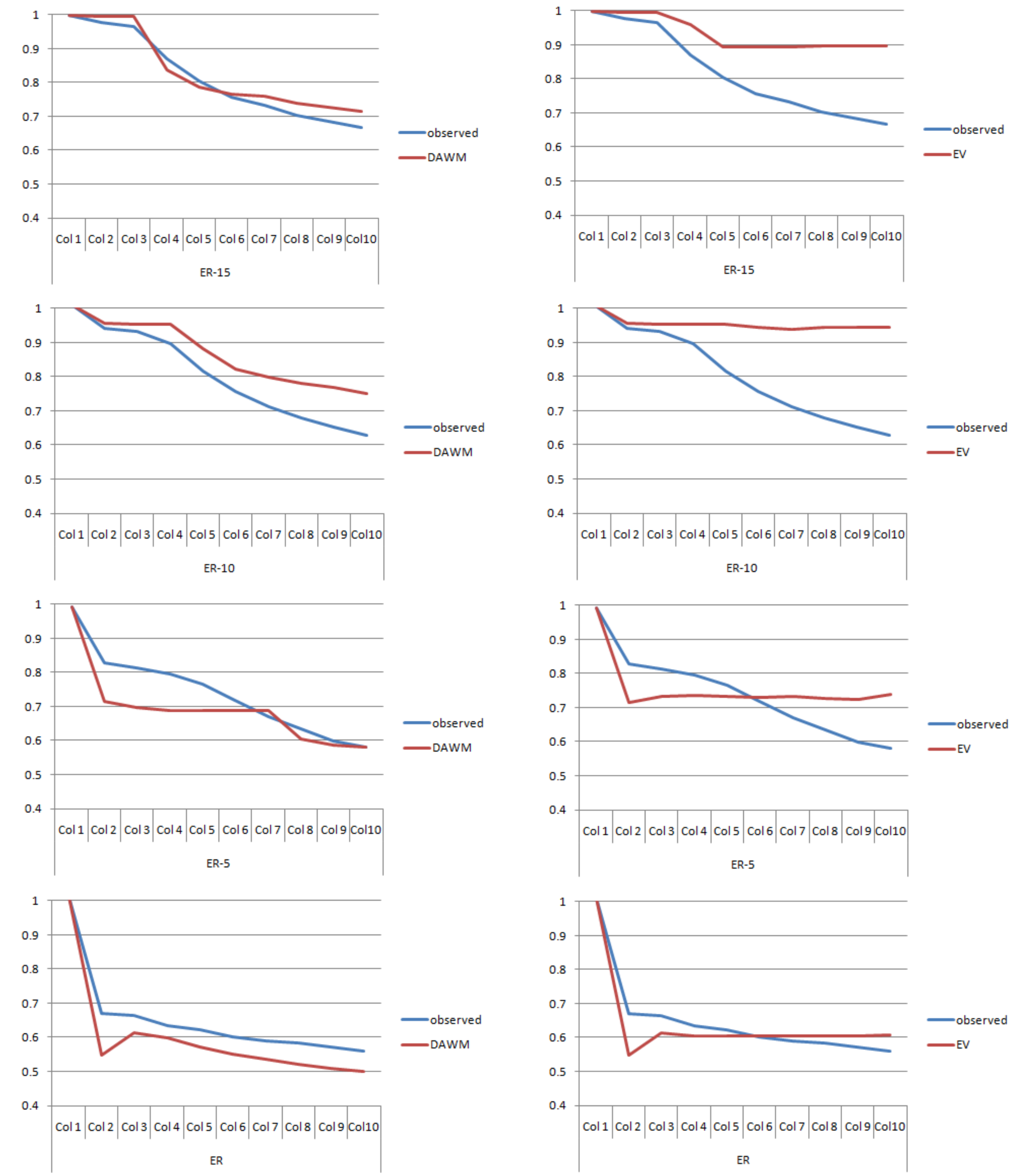

Figure 3a. Comparison of predicted and observed output for DAWM (left) and the EV model (right) at Horns Rev for direction cases ER-15 (top row), ER-10 (second row), ER-5 (third row), and ER (bottom row), at 10 m/s.

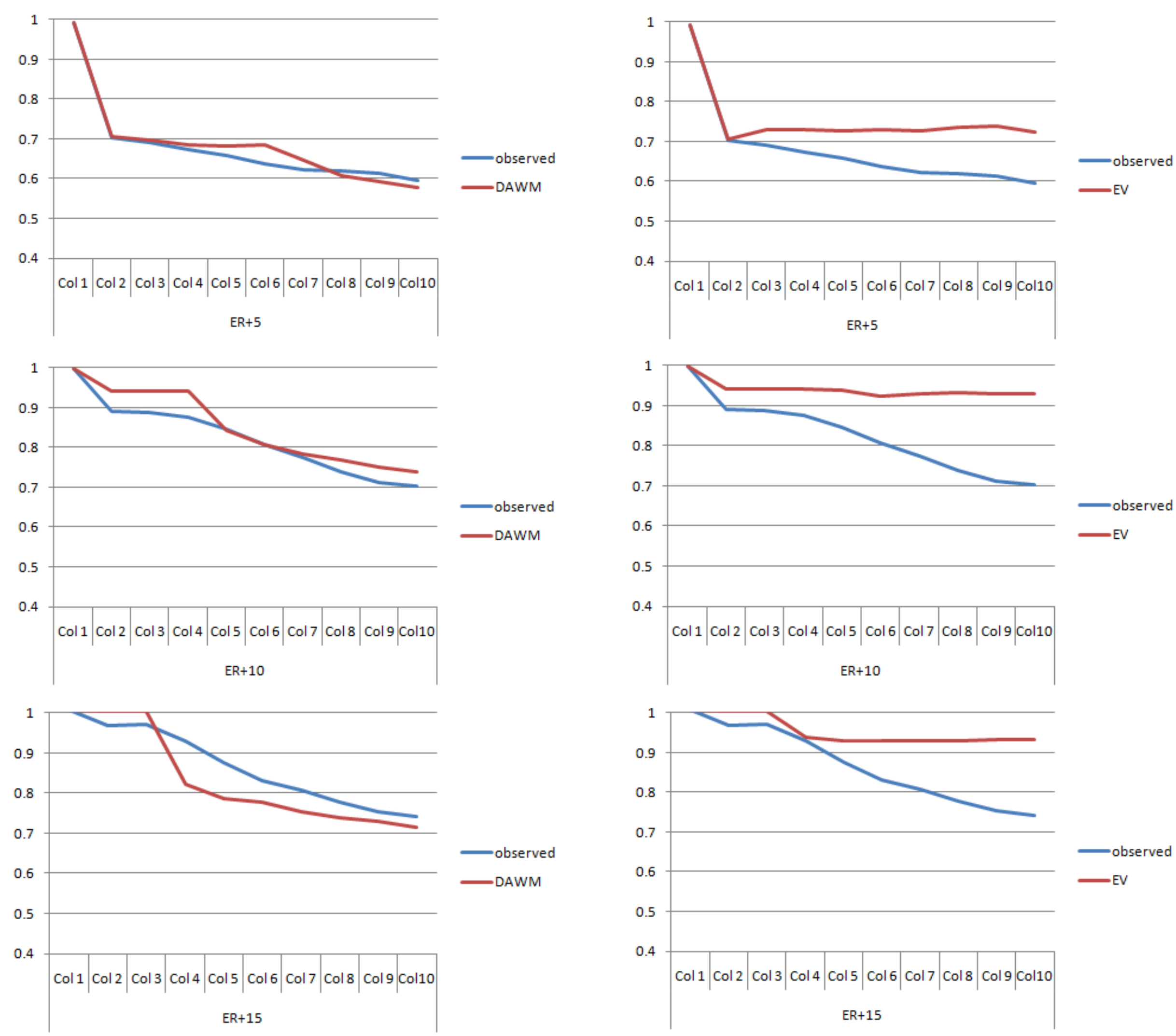

Figure 3b. The same as Figure 3a for direction cases ER+5 (top), ER+10 (middle), and ER+15 (bottom).

By testing a range of roughness values (Table 3), we determined the best-fit roughness to be 1.12 ± 0.17 m.[7] The mean bias is virtually zero (as a result of the tuning), and the overall RMSE is 6.5%. The roughness appears to be broadly consistent with Frandsen's theory, which predicts an effective array roughness of 0.83 m for a mean spacing of 7x7 RD and C_T of 0.8 (the approximate value for this turbine in this range of speeds). Considering that each turbine is modeled as a discrete area of elevated roughness, it is not surprising that the required roughness value should be greater than that estimated for the array as a whole.

Table 3. Best-fit (P50) and range of DAWM turbine roughness values for Horns Rev 1. P84 and P16 refer to the 67% confidence interval, while P95 and P05 refer to the 90% confidence interval.

Confidence	P95	P90	P84	P50	P16	P10	P05
Roughness (m)	0.86	0.92	0.96	1.12	1.29	1.34	1.40

[7] The uncertainty band quoted here and elsewhere is the 67% confidence interval based on the scatter of the mean biases among the cases.

OFFSHORE TEST SITE 2: NYSTED

The second offshore test site is Nysted, a plant located about 10 km off the southeastern coast of Denmark, which is owned by DONG Energy. The test dataset is described in detail elsewhere.[8] In summary, the Nysted wind farm consists of 72 Siemens 2.3MW turbines arranged in an oblique grid. The turbines have a rotor diameter of 82.4m and a hub height of 80m. The turbine spacing at Nysted is 5.8 rotor diameters in the north-south direction and 10.5 rotor diameters in the west-east direction. For the wind directions under consideration here, the sea fetch is a little less than 70 km.

The test cases studied here are the same as those evaluated by Barthelmie (2010).

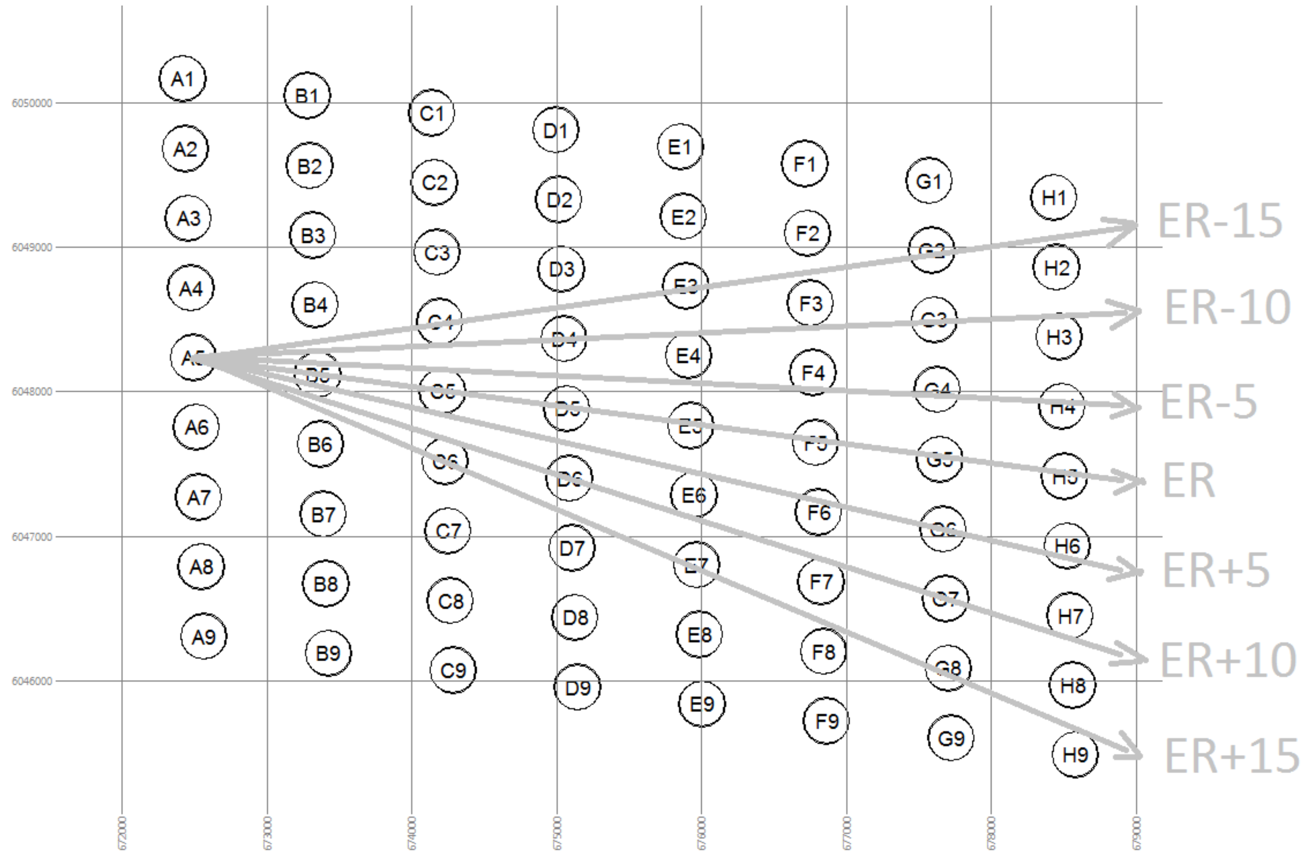

Figure 4. Nysted layout with test case directions. ER is the case in which the turbines are directly in line, one behind the other. The numbers (e.g., ER+15) refer to positive and negative direction shifts, in degrees, from ER.

Tables 4 and 5 show the RMS error for the various direction and speed cases for the two wake models. As in the case of Horn Rev 1, the EV model does relatively well when the wind is in line with the turbines (ER), but much worse for other directions. The average RMSE ranges from 12.1% to 17.1%, and decreases markedly with increasing wind speed. DAWM's errors are substantially smaller than the EV model's errors overall, including the ER case, and average only 4.7% to 8.8%.

The charts in Figure 5 are for 10 m/s, but the results are similar at other speeds. The left-hand charts compare the turbine production predicted by DAWM with the observed, while the right-hand charts do the same for the EV model. As was evident in the case of Horns Rev, the EV model generally underestimates the wake loss. The best-fit DAWM roughness, obtained by testing the average RMSE for a range of roughness values (Table 6), is 1.14 ± 0.12 m, and the RMS error is 6.7%. These results are very similar to those obtained at Horns Rev 1.

[8] Barthelmie, R. J., et al., 2010: Quantifying the Impact of Wind Turbine Wakes on Power Output at Offshore Wind Farms. *J. Atmos. Oceanic Technol.*, **27**, 1302–1317.

Table 4. RMSE at Nysted for the openWind EV wake model.

Wind Speed [m/s]	RMS Error [%]By Direction							
	ER-15	ER-10	ER-5	ER	ER+5	ER+10	ER+15	Average
6	12.8	17.4	18.7	7.8	20.9	21.9	15.5	17.1
8	11.6	13.8	17.4	6.4	12.3	16.3	11.9	13.3
10	10.9	10.3	14.2	9.0	15.5	12.8	10.6	12.1

Table 5. RMSE at Nysted for DAWM for a turbine roughness of 1.14 m.

Wind Speed [m/s]	RMS[%] Error By Direction For Deep Array Wake Model (DAWM)							
	ER-15	ER-10	ER-5	ER	ER+5	ER+10	ER+15	Average
6	7.0	9.7	9.1	7.1	8.5	11.6	7.8	8.8
8	4.0	6.3	4.0	5.6	9.1	6.2	5.8	6.1
10	4.1	4.5	4.7	3.9	7.0	2.8	4.8	4.7

Table 6. Best-fit (P50) and range of DAWM turbine roughness values for the Nysted test cases. P84 and P16 refer to the 67% confidence interval, while P95 and P05 refer to the 90% confidence interval.

Confidence	P95	P90	P84	P50	P16	P10	P05
Roughness (m)	0.95	0.99	1.03	1.14	1.26	1.29	1.34

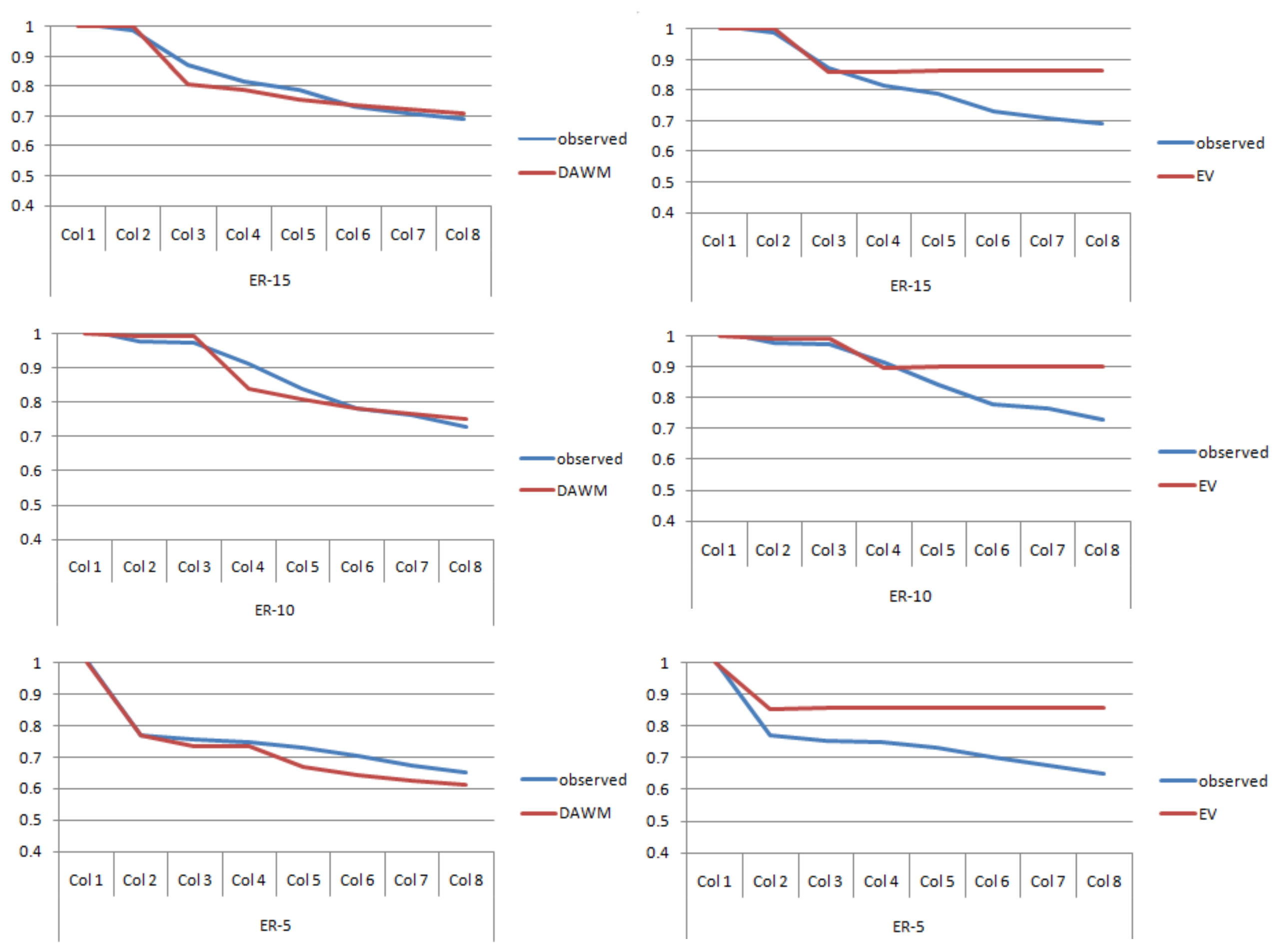

Figure 5a. Comparison of predicted and observed output for DAWM (left) and the EV model (right) at Nysted for direction cases ER-15 (top), ER-10 (second row), and ER-5 (bottom row), at 10 m/s.

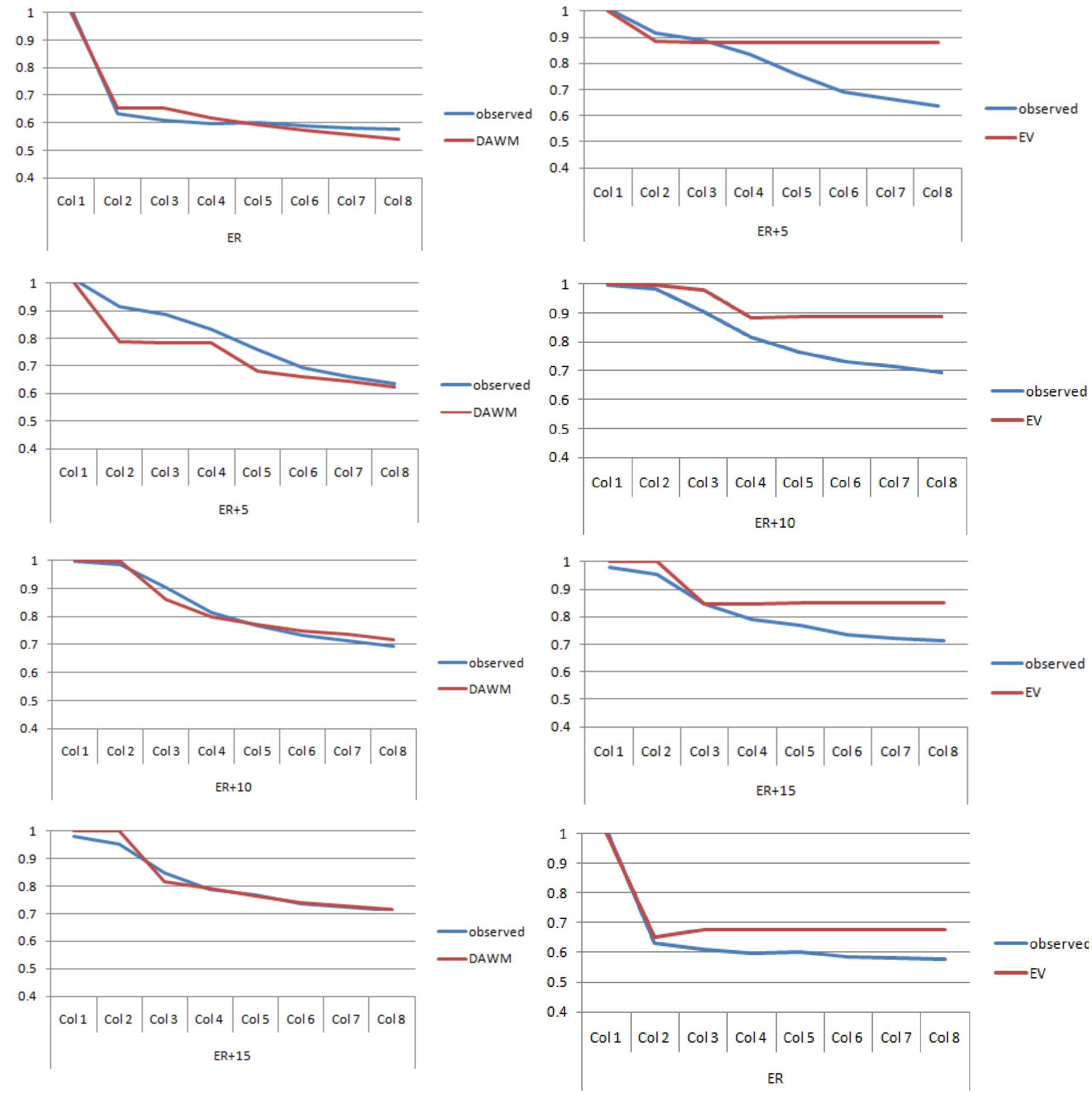

Figure 5b. The same as Figure 5a for direction cases ER (top), ER+5 (second row), ER+10 (third row), and ER+15 (bottom).

ONSHORE TEST SITE 1

The first onshore test site is in the Midwestern United States.[9] The project is composed of several rows of 2 MW turbines oriented east-west with an intra-row spacing of around five rotor diameters and an inter-row spacing of around 19 rotor diameters. The terrain around the wind plant is flat, open farmland for many kilometers. SCADA data were obtained from the project owner covering a period of seven months. The data included 10-minute production and nacelle anemometer readings for each turbine, 10-minute directions and wind speeds from two tall towers located within the array, and a count of the number of turbines online at each time. The data were filtered to include only records when all turbines were online (100% availability). The data were further segmented into 25-degree direction sectors and 1-m/s speed bins, as defined for a particular direction by whichever of the two towers was not directly waked.

DAWM was run for a range of turbine roughness values in an attempt to match the observed output as closely as possible (Table 7). The best-fit roughness over all cases was found to be 1.37 m ± 0.69 m. It is encouraging that the central value is similar to that derived in the Horns Rev 1 (1.12 m) and Nysted (1.14m) tests, though it is somewhat larger than that estimated in the Frandsen theory (0.4 m for a 10x10 RD array and C_T of 0.80). However, the uncertainty is much larger than that for the Horns Rev 1 and Nysted tests because of the relatively large amount of scatter in the observed turbine output compared to the presumed deep-array effect.

The charts in Figure 6 compare the power output predicted by the two wake models with the observed output derived from the operational data, for northerly winds (i.e., perpendicular to the rows) and for speeds ranging from 6 m/s to 10 m/s (top to bottom). The DAWM results, shown on the left, are for the best-fit turbine roughness of 1.37 m. Although there is more scatter than was observed at the two offshore sites, the results appear to demonstrate a significant deep-array effect from this direction. The EV model predictions tend to diverge from the observed output in the back rows (to the right in these charts), whereas the DAWM predictions are more closely aligned.

The charts in Figure 7 present a similar set of results for winds of direction 300 degrees, or west-northwest, for the same range of speeds. The deep-array effect is not as easy to discern for this direction, and the patterns are more confused because the wake loss varies greatly within rows as well as between rows. Neither model does well at the higher wind speeds. (Note that the turbine numbering is from west to east by row and north to south between rows in all charts.)

Table 7. Best-fit (P50) and range of DAWM turbine roughness values for Onshore Test Site 1. P84 and P16 refer to the 67% confidence interval, while P95 and P05 refer to the 90% confidence interval. “None” indicates the turbine roughness equals the ambient roughness.

Confidence	P95	P90	P84	P50	P16	P10	P05
Roughness (m)	none	none	0.617	1.37	2.002	2.206	2.553

[9] The name, location, and exact size and turbine model of the project have been withheld to protect confidential client data.

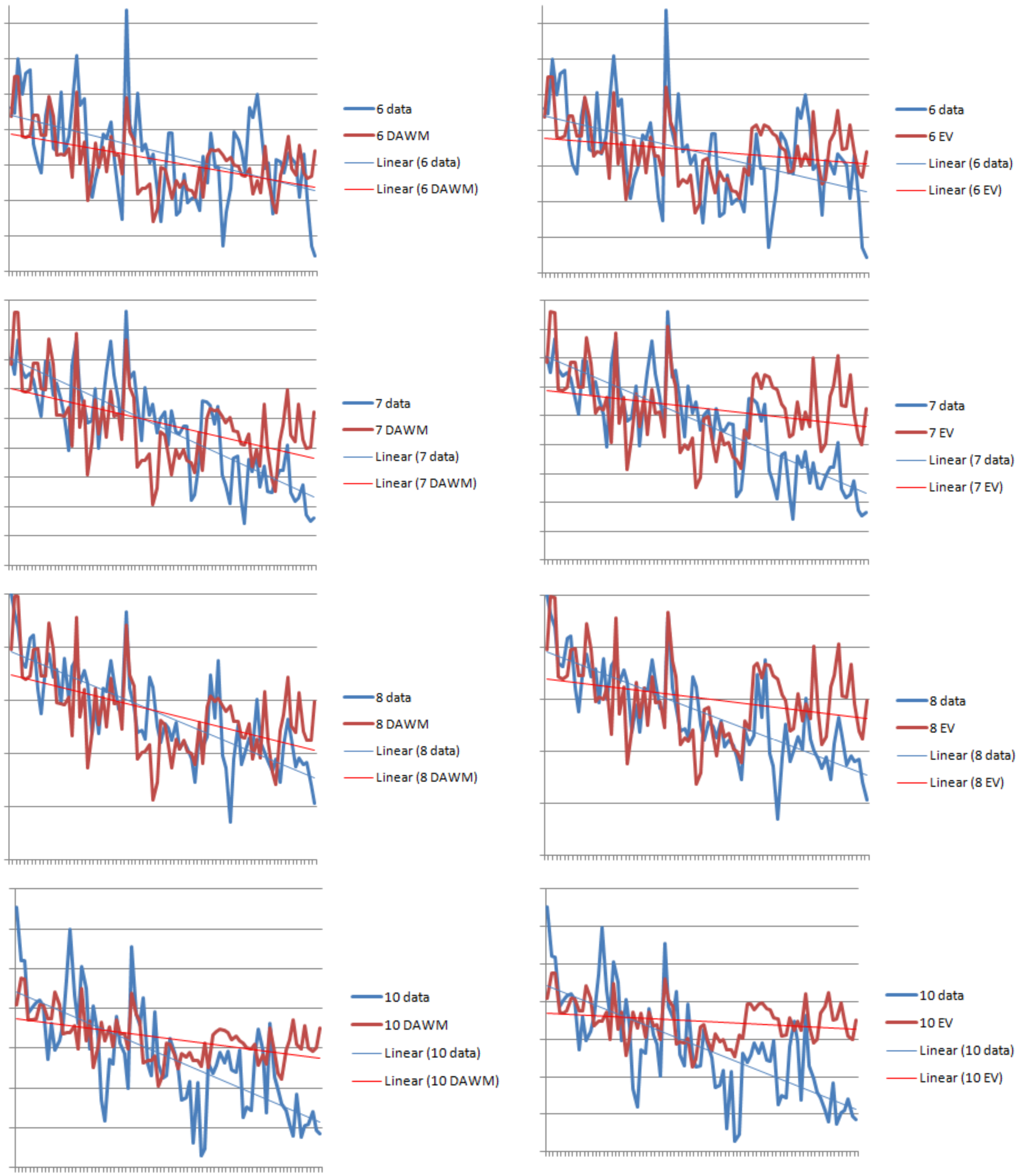

Figure 6. Comparison of predicted and observed output for DAWM (left) and the EV model (right) at Onshore Test Site 1 for a 25-degree wide direction sector centered on due north. Each row of charts represents a different mean wind speed: 6 m/s (top), 7 m/s (second), 8 m/s (third), and 10 m/s (bottom).

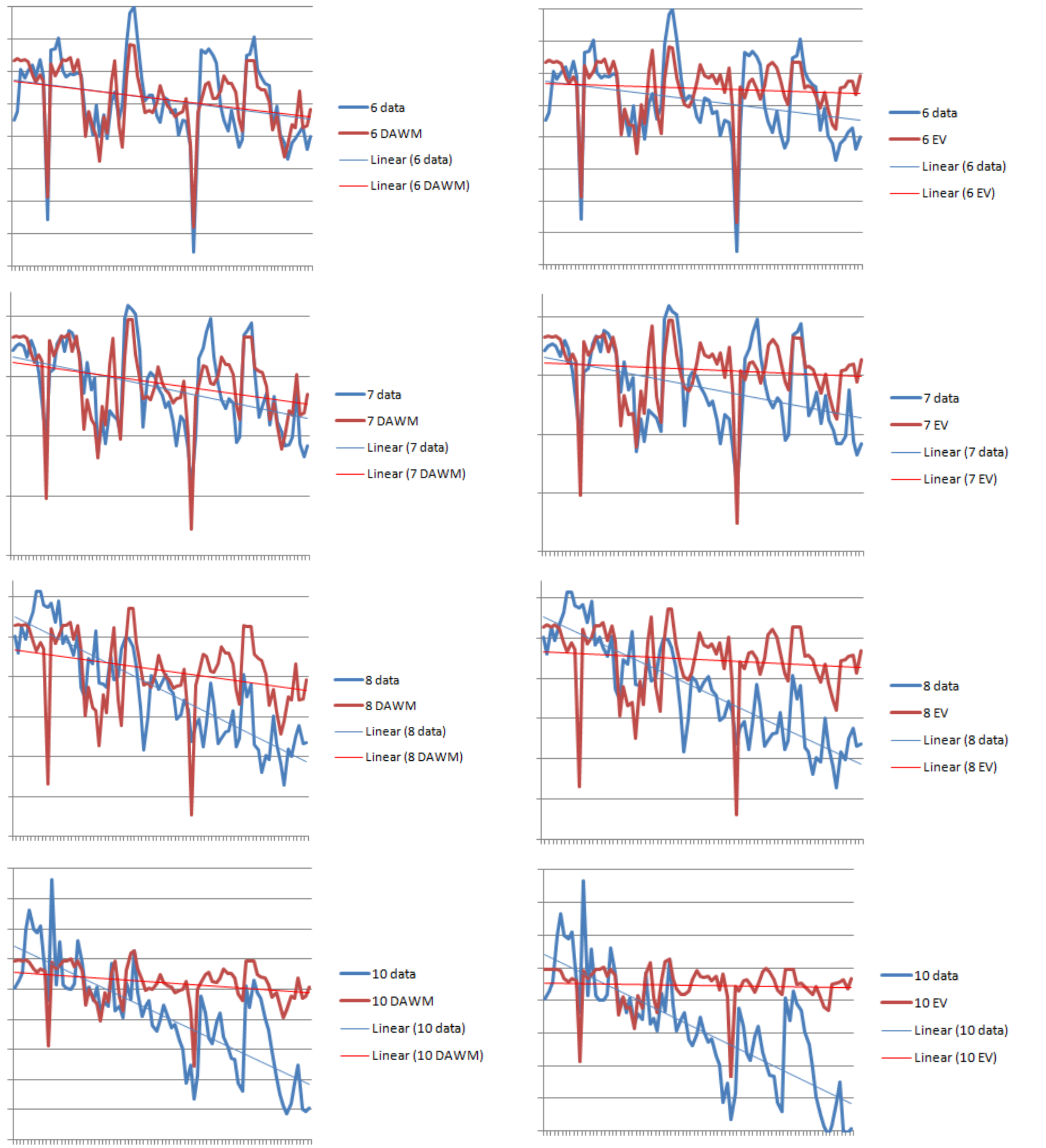

Figure 7. The same as Figure 6, for a direction of 300 degrees (west-northwest).

ONSHORE TEST SITE 2

The second onshore test site is also in the Midwestern United States.[10] This project consists of around 140 1.5 MW turbines with irregular spacing of at least 4 rotor diameters. The terrain around the wind-farm is flat open farmland for many kilometers. SCADA data were obtained from the project owner for a period of about one year. The data included 10-min production and nacelle anemometer speeds for each turbine, 10-min directions and speeds for four tall towers surrounding the array, and a count of the number of turbines online at each time. As before, the data were filtered to include only records with 100% availability. The data were then segmented into 25-degree direction sectors and 1-m/s speed bins determined by measurements from an un-waked tower.

The data for most directions were very sparse, with many bins unpopulated and many more with only a handful of cases. In order to avoid unrepresentative data skewing the analysis, a minimum of 60 samples was required. This meant that the only cases studied were 30 degrees from 5 m/s to 11 m/s and 180 degrees at 10m/s.

The same method was applied to this site as before to tune the turbine roughness to produce the best fit to the data. The results are given in Table 8. The resulting "best-fit" roughness is 1.53 m ± 1.10 m, which is consistent with that obtained for the first onshore test site as well as for the two offshore test sites.

Table 8. Best-fit (P50) and range of DAWM turbine roughness values for Onshore Test Site 2.
P84 and P16 refer to the 67% confidence interval, while P95 and P05 refer to the 90% confidence interval. “None” indicates the turbine roughness equals the ambient roughness.

Confidence	P95	P90	P84	P50	P16	P10	P05
Roughness (m)	None	None	None	1.53	2.206	2.376	2.599

ONSHORE TEST SITE 3

The third onshore test site is a wind project consisting of roughly 100 turbines of approximately 1 MW rated capacity located in relatively flat terrain in the upper Midwest of the United States.[11] The array is irregular, with one axis oriented northwest to southeast and another axis oriented south-southwest to north-northeast. The mean turbine spacing averaged over all directions is about 10 rotor diameters.

Over seven years of SCADA data from the project were obtained from the project owner. The data included 10-minute turbine output, nacelle anemometer readings, and wind speed and direction readings from two wind monitoring masts. After eliminating times when one or more turbines were unavailable, the data were divided into 96 cases corresponding to 8 wind speed bands and 12 direction bands (defined by un-waked mast readings). The wind speed bands were 1 m/s wide, with central values ranging from 5 m/s to 13 m/s. The direction bands, each 25 degrees wide, are shown in Table 9.

Table 9. Central directions for onshore wind project test cases, in degrees. Each sector is 25 degrees wide.

Mast 1	Mast 2
270	60
300	90
330	120
0	150
30	180
	210
	240

[10] The name, location, and exact size and turbine model of the project have been withheld to protect confidential client data.

[11] The name, location, and exact size and turbine model of the project have been withheld to protect confidential client data.

As the table indicates, the cases were divided into two sets, each set spanning directions from which one of the masts is free of direct wake effects from nearby turbines. Although the entire period of record is several years, a faulty anemometer meant that the majority of the records had to be discarded. Approximately 6300 records were available for the Mast 1 cases and 6800 records for the Mast 2 cases. Since the records covered all times of day and year, it is assumed they provide a representative sample of atmospheric conditions. Also, turbulence intensity data was not available and so a default turbulence intensity value of 10% was used globally for this site.

The results of the roughness tuning are shown in Table 10. The best-fit roughness is 0.75 m ± 0.5 m. This is smaller than the value obtained in the other test cases. It should be noted that the data associated with the two different masts behave very differently, and work is continuing to determine the reason for this. For the cases associated with Mast 1, DAWM appears to require a turbine roughness of around 2.4 m, whereas the cases associated with Mast 2 exhibit very little excess wake loss beyond that predicted by the EV model. The lack of turbulence intensity data might explain these differences, as turbulence intensity has a significant impact on the rate of wake dissipation in the EV model.

Table 10. Best-fit (P50) and range of DAWM turbine roughness values for this onshore test project. P84 and P16 refer to the 67% confidence interval, while P95 and P05 refer to the 90% confidence interval. "None" indicates the turbine roughness equals the ambient roughness.

Confidence	P95	P90	P84	P50	P16	P10	P05
Roughness (m)	None	None	None	0.75	1.094	1.176	1.281

CONCLUSIONS

This research indicates that DAWM is significantly more accurate than the EV model for large, offshore wind projects. The best-fit turbine roughness is almost identical for the two projects – 1.12 m for Horns Rev and 1.14 m for Nysted. The consensus value is 1.13 m ± 0.10 m.

For onshore wind projects, the uncertainties are much larger because of the greater variability of turbine output due to topographic and other influences, and also because the deep-array effect appears to be attenuated by the greater background roughness. Additional problems may be introduced by wakes affecting the reference wind speed measurements and by a lack of turbulence data at one project. Nevertheless, the findings suggest that deep-array effects occur at onshore projects, and the best-fit turbine roughness falls in a range (0.75 m to 1.53 m) that is broadly consistent with the offshore findings. The consensus value is 1.14 m ± 0.39 m. However, there are marked inconsistencies in the data for the third onshore project. Removing this case from the sample results in a consensus roughness value of 1.45 m ± 0.10 m.

Based on these findings, AWS Truepower recommends a turbine roughness value of 1.14 m for offshore sites and 1.30 m for onshore sites. The full set of default parameters for both offshore and inland are given in Appendix A.

ACKNOWLEDGEMENTS

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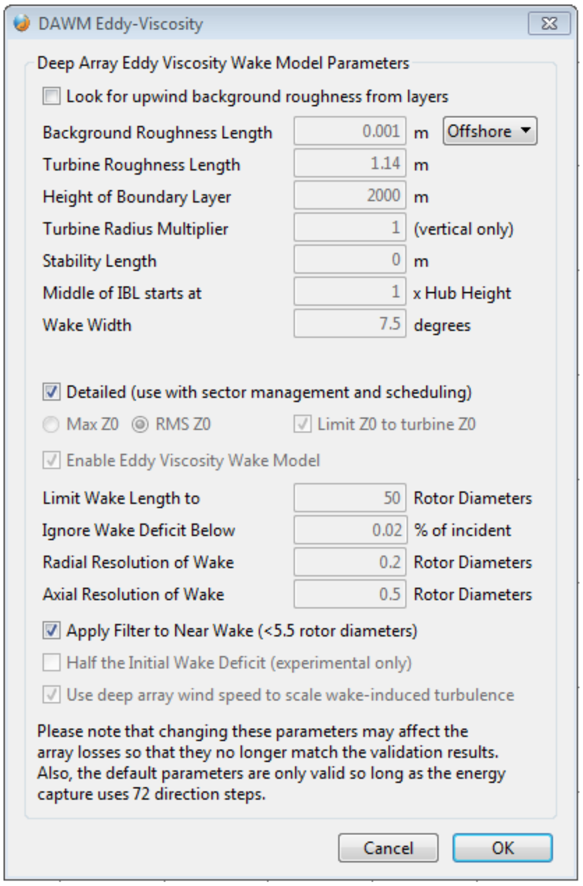
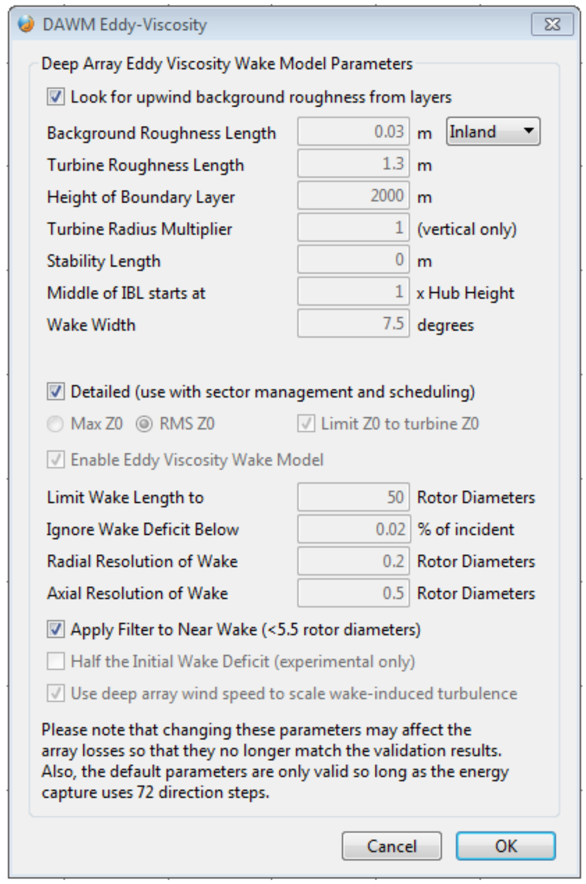
APPENDIX A

The following screenshots give the recommended values for the deep array eddy-viscosity wake model for the offshore (left) and onshore (right) cases.





The model can run faster by un-checking the "Detailed" checkbox. This option is necessary only when using sector management or turbine scheduling.