Investigation and validation of wake model combinations for large wind farm modelling in neutral boundary layers

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ABSTRACT

An original approach consisting on the combination of two wake patterns – a single wake model with a neutral boundary layer modification - is investigated in order to model large wind farm wake effect. Sensitivity studies of boundary layer parameters are carried out to optimize the velocity and power corrections whatever the type of wind farms and the wind directions. Two single wake models (Park and Fast EVM) were combined to a refined boundary layer model and validated against measurements and four standard wake models. This very promising model combination allows us to take into account the slowdown in large wind farms.

1 Introduction

When air under neutral conditions flows from one surface through a wind turbine with a different roughness, the air is slowed [1][2], an internal boundary layer growing downwind from the roughness change [3][4][5]. The region in the flow behind the turbine is called the wake of a wind turbine. Its effects are seen as wake effects.

It is thus important to evaluate and model these effects and boundary layer changes to estimate the amount of power remaining downstream of the turbine.

Wind resource softwares like WindFarmer [6], Wakefarm [7], WaSP [8][9], NTUA [10] or Meteodyn WT [11] were evaluated for small wind farms [12] or single wakes [13]. However, it has become apparent that standard single wake models as Park [14][15] and Fast EVM [16] models tend to underestimate wake losses in large wind farms as offshore arrays [17].

In this paper, an original approach consisting on the combination of two wake patterns – a single wake model with a neutral boundary layer modification - is investigated and validated against measurements and four standard wake models as in [18] in order to model large wind farm wake effect and compute velocity deficit.

2 Measurements

Wind turbine power production data from two large offshore wind farms, Horns Rev and Nysted, are used to validate our large wind farm model results as in [18]. The normalized power (with respect to the power of the first wind farm column, see figure 1) at each turbine is calculated for seven wind direction sectors centered on an exact wind farm row (ER) (270° +/- 2.5° at Horns Rev and 278° +/- 2.5° at Nysted), and for mean wind directions of +5°, +10°, and +15° and -5°, -10°, and -15° from ER. Flow down at ER thus represents the likely maximum wake effect, while the wind directions that are slightly offset from ER assist in assessing the wake width.

In both cases, wake effects is evaluated for a free-stream velocity mainly coming from the west (not shown) and equal to 8 $m.s^{-1}$ as in [18].

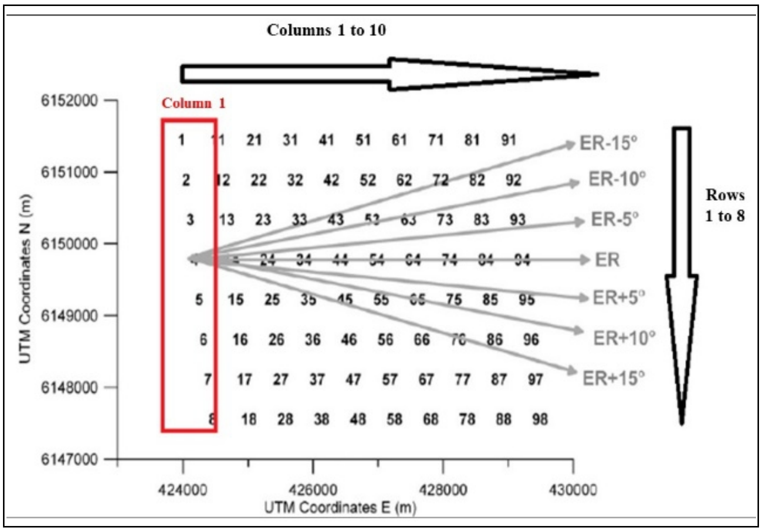

Figure 1: Horns rev wind farm layout [18].

3 Large wind farm model: parametrization and activation

Single wake models don’t consider the change of the atmospheric boundary layer by the additional roughness associated with wind turbines. An original approach consists on calculating the velocity deficit in each point of the wind farm by combining a wake effect from a single wind turbine with the boundary layer modification.

Two single wake models (Park and Fast EVM) used in Meteodyn WT software [11] and a large wind farm model taking into account inner boundary layer (IBL) modification are combined and named WT Park+IBL and WT Fast EVM+IBL.

The boundary layer profile is then expressed as a function of the equivalent roughness z'_0 and the wind position relative to the upstream turbine.

Three steps and sensitivity studies are necessary to optimize and compute the velocity deficit via combined wake models:

1. Equivalent roughness z'_0 computation
2. Boundary layer profile estimation
3. Large wind farm model activation

3.1 Roughness z'_0 influence

The equivalent roughness z'_0 is calculated with the method of Frandsen [19][20] for each wind direction and wind speed at each turbine. It depends on the spacing between two rows of wind turbines along the wind direction S_d and the crosswind direction S_c. S_c has a huge influence on the roughness (example on Figure 2 for the wind turbine WT74 at the Horns Rev with $S_d = 7$). It impacts directly the normalized power with respect to the wind turbine WT04, going down to 10% if $S_c = 3$ (see Table 1).

An algorithm has been developed to optimize S_c and S_d whatever the type of wind farms and the wind directions. Figure 3 presents an example of S_c and S_d evolutions at Horns Rev for ER incidence (other incidences not shown here).

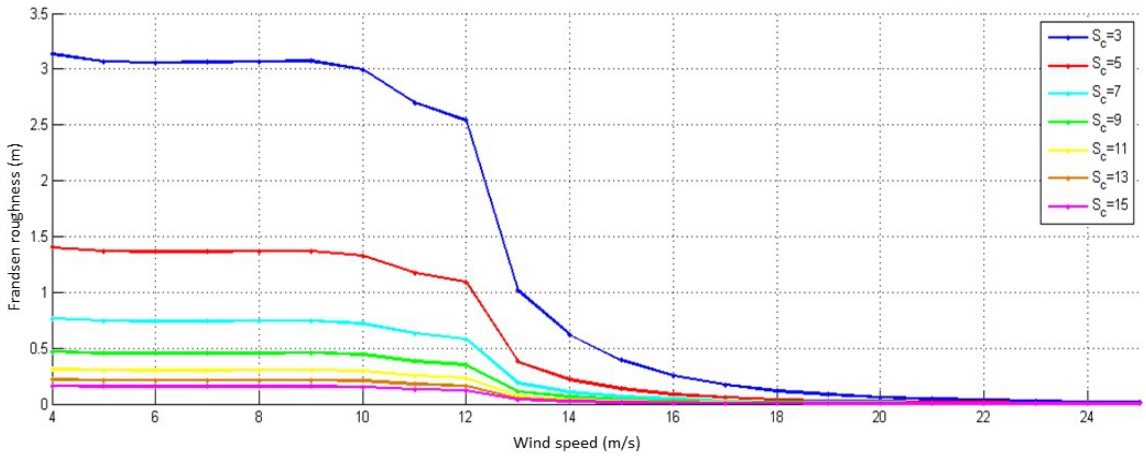

Figure 2: Frandsen roughness function of wind speed and S_c with S_d=7 at ER incidence and wind turbine WT74 at Horns Rev

S_d	S_c	z'_0(m)	Normalized power PWT74/PWT04
7	3	3.0679	0.10
7	5	1.3671	0.24
7	7	0.7433	0.30
7	9	0.4551	0.37
7	11	0.3022	0.45
7	13	0.2129	0.49
7	15	0.1570	0.53

Table 1: Normalized power evolution function of z'_0, S_c and S_d

The number of upstream wind turbines for a specific position is increasing for a wind turbine going far away from the first column of the array. S_c and S_d are homogeneous over the all wind farm considering at least one wind turbine is detected upstream. S_c and S_d has been found equal to 7 for both wind farms in Denmark.

3.2 Inner boundary layer influence

The velocity deficit coefficient correction is the ratio between the wind speed in the IBL and the wind speed taken at the same height before the roughness change. However, an offset H_{start} (function of the fetch and z'_0.) from which the boundary layer starts and the IBL height h_{ibl} influence it. Sensitivity studies of H_{start} and h_{ibl} are then carried out at Horns Rev with the two combined wake models in order to optimize wind speed and power corrections:

- As shown in Table 2, the more H_{start} is low, the more velocity and power deficits are low. On the contray to [6] proposing H_{start} = 2/3 h_{hub} (with h_{hub} the hub height), the optimum H_{start} is equal to zero, meaning the inner boundary layer influence starts from the ground.
- According to [21], $0.05h \leq h_{ibl} \leq 0.09h$, where h is the boundary layer height. Comparisons between both combined models and observations in Figure 4 show a better agreement for $h_{ibl}=0.05h$ (case B/) against 9% of h in [6]. The same is observed for all other directions, except for ER-15° and ER-10° (not shown).

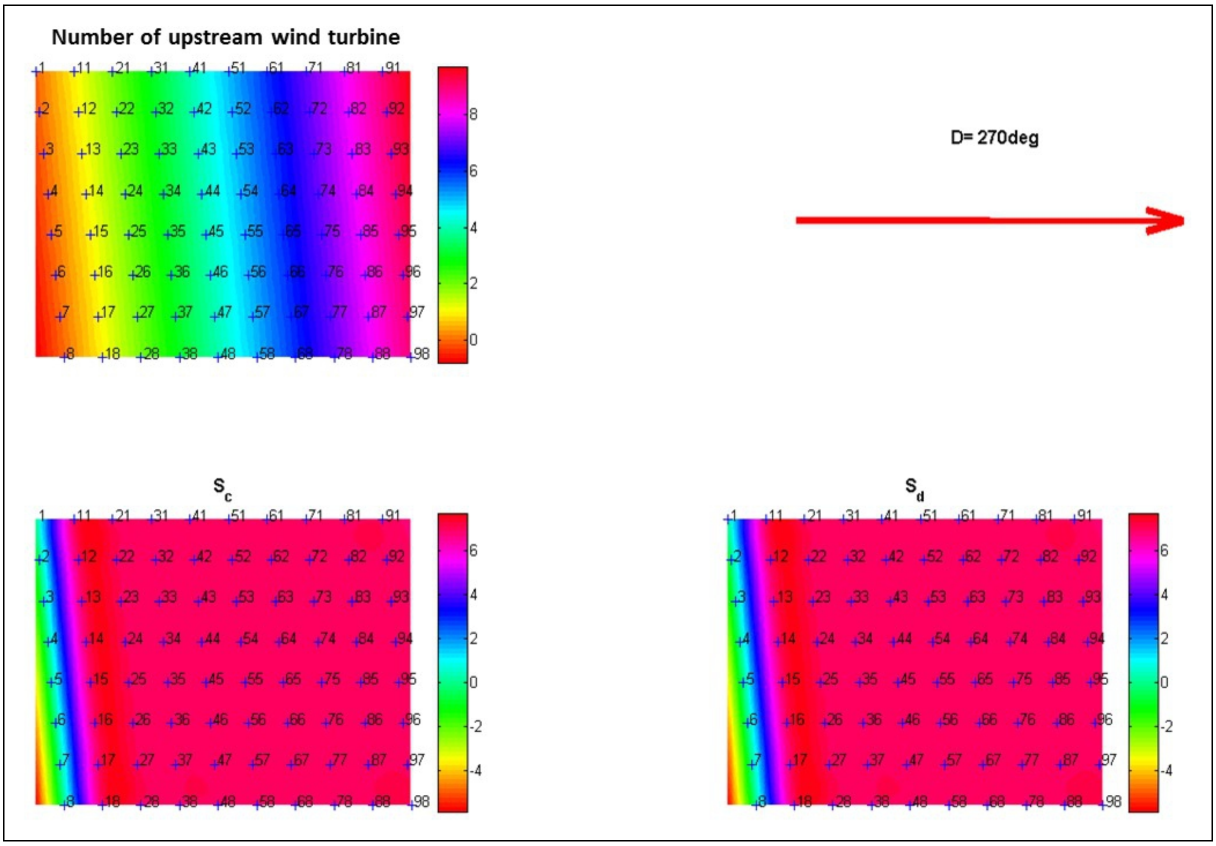

Figure 3: Evolution of S_c and S_d at ER incidence at Horns Rev

H_{start}	Correction coefficient WT74	Power correction WT74
0	0.80	0.51
1/4 h_{hub}	0.78	0.46
1/3 h_{hub}	0.76	0.43
h_{hub}-D_{rotor}/2	0.75	0.41
2/3 h_{hub}	0.73	0.37

Table 2: Evolution of wind speed and power correction function of H_{start} for the wind turbine WT74 at incidence ER at Horns Rev (WT Park+IBL model). D_{rotor} is the rotor diameter.

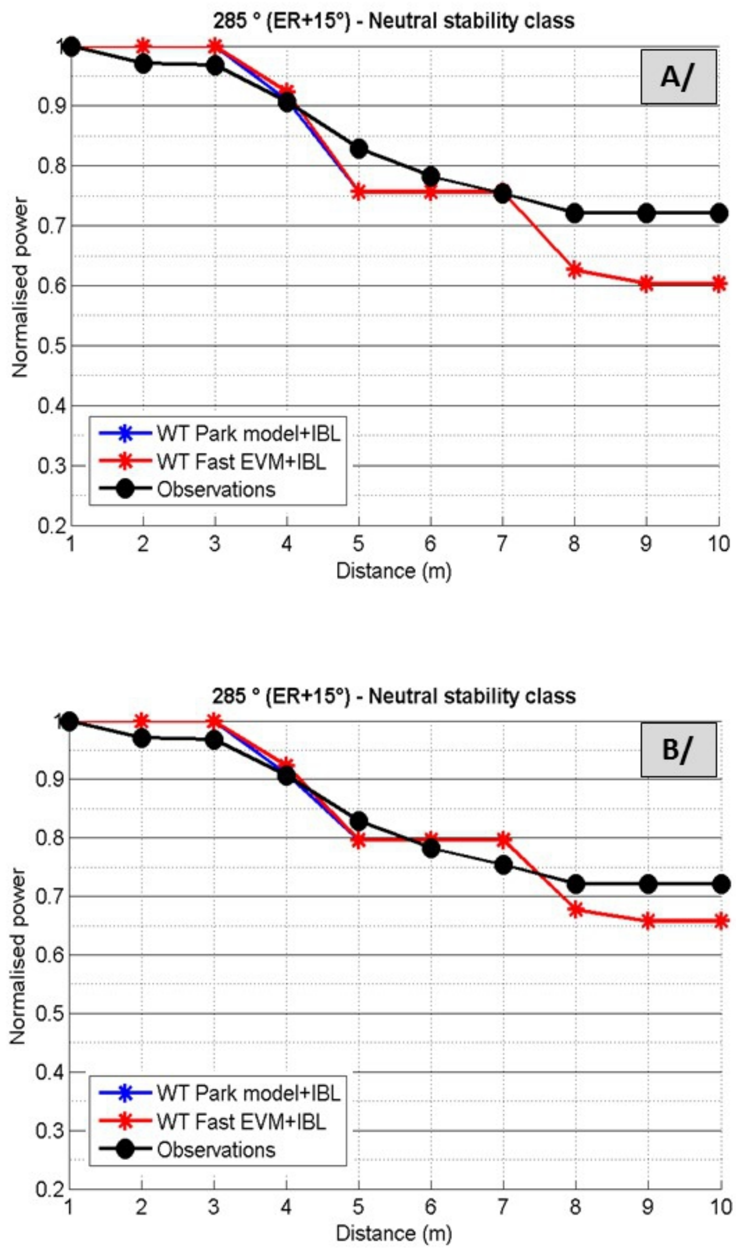

Figure 4: Normalized power at ER +15° at Horns Rev for *ibl* = 0.09 (A/) and 0.05 (B/).

All these optimized parameters are considered by default in the next validation section 4.

3.3 Large wind farm model activation

A geometric measure of turbine density is used to activate the large wind farm model. Considering the turbine density for 5° sectors, the large wind farm correction to ambient wind speed is applied if there is at least one turbine in the selected sector. Moreover, this model is always activated from the fourth wind farm column.

Finally, the velocity deficit is computed as the velocity deficit minimum taken between the large wind farm model and the single wake Park or Fast EV models.

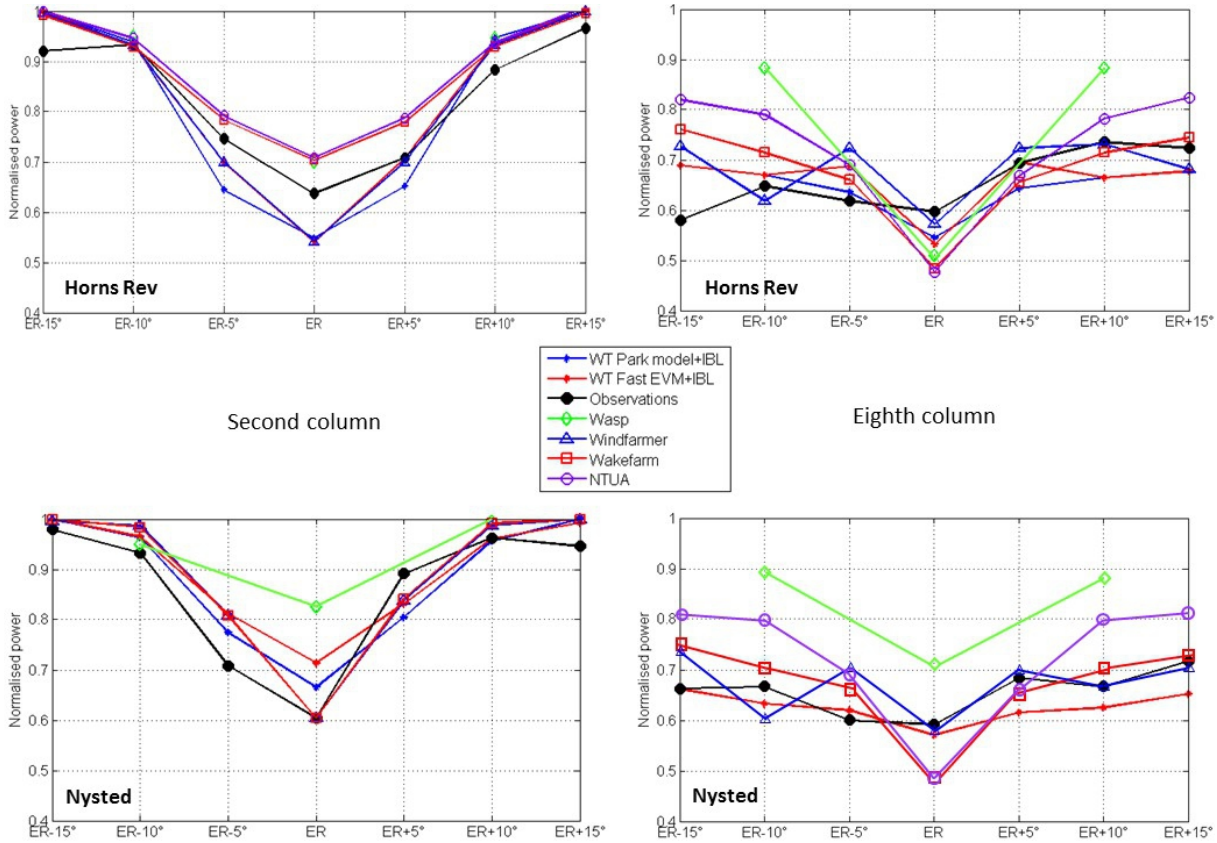

Figure 5: Mean normalized power from Horns Rev (top), Nysted (down) and model simulations for the second (left) and the eighth (right) columns of wind turbines.

4 Model comparisons with offshore wind farm data

A model intercomparison is performed at the two offshore wind farms for four different wake models as in [18] and the two combined models.

4.1 Wake width

As for other models, WT Park and Fast EVM models+IBL capture well the wake width at the second column of wind turbines (Figure 5) and show greater agreement with the observed wake depth than WaSP though both overestimate (respectively underestimate) the magnitude of the wake width at Horns Rev (Nysted).

For the entire wind farm (column 8), normalized powers of both combined models fit better with observations than other models even if they tend to overestimate (underestimate) the power for sectors less (greater) than ER.

In general, the root-mean-square error (RMSE) of normalized power shown in Table 3 indicates that WT Park+IBL and WT Fast EVM+IBL models perform better (i.e., exibit lower RMSE) for direct flow down the row (i.e, ER) than for oblique angles.

4.2 Power deficit by downwind distance

In Figures 6 and 7, both combined models appear to capture the shape of power deficit as a function of distance into both wind farms. In general, WT Fast EMV+IBL model has a very good agreement with Windfarm and WindFarmer models, being even better at an incident wind directions of 255°, 260°, 275°, 285° for Horns Rev and 263°, 268°, 273°, 283° for Nysted.

Horns Rev						
Direction (°)	WT Park+IBL	WT Fast EVM+IBL	WindFarmer	Wakefarm	WAsP	NTUA
255	0.13	0.13	0.15	0.17		0.07
260	0.05	0.04	0.05	0.07	0.17	0.11
265	0.02	0.02	0.05	0.03		0.03
270	0.05	0.06	0.04	0.08	0.06	0.08
275	0.05	0.01	0.04	0.05		0.04
280	0.02	0.03	0.03	0.03	0.11	0.03
285	0.01	0.01	0.07	0.03		0.10

Nysted					
Direction (°)	WT Park+IBL	WT Fast EVM+IBL	WindFarmer	Wakefarm	WAsP
263	0.01	0.01	0.09	0.05	
268	0.03	0.03	0.05	0.04	0.21
273	0.04	0.05	0.13	0.10	
278	0.02	0.04	0.04	0.06	0.09
283	0.04	0.03	0.04	0.03	
288	0.00	0.01	0.04	0.03	0.12
293	0.01	0.01	0.03	0.04	

Table 3: RMSE of normalized power from the models vs observations at Horns Rev (top) and Nysted (down).

5 Conclusion

Investigation for large wind farm modelling under neutral conditions have been carried out by combination of two single wake models (Park and Fast EVM) with a refined version of boundary layer models based on [6] and [21].

Sensitivity studies of IBL parameters (S_c , S_d, H_{start} and h_{ibl}) allow us to design optimum combination whatever the type of wind farms and wind directions.

The large wind farm models are then validated against measurements and four standard wake models, suggesting combined wake models well represent the losses in those wind farms.

In the future, a linear combination of single wake models with the boundary layer modification will be investigated to compute velocity and power deficits.

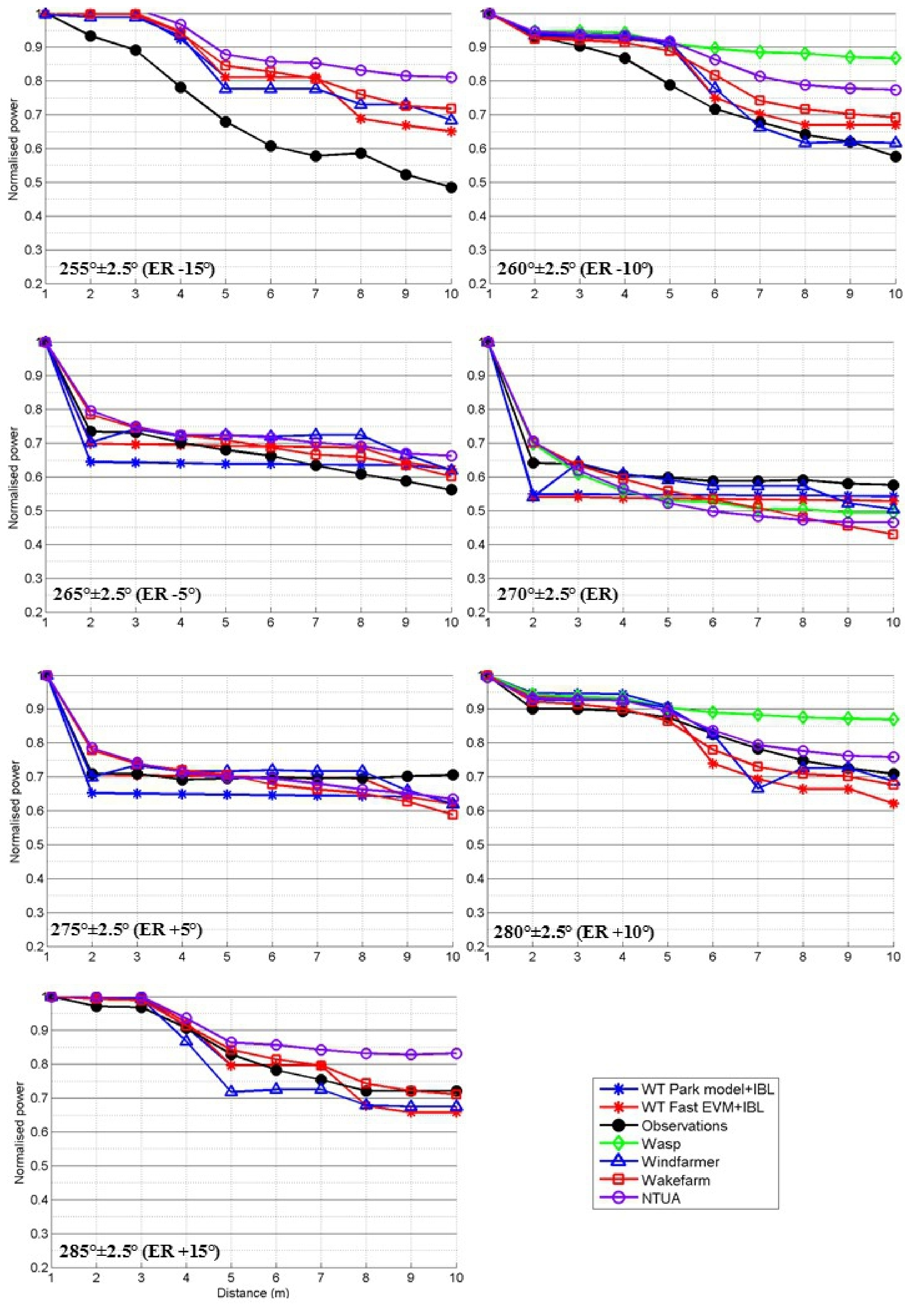

Figure 6: Normalized power at Horns Rev.

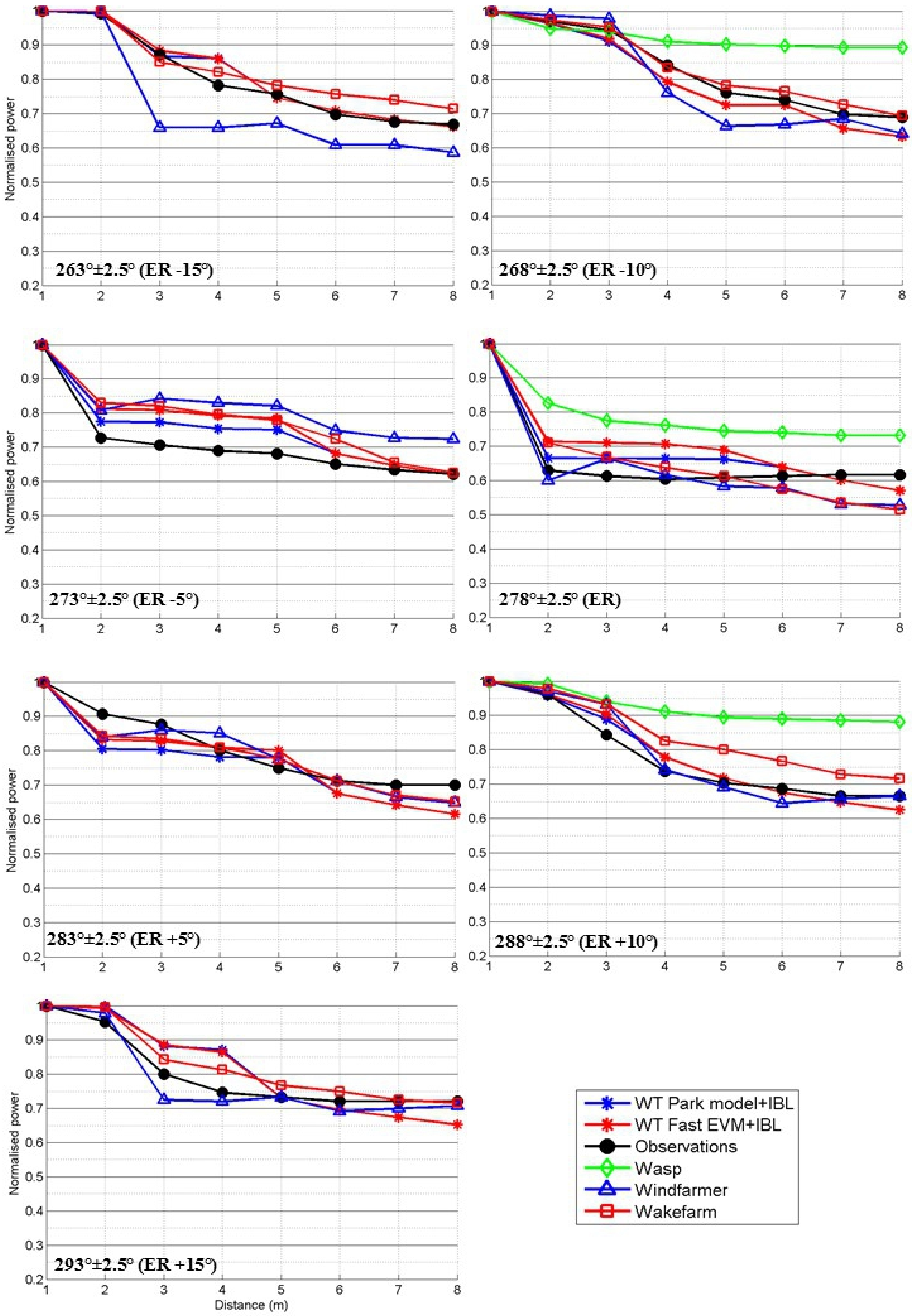

Figure 7: Normalized power at Nysted.

References

[1] Crespo, A, J. Hernandez and S. Frandsen, Survey of modelling methods for wind turbine wakes and wind farms, Wind Energy, Vol. 2, pp. 1-24, 1999.

[2] Vermeer, L.J., J.N. Sørensen and A. Crespo, Wind turbine wake aerodynamics, Progress in Aerospace Sciences, Vol. 39, pp. 467-510, 2003.

[3] Bradley, E.F., A micrometeorological study of velocity profiles and surface drag in the region modified by a change in surface roughness, Quart. J. R. Met. Soc., **94**, pp. 361-379, 1968.

[4] Jensen, N.O., Change of surface roughness and the planetary boundary layer, Qart. J. R. Met. Soc., **104**, pp. 351-356, 1978.

[5] Rao, K.S., J.C. Wyngaard and D.R. Coté, The structure of the two-dimensional internal boundary layer over a sudden change of surface roughness, J. Atmos. Sci., **26**, pp. 432-440, 1974.

[6] Schlez W., and A. Neubert, New developments in large wind farm modelling, Proc. European Wind Energy Conf., Marseille, France, EWEA PO.167, 8 p., 2009.

[7] Schepers, J.G., ENDOW: Validation and improvement of ECN's wake model, Energy Research Center for the Netherlands rep. ECN-C-03-034, 113 p., 2003.

[8] Mortensen, N.G., Heathfield, D.N., Myllerup, L., L. Landberg and O. Rathmann, Wind atlas analysis and application program: WAsP 8 help facility, Risø National Laboratory, Roskilde, Denmark, 2005.

[9] Rathmann, O., R.J.Barthelmie and S.T. Frandsen, Turbine wake model for wind resource software, Proc. European Wind Energy Conf., Athens, Greece, EWEA, BL3.313, 2006.

[10] Magnusson, M., K.G. Rados and S.G. Voutsinas, A study of the flow down stream of a wind turbine using measurements and simulations, Wind Eng., **20**, 389-403, 1996.

[11] Li, R., D. Delaunay, and Z. Jiang, A new Turbulence Model for the Stable Boundary Layer with Application to CFD in Wind Resource Assessment, EWEA Proceedings, 9 p., Paris, France, 17-20 November, 2015.

[12] Barthelmie, R.J. And Coauthors, Efficient development of offshore windfarms (ENDOW): Modelling wake and boundary layer interactions, Wind Energy, **7**, 225-245, 2004.

[13] Barthelmie, R.J., Folkerts, L., Rados, K., Larsen, G.C., Pryor, S.C., Frandsen, S., B. Lange, and G. Schepers, Comparison of wake model simulations with offshore wind turbine wake profiles measured by sodar, J. Atmos. Oceanic Technol., **23**, 88-901, 2006.

[14] Jensen, N.O., A note on wind generator interaction, Technical report from the Risø National Laboratory (Risø-M-2411), Roskilde, Denmark, 16 p., 1983.

[15] Katic, I., J, Hojstrup, N.O. Jensen, A simple model for cluster efficiency, EWEC Proceedings, Rome, Itally, 5 p., 1986.

[16] Ainslie, J.F., Calculating the flowfield in the wake of wind turbines, I. Wind Eng. And Ind Aero., Vol. 27, pp. 213-224, 1988.

[17] Beaucage, P., Robinson, N., M. Brower and C. Alonge, Overview of six commercial and research wake models for large offshore wind farms, EWEA Proceedings, 10 p., Copenhagen, Germany, 16-19 April, 2012.

[18] Barthelmie, R.J., Pryor; S.C., Frandsen, S.T., Hansen, K.S., Schepers, J.G., Rados, K., Schlez, W., Neubert, A., L.E. Jensen and S. Neckelmann, Quantifying the Impact of Wind Turbines Wakes on Power Output at Offshore Wind Farms, Journal of Atmospheric and Oceanic Technology, Vol. 27, pp. 1302-1317, 2010.

[19] Frandsen, S., Barthelmie, R., Pryor, S., Rathmann, O., Larsen, S., Højstrup, J., and M. Thøgersen, Analytical modelling of wind speed deficit in large offshore wind farms. Wind Energy, 9, 2006.

[20] Frandsen, S.T., Turbulence and Turbulence-Generated Structural Loading in Wind Turbine Clusters, Technical report from the Risø National Laboratory (Risø-R-1188), Roskilde, Denmark, 130p., 2007.

[21] Larsen, Søren Ejling; Mortensen, Niels Gylling; Sempreviva A. M.; Troen, Ib.; Response of neutral boundary layers to changes of roughness, Meteorology and Wind Energy Department. Annual Progress Report. 1 January - 31 December 1987 (pp. 15-43). Risø National Laboratory, Denmark. Forskningscenter Risoe. Risoe-R; No.560), 1988.