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Preface

This report describes the revised Park-model, Park2, and the validation and calibration of it. The Park2 model is implemented the WAsP 12 software package.

Roskilde, April 2018

Ole Steen Rathmann
Senior Researcher

Content

Summary

The WAsP Park wake model has been revised to ensure physical consistency. For off-shore conditions the revised Park2 wake model has been calibrated and validated against production data from a number of off-shore wind farms. For on-shore conditions, the Park2 wake model has been calibrated against predictions by the original Park model for a number of on-shore wind farms. The calibrations have resulted in recommended values for the wake decay constant of the revised Park2 wake model.

1. Introduction and Background

The DTU Wind Energy Wind Atlas and Analysis and Application Program (WAsP) has for a long time used the Park wake model – hereafter referred to as Park1 - to calculate wake effects within wind farms. Park1, originally a stand-alone program (Katic et al., 1986), (Sanderhoff, 1983), is based on the so-called NOJ wake model (Jensen N.O., 1983) that uses a simple top-hat speed profile in the wake downwind of a wind turbine, the wake expanding simply linearly like a cone. However, for the interaction of wakes inside a wind farm, Park1 does not follow the NOJ wake model strictly, but uses an empirical procedure. The empirical procedure consists of an unconventional formulation of the speed deficit contribution from a certain in-farm wind turbine (in-farm: a turbine itself in the wake of another turbine), and a wake superposition model based on a quadratic summation rule for adding speed deficit contributions. In addition, wake interaction with the ground or water surface is represented by simple reflection. Others have adapted the same formulation (Nygaard 2015).

The empirical procedure, however, has a consistency flaw since it will predict a ghost-turbine[1] to have an unphysical effect on turbines downwind of it. Thereby a ghost-turbine will also have an unphysical effect on the total production of the wind farm.

Park2 is a revision of the Park1-model, still with the simple wake representation by a top-hat profile based on the NOJ-model, but with a changed speed deficit and wake interaction formulation that removes the consistency flaw.

2. The consistency flaw of Park1

The original Park1 model was based on the NOJ-wake model (Jensen 1983), and below we will give the most relevant details from this formulation.

2.1 The NOJ formulation

In his original publication, N.O.Jensen (Jensen, 1983, eq.2) states the following approximate expression for the speed in the wake at a distance x downwind of a single turbine:

$$V(x) = U_0\left(1 - 2a\left(\frac{R}{R+kx}\right)^2\right) \qquad \text{(2.1.1a),}$$

corresponding to a speed deficit of

$$\Delta V(x) = U_0 - V(x) = U_0 2a\left(\frac{R}{R+kx}\right)^2 \qquad \text{(2.1.1b)}$$

Here a is the factor of influence with $2a = 1-\sqrt{1-C_t}$ where C_t denotes the thrust-coefficient[2]. (In his publication Jensen actually uses the optimum value a=1/3). R of course denotes rotor radius $=½D$, and k is a wake decay constant. A top-hat speed-deficit profile is assumed where inside the wake of diameter $R_i + k(x - x_i)$ the speed deficit has a value as given by eq. (2.1.1b) but is zero outside the wake.

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[1] Ghost-turbine: A turbine with zero or very small thrust and power production for all wind speeds.

[2] Thrust on the rotor $T = ½\rho_{air} A^{rotor} V^2 * C_t$

Further, in the same publication (eq.7) N.O.Jensen states the following approximate expression for the incident wind speed at rotor #2 in a single row along the wind speed under the impact of the two upwind turbines #0 and #1:

$$\frac{V_2^{inc}}{U_0} = 1 - \left(1-(1-2a)\frac{V_1^{inc}}{U_0}\right)\left(\frac{R}{R+k\Delta x_{1,2}}\right)^2 \qquad (2.1.2)$$

This corresponds to a speed deficit of

$$\Delta V_2^{inc} = U_0 - V_2^{inc} = \left(U_0 - V_1^{inc}(1-2a)\right)\left(\frac{R}{R+k\Delta x_{1,2}}\right)^2 \qquad (2.1.3)$$

Here it should be observed that Jensen's eq.(7) is stated as an approximation to the resulting reduced wind speed – i.e. eq.(2.1.3) above should be seen as an approximation to the total speed deficit originating from the wakes of turbine #0 and #1.

2.2 Park1 formulation

In the original Park model (Katic et al. 1986; Sanderhoff 1993) as well as in the present WAsP/Park model (WAsP8-WAsP11) the wake speed deficit originating from a certain in-Park turbine #i, based on the NOJ-wake model (Jensen 1983), is taken to be

$$\Delta V_i(x) = \left(U_0 - V_i^{inc}\sqrt{1-C_t(V_i^{inc})}\right)\left(\frac{D_i}{D_i+2k(x-x_i)}\right)^2 \qquad (2.2.1)$$

Here x is the downwind coordinate (x_i being the x-coordinate of turbine #i) and V_i^{inc} is the incident wind speed on rotor #i, and as in the NOJ-model a top-hat speed-deficit profile is assumed. It should be noticed that the turbine thrust coefficient C_t is evaluated on basis of the incident wind speed at a turbine (NOT on basis of the free wind speed).

For the incident wind speed at some turbine #j, downwind of turbine #i, a factor is included to account for partial overlap between the wake and the rotor area of turbine #j:

$$\Delta V_i^{eff}(x_j) = \Delta V_i(x_j)\frac{A_{i,j}^{overlap}}{A_j^{rotor}} \qquad (2.2.2)$$

The resulting incident wind speed at a rotor #j is found using an empiric quadratic summation rule for all the speed deficits of all relevant wakes (originating from upwind turbines):

$$V_j^{inc} = U_0 - \sqrt{\sum_i^{upwind\ turbines} \Delta V_i(x_j)^2} \qquad (2.2.3)$$

As wake interaction with the surface is represented as simple reflection, the sum in the above eq.(2.2.3) includes wakes originating from real turbines as well as from "reflected turbines", i.e. turbines with the same horizontal positions as the real turbines but with a formal hub-height of $-h_i$ (h_i being the hub height of real turbine #i).

Others have adopted that same formulation (e.g. Nygaard, 2015).

The above empirical formulation has the obvious unphysical consequence – *inconsistency* – that a "ghost-turbine" will have a speed-deficit impact just from the fact that it has a non-zero incident speed deficit, i.e. if $U_0 - V_i^{inc} > 0$. It is obvious that a physical formulation should fulfil the requirement that the speed deficit impact from some turbine should tend to zero when the C_t of that turbine tends to zero.

Now, simple inspection reveals that eq.(2.2.1) is in fact identical to Jensen's eq.(2.1.3), and it is tempting to think that the inspiration to use eq.(2.2.1) is in fact Jensen's eq.(7) – or eqs.(2.1.2) and (2.1.3) above.

However, where Jensen's eq.(7) and eq.(2.1.3) is an approximation to the total speed deficit (from wakes #0 and #1), eq.(2.2.1) is used as the contribution from just a single upwind turbine: the total resulting speed deficit is obtained by combining the contributions from the individual wakes from upwind turbines using quadratic summation, eq.(2.2.3). Thus, by using eqs.(2.2.1)-(2.2.3) the impact of upwind turbines is in fact included twice. Consequently, we do not consider it correct to use formulation (2.2.1).

The relative success of the inconsistent formulation (2.2.1)-(2.2.3) could be due the use of quadratic summation, which mainly considers the large contributions and thus counteracts the double inclusion of upwind wake effects as described above.

3. Park2: The consistent formulation.

As stated previously, in the Park2 model we stick to the simple NOJ single-wake model with its top-hat profile and its linear wake expansion.

Now, contrary to Park1, the Park2 model takes the partial effect of a certain turbine to be equal to the wake effect downwind of that turbine in the following virtual situation: (1) had there been no other turbines, and (2) had the virtual free wind speed been the actual incident wind speed at that turbine.

Thus, based on eq.(2.1.1b), the partial speed deficit originating from a certain turbine #i is

$$\Delta V_i(x) = V_i^{inc}\left(1-\sqrt{1-C_t(V_i^{inc})}\right)\left(\frac{D_i}{D_i+2k(x-x_i)}\right)^2 \qquad \text{(3.1 a)}$$

For easy notation we introduce the wake diameter $D_i^{wake}(x) = D_i + 2k(x-x_i)$, thus

$$\Delta V_i(x) = V_i^{inc}\left(1-\sqrt{1-C_t(V_i^{inc})}\right)\left(\frac{D_i}{D_i^{wake}(x-x_i)}\right)^2 \qquad \text{(3.1 b)}$$

This formulation (3.1) ensures consistency since a C_t tending to zero will imply that ΔV_i tends to zero as well.

When estimating the combined effect of overlapping wakes Park2 uses classical perturbation theory, thus assuming that, at some point, the *speed-deficit effects from the individual turbines are sufficiently small that they may be simply added*. In other words, we apply a linear wake superposition.

So, taking into account the effect of partial overlap between a wake and a rotor we find the resulting incident wind speed at a turbine #j

$$V_j^{inc} = U_0 - \sum_i^{upwind\ turbines} \Delta V_i(x_j)\frac{A_{i,j}^{overlap}}{A_j^{rotor}} \qquad \text{(3.2)}$$

Here A^{rotor} and $A^{overlap}$ denote the rotor area and the area of the part of the partial wake overlapping the rotor, respectively.

3.1 Surface reflection

The Park1 model (Katic et al., 1986), (Sanderhoff, 1983) used surface reflection of the individual wakes to represent the interaction with ground- or water-surface. The reflected wakes were then treated as “additional wakes” added up together with “true” wakes in the wake superposition procedure.

However, use of surface reflection together with the consistent formulation and using linear wake superposition (eqs. (3.1), (3.2)) seems problematic. Initial investigations (section 4.2) showed that very large values of the wake decay constant would have to be assumed to get results similar to what has been observed in large off-shore wind farms.

In addition, CFD-studies (Ott, 2011, Ott, 2014) have indicated that the wake-interaction with the surface is not described correctly by simple reflection since the wake expansion is a diffusion-like process occurring in a flow with a log-like vertical profile. Consequently, the speed deficit must tend to zero at the surface, which is not fulfilled by a reflection model. Hence, in Park2 *wake surface reflections are simply omitted*.

4. Selected Off-shore Wind Farm Data for Comparison

Operational data from three “primary” Danish and Swedish off-shore wind farms, including production details for individual turbines, have been used for qualitative validation and calibration of the Park2 model:

a) The Horns Rev wind farm, 1.Jan. 2005 – 31.Dec. 2009;
b) the Nysted wind farm, 24.May 2004 – 16.Nov.2006; and
c) the Lillgrund wind farm. 1.Jan. 2008 – 31.Dec. 2012.

Data from a “secondary“ wind farm was included, but only as a reference regarding total wind farm production: Anholt wind farm, Jan.2013-June 2015.

Wind farm	Country	Number of turbines	Turbine			Wind farm rated power (MW)	Comparison use
			Rated power (MW)	Hub height (m)	Rotor diameter (m)		
Primary Wind Farms							
Horns Rev 1	DK	80	2	69	80	160	Turbine power production
Nysted	DK	72	2.33	69	82	167.8	
Lillgrund	S	48	2.3	65	92.6	110.4	
Secondary wind farm							
Anholt	DK	111	3.6	81.6	120	399.6	W.F.power production, for reference only

The locations and the layouts of the wind farms are shown below.

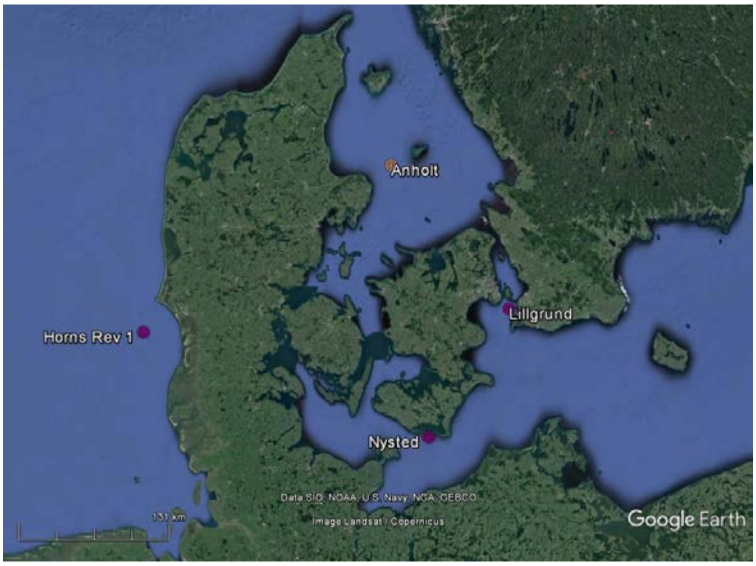

Figure 1. Locations of the wind farms used in this study.

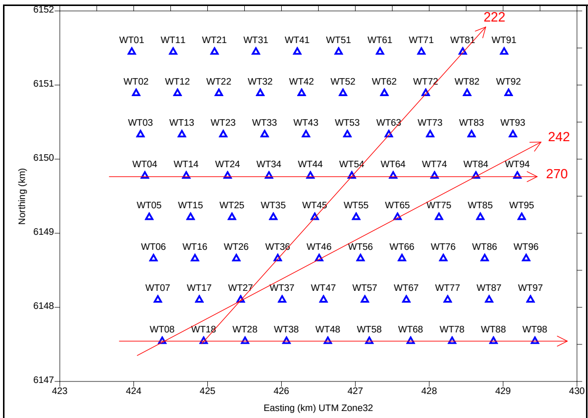

Figure 2. The Horns Rev wind farm layout with selected wind directions.

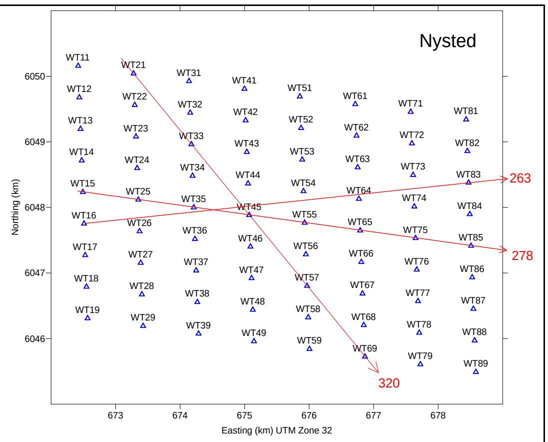

Figure 3. The Nysted wind farm layout with the selected wind directions.

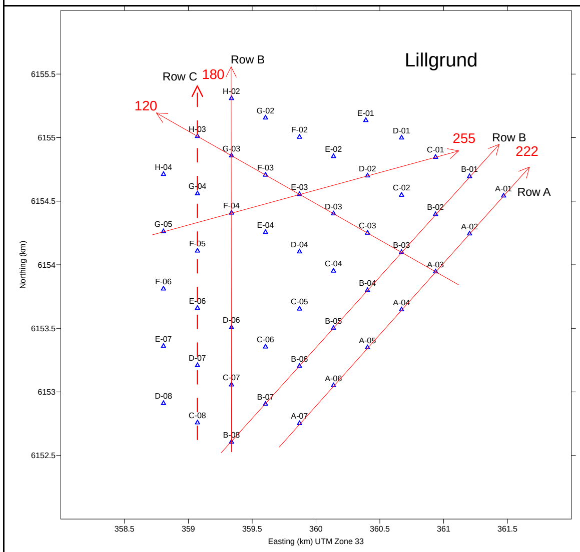

Figure 4. The Lillgrund wind farm layout with the selected wind directions.

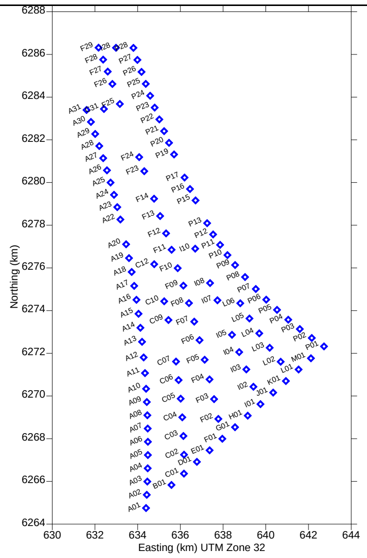

Figure 5. The Anholt wind farm layout.

For each of the three primary wind farms, a number of flow cases have been selected and used for validation and calibration. For all three wind farms the following three speed-cases were used:

Hub-height Wind Speed		
8.0 +/- 0.5 m/s	10.0 +/- 0.5 m/s	12.0 +/- 0.5 m/s

Each wind speed case was used in combination with 3 or 4 wind direction-cases:

	Hub-height Wind Direction			
Horns Rev 1	222.0 +/- 7.5 °	242.0 +/- 7.5 °	270.0 +/- 7.5 °	
Nysted	263.0 +/- 7.5 °	278.0 +/- 7.5 °	320.0 +/- 7.5 °	
Lillgrund	120.0 +/- 7.5 °	180.0 +/- 7.5 °	222.0 +/- 7.5 °	255.0 +/- 7.5 °

5. Qualitative comparison of the effect of Park2-features to offshore windfarm data

As an initial test the above primary off-shore wind farm flow cases were used in a comparative study to see the separate effects of the 3 features introduced relative to Park1: a) Consistent formulation; b) Linear wake-superposition; c) Omission of surface reflection.
Predictions were made for these flow cases in four steps: by the Park1-model, by hybrid models, where first feature a) and then feature b) are introduced; and by the Park2 model (all features a) b) and c) introduced):

Step		Speed-deficit Formulation	Wake superposition	Wake Surface-reflection
0	Park1 standard	Inconsistent	Quadratic	YES
I	Park hybrid B	Consistent	Quadratic	YES
II	Park hybrid C	Consistent	Linear	YES
III	Park2	Consistent	Linear	NO

The following wake decay constants were used: Park1 and Park hybrid B: Park1 recommended value (k =0.05); Park hybrid C: the value giving closest agreement (k =0.14); Park2: the value, later found to be recommended (k =0.06). The model predictions were averaged over the same speed- and direction intervals as those used for sampling observations within each flow case. The results are shown below.

5.1 Test results

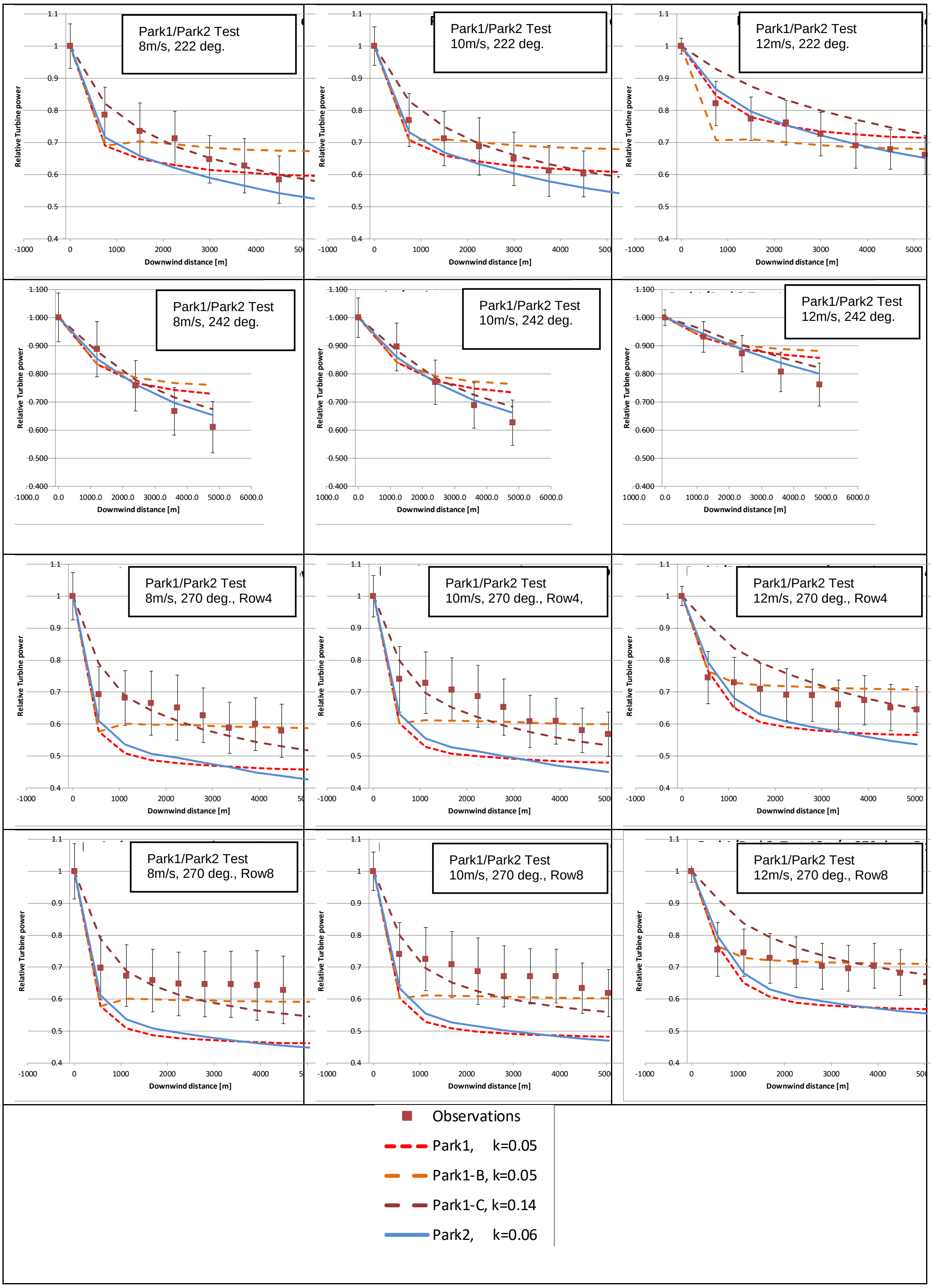

Figure 6. Horns Rev 1 – Effect of Park2-features a), b) and c), introduced one by one, compared to Park1 and to observations.

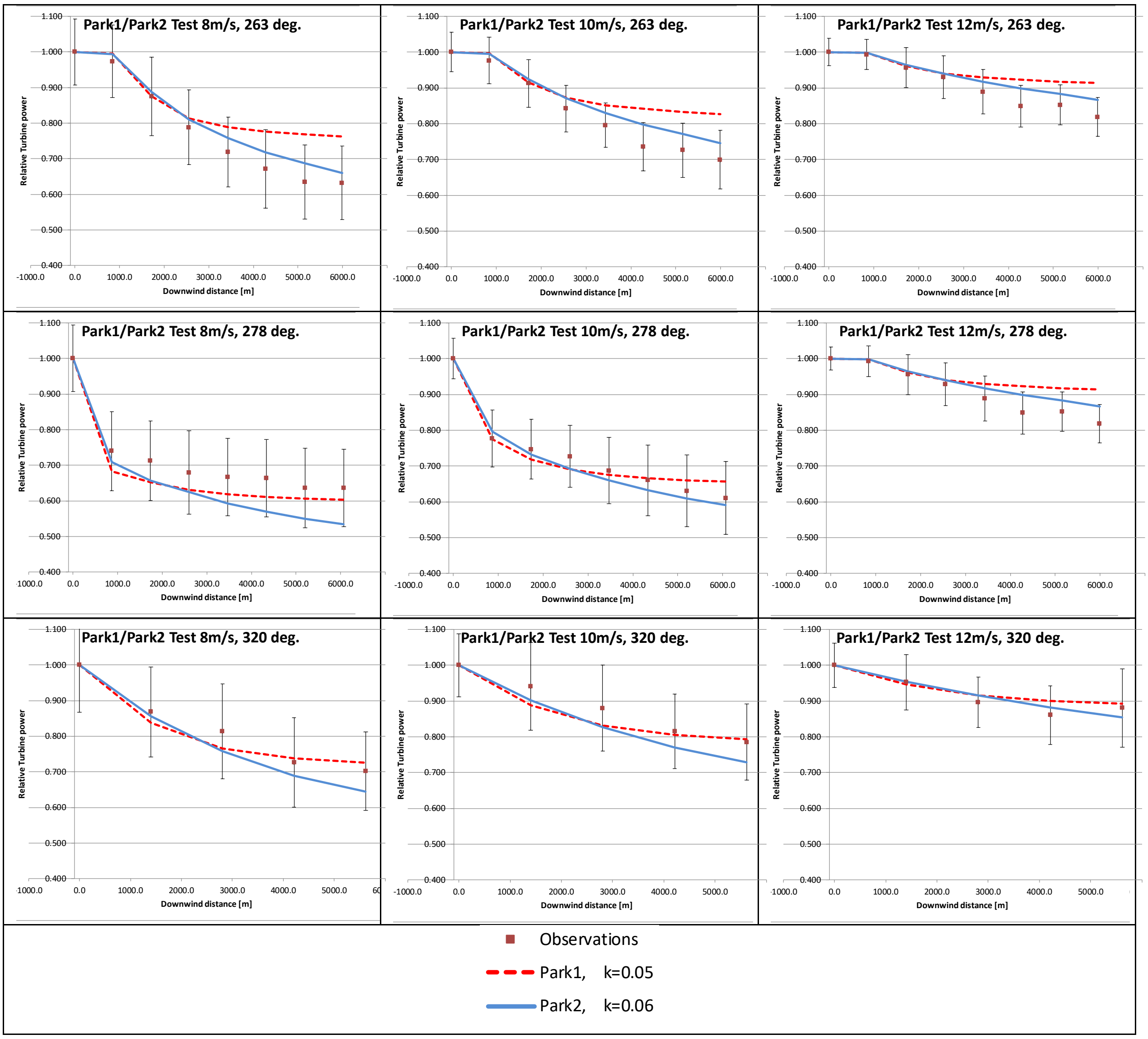

Figure 7. Nysted – Effect of all Park2-features, a)+b)+c), compared to Park1 and to observations. Only the results of step 0 and step III are shown.

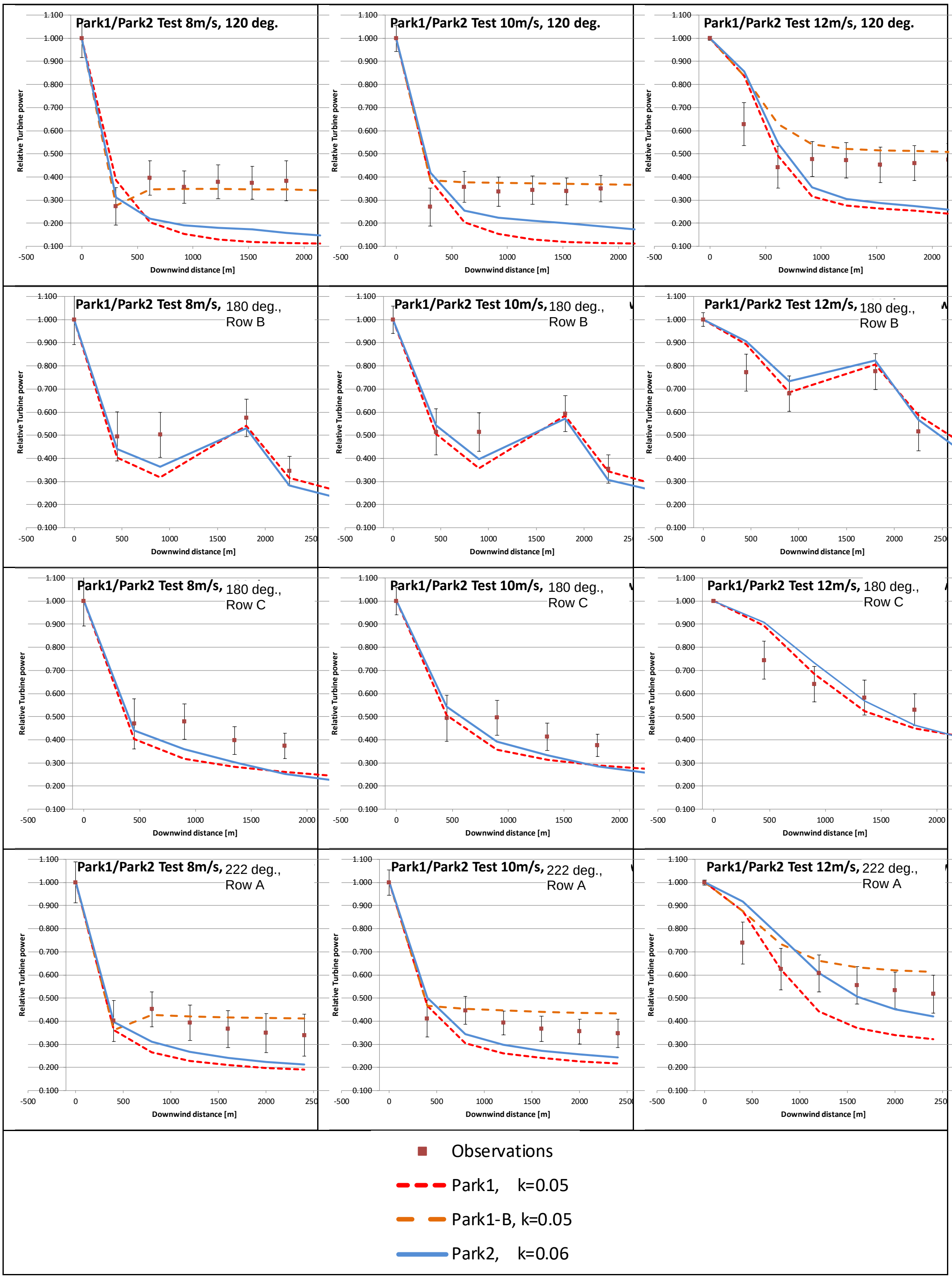

Figure 8. Lillgrund – Effect of Park2-features. (To continue on the following page.)

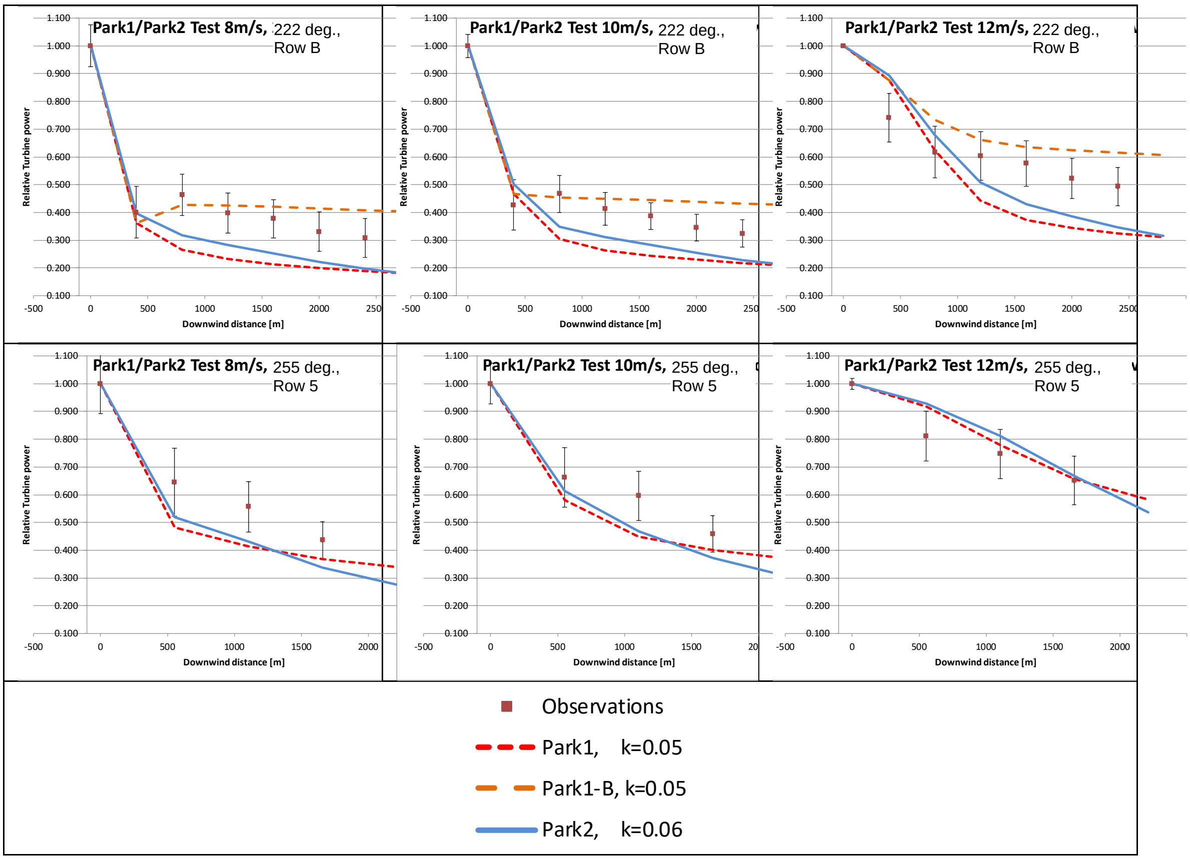

Figure 8. Lillgrund – Effect of Park2-feature a) (Park1-B) and features a)+b)+c) (Park2) compared to Park1 and to observations. Only the results of steps 0, I and III are shown.

5.2 Findings from the qualitative comparisons of the effect of the Park2-features

- The consistent speed-deficit formulation in combination with *quadratic wake superposition* (Park hybrid B) does not represent properly the way the turbine power production decreases downwind into the wind farm. Park hybrid B predicts the power production to drop from the first to the second turbine – but thereafter nearly without any further decrease; this is in contradiction to the observations which show a gradual decrease in turbine power production downwind along a turbine row. When introducing linear speed deficit summation the predicted downwind decrease of turbine power production resembles the observations to a much higher degree.
- The consistent speed-deficit formulation in combination with linear speed-deficit summation rule, but still with wake surface reflection (Park hybrid C), requires a very high wake decay constant value (k=0.14) in order to match the observed power production deficits. However, from eddy-diffusivity arguments (Rathmann, 2017) the k -value should have a clearly lower value like the ones found to match observations when surface reflection is omitted. This – together with the aerodynamic arguments already presented in section 3.1 – supports the decision to omit surface reflection in the Park2 model.

6. Quantitative validation and calibration of Park2 based on offshore wind farms.

This validation and calibration study (Murcia, 2017b) was based on production time series from the offshore wind farms Horns Rev, Nysted, Lillgrund and Anholt. The time series were preprocessed to avoid impact from the situations where one or more turbines were out of operation. The Park2-model was represented by a number of farm-specific look-up tables of total wind farm production as a function of hub-height wind speed and wind direction. The look-up tables covered a k-value range of 0.05 ... 0.16. A so-called Bayesian calibration procedure (Kennedy, 2001; Murcia, 2017a) was applied to deduce the k-value to be recommended. In short, for each single observation of wind farm production a probability density function, PDF, for k was calculated on basis of the look-up tables. By then combining the PDFs for all production observations, taking into account the uncertainty of these observations, a “total” Gaussian-like PDF for k was constructed, resulting in a mean value and a spread of the k-value, see table 7.1 and fig. 9.

	Wind farm	µ	σ
	Horns Rev 1	0.061	0.005
	Nysted	0.057	0.007
	Lillgrund	0.064	0.004
Recom-mended value	All	0.06	0.006
	Anholt	*0.051*	*0.006*

Table 8.1. Results for the Bayesian calibration of k.

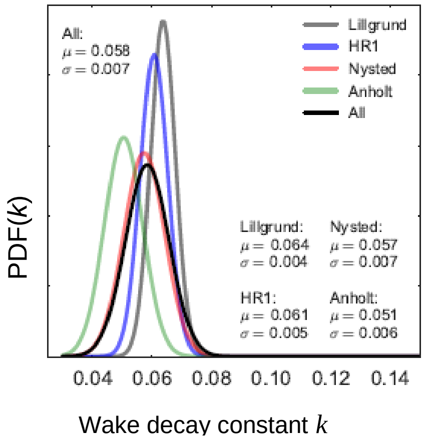

Figure 9. PDF of the k-value (Bayesian calibration)

The wind field over the Horns Rev 1, Nysted and Lillgrund wind farms may be assumed rather homogeneous, whereas the wind field over the Anholt wind farm is known to have large gradients due to variations in the distance to nearest coast – gradients not taken into account when producing the look-up tables for the Anholt wind farm. The k-value to recommend for offshore wind farms is therefore based on the results for Horns Rev, Nysted and Lillgrund only, as given in table 8.1.

It should be noted that the deduced k-value for Anholt – although differing somewhat from the recommended value – within error bars in fact overlaps with the recommended value.

7. Qualitative Validation of Park2 against offshore wind farm data.

A validation for off-shore with a series of candidate k-values (0.05, 0.06, .., 0.10), including the recommended value, was performed using the observations for the off-shore wind farm flow cases listed in section 4. In the model predictions speed- and direction-averaging were applied over the same speed- and direction intervals as those used for sampling observations within each flow-case. The results of this validation are shown in the following plots.

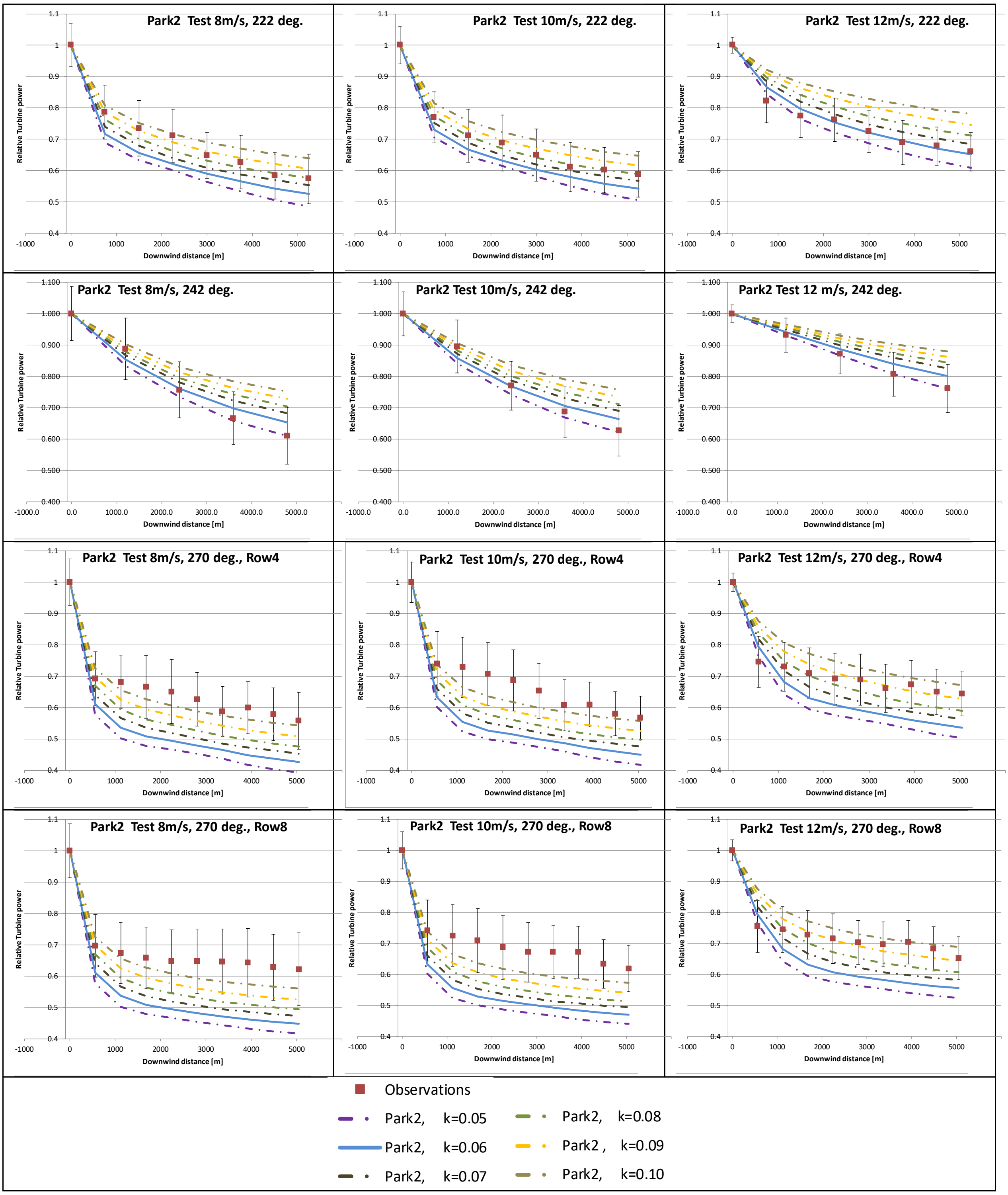

Figure 10. Horns Rev 1. Qualitative validation of Park2 with various k-values.

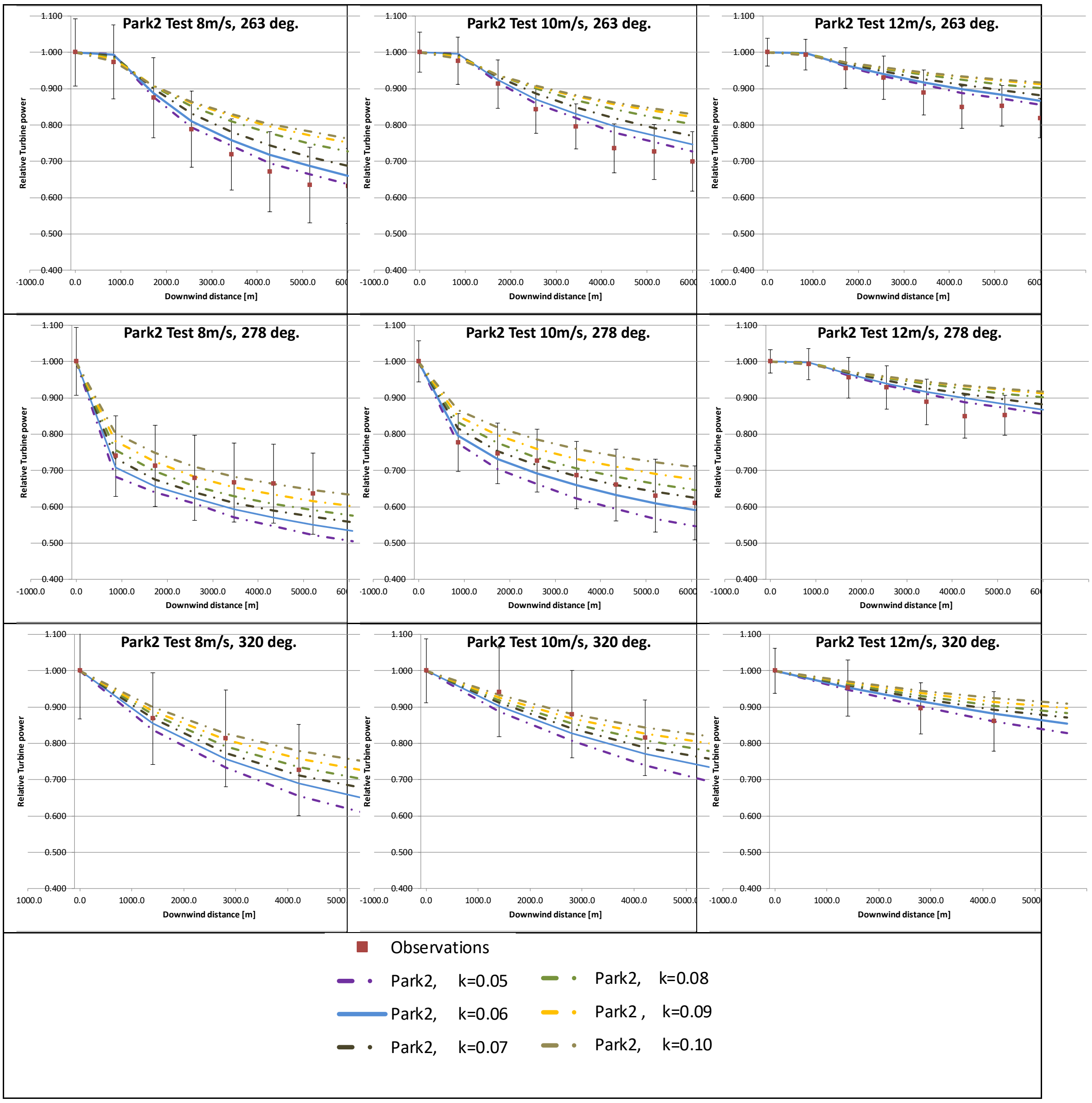

Figure 11. Nysted. Qualitative validation of Park2 with various k-values.

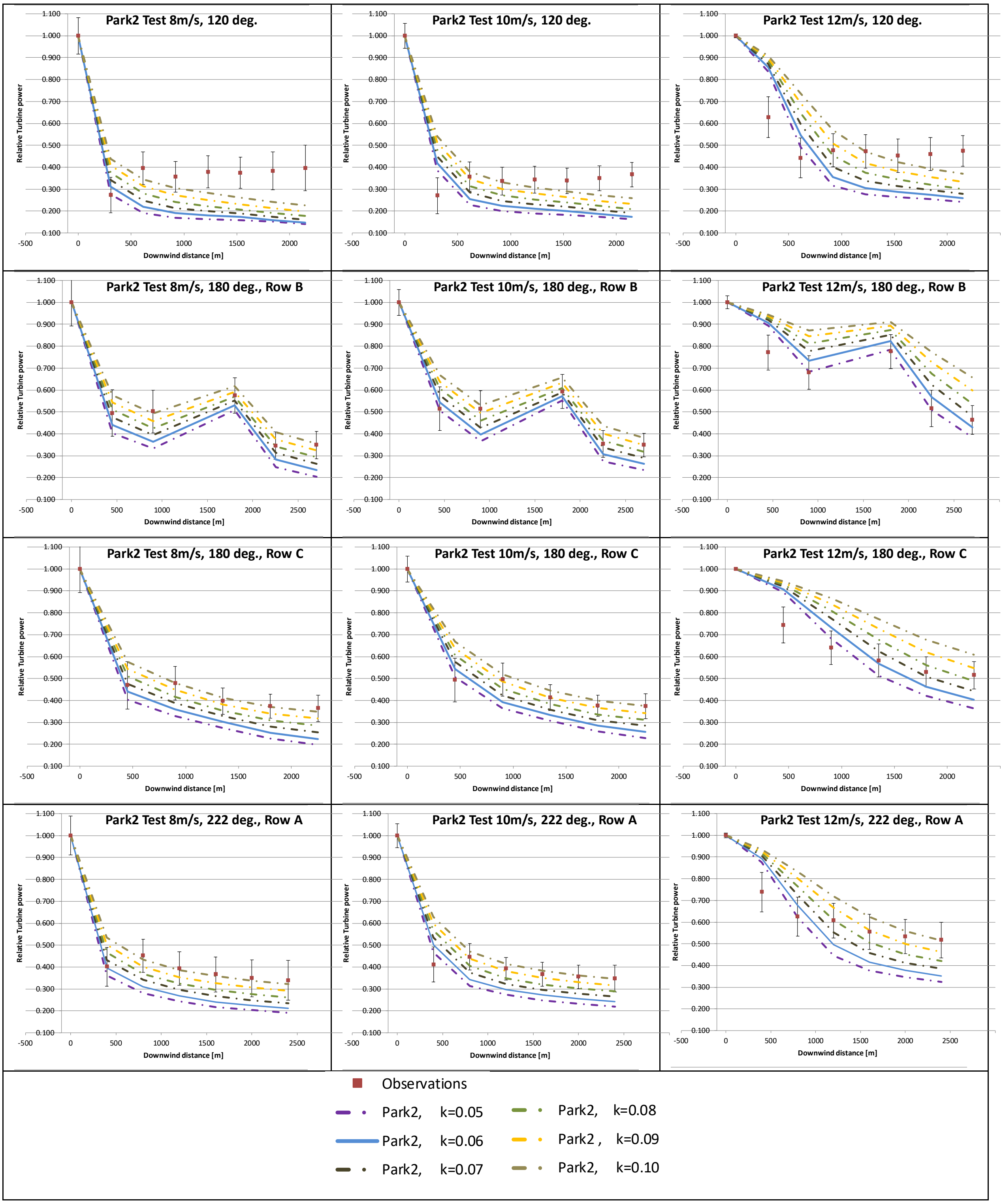

Figure 12. Lillgrund. Qualitative validation of Park2 with various k-values. (To continue on the following page.)

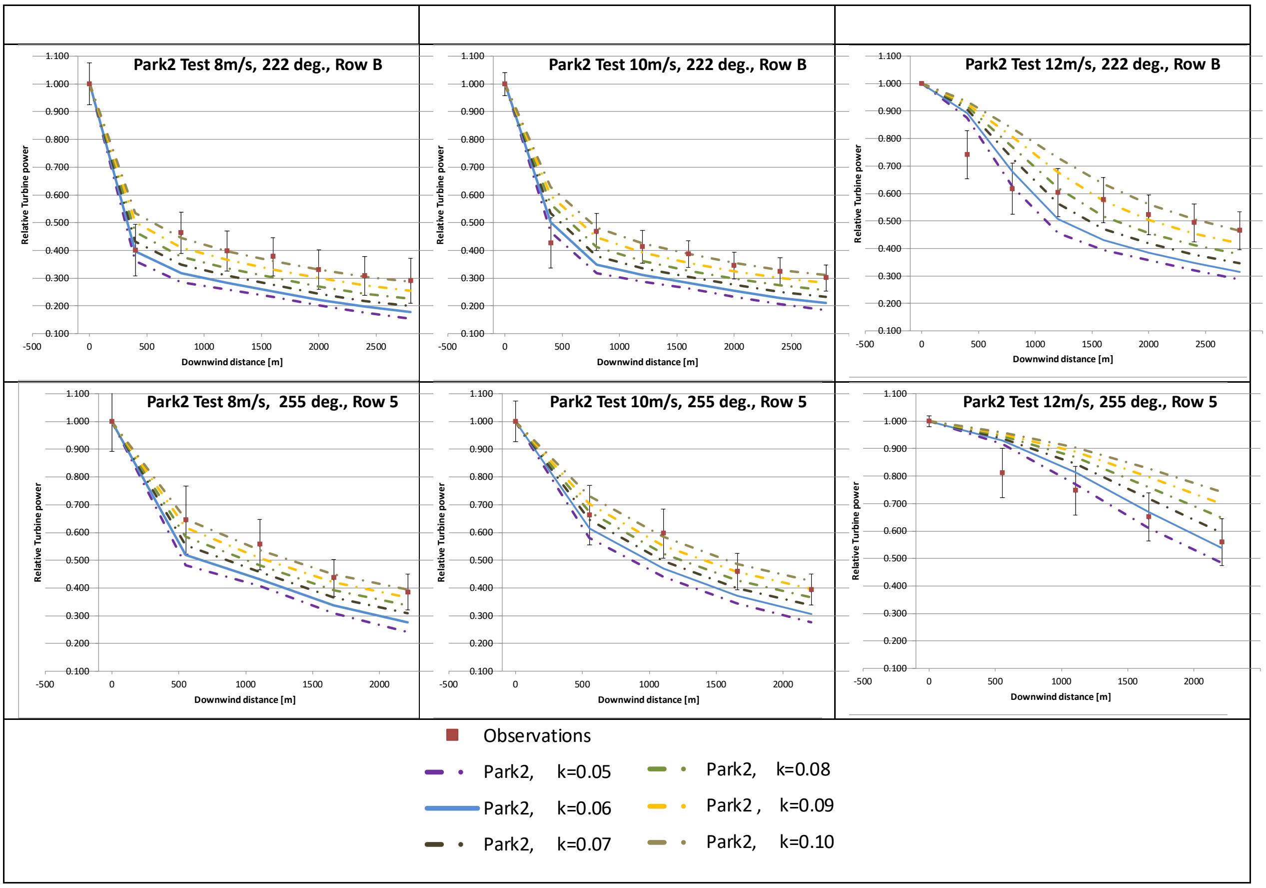

Figure 12. Lillgrund. Qualitative validation of Park2 with various k*-values.*

7.1 Findings from the qualitative validations.

The comparisons of the results from the Park1 model (section 5) and from the Park2 model (this section) to the observations indicate:

- The Park2-model with k=0.06 gives an over-all agreement with observations which is at least as good as for the Park1-model with the recommended k-value of 0.05 for offshore wind farms (figures. 10-12).
- The qualitative validation also reveals that the optimal k-value clearly depends on the wind speed and wind direction. Thus, for a number of the lowest-speed cases – e.g. Horns Rev 222° and 270°, k=0.08 or even 0.09, would give the best fit. For some of the highest speed cases (12 m/s) – e.g. Lillgrund 180° and 255° - k=0.05 would give the best fit. This indicates, that for high wind speeds the model exaggerates the effect of the lower turbine thrust-coefficient on the wake speed deficit, thus leading to an under-prediction of the wake effects. Presumably, the inability of Park2 to model all speed and directional effects is due to the simplifications in the model.
- However, it should be recalled that the qualitative validation only concerns a limited number of wind directions, typically along wind farm “rows”. Therefore the calibration of the over-all k-value cannot be based on these comparisons alone; in addition it is needed to take all available production data into account – as is done in the section 6, “Quantitative validation and calibration based on offshore wind farms”.

8. Calibration of Park2 for on-shore conditions vs. Park1

No proper on-shore wind farm operational data have been readily available for validation and calibration of Park2 for on-shore conditions. Instead, a ‘calibration’ has been undertaken, using AEP-calculations by Park1 for a number of existing or projected on-shore wind farms. Thus a recommended Park2 wake decay constant k for on-shore conditions is found, that gives essentially the same AEP results as those obtained by using the original Park model, Park1, with its on-shore standard k-value (0.075).

14 different on-shore wind farms were used (Mortensen, 2015; Mortensen, 2017):

Wind farm name	Country	Rated power	Index	Wind farm name	Country	Rated power	Index
CREYAP 1	GB	14 × 2MW	1	Capel Cynon (6 wind farms)	GB	18 × 2MW	7
CREYAP 2	GB	22 × 1.3MW	2			6 × 3MW	8
Napier	ZA	27 × 3.45MW	3			7 × 2MW	9
Jasseines (2 wind farms)	FR	6 × 2MW	4			9 × 2MW	10
		4 × 1.8MW	5			4 × 3MW	11
La Ventosa	MX	51 × 2MW	6			6 × 0.81MW	12
Vredensburg	ZA	34 × 3.6MW	13	Ras Ghareb	EG	100 × 3.02MW	14

Table 8.1. Onshore wind farms used for the calibration.

The result of the fitting-procedure to find the matching Park2 k-value is shown in figure 8.1 below. The error bars indicate the k-values where the Park2 production calculation differs ±0.15% from Park1.

The resulting recommended k-value (average value) with associated uncertainty is given in table 8.2.

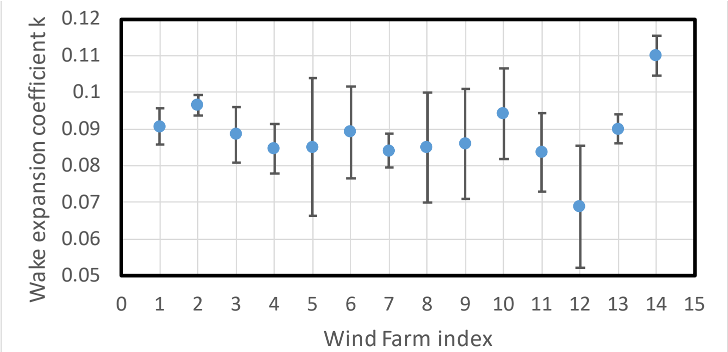

Figure 8.1. Best-fit wake decay constants for Park2 vs. Park1.

k	μ	0.088
	σ	0.009

Table 8.2. Resulting recommended k-value with uncertainty.

9. Conclusion

The Park wake-model for wind farms has been modified. In the modified Park-model, Park2, we introduce a consistent formulation for the speed-deficit in the wakes. In addition, a more physically based superposition rule is introduced: linear superposition; and for aerodynamic reasons, wake reflection in the surface is omitted.

For offshore conditions, the Park2 model was calibrated and evaluated by means of a number of observed production data sets from offshore wind farm flow cases. The calibration resulted in a recommended value for the wake decay constant k. With this recommended k-value Park2 was found to produce predictions at least as close as Park1 to observed offshore wind farm productions.

Observed production data from on-shore wind farms for calibration and evaluation were not readily available. Consequently, for on-shore conditions Park2 has been calibrated against Park1-predictions of annual energy production (AEP) for a number of on-shore wind farms, resulting in a recommended value for the wake decay constant k for onshore conditions.

The recommended wake decay constant values are given in table 9.1 below:

Windfarm type		Offshore	Onshore
k	μ	0.06	0.09
	σ	0.006	0.009

Table 9.1. Recommended wake decay constant values with associated uncertainty.

References

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