

# **Farm Efficiencies In Large Wind Farms**

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## **Summary**

Commonly used wake models (WM) were calibrated and tested in small to medium sized wind farms. As experience has shown, when using the default settings in the assessment of larger wind farms (e.g. more than 30 wind turbines), the wake losses are underestimated. Furthermore, not only the developed WMs result in different efficiency and energy estimations, but also the different software implementations. Thus, in the current study suitable settings of the WMs are investigated by means of a sensitivity analysis for two different wind farms, of which the real energy yields are evaluated and compared with the model assessments. The results are not only leading to the reconsideration of standard parameters, but also pinpointing boundary conditions of the models.

## **1. Introduction**

Mainly two numerical models are available in daily use for the assessment of farm efficiency calculations. These are the PARK (Jensen) [1,2] and Ainslie [3] models. Furthermore, the so-called Larsen model [4-5], has been recently implemented in one of the software. The use of these models leads to different farm efficiencies and all models are underestimating the losses, due to the crosswise shading effects, occurring in large wind farms when using the default or generally recommended settings.

Firstly, the basic characteristics of all models are presented. Secondly, a quantitative analysis of real energy yields in two exemplary wind farms -a middle scale one with quite simple terrain-orography and a large scale one with more complex topography- in comparison to the farm efficiencies as calculated with the different models and software implementations is performed. Last but not least, a sensitivity analysis on the boundary conditions of the different models is carried out, aiming in the most realistic modeling of the farm efficiencies in large wind farms.

## **2. Models' Description**

### **2.1 Jensen (PARK) Wake Model [1,2]**

The Jensen WM is a simple, single wake kinematic model, in terms of an initial velocity deficit and a wake decay constant ( $k$ ). It is based on the assumption that the wake right behind the Wind Turbine (WT) has a starting diameter equal to the rotor diameter ( $D$ ) and is linearly expanding as a function of the downwind distance  $X$ . Recommended  $k$  values for onshore and offshore wind farms are 0.075 m and 0.040 m, respectively.

### **2.2 Ainslie (Eddy Viscosity) Wake Model [3]**

The Ainslie model is based on a numerical solution of the Navier-Stokes equations with an eddy viscosity closure, in cylindrical coordinates. The eddy viscosity is described by the turbulent mixing due to the induced turbulence, generated within the shear layer of the wake, and the Ambient Turbulence ( $I_a$ ). The wake is considered axi-symmetric.

### **2.3 Larsen Wake Model [4,5]**

The model is semi-analytical and is assumed that the wake region can be adequately described by Prandtl's rotational symmetric turbulent boundary layer equations. These equations can be considered as an asymptotic version of Navier-Stokes equations for large Reynolds numbers.

## **3. Software's Implementation**

Three commonly used software packages are utilised for the elaboration of this study. All three software introduce different options for running the models. Thus, the configurations have been performed with the aim of approaching the best agreement among the background of the calculations (free energy yield), for relative investigations. The free energy yield calculated from all software varies between 0.06% and 0.6% only, whereas the farm net yields (after wake losses) differ significantly.

## **4. Case Studies**

### **4.1. Site 1**

#### **4.1.1. Outline**

The Wind Farm (WF) in site 1 consists of 34 WTs. The area is situated in Northeast Germany, very close to the coast of the North Sea (less than approx. 2 km). It is placed in an open flat field, where the roughness is quite low (approx. 0.05 m on average) and the orography is of a minor consideration.

All turbines are AN Bonus 600 kW, with 55 m Hub Height ( $z$ ), 44 m  $D$  and stall control. In the vicinity of the wind farm there are various individual wind turbines and wind farms. However, in the calculations only (five) turbines, situated in a radius of approx. 1.5 km, are taken into consideration.

#### **4.1.2. Data Evaluation**

Monthly energy yield data of the wind turbines are available for the period January 2002 – December 2005. The data of each WT have been corrected (regarding its given availability) with the view to meet 100% availability, under the assumption that during the non-availability, the monthly average energy yield was gained. They can be considered quite

reliable, since the availability of the turbines is high (mean avail. 97 %).

A met mast being erected on site is providing wind source data for the period June 2002 – December 2005, at z. Because of some data gaps (from minutes up to months) the data have been correlated with these of a nearby 130 m-anemometer mast. Fig. 1 presents the wind direction distribution for site 1.

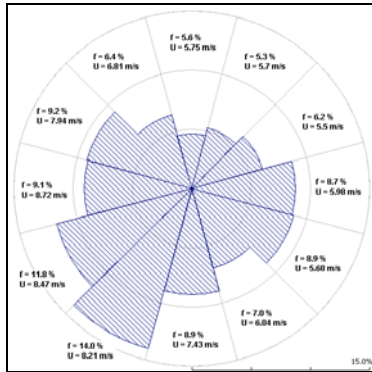


Fig. 1 Site 1 - Wind Rose

## 4.2. Site 2

### 4.2.1. Outline

91 WTs compose the second wind farm, which is located in Brandenburg, Germany. The terrain is more complex ( $z_0$  is approx. 0.09 m on average) including a small hill, where the WTs are erected and surrounded by afforestations. There are several types of WTs and z, such as NEG Micon NM72C (1.5 MW, z: 80.0 m & 98.0 m, D: 72 m, active stall) and NM82 (1.5 MW, z: 93.6 m, D: 82 m, active stall), Enercon E-66/18.70-3 (1.8 MW, z: 98.0 m, 86.0 m & 114.0 m, D: 70 m, pitch) and Enercon E40/5.40 (0.5 MW, z: 65.0 m, D: 40.3 m, pitch).

### 4.1.2. Data Evaluation

Monthly energy yield data of the wind turbines are available for the period April 2004 – July 2005, with the exception of February 2005. The aforementioned for Bassens WF mean availability stands for this one, as well and the energy data of the WTs have been treated similarly. The energy data are fairly reliable.

The wind data used are collected from a 10 m met mast in Holzdorf, approximately 30 km away. For this reason the data set has been scaled for the turbine WT02, which is the one with the lowest shading effects from the rest WF, not only for the prevailing wind directions and the higher sector wise mean wind velocities, but also for approx. the 68% ( $135^{\circ}$ - $330^{\circ}$ ) of the overall distribution (Fig. 2). Furthermore, from former investigation, it has been proved that it has the best and most reliable performance of the cluster facing the prevailing wind directions. The scaling has been performed regarding the net energy yield (wake losses for the rest sectors included), as calculated by Software C, with the Jensen WM and  $k=0.075$  m. Fig. 2 presents the wind direction distribution for site 2.

## 4.3 Site 1 & 2 Wake Calculations

### 4.3.1 Jensen Model Sensitivity Analysis

The model is tested for various constant k values within a margin of 0.03 m - 0.10 m.

### 4.3.2 Ainslie Model Sensitivity Analysis

This model is tested for different  $I_T$  sources, measured Standard Deviation ( $\sigma$ ) and  $Z_0$ , (the following are not presented) turbulence models,  $k_1$  values, calculation grid size, wake lengths and wake recovery percentages.

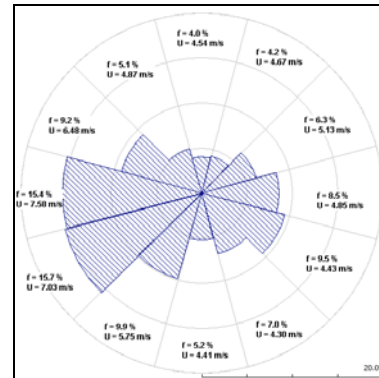


Fig. 2 Site 2 - Wind Rose

### 4.3.3 Larsen Model Sensitivity Analysis

Since recently implemented and not widely used, the options for this model are limited. Thus, the model is used with different turbulence models and for the different  $I_T$  sources.

### 4.3.4 Results

#### 4.3.4.1 Jensen Wake Model

Varying k for a range of 0.03 to 0.1 m, the farm efficiency ( $\eta$ ) fluctuates approx. up to 7% (Fig. 3). For the large wind farm the variation is up to 13%. Furthermore, a deviation among the software is appearing, where software B estimates approx. 1% higher efficiency for site 1 and 3% for site 2.

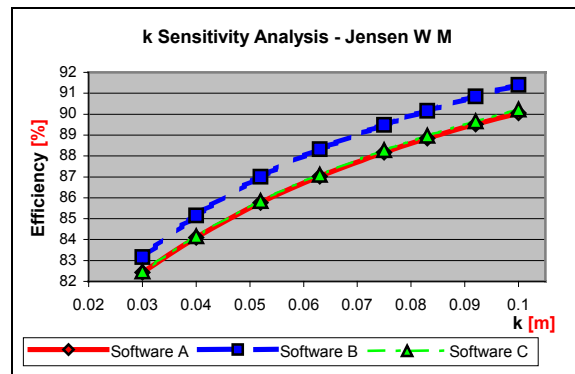


Fig. 3  $\eta$  vs. k / Jensen WM – Site 1

Despite the recommended for onshore WFs value of  $k=0.075$  m, it is obvious that lower k, in the margin of 0.04 to 0.05 m, lead to lower farm efficiencies (Fig. 3) and consequently lower energy yield. The yield calculated for such k values result in lower, or even zero, energy deviation ( $\Delta E$ ) from the real energy yield (Fig 4).

Fig. 5 depicts the gradually increasing individual  $\Delta E$  towards the centre of the farm (up to 7%

overestimation - 1% underestimation). The formation of the  $\Delta E$  steps is strongly dependent in the wind distribution of the site (Fig. 1). Despite the prevailing wind direction (Southwest), the rest of the distribution is sharing approx. 74%, in a fairly even way. Turbine 30 has been excluded from the mean  $\Delta E$  estimations, since the available energy data are erroneous, as can be noticed. The farm  $\eta$  is 88.2%.

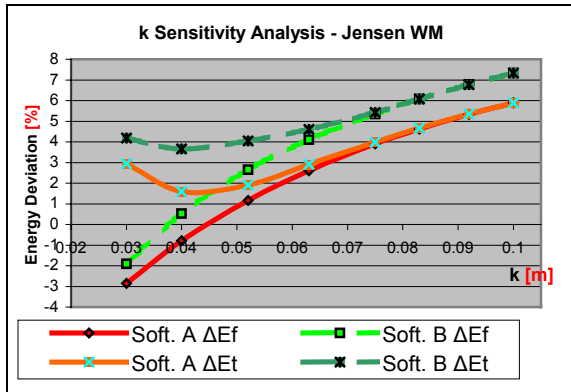


Fig. 4  $\Delta E$  vs.  $k$  / Jensen WM – Site 1

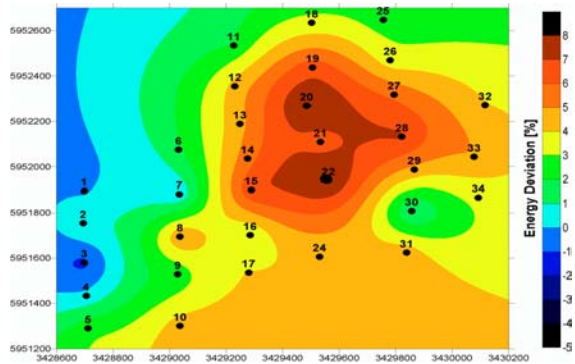


Fig. 5 Energy Deviation Map / Default  $k$  – Site 1 (Software A)

Differently, in Fig. 6, where the best fitting, for Software A,  $k$  (0.0445 m) has been used, the individual  $\Delta E$  has been decreased significantly (3% overestimation). On the other hand, the underestimating  $\Delta E$  is up to 4%. The farm  $\eta$  reduces to 84.8%.

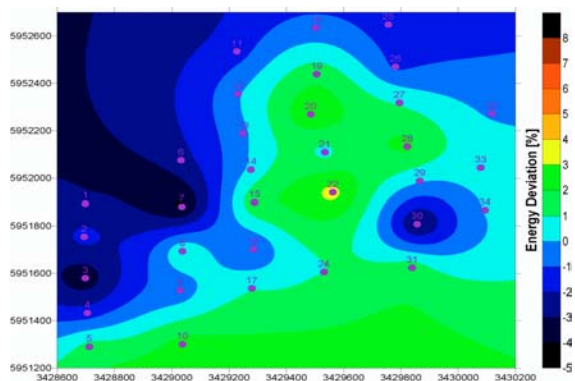


Fig. 6 Energy Deviation Map / Best Fitting  $k$  – Site 1 (Software A)

The sensitivity analysis performed for the large and complex wind farm confirms the previous results.

The best fitting  $k$  is around 0.05 - 0.06 m (Fig. 7). The tendency to lower  $k$  is obvious for both case studies.

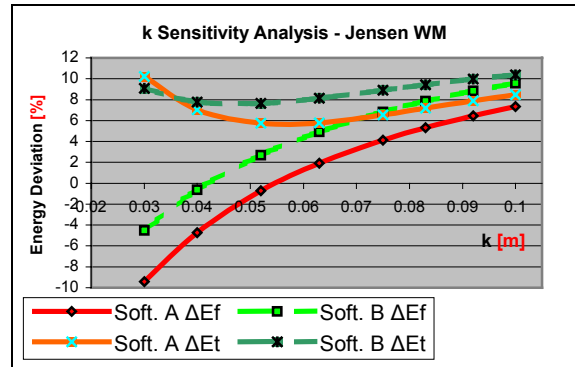


Fig. 7  $\Delta E$  vs.  $k$  / Jensen WM - Site 2

In site 2 the overestimation in the back rows (regarding the prevailing wind direction - Southwest) is reaching 22% for the default  $k$ . The farm  $\eta$  is 83.6%. Adversely, the best fitting value (0.055 m) lowers the overestimation considerably, but leads to high underestimations up to 17% for the south-eastern WTs. The farm  $\eta$  reduces to 80.3%.

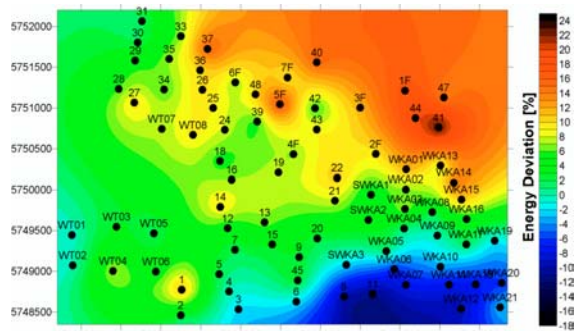


Fig. 8 Energy Deviation Map / Default  $k$  – Site 2 (Software A)

The  $\Delta E$  Map for case study 2 presents different formation of the deviation steps, since the wind distribution is concentrated to fewer sectors and in particular for west winds (Fig. 2).

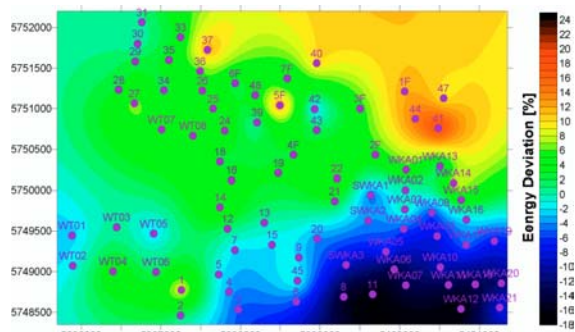


Fig. 9 Energy Deviation Map / Best Fitting  $k$  – Site 2 (Software A)

#### 4.3.4.1 Ainslie & Larsen Wake Models

Commonly, there are two ways to evaluate the  $I_a$ ; either from the measured  $\sigma$  or from the  $z_0$  using the following equation stemming from the boundary layer theory:

$$I_T = A_x \cdot \kappa \cdot \left[ \frac{1}{\ln\left(\frac{z}{z_0}\right)} \right] \quad (1)$$

where,  $\kappa$  is the Von Karman Constant (0.4),  $z_0$  the roughness length and  $A_x$  a constant varying from 1.8 – 2.5. 2.5 is generally recommended. On the contrary, as can be seen in Fig. 10, the value 1.8 gives more realistic results for energy calculations, since the  $\Delta E$  is decreased 2% in the case of Larsen WM and 1% for Ainslie WM. Moreover,  $I_T$  is even lower, when using the  $\sigma$  measurements and the deviation decreases further for both WMs.

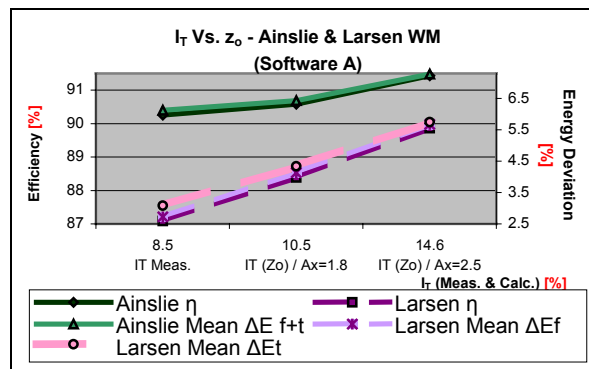


Fig. 10  $\Delta E$  vs.  $k$  / Ainslie & Larsen WM – Site 1 (Software A)

The previous results are partly confirmed in the second case study, where using  $A_x=1.8$  the  $\eta$  and  $\Delta E$  are decreased approx. 1.5% and 3%, for Ainslie and Larsen, respectively.  $\sigma$  data are not available for this site.

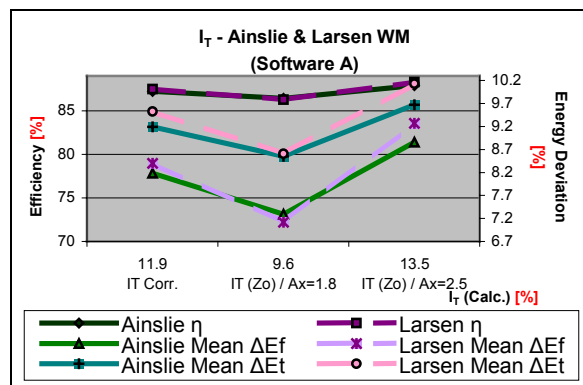


Fig. 11  $\Delta E$  vs.  $k$  / Ainslie & Larsen WM – Site 2 (Software A)

## 5. Conclusions

- Differences in the efficiency calculation among the software have been detected. Since the deviation in the free energy yield is limited, the main reason could be the different approaches considered on the assessment of the uniform wake velocity over the rotor area, the multiple and partial wakes.

- It has been noted that the  $\eta$  and  $\Delta E$  are wind distribution dependent.

- **Jensen WM:** From the two case studies, it seems that the recommended  $k$  ranges should be reconsidered, since lower values tend to be more realistic. Waldl [6] suggests a value of 0.06 m for 17 WT's already (simple terrain). Despite the fact being a simple model and with a more empirical basis, it seems to be the most precise and reliable one.

- **Ainslie & Larsen WMs:** Lower  $I_T$  could lead to more realistic results, regarding the efficiency assessment. That is because lower  $I_a$  renders a more persistent wake, due to the decreased mixing of the free stream and wake stream in the wake, and slower wake recovery. Therefore higher wake losses occur. Nevertheless, both models seem to generally underestimate the losses. The Larsen WM, even though not very widely implemented seems a reliable model.

- From a practical only point of view, adjustments could yield fairly representative results, but further research is necessary. All, three wake models should be revised, whereas the individual-turbine  $\Delta E$ s are varying remarkably and only the compensation among them leads to more realistic overall results.

The following points could be noted shortly:

- The resolution (dimensions and directional steps) of the calculation can be a critical factor, if too low.
- The length of the wake should not be underestimated.
- Measured on site wind data recommended.  $I_T$  ( $\sigma$ ) excels  $I_T$  ( $z_0$ ) in accuracy of the results.
- Applying "Inner Roughness" in the wind farm, it is a commonly recommended technique by several authors. This method influences only the estimated free energy yield and the effect on the wake losses calculation is negligible. However, the roughness steps classification, in terms of magnitude, number of changes and roughness loops placement, is difficult to be defined.

## 6. References

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