# Modelling Tools for Wind Farm Upgrading

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ABSTRACT: Planning of modifications of existing wind farms by adding or replacing turbines makes new demands on wind farm modelling. Emphasis shifts from the calculation of the mean efficiency of the farm to that of individual turbines. Additionally, modelling has to deal with different turbine types and hub heights combined in one farm. Full scale measurements at two wind farms in Northern Germany provide test cases for investigating the capability of wind farm models to predict the power output of individual turbines. Calculations are performed with a kinematic and an eddy-viscosity model. Both procedures result in systematic deviations from the measured single turbine performance. These are believed to be due to the increase in turbulence intensity in wakes, which is not modelled adequately. Simple modifications are proposed to enhance the accuracy of the models. The analysis of the wake losses in the case of turbines with different hub heights shows that both models give results within the limit of the measurement uncertainties.

Keywords: Wind Farm, Power, Full Scale Measurements, Models (Mathematical)

## 1 Introduction

Wind turbine technology has developed fast in recent years, increasing the economics of wind energy with larger turbine types and higher hub heights. Therefore, the upgrading of older wind farms by extension or replacement of turbines becomes more and more attractive. At least if an older turbine needs major repair a replacement has to be considered. For the planning of such modifications not only the performance of the total farm is of interest but also that of the individual turbines within the farm. This requires a higher accuracy in wind farm modelling. Since a replaced turbine will almost inevitably be larger and of a higher hub height than the others, it is critical to be able to model wind farms with different turbine types and hub heights.

## 2 Method of approach

### 2.1 Wind farm models

For the calculation of the wind turbine wakes two wake models have been investigated which follow different concepts:

- The kinematic wake model by Jensen [1] (Risø-model) is quite simple and therefore allows wind farm modelling with very short calculation time. It is implemented in the commonly used wind farm program PARK [2]. The description of the wake development is governed by the entrainment constant which is a free parameter of the model.
- The hydrodynamic wake model by Ainslie [3] (Ainslie-model) solves a simplified axial symmetric Reynolds equation to determine the development of the wake. It is therefore much more costly in terms of calculation time.

These wake models have been embedded in a model calculating the power output of the turbines. Momentum deficits of all wakes incident on the rotor are added and integrated over the rotor area to define an effective wind speed for the turbine. The measured power curve of this turbine is than used to determine its power output. Differences due to a vertical wind speed profile are neglected.

### 2.2 Measurements

Meteorological and power output measurements were made at two wind farms in flat coastal terrain in Northern Germany which follow very different layout concepts.

In Hamswehrum wind farm 12 turbines are set up in two rows (see Figure 1). They are pitch controlled variable speed turbines with a rated power of 330 kW (WT 12: 430 kW). This farm is used to study the modelling of the power output of individual turbines. Here the investigation concentrates on the different impact of single and multiple wakes on the power output of a downwind turbine. Due to the geometry of the farm single wakes as well as multiple wakes of up to five subsequent turbines are present.

Husum wind farm consists of 15 turbines in a complex layout with two different turbine types (see Figure 2). Both types are stall controlled fixed speed turbines with a rated power of 250 kW. The farm was planned to demonstrate the concept of a 'bush and tree' layout which aims to minimise wake effects by combining turbines of different hub heights in one farm. With this farm geometry it is possible to study the wake effects of turbines with different hub heights.

### 2.3 Comparison of Measurement and Calculation

At the two sites data series containing the measured wind speeds at the appropriate hub heights, the wind direction and the power outputs of all turbines were meas-

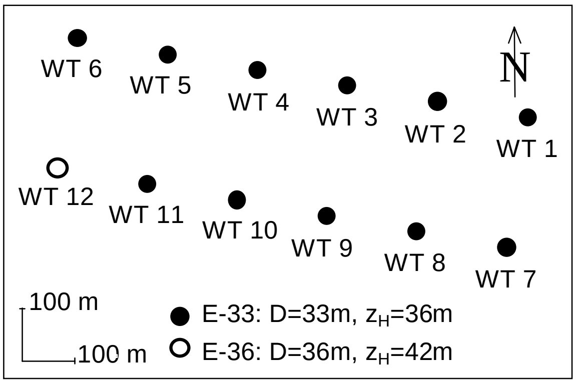


**Figure 1**: Geometrical set up of Hamswehrum wind farm (D = rotor diameter; $z_H$ = hub height).

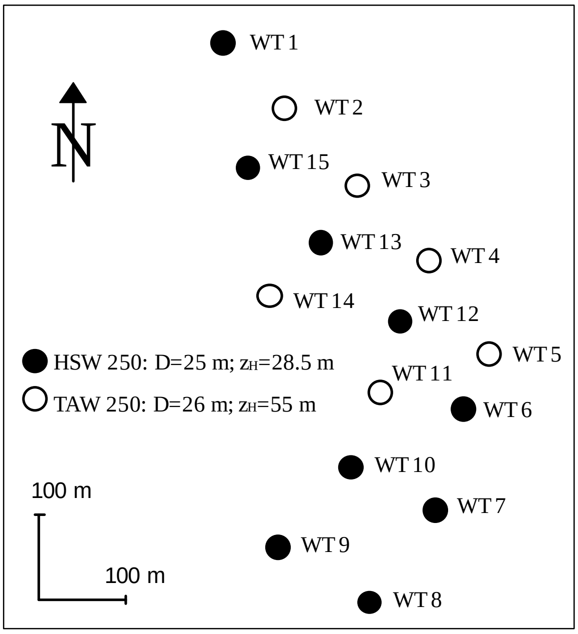


**Figure 2**: Geometrical set up of Husum wind farm.

ured. The measured wind speed and direction are used as input values for the wind farm models to obtain similar time series of modelled power outputs. All power output data is normalised using power curves measured for each turbine. The resulting data series of measured and modelled efficiencies are bin-averaged for wind direction. A bin width of 5° is used with steps of 1°.

## 3 Modelling of the power output of individual turbines of a wind farm

To increase the prediction quality for extension of wind farms or replacement of turbines, emphasis should be put on the improvement of modelling the power output of individual turbines of a farm. With this aim, two effects have been selected for detailed investigation:

- For Hamswehrum wind farm both models under investigation show deviations between measured and calculated power outputs. These are more pronounced for individual turbines than for the total power output of the farm. The deviations depend on the treatment of single and multiple wakes in the modelling.
- Modelling turbines of different hub heights can be vital for the prediction of the power output of individual turbines. Very little model verification with full scale measurements is known so far.

### 3.1 Single and multiple wake modelling

The development of a wake depends on the turbulence of the surrounding flow. Inside the region of a wake, turbulence is increased by rotor induced turbulence and turbulence due to the wind sheer of the wake itself [4]. Thus for a wake developing inside of another wake, the effective ambient turbulence is higher than in free stream conditions. In most wind farm models (e.g. [2]) no difference is made between these two situations.

#### 3.1.1 Measurements

The turbine WT 2 of Hamswehrum wind farm (see Figure 1) serves as an example to demonstrate the effect of single and multiple wake modelling for an individual turbine of a wind farm. Figure 3 shows the measured efficiency of the turbine. Each data point represents a 10-minute average. The bin-average is also shown along with its single confidence level. The multiple wake of turbines WT 3 to 6 (at 280°) and single wakes from turbines WT 7 to 12 can be seen. Wind directions where the meteorological mast was shaded by the farm and those with only very few data were not used.

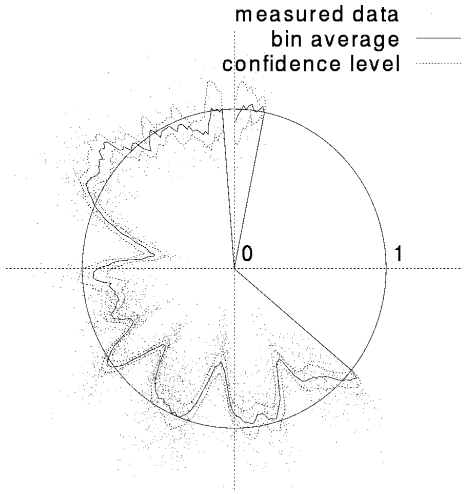


**Figure 3**: Measured efficiencies of turbine WT 2 of Hamswehrum wind farm versus wind direction for wind speeds from 5 to 8.5 m/s. The wake in westerly direction is a multiple wake from four turbines in a row, the other efficiency reductions are due to single wake situations.

#### 3.1.2 Modelling with the Ainslie-model

The Ainslie-model requires the input of the ambient turbulence intensity $I_{amb}$. An estimate of $I_{amb}$ is gained via:

$$I_{amb} = \frac{1}{\ln\left(\frac{z_{Hub}}{z_0}\right)}$$

where $z_0$ gives the roughness length of the surrounding terrain and $z_{Hub}$ the hub height of the turbine.

Since the wind farm is situated in a terrain with low surface roughness, the estimated mean turbulence intensity is only 10%. Variation of this value in the modelling shows the adequacy of this estimation. Figure 4 shows a comparison of measured and calculated (original model) efficiencies for WT 2. It may be seen that the power reduction due to the multiple wake (at 280°) is overestimated, while the reductions stemming from the single wakes are modelled well.

#### 3.1.3 Modelling with the Risø-model

In the Risø-model the development of the wake is governed by the entrainment constant which is a free parameter. For this investigation the value of this parameter is found by a fitting procedure comparing the predicted efficiencies with the respective measured ones. The optimal value is found to be 0.06 (compared to the standard setting 0.08). Figure 5 shows a comparison of measured and calculated efficiencies for WT 2. The result is similar to that from the Ainslie-model: The power reduction due to the multiple wake (at 280°) is overestimated. Additionally, the power reduction from the single wakes are underestimated by the Risø-model.

#### 3.1.4 Model modifications

For both models the comparison with the measurement seems to suggest that single and multiple wakes should be modelled differently. The simplest way to do this is to use

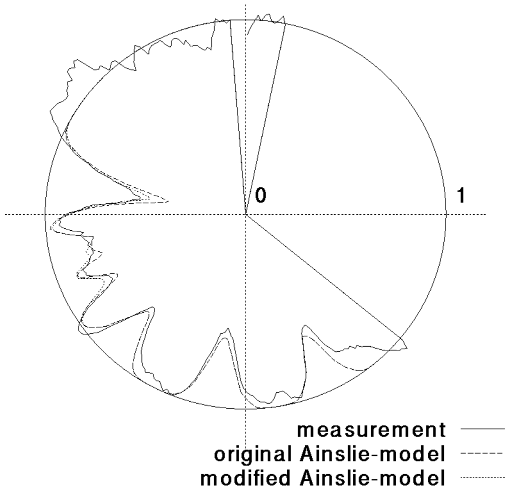


**Figure 4**: Measured and calculated (original and modified Ainslie-model) efficiencies of turbine WT 2 versus wind direction for wind speeds from 5 to 8.5 m/s. The efficiency reduction in westerly direction is due to a multiple wake. Their agreement is better for the modified model.

two different values for the parameter which determines the wake development in the models, i.e. the entrainment constant in the Risø-model and the ambient turbulence intensity in the Ainslie-model.

The mean turbulence intensity in wakes is estimated using an empirical formula by Quarton [4]. In Hamswehrum wind farm the turbulence intensity in double wakes is estimated to be 15%. For multiple wakes with two or more preceding turbines the calculation shows almost equal turbulence intensities of 19%. From this a mean turbulence intensity for multiple wakes of 18% is estimated. Again a variation of the used turbulence intensity in wakes shows the adequacy of this estimation procedure. Figure 4 shows a comparison of measured efficiencies with calculations of the Ainslie-model with and

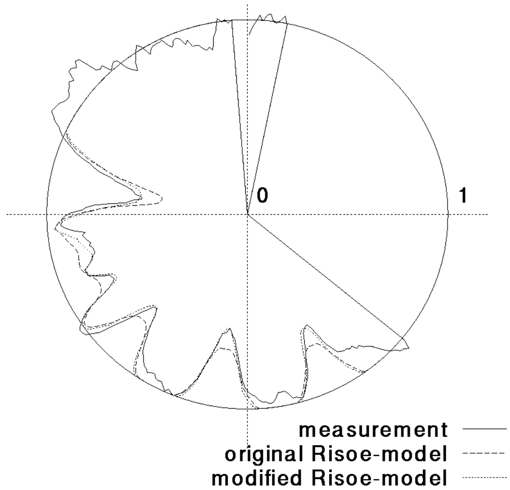


**Figure 5**: Measured and calculated (Risø-model) efficiencies of turbine WT 2 versus wind direction for wind speeds from 5 to 8.5 m/s. The original model overestimates power reductions due to the multiple wake (at 280°) and underestimates those due to single wakes. For all wakes agreement is better for the modified model.

without modification for WT 2. The power reduction due to the multiple wake (at 280°) is not longer overestimated when single and multiple wakes are modelled differently.

For the Risø-model the values for the entrainment constant for both single and multiple wake situations are fitted separately. They were found to be 0.04 for single and 0.08 for multiple wakes. Since the entrainment constant does not have a direct physical interpretation, no estimating procedure is known here. Figures 5 and 6 show a comparison of measured efficiencies and the prediction of the Risø-model with and without modification. Figure 5 gives the result for WT 2 while figure 6 shows the comparison for all turbines of the wind farm. The positions of the efficiency-curves of the turbines have been placed ac-

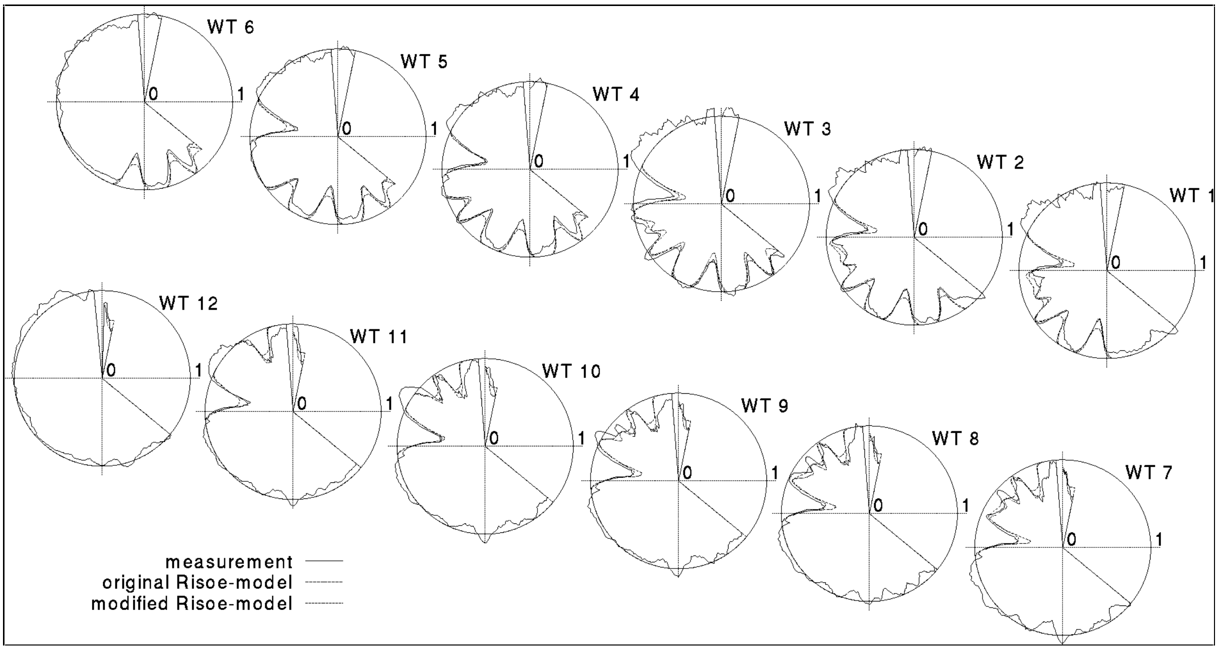


**Figure 6**: Measured and calculated (original and modified Risø-model) efficiencies of all turbines in Hamswehrum wind farm. The positions of the efficiency-curves of the turbines have been placed according to the geometrical set up of the farm. Modelling of power reductions due to single and multiple wakes is substantially better with the proposed modifications.

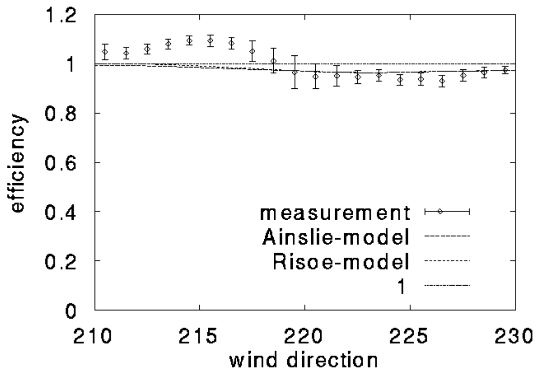


**Figure 7**: Measured and calculated efficiencies of the low WT 13. The incident wake is due to the high WT 14.

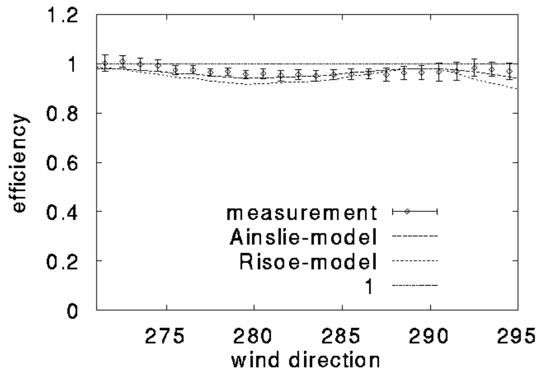


**Figure 8**: Measured and calculated efficiencies of the high WT 4. The incident wake is due to the low WT 13.

cording to the geometrical set up of the farm (see Figure 1). It can be seen that both, the power reduction due to single and multiple wakes, is represented much better by the modified model.

### 3.2 Modelling of wind farms with turbines of different hub heights

Husum wind farm consists of turbines with two different hub heights of 28.5 m and 55 m. The difference in hub heights therefore is more than one rotor diameter.

The farm is modelled using both wake models without modification. The ambient turbulence intensity is estimated to be 14%, the optimal entrainment constant is found to be 0.08. Figures 7 and 8 show examples of measured and calculated efficiency reductions due to wake effects involving turbines of different hub heights.

As expected from the big difference in hub heights, the measured reduction of the efficiency is small and therefore difficult to separate from measurement uncertainties. Deviations between measured and modelled efficiencies were found to be within the bounds of the measurement uncertainties.

Since for turbines of different hub heights the overlapping region of wake and rotor is small, an appropriate description of the wake width is critical. Even though the Jensen wake model uses a very simple description for the wake profile and width, it does not differ substantially from the Ainslie-model for the calculated efficiency reductions.

## 4 Conclusion

Measurements show that power output reductions due to wake effects depend on whether the wake is developing in the free stream or within another wake. This is believed to be a result of an increase of turbulence in the wake region. The quality of modelling is improved substantially by using a simple modification of the wind farm model: different values are taken for the parameter describing the development of the wake in the two cases of a single and a multiple wake. For the Ainslie-model these values (the turbulence intensities) may be estimated from known correlations. For the Risø-model no respective procedure is known to guess the entrainment constant.

For the planning of wind farm upgradings, the effect of this modifications on the calculated annual mean losses due to wake effects are the most important result. These are illustrated in Table 1 for the case of Hamswehrum wind farm modelled with the Risø-model. An effect on the total farm loss can clearly be seen even for this small farm. Differences for individual turbines are more pronounced and also very different for each turbine. The proposed model modifications are a valuable tool for predicting their wake losses.

Measurements of a 'bush and tree' wind farm show that the concept of minimising wake effects by combining two different hub heights is working well. Power reductions due to wake effects between turbines of very different hub heights are small and deviations between measured and modelled efficiencies were found to be within the bounds of the measurement uncertainties for both wake models under investigation. Differences between the two models were found to be small, even though the modelling of the wind velocity profile in the wake is very simple in the Risø-model.

Further measurements of wind farms with other hub height differences are necessary for the development and verification of better models for the representation of the vertical wind velocity profile.

**Table 1**: Modelled mean losses in % in Hamswehrum wind farm with the original and modified Risø-model. Differences vary for individual turbines.

| | Total farm | WT 2 | WT 5 | WT 7 |
|---|---|---|---|---|
| original model | 5.09 | 6.35 | 5.18 | 4.12 |
| modified model | 5.32 | 6.76 | 5.59 | 4.07 |
| Difference [%] | -4.2 | -6.07 | -7.33 | 1.23 |

## References

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