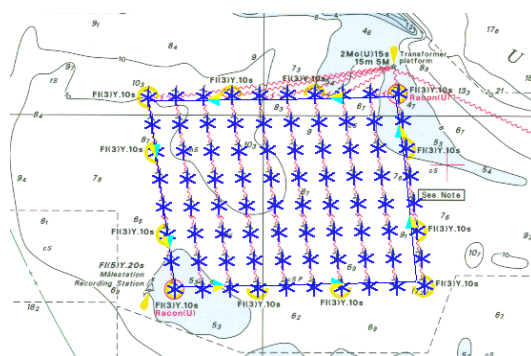
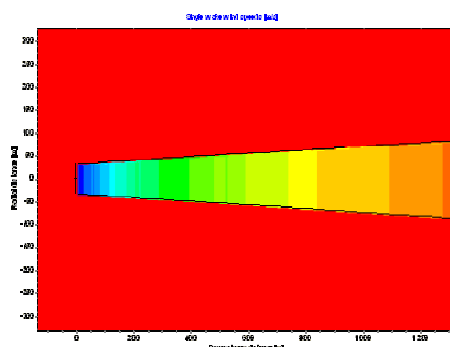


## Adapting and calibration of existing wake models to meet the conditions inside offshore wind farms.



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## Summary

The project "Adapting and calibration of existing wake models to meet the conditions inside offshore wind farms" has as purpose to improve the existing PARK models for calculating the wake loss within wind farms with a special emphasis on large offshore wind farms.

The existing models are based on wind farms consisting of few onshore turbines and while there is work underway to produce better models, developers and planners have to use the existing models. These existing models are suspected of being inadequate at handling large offshore wind farms, but as this project shows, an intelligent use of model parameters can reduce the error and uncertainty when using them.

The project is partly a continuation of work EMD has done through the "Storpark project" (The necessary distance between large wind farms offshore – study; Risø National Laboratory Roskilde, Denmark, August 2004) through implantation and documentation of existing models. Sensitivity studies are made and the models are tested and demonstrated through three case examples.

EMD has made its work available through the software WindPRO and on the EMD homepage <http://www.emd.dk/ParkKalibrering>.

## Sammenfatning

Projektet "Tilpasning og kalibrering af eksisterende skyggevirkningsmodeller til forholdene inde i store offshore mølleparker" har som formål at forbedre eksisterende PARK modeller til beregning af rækkefab for vindmølleparker med fokus på store havmølleparker.

De eksisterende modeller er baserede på vindmølleparker bestående af få landbaserede møller, og mens der er arbejde igang med udarbejde bedre modeller, så er projektudviklere og planlæggere nødt til at bruge de eksisterende modeller. Disse eksisterende modeller er mistænkte for at være utilstrækkelige til at håndtere store havmølleparker, men som dette projekt viser så kan en intelligent brug af model parametrene reducere fejlen og usikkerheden ved at bruge dem.

Projektet er til dels en opfølgning af det arbejde EMD har udført gennem "Storpark projektet" (Den nødvendige afstand mellem store havmølleparker, Risø, August 2004), gennem implementation og dokumentation af eksisterende modeller. Følsomhedstest er udført, og modellerne er testet og demonstreret gennem tre demonstrationseksempler.

EMD har gjort sit arbejde tilgængeligt gennem programmet WindPRO og på EMD's hjemmeside <http://www.emd.dk/ParkKalibrering>.

Frontpage illustration:

Calculation of the wind speed deficit behind a wind turbine using the N.O. Jensen method and an outline of the Horns Rev offshore wind farm layout.

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## 1. Purpose of project

The aim of the project is through model adjustments to improve already existing wake loss models for wind farms so that they can be used for large offshore wind farms.

The newest measurement data from offshore wind farms at Nysted and Horns Rev are to be analysed with the intent to validate, calibrate and fit existing, validated wake loss models. The wake loss models are, for the most part, developed for small land based wind farms and should therefore be modified for use on large offshore wind farms.

The projects primary focus is prediction of production for individual turbines in the wind farm, secondarily prediction of mean wind speed and turbulence in the wind shadow.

## 2. Execution of project

The initial plan for the project was to obtain measurement data from the two principal Danish offshore wind farms, Nysted and Horn Rev and use these to calibrate and revise existing models. These data, including wind measurements from meteorological towers and individual turbine production would have constituted a unique data source for calibration of models in an offshore environment.

Unfortunately it became clear in the process of the project that the two operators ELSAM and SEAS were not interested in sharing this information with a project like this.

Thanks to good contacts with ELSAM we managed to obtain some turbine measurement data from Horns Rev, which enabled some analysis, but Nysted was entirely off-limits.

When the utilities were reformed into DONG and Vattenfall new attempts were made and while it seems these organisations are more willing to share the data, there was no progress by the time of the deadline of the project.

The project therefore had to be executed without the most essential background data material. Instead data have been found for sites, which to some extent are similar to offshore wind farms and data for these are analysed instead. The project has therefore shifted from been an analysis and calibration using ideal data to an exercise in "the art of the possible" where a maximum of information has been gleaned from imperfect data. Nevertheless the targets of the project have been pursued.

A number of wake models and turbulence models have been implemented in the software package WindPRO.

The models are tested against a number of case studies with the purpose of improving the parameterisation of the models.

Results from these studies have been disseminated through software, articles and through an Internet site.

It is the hope that the crucial information from Horns Rev and particularly Nysted will become available at a later stage, so the model suggestions of this study can be tested/verified.

## 3. Model implementation

EMD develop, sell and support the software package WindPRO. It is used world wide by developers, planners, manufacturers and consultants to design wind farm layout and calculate wind farm production and environmental impact.

In this environment EMD has implemented the most common wake models:

- The N.O. Jensen model
- The Eddy viscosity model (Ainslie)
- The EWTS II model (Larsen)

Also EMD have implemented a new version of the traditional N.O. Jensen model, called New N.O. Jensen (EMD 2005). This is done in order to make it possible to calculate turbulence from the wakes.

This implementation was done prior to the present project.

A new improved model from Risø was anticipated, but it was not reported ready at the deadline of this project.

The model implementation is fully described in the associated document “WindPRO /PARK – Introduction to Wind Turbine Wake Modelling and Wake Generated Turbulence”.

As part of this project the model parameters in each model is described in the document and it was made possible to modify these parameters in WindPRO.

Also a number of wake induced turbulence models were implemented and described in the document. These were:

- The Danish Recommendation turbulence model
- The Fandsen turbulence model and the German DIBt Richlinie implementation of this.
- The Quarton and Ainslie turbulence model and the Dutch TNO modification of this.
- The Larsen turbulence model

In addition to these models a tool was developed to analyse the wind field inside the wind farm. This tool calculates the wind speed inside the wind farm and through the PPV (Park Performance Verification) tool it is possible to link the output of the wind farm with measurements in a particular point.

The tool is described in the above-mentioned document.

It was intended that this tool should have a central role in the analysis of the wind farm cases, but due to the nature of data available it was only used to a limited extend. The tool is however available for user of the software and can be used for future analysis.

## **4. Model test**

### **4.1 Analysis of wind data**

The analysis of actual wind measurements from offshore wind farms had to be aborted due to lack of data.

### **4.2 Preliminary case study**

Early in the process two cases were examined:

Horns Rev offshore wind farm

And

Nørrekær Enge onshore wind farm

On Horns Rev the wake loss models were studied based on data received from Elsam.

The Nørrekær Enge case based on data from Jørgen Højstrup (former Risø) tested the turbulence models with actual measurements of turbulence.

Both were preliminary studies to illustrate the problem at hand and used to guide the investigation further on. In the case of the Nørrekær Enge case it became clear how difficult it is to verify turbulence models with actual measurement, but it also suggested a methodology that could be tested with actual wind data on an offshore wind farm. As it happened those data was not made available for the project.

The Horns Rev case served as inspiration for further case studies which to some extend was implementable.

Both cases were publicized as posters on the EWEC 2006 conference and the resulting articles are enclosed this report.

### 4.3 Analysis through case studies

The wake models have been tested against real data through three case studies. These have been chosen due to their relevance for large offshore wind farms and from the availability of data. Thus it may be possible to find more appropriate wind farms, or better data but not in combination.

The three case studies are tabulated below.

<b>Name</b>	<b>Klim Fjordholme Wind Farm</b>
<b>Number of turbines</b>	35
<b>Size of wind farm</b>	21 MW
<b>Location</b>	Denmark, Northern Jutland
<b>Environment</b>	Onshore, flat open farmland
<b>Production data available</b>	4 years of monthly production for each turbine, 89 days of daily production for each turbine
<b>Wind data available</b>	General wind atlas for Denmark. Alternatively 10 minute measurements from a 10 m mast 35 km from the site
<b>Special feature / relevance of site</b>	The wind farm is relatively large and arranged in a regular geometrical layout not unlike a typical offshore wind farm. The landscape is open and there are a high quality data available for a long period
<b>Investigations made</b>	Available wake models are tested against actual wake loss. Compensation techniques are tested: increased roughness inside windfarm, changing model parameter Wake Decay Constant and some available parameters for Eddy viscosity and EWTS models

<b>Name</b>	<b>Zafarana Wind Farm</b>
<b>Number of turbines</b>	222
<b>Size of wind farm</b>	140,2 MW
<b>Location</b>	Egypt, on the Red Sea coast
<b>Environment</b>	Onshore, flat very open desert
<b>Production data available</b>	6 months concurrent with wind data
<b>Wind data available</b>	Data from several masts available. One mast is undisturbed with 6 months of data concurrent with production
<b>Special feature / relevance of site</b>	The wind farm is very large with 11 rows perpendicular to wind direction. Low roughness is similar to offshore, though stability is probably different. Wind direction is always the same
<b>Investigations made</b>	Available wake models are tested against actual wake loss. Compensation techniques are tested: increased roughness inside windfarm, changing model parameter Wake Decay Constant and some available parameters for Eddy viscosity and EWTS models

<b>Name</b>	<b>Horns Rev offshore wind farm</b>
<b>Number of turbines</b>	80
<b>Size of wind farm</b>	160 MW
<b>Location</b>	Denmark, North Sea
<b>Environment</b>	Offshore, 13 km from the coast
<b>Production data available</b>	Congregated park efficiency data for approximately 2 years
<b>Wind data available</b>	None
<b>Special feature / relevance of site</b>	An actual large scale offshore wind farm. Observed park efficiency sorted by equivalent stability
<b>Investigations made</b>	Available wake models are tested against actual wake loss. Compensation techniques are tested: increased roughness inside windfarm, changing model parameter Wake Decay Constant and some available parameters for Eddy viscosity and EWTS models, compensating for equivalent stability.

## 5. Results from case studies

The three case studies have provided insight into the performance of wake loss models, but not necessarily exactly consistent results. This is partly due to the different nature of the available data, but also likely due to the different environment of the sites. However several trends and tendencies have been observed and it is possible to give a number of recommendations.

### 5.1. Typical results using default parameters

When considering the total park efficiency (defined as the wake reduced production compared to the unobstructed production) of the entire wind farm the available wake models rate in their performance consistently throughout the test cases.

In the default runs all models are using the default parameters in WindPRO as described in the manual document [1].

The original (old) N.O. Jensen model will result in the largest wake loss (lowest park efficiency), which will usually also tend to be closest to the observed wake loss.

This is followed closely by the new revised version of the N.O. Jensen model, which typically result in 1 to 2% of production lower wake loss.

Even lower wake loss is calculated with the Larsen (EWTS) model. This is typically further 2-3% production lower in wake loss.

The lowest wake loss, meaning the highest park efficiency is obtained using the Eddy viscosity (Ainslie) model. It results in a ½ to 1 % production lower wake loss, which means 4 – 5% higher resulting production output than the old N.O. Jensen model. This is not entirely consistent though as the Zafarana case actually demonstrated that the Eddy viscosity model here gave the same results as the N.O. Jensen model

These figures will of course vary depending on the magnitude of wake loss. These sites are all in the scale of 85 to 90% park efficiency. Also the relative difference in wake loss seems to vary from site to site.

Another tendency observed is that the wake loss is increasing down wind in large wind farms more than the models predict. This is consistent for all models and means that small wind farms would typically be well predicted, but the larger the wind farms get the more likely the wind farms is to become over predicted (predicting too low a wake loss).

Zafarana with a very uniform wind direction indicates that this is a process that begins already after 3 rows of turbines. Wind farms with more variation in wind direction should be expected to require more rows before this deficit set in, though Klim indicates that this could be already after row 2. The effect was not researched at Horns Rev.



At Horns Rev was instead observed how the precision of the wake models is a function of direction. While some directions get the wake loss over predicted, some specific directions get the wake loss grossly under predicted. These directions seem to coincide with the diagonals of the wind farm and could therefore be due to more turbines upwind or simply a deeper fetch influenced by wakes. (The distance across the wind farm is longest along the diagonals). Though at this point this is purely speculation.

## 5.2. Influence of WDC (N. O. Jensen model).

The Wake Decay Coefficient (WDC) has a great influence on the result of the wake loss calculation.

The Wake Decay Constant gives the rate of expansion of the wake and at the same time the rate at which the wind speed deficit recovers [1]. As such it is closely linked to the ambient turbulence of the wind. Low turbulence means low Wake Decay Constant, which in turn means higher wake loss (lower production).

Measured turbulence has not been considered for any of the cases, but it is well known that ambient turbulence to a large extent is a function of the terrain roughness [1]. Appropriate WDC should therefore be deduced from the landscape type. Default in WindPRO open land is set to a WDC of 0.075, while open water is set to 0.04.

Ambient turbulence is also a function of meteorological stability so that unstable conditions (warm surface temperature – colder air temperature) lead to a increase in mixing meaning more turbulence. Conversely stable conditions (cold surface warmer air temperature) leads to less mixing, meaning less turbulence. It is therefore reasonable that turbulence should influence on the choice of the right Wake Decay Constant.

The cases have demonstrated the importance of selecting a proper Wake Decay Constant. The Klim case shows that the wake loss may change by 30% (from 11.6% with 0.075 to 15.6% with a WDC of 0.04), while the Horns Rev show a difference of 37%.

On the Klim case a fairly high WDC seem the right choice for the total output calculation. The default WDC of 0.075 is only 9.7% off (1.2% production).

At Zafarana default was selected at 0.075, but it took a value of 0.03 to get close to the total observed wake loss.

Horns Rev, being an offshore site was by default set to 0.04. This however seemed to be too low.

All three cases however showed that the problem is not simply solved by setting the correct WDC. As mentioned in section 5.1 the precision of the wake model is a function of direction and location in the wind farm. Prediction a correct total wake loss seem to mean that the first rows get their wake loss over predicted, while the back rows get their wake loss under predicted. Similarly some directions will be predicted better than others.

This problem is not solved by shifting to the other wake models. They all suffer from these issues.

Therefore it is clear a more elaborate model is needed that can deal with these larger wind farm issues.

## 5.3. Influence of increasing internal roughness.

Such an attempt was made by introducing an internal roughness zone.

The idea is that the internal roughness zone will introduce an energy drain that is a function of the size of the wind farm. By increasing the roughness in an area outlined by the boundaries

of the wind farm the calculated production output of the wind farm will be reduced. The reduction will be most severe in the sectors where the fetch with turbines is longest. That means that back row turbines will be reduced most while front row turbines will be reduced the least. The equivalent wake loss is then calculated as the resulting production compared to the undisturbed turbine without increased roughness.

The most obvious success of this approach is for the Zafarana case. Here a proper choice of internal roughness (roughness class 1.8 or roughness length 0.079 m) manages to bring all the rows into alignment (to a correct relation actual/calculated production).

The success is not as obvious for the Klim case. Here the total wake loss gets closer to the observed wake loss, but the rows are not so clearly brought into alignment. Probably due to the higher background roughness a much higher roughness is needed here.

The individual turbine-by-turbine wake loss was not examined in the Horns Rev case. Therefore it is not possible to tell if the increased roughness was able to bring the rows into alignment. However the total calculated wake loss became highly exaggerated, even for a much higher than default Wake Decay Constant.

It is documented through the cases that a progressive energy drain that increases with depth of wind farm is a good idea. The questions remain however if a roughness increase is the right solution and if it is, how the roughness increase is a function of spacing, depth, wind direction and background roughness of the wind farm.

Since the increased roughness zone method simply offsets the total calculated wake loss, there is no difference to the impact on the different methods. They all get offset by the same magnitude.

## 5.4. Special parameters for the Eddy viscosity model

Some experiments have been made with the parameterization of the Eddy viscosity model in the cases. The focus has been on the  $k_1$  constant and the axial grid size for the numerical solving of the model.

$K_1$  is an empirical value which previous studies [1] have found to be 0.015.

In the Klim case a value of 0.02 was tested and in Zafarana 0.025 was tried, but in but cases the differences were negligible.

The grid size for the solution of the model is in radial direction default set to 0.1 times rotor diameter, while in axial direction this is extended to 0.25 times rotor diameter. This is a very time consuming calculation and it makes sense to compromise on the grid size if it can reduce computation time.

In Klim and Horns Rev cases the axial grid size was reduced to 0.1 times rotor diameter, which is the same as in radial direction and in both cases that has significant effect. In the Klim case reducing the grid size like this reduces the error from 43% to 33% (1% of total production), while in the Horns Rev case the error is reduced from 37% to 29%.

Despite the increase in computation time it can be concluded that a lowering of the grid size result in a markedly improvement on the performance of the Eddy viscosity model.

## 5.5. Special parameters for the Larsen (EWTS II)

Only one parameter can be set for the Larsen model. That is whether to use a first or second order approach. This variation was tested in the cases, but turned out to have no influence at all on the result. The reason for this is that choice of order is only relevant for the zone directly behind the rotor and none of the wind farms have layouts with so close a spacing that this zone becomes relevant.

## 5.6. Suggestion concerning stability correction

In the Horns Rev case the park efficiency data showed a clear correlation with the temperature difference (water to air) measurements. Since these temperature measurements are related to the meteorological stability conditions, we can say that we have observed a clear connection between wake loss and meteorological stability.

This is in line with the considerations mentioned in section 5.2, where stability is linked to ambient turbulence, which is in turn linked to Wake Decay Constant, which in turn is linked to magnitude of wake loss.

For the Horns Rev case a correction is suggested to modify the wake loss calculation using N.O. Jensen method to stability correct the wake loss.

The method is limited to stability data obtained in precisely the same manner as on Horns Rev and to data with limited variation of stability with wind speed and most importantly, due to lack of Nysted data it has not been possible to verify the stability correction method.

If the method can be verified it offers a possibility to improve the simple, fast and easy accessible N.O. Jensen model for offshore use.

## 6. General recommendations

Based on the model implementation studies and the case studies a number of recommendations can be made.

1. Use the original N.O. Jensen model for wake calculations

In the three cases the original N.O. Jensen model is consistently better than or as good as the other models. In Klim and Horns Rev the margin is significant.

2. For small wind farms the default Wake Decay Coefficients are a good, reliable choice. The first rows at Zafarana and Klim are predicted well with standard conditions

3. Large wind farms need additional deductions downwind in the wind farms. While Klim and Zafarana clearly showed the benefit of adding a zone with increased roughness inside the wind farm, there is no clear recommendation to the magnitude of the roughness needed. Worse is that such a roughness zone is not needed at all at Horns Rev. The recommendation is therefore that in order to avoid an under prediction of the wake loss (over prediction of the production), an internal roughness zone approximately class 1 above the background roughness can be added. One has to be aware however of the risk of over predicting the wake loss.

4. Offshore wind farms are susceptible to influence from the meteorological stability and may benefit from a stability correction. This correction is still purely experimental. At this point we will simply recommend looking out for any unusual stability distribution.

## 7. Future research

The case studies have highlighted a number of issues that would benefit from further research. These are summarized in the following.

### 7.1. Improving wake model

The obvious research suggestion is to come up with a new and improved wake model to replace the existing. The case studies have shown the problems associated with compensating for the deficiencies of the existing models.

A new model should as a minimum address the problem of progressive wake loss downwind in the wind farm.

Also, or more likely as part of this problem, the ambient and wake turbulence should be dealt with in a manner where observed ambient turbulence on site can be used as input, so a correct WDC is automatically used.

## **7.2. Improved internal roughness**

As long as we are stuck with the existing model we need more knowledge on the influence of internal roughness. The cases showed us that the benefit of this internal roughness zone is not universal and we need to know if that is a general trend or just a quirkiness of the Horns Rev case. It is possible that a combination model of WDC and internal roughness can prove generally applicable, but this requires more case studies, most importantly more large offshore case studies.

## **7.3. Test of stability correction method**

The stability correction method suggested in the Horns Rev case must be validated in future case studies. Until that happens it cannot be considered generally valid.

# **8. Dissemination of results from the project**

The dissemination of the results from the project has been a continuous process that has involved EMD activities on several levels. As experiences and results have become available they have been incorporated into EMD material used for general dissemination.

These activities include the following:

- The WindPRO software package.
- Manuals for the WindPRO software package
- Training courses in using the WindPRO software
- General presentations on wind energy issues
- Posters and articles for conferences.
- Project home page

## **8.1. The WindPRO software package.**

EMD International A/S develops, market and support the software package WindPRO.

WindPRO is a package offering tools for the wind project designer within wind resource assessment and environmental impact assessment and is as such similar to a GIS environment. Currently WindPRO is widely used on a global scale and a leading product within its field.

Assessment of wake losses is an important part of the design of wind farms. Optimal layouts are those that can combine high efficiency with minimal land use and high installed capacity. An improved understanding of wake losses in the form better application of wake model is therefore a benefit for most users of the WindPRO package.

EMD have implemented the models described under this study in WindPRO and adjusted parameters along the way to reflect our best experience.

The description of the models as they are implemented in WindPRO has been included in the beginning of this report.

The user can now choose between 4 wake models and 8 turbulence models, each with a number of variable parameters. EMD have pre-selected defaults that correspond to the results of this study.

## **8.2. Manuals for the WindPRO software package.**

The full documentation of the wake models and their parameterization included at the beginning of this report has been included as part of the manual and has as such reached all users of the WindPRO software.

## **8.3. Training courses in using the WindPRO software**

EMD conduct on average 8 standard WindPRO courses and 2 advanced WindPRO courses per year. In 2007 alone the figures were 10 standard and 2 advanced courses, including a total of approx. 140 attendees. In addition, round 10 – 20 tailor-made courses at software customers, where most of them included wake losses.

While the courses focus on the general use of the software this includes training in best use of wake models. For the advanced course particularly an entire segment is allocated wake models and their parameterization with special focus on offshore wind farms. Here attendees have been updated with the latest results of the present project including the articles and manuals produced through the project. These advanced courses have also functioned as discussion forums where experienced users of the software have given their comments on the model results.

## **8.4. General presentations on wind energy issues**

EMD have conducted a few general training courses in wind energy issues. These sessions have not been focused on the WindPRO software, but rather been concerned with general issues on wind energy within EMD's field of expertise.

These presentations have been occasions where EMD have been able to disseminate results from the present project.

Examples of such presentations:

Wind farm design, Kristiansand, Norway – 5/12-2006  
Investment in wind farms, Fredericia - October 29, 2007  
Best Practice within Wind Farm Development – Beijing, January 10-11, 2008

## **8.5. Posters and articles for conferences.**

Two posters were presented at the European Wind Energy Conference 2006 in Athens. They were published along with two articles.

### **Posters and papers:**

**Title:** Recalibrating Wind Turbine Wake Model Parameters – Validating the Wake Model Performance for Large Offshore Wind Farms

**Authors:** Thomas Sørensen, M.Sc, Per Nielsen, M.Sc. & Morten Lybech Thøgersen, M.Sc.  
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**Location:** EWEC 2006, Athens

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**Title:** Evaluating Models for Wind Turbine Wake Added Turbulence – Sensitivity Study of Models and Case Study.

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**Location:** EWEC 2006, Athens

## 8.6. Project home page

The full project report is publicly available from the EMD homepage at

<http://www.emd.dk/ParkKalibrering>

This includes manual, case studies and articles.

WindPRO project files are available for the case studies used, though confidential data is not available.

## 9. References

1. Thøgersen, Morten, "WindPRO / PARK, Introduction to Wind Turbine Wake Modelling and Wake Generated Turbulence", EMD International A/S

# Case study 1: Klim

## 1. Abstract

The Klim wind farm is a typical onshore wind farm with a regular layout, which is typical for many other larger onshore sites in non-complex terrain. Results from this site are therefore applicable on most onshore sites in general.

The experiments show that it is difficult to calculate the wake losses of the individual turbines correctly, but that it is possible to get close through proper use of the models available.

A host of wake models have been tested and the best fitting model seem to be the original N.O. Jensen model. While a scenario based on actual concurrent wind and production measurements indicates that a Wake Decay Constant of 0.04 would be more appropriate for the back row, a scenario based on a long term average wind climate indicated that an intermediate WDC between typical onshore and typical offshore would fit better on the back rows and 0.075 would fit well on the front rows.

Compensating for the energy drain with an internal roughness improves the result, but is not as effective as on a smooth surface. Applying an internal roughness area of class 2.4 (0.174m) reduces the error on the prediction of the actual park efficiency to 0.3% of total production, which corresponds to an error of 2.7% on the wake loss parameter.

## 2. Introduction

The Klim wind farm is located in north-western Denmark as indicated in Figure 1. It consists of 35 Vestas V44 600 kW wind turbines with a hub height of 44 m. The turbines are placed in a simple geometric shape with 4 rows and 10 columns (half of these have only 3 rows). The rows are facing southwest which is the predominant wind direction in Denmark and the rows can therefore be labelled 1 to 4 with 1 being the front row (Figure 1).

The typical spacing between the turbines is 4.5 times rotor diameter within the rows and 5.5 to 7 between the rows.

Nordjyllandsværket, a local power plant now operated by Vattenfall, erected the turbines in the years of 1996 to 97. An extensive amount of production data is publicly available and the operator has supplied more detailed data.

This availability and history of data together with the regular layout is what is making this site interesting.



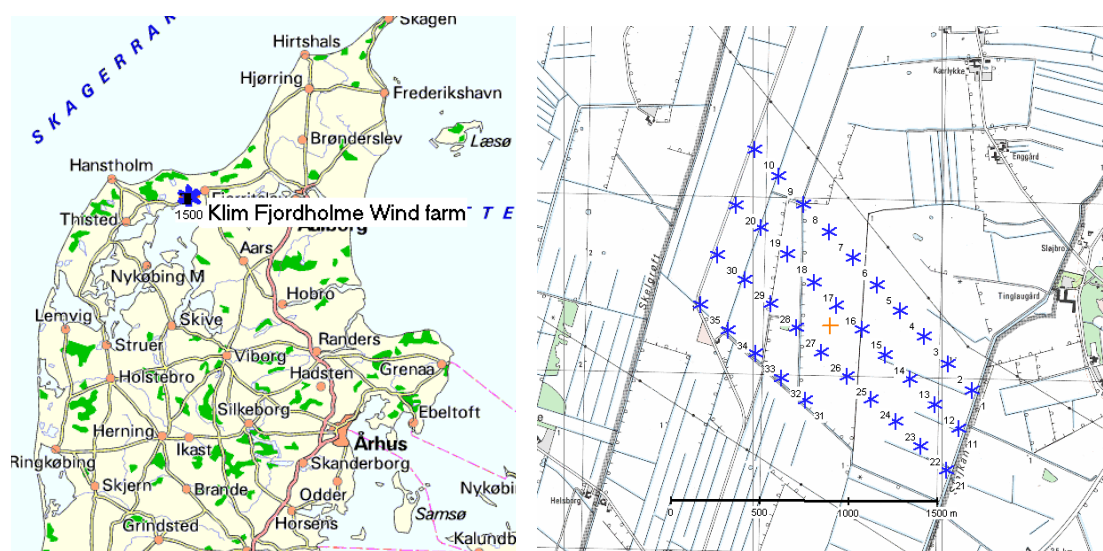


Figure 1. Map of the Klim site and the layout. The numbering of the turbines is used throughout the case study. Maps courtesy of the National Survey and Cadastre (KMS).

### 3. Scope of study

The objective of studying the Klim project is to test if the wake loss calculation models (Park models) currently in use are able to predict the observed wake losses in the wind farm.

The focus is the effect of varying the models and the parameters of the models to test their influence on the wake loss calculation.

### 4. Data background

As is common for projects in Denmark the project was developed without local measurements. Instead the common Danish wind statistic (wind atlas) DK'92 was used, as it would still normally be for projects in Denmark.

DK'92 is based on old measurements from the site Beldringe on the island of Funen, which has been calibrated with production data from local wind turbines providing regional correction factors. For the Klim wind farm the correction factor is 1.13. Since the direction distribution used is directly adopted from Beldringe, it is possible it will be slightly different for Klim. The energy rose is displayed in Figure 2, and indicate a predominant wind direction from south-southwest to west, which match the orientation of the wind farm.

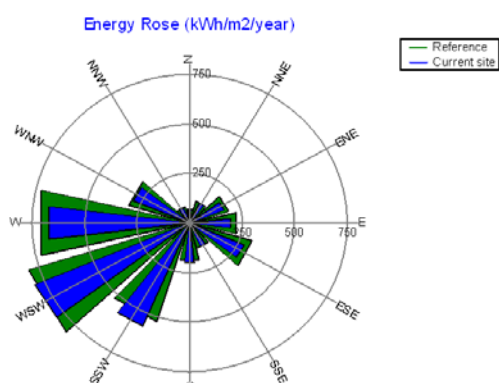


Figure 2. Energy rose for the DK92 wind statistic. The green rose is for a flat roughness class 1 site, while the blue rose is for the Klim site.

A second wind data set is used for a short period of 89 days in 1998. Here data from a 10 m mast at Silstrup, 35 km to the west is matched with a set of complete daily data from Klim.



This 89 day period was a relatively high wind speed period with a concentration of wind from west southwest to west northwest (Figure 3). This angle is a bit off the orientation of the wind farm.

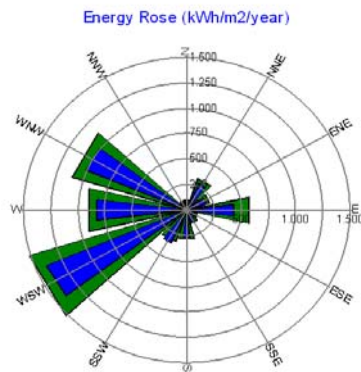


Figure 3. Energy rose for the Silstrup 89 days wind statistic. The green rose is for a flat roughness class 1 site, while the blue rose is for the Klim site.

The landscape texture in terms of roughness is obtained from the wind resource map for Denmark, an earlier project from EMD and Risø [1]. Here the terrain is digitized in 1 by 1 km tiles based on the density of shelterbelts and villages, while major elements like forests, coastlines, towns and lakes are digitized separately. An extract of this map is shown in Figure 4. The average roughness for the Klim site is class 1.4. While the site is relatively compact and orientated parallel to the coastline the experienced roughness does not change much throughout the wind farm.

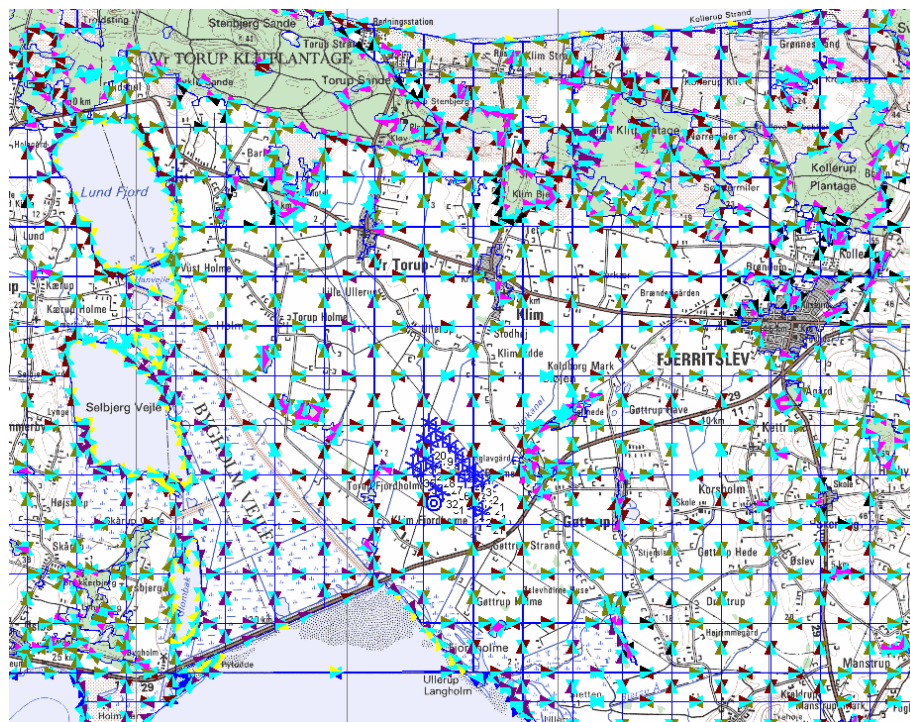


Figure 4. Roughness map of the surrounding area. The roughness map was originally used for the Danish wind resource map, and is describing roughness in tiles of 1x1 km. Maps courtesy of the National Survey and Cadastre (KMS).

The site is entirely flat so no height model is used.

Production data is available for the wind farm as two sets of data.

- a) Monthly production data from installation (September 1996 until May 2000) from the internal computer for each of the turbines.

- b) Complete production record for the year of 1998 as 10 minute production figures for each turbine.

The first of the two data sets have been used to set up the average yearly production for each turbine by correcting for availability loss and other irregularities and adjust it with monthly wind indexes to obtain the normal production. This normal production is comparable to calculation results using the general DK'92 basis. The yearly production figures are shown in Figure 5.

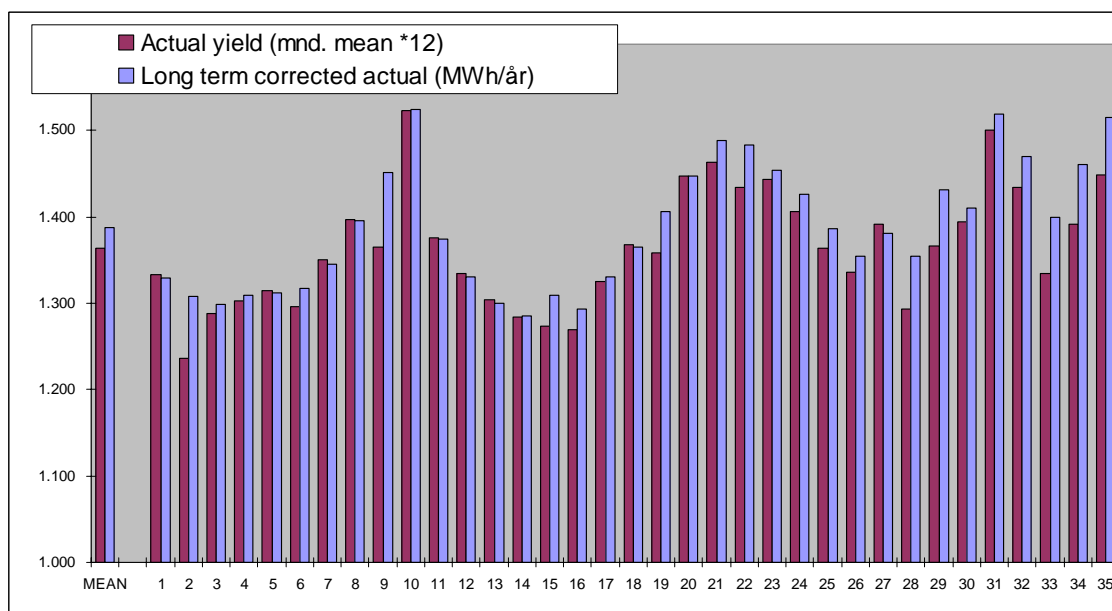


Figure 5. Actual production and normalised production for the turbines of the Klim wind farm based on the period 1996 to 2000.

The second dataset is aggregated into daily production figures. The days in which all turbines are fully available are isolated and amounts to 89 days. For this period any deviation from the ideal production will be due to wake losses. This production period corresponds to the wind regime identified from the Silstrup mast. If the production was representative it would correspond to annual production figures as shown in Figure 6.

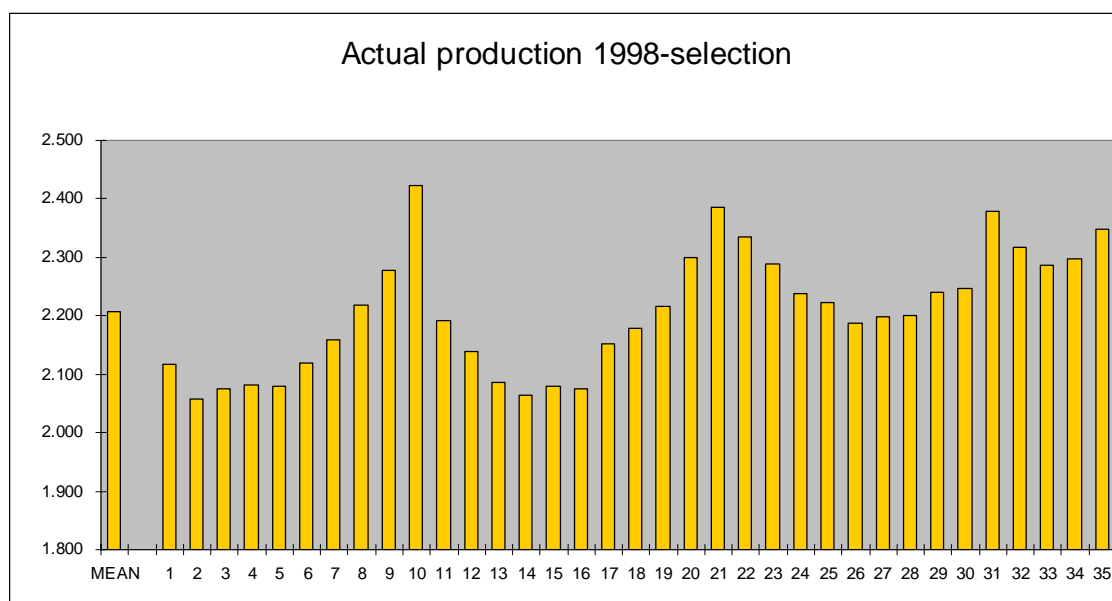


Figure 6. Actual production from the 89 days of full availability scaled up to a full year.

The turbines used in the Klim wind farm are Vestas V44-600 kW turbines and the power curve used is the official power curve as informed by the manufacturer. A comparison with the standard HP curves reveal that the power curve used is approximately 4% pessimistic at the 7m/s mean wind speed which is the average wind speed at hub height for this site. For the Silstrup matching period the average wind speed is somewhat higher at 8.6 to 8.7 m/s. Here the HP correction is approaching 7%.

HP curve comparison							
Vmean	[m/s]	5	6	7	8	9	10
HP value	[MWh]	706	1.163	1.637	2.099	2.489	2.835
Manufacturer 24/8-2000	1.225	20.00	0.00	[MWh]	686	1.124	1.576
Check value				[%]	3	3	4
					5	7	9

Figure 7. HP check for the Vestas V44-600 kW turbine.

The air-density of the air at hub height has been set to standard 1,225 kg/m<sup>3</sup> since this is the air density with which the DK'92 wind statistic is calibrated.

## 5. Calculation results

### 5.1. Principle

The wake loss calculations are tested by comparing results from the available wake models with the actual wake loss for the two scenarios: Normal wind statistics and Silstrup wind statistics.

This exercise will allow us to evaluate which model if any will be appropriate for calculating this type of site.

### 5.2. First calculation – establishing the actual wake loss.

The first calculation is a basic setup using standard parameters for an onshore project in non-complex terrain. That means:

Park model: N.O. Jensen

WDC: 0.075

Roughness: Standard roughness description.

This results in a calculated annual production for each turbine including calculated wake losses.

If the calculated production is adjusted to remove the wake losses the freestanding turbine production is obtained. Using the general wind statistics this production figure vary from +/- 1.7% with a standard deviation of 0.9%. With the Silstrup wind statistics the production figure vary +/- 1.4% with a standard deviation of 0.7%.

This means that according to the WAsP model set up for this project there is very little variation across this wind farm, however it is not reasonable to simply assume that a free standing turbine would produce the same anywhere in the wind farm.

The most freestanding turbines in the wind farm (the ones with the lowest wake losses) are turbine 10 and 35 in the northwest and southwest corners. Using the general wind statistics they have a park efficiency of 95.2% and 94.3%. For the Silstrup statistics the park efficiency is 96.8% and 95.4% (see Figure 8). If we assume that this minor wake loss is correctly calculated the freestanding production can be calculated by removing this wake loss. The averages of these two turbines are then used as the base production. Each of the turbines in the wind farm is then adjusted with the deviation from 10 and 35 that WAsP predicts.

Normal model

Turbine	Actual production, MWh/y	Park eff. %	Free standing production, MWh/y
10	1524	95,2	1601
35	1515	94,3	1607
average			1604

Silstrup model

Turbine	Actual production, MWh/y	Park eff. %	Free standing production, MWh/y
10	2422	96,8	2502
35	2349	95,4	2462
average			2482

Figure 8. Calculation of base production uninterrupted by wakes. The actual production of turbine 10 and 35 is cleaned of wake loss and the average is corrected for the WASP predicted difference for each turbine and used as base production

The actual wake loss is then found by comparing the average actual production of the turbines in the wind farm with the average base production of the individual turbines. This results in a park efficiency for the normal model of 87.2% (12.8% wake loss) and 89.5% (10.5% wake loss) for the Silstrup model.

For the individual turbines the actual park efficiency can be found by dividing the actual production with the average base production for the wind farm and multiplying with the average park efficiency.

If we now compare the calculated free standing production of the wind farm with the actual free standing production (actual production corrected for actual wake loss) (Figure 9 and Figure 10) we find that on average the actual production using the general wind statistics is 3.1% higher than the calculated production. For the Silstrup wind statistics the actual production is 6.4% higher than the calculated production. This is interesting because this is very close to what the HP curve check tells us that the power curve is offset.

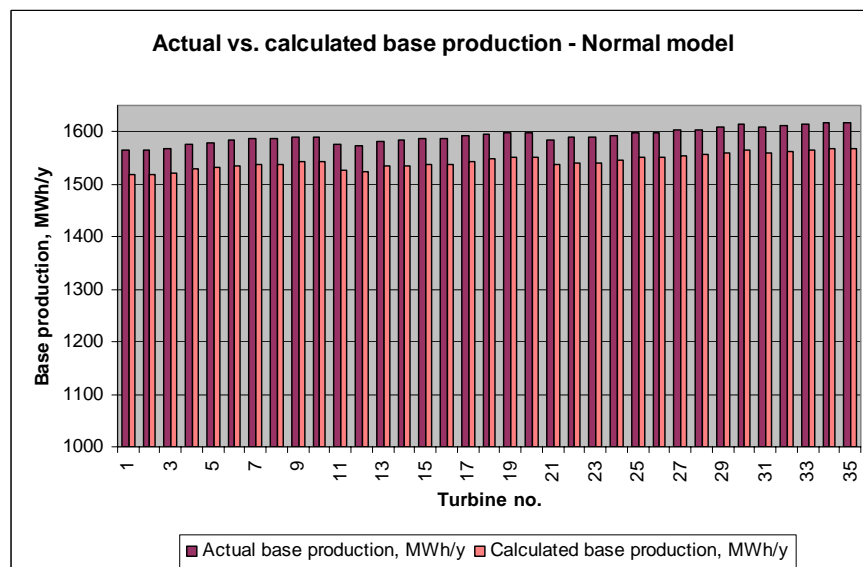


Figure 9. Actual vs. calculated base (free standing) production reveals a deficit. For the general wind statistics this is 3.1%.

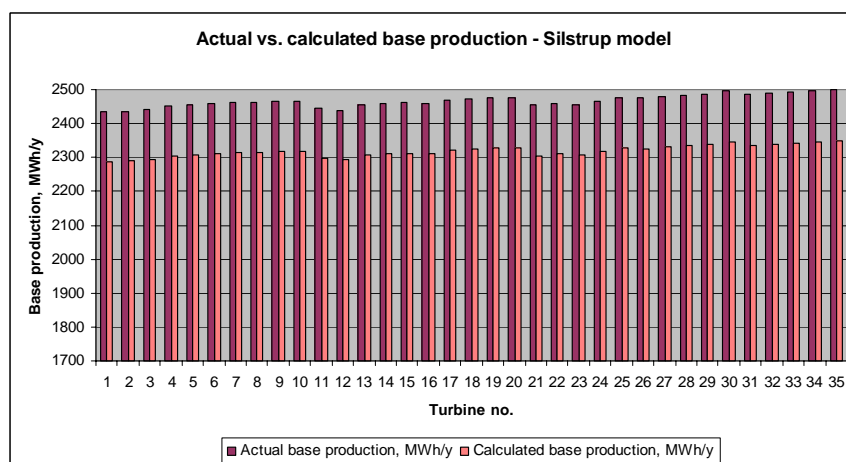


Figure 10. Actual vs. calculated base (free standing) production reveals a deficit. For the Silstrup wind statistics this is 6.4%.

### 5.3. Standard method – changing the WDC.

The first test of the wake models is a test of the standard N.O. Jensen model, used by WindPRO and WAsP as the default method

The calculations are using the standard settings described above except that the Wake Decay Constant (WDC) is set to 0.04, 0.075 and 0.1. Figure 11 show the results using the general wind statistics, while Figure 12 gives the result for the Silstrup wind statistics.

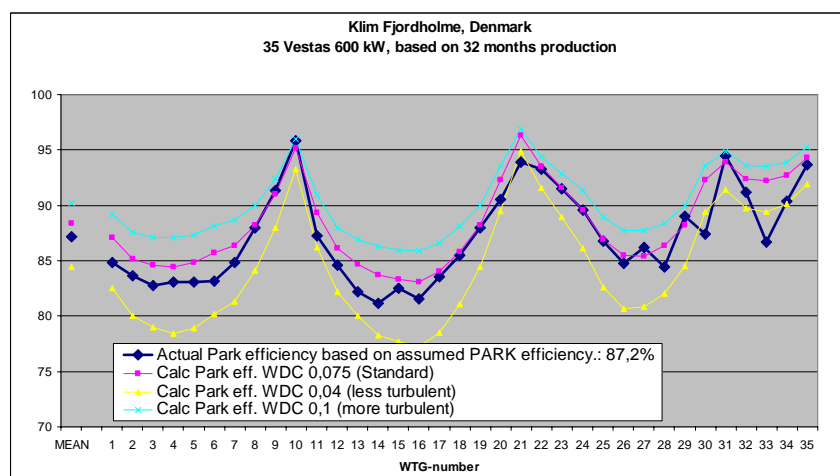


Figure 11. Comparing park efficiency (inverse wake loss) using the N.O. Jensen model with actual park efficiency. General wind statistics.

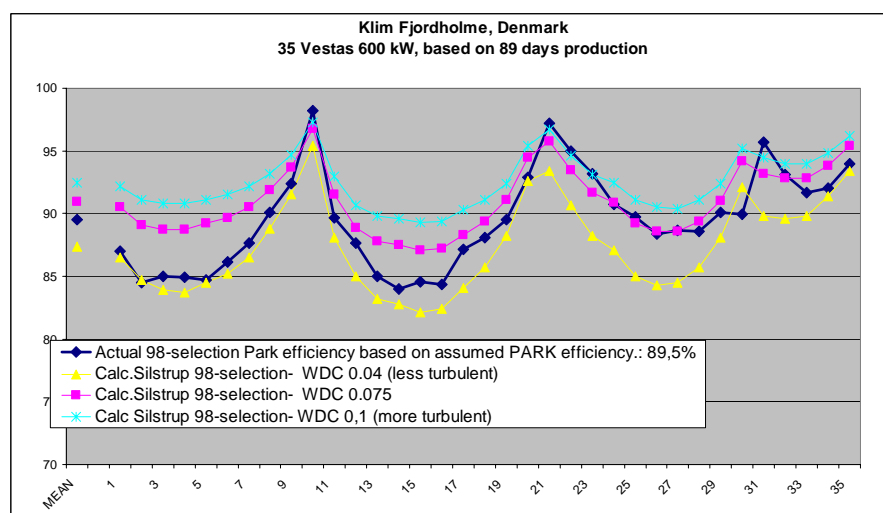


Figure 12. Comparing park efficiency (inverse wake loss) using the N.O. Jensen model with actual park efficiency. Silstrup wind statistics.

According to the general wind statistics the standard onshore WDC of 0.075 seem to fit the second row quite well while the third and fourth row are over-predicted. That is, the wake model does not calculate a large enough wake loss. The difference however is not large. The prediction of the first row is oddly under-predicted, but that may be due to a possible too low calculation of the actual production of turbine 33. On average the difference between actual and calculated wake loss is 1.2% of total production (Figure 13).

The low-turbulence 0.04 setting of WDC significantly under-predict the park efficiency, even in the back rows while the higher turbulence WDC of 0.1 over-predict the park efficiency.

Normal wind model	Park efficiency %	Wake loss %	Difference from actual wake loss in percentage of production %	Difference from actual wake loss relative to actual wake loss %
Actual park efficiency	87,2	12,8		
N.O. Jensen WDC 0,075 (Standard)	88,4	11,6	-1,2	-9,4
N.O. Jensen WDC 0,04	84,4	15,6	2,8	21,7
N.O. Jensen WDC 0,1	90,3	9,7	-3,1	-23,8

Figure 13. Average park efficiency (wake loss) for the general wind statistics.

For the Silstrup wind statistics the situation is somewhat different. Here the standard WDC of 0.075 fit best for the front rows while 0.04 fit best for the back row with row 3 being a transition row between the two. On average WDC of 0.075 over-predicts the park efficiency by 1.4% while 0.04 under-predicts by 2.1%, which as a whole is not so far from the results using the general wind statistics.

Silstrup wind model	Park efficiency %	Wake loss %	Difference from actual wake loss in percentage of production %	Difference from actual wake loss relative to actual wake loss %
Actual park efficiency	89,5	10,5		
N.O. Jensen WDC 0,075 (Standard)	90,9	9,1	-1,4	-13,7
N.O. Jensen WDC 0,04	87,4	12,6	2,1	20,3
N.O. Jensen WDC 0,1	92,5	7,5	-3,0	-28,4

Figure 14. Average park efficiency (wake loss) for the Silstrup wind statistics.

## 5.4. Alternative models

A second test change is to try the different models EMD has implemented in WindPRO. These are all described elsewhere in the report [2]. Here the following models have been

tested, all using default WindPRO settings where nothing else is stated (WDC in all cases = 0.075).

N.O.Jensen old  
 N.O.Jensen new  
 Ainslie default settings  
 Ainslie (axial grid 0.1 x rotor diameter)  
 Ainslie ( $k_1=0,020$ )  
 EWTS (1<sup>st</sup> order)  
 EWTS (2<sup>nd</sup> order)

The two parameters modified in the Eddy viscosity (Ainslie) calculation is the grid density which in the axial direction (away from the turbine) normally is 0.25 x rotor diameter, and the  $k_1$  factor which is normally set to 0.015.

The result from using the newer version of the N.O.Jensen model is shown in Figure 15 and Figure 16. In both cases the results are marginally poorer with the new model than the old model and on average the park efficiency is 2.1% too high for both wind models (Figure 21).

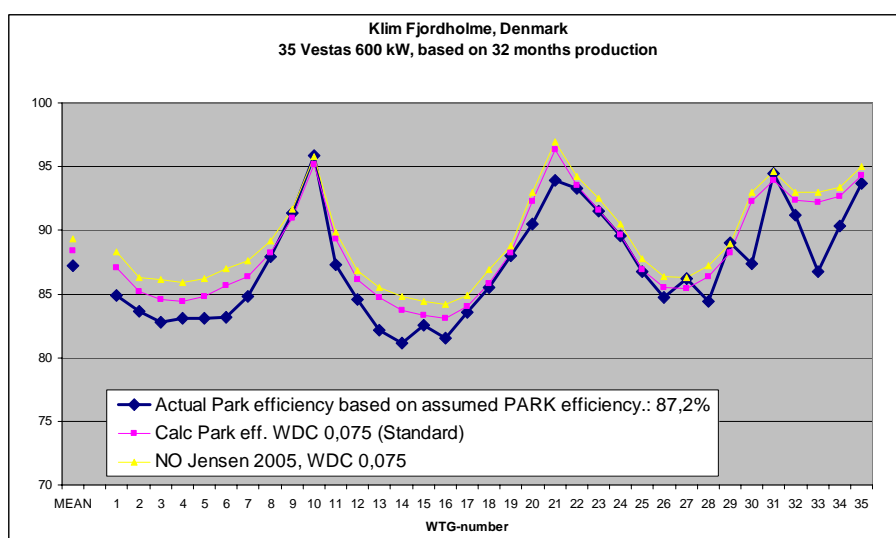


Figure 15. Test of N.O. Jensen 2005 model against original N.O. Jensen and actual park efficiency. General wind statistics.

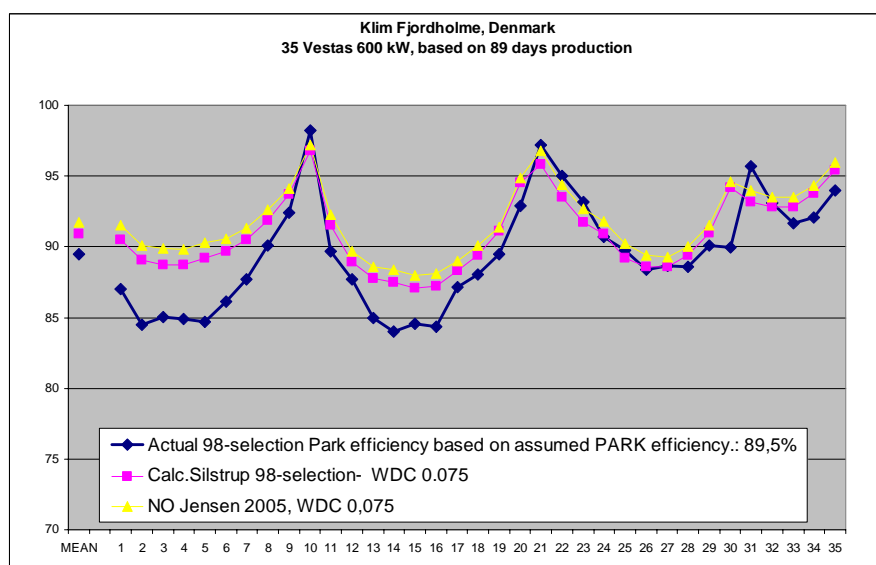


Figure 16. Test of N.O. Jensen 2005 model against original N.O. Jensen and actual park efficiency. Silstrup wind statistics.



The Ainslie varieties are shown in Figure 17 and Figure 18. Here it is quite clear that none of the varieties are able to predict the actual park efficiency. Reducing the axial grid size to a tenth of the rotor diameter helps, but the result is still significantly poorer than using the standard N.O. Jensen model. The modification of the  $k_1$  value however does not seem to make any difference. The error range from 3.5% to 5% of total production (Figure 21).

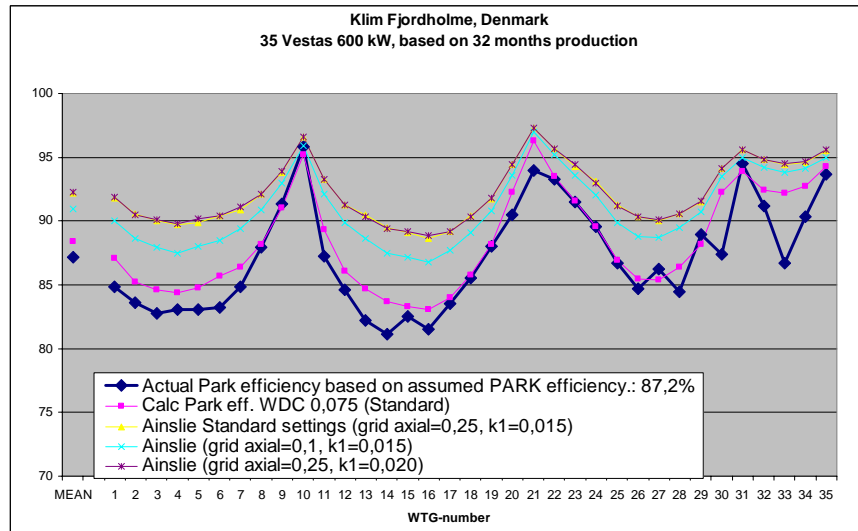


Figure 17. Test of Ainslie model against original N.O. Jensen and actual park efficiency. General wind statistics.

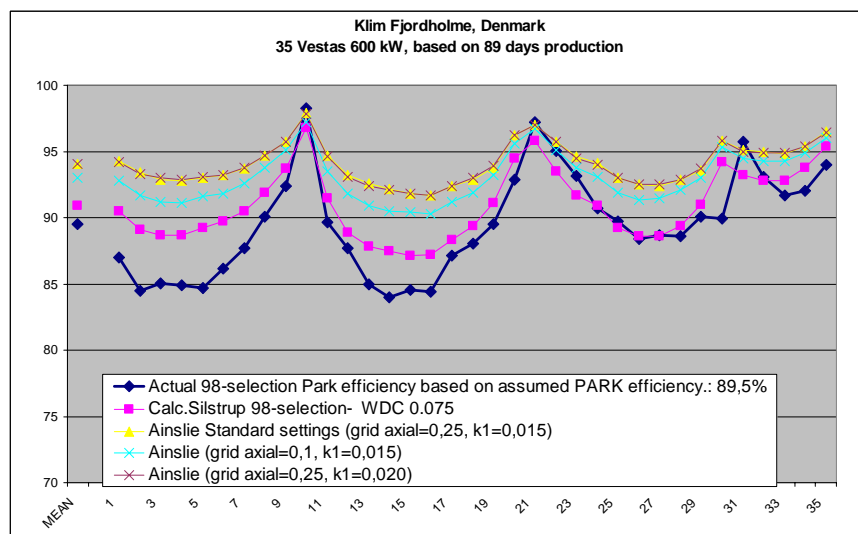


Figure 18. Test of Ainslie model against original N.O. Jensen and actual park efficiency. Silstrup wind statistics.

Finally it is tested how the EWTS model performs compared to actual park efficiency. This is shown in Figure 19 and Figure 20. Here we can see that there is absolutely no difference whether we use the 1<sup>st</sup> or 2<sup>nd</sup> order version of the model. For both our scenarios the EWTS is insufficient at calculating the actual wake loss. On average EWTS is 3.5 to 4.2% of total production off.



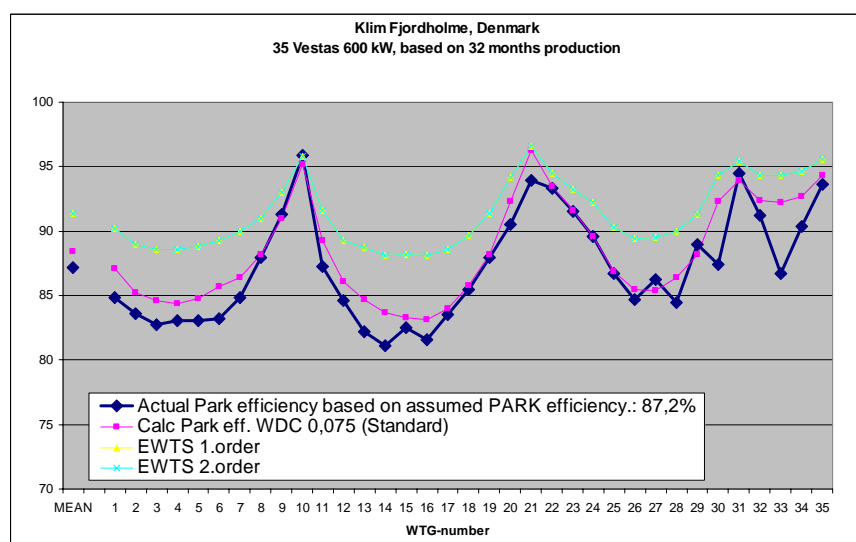


Figure 19. Test of EWTS model against original N.O. Jensen and actual park efficiency. General wind statistics.

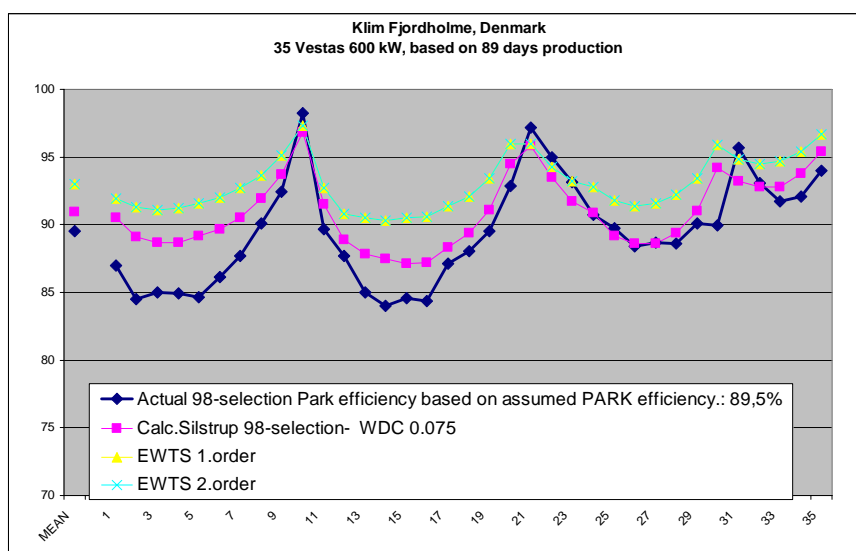


Figure 20. Test of EWTS model against original N.O. Jensen and actual park efficiency. Silstrup wind statistics.

It would appear that none of the alternative methods, even when adjusting their parameters, are better suited than the original N. O. Jensen model. The average park efficiency and the deviation from the actual park efficiency are listed in Figure 21.

Normal wind model	Park efficiency %	Wake loss %	Difference from actual wake loss in percentage of production %	Difference from actual wake loss relative to actual wake loss %
Actual park efficiency	87,2	12,8		
N.O. Jensen WDC 0,075 (Standard)	88,4	11,6	-1,2	-9,4
N.O. Jensen 2005 WDC 0,075	89,3	10,7	-2,1	-16,5
Ainslie Standard settings	92,2	7,8	-5,0	-39,0
Ainslie (grid axial=0,1, k1=0,015)	91,0	9,0	-3,8	-29,5
Ainslie (grid axial=0,25, k1=0,020)	92,2	7,8	-5,0	-39,3
EWTS 1.order	91,4	8,6	-4,2	-32,5
EWTS 2.order	91,4	8,6	-4,2	-32,5

Silstrup wind model	Park efficiency %	Wake loss %	Difference from actual wake loss in percentage of production %	Difference from actual wake loss relative to actual wake loss %
Actual park efficiency	89,5	10,5		
N.O. Jensen WDC 0,075 (Standard)	90,9	9,1	-1,4	-13,7
N.O. Jensen 2005 WDC 0,075	91,7	8,3	-2,2	-21,1
Ainslie Standard settings	94,0	6,0	-4,5	-43,3
Ainslie (grid axial=0,1, k1=0,015)	93,0	7,0	-3,5	-33,6
Ainslie (grid axial=0,25, k1=0,020)	94,0	6,0	-4,5	-43,2
EWTS 1.order	93,0	7,0	-3,5	-33,3
EWTS 2.order	93,0	7,0	-3,5	-33,3

Figure 21. Average park efficiency (wake loss) using different wake models and parameter settings.

## 5.5 Adjustment of internal roughness

Since the majority of the turbines are over-predicted, especially in the back rows, it seems the model is lacking an energy drain. One of the suggestions regularly mentioned [3] is that large wind farms themselves are increasing the roughness of the surface they stand on, especially when that surface is very smooth. This particular site however is not very smooth, but typical for the open land with an average roughness of roughness class 1.4 (0.05m).

The energy drain can be introduced by creating a zone of increased roughness inside the wind farm. In order to do this the original roughness description have to be discarded and a new is made that allows the wind farm and nearest surrounding area to have a uniform roughness in which the internal roughness can be placed. The new roughness map including the internal roughness area is shown in Figure 22.

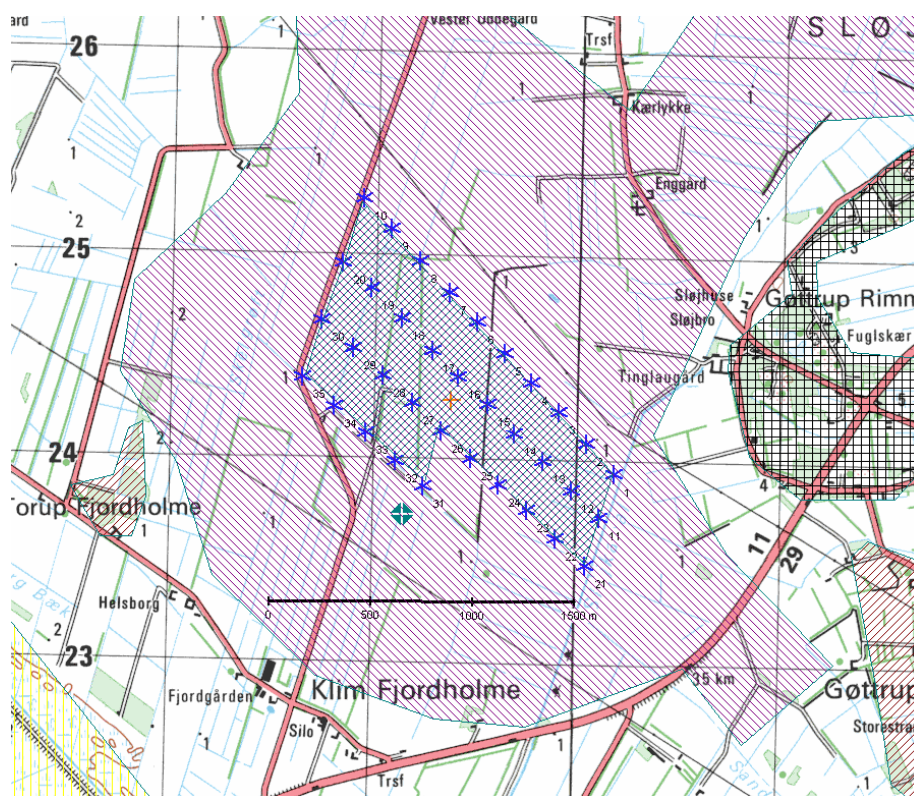


Figure 22. A revised roughness map including an internal roughness area. Maps courtesy of the National Survey and Cadastre (KMS).

While the background roughness of the field on which the wind farm is placed is class 1.2 (0.038m) the internal roughness areas must be substantially higher. A number of different roughnesses were tested of which two are reported here.

Case 1: Internal roughness class 1.8 (0.079m)

## Case 2: Internal roughness class 2.4 (0.174m)

The resulting calculation can be seen in Figure 23 and Figure 24.

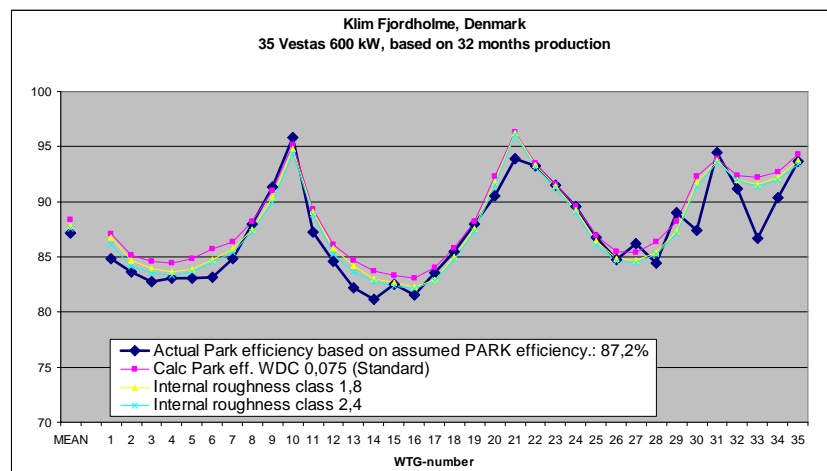


Figure 23. The figure shows the effect of including an increased internal roughness as an energy drain. General wind statistics.

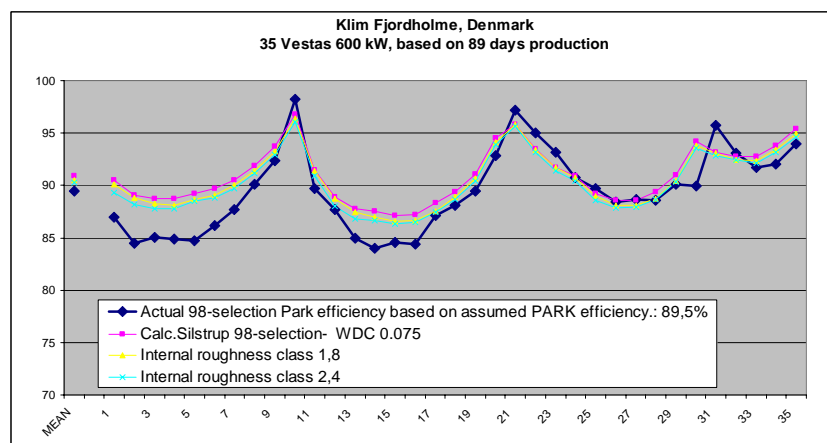


Figure 24. The figure shows the effect of including an increased internal roughness as an energy drain. Silstrup wind statistics.

The effect of including an internal increased roughness inside the wind farm is less than observed on wind farms in very smooth terrain and the roughness needed is much higher. This is probably because the terrain at Klim is rougher in general than those sites so it takes more to make a difference. Also it can be noted that the step from no area to class 1.8 is bigger than the step from 1.8 to 2.4, so there are limits to how much this kinds of compensation can be used. Even with class 2.4 the model is not able to predict the actual park efficiency. On average the prediction has improved (Figure 25), but the back rows are still not well predicted with the Silstrup model.

Normal wind model	Park efficiency %	Wake loss %	Difference from actual wake loss in percentage of production %	Difference from actual wake loss relative to actual wake loss %
Actual park efficiency	87,2	12,8		
N.O. Jensen WDC 0,075 (Standard)	88,4	11,6	-1,2	-9,4
Internal roughness class 1,8	87,8	12,2	-0,6	-5,0
Internal roughness class 2,4	87,5	12,5	-0,3	-2,7

Silstrup wind model	Park efficiency %	Wake loss %	Difference from actual wake loss in percentage of production %	Difference from actual wake loss relative to actual wake loss %
Actual park efficiency	89,5	10,5		
N.O. Jensen WDC 0,075 (Standard)	90,9	9,1	-1,4	-13,7
Internal roughness class 1,8	90,5	9,5	-1,0	-9,9
Internal roughness class 2,4	90,2	9,8	-0,7	-7,1

Figure 25. Average park efficiency (wake loss) when applying internal roughness.

## 6. Conclusion.

The Klim wind farm is a typical onshore wind farm with a regular layout, which is typical for many other larger onshore sites in non-complex terrain. Results from this site are therefore applicable on onshore sites in general.

The experiments show that it is difficult to calculate the wake losses of the individual turbines correctly, but that it is possible to get close through proper use of the models available.

In general the general wind statistics situation letting the general Danish wind distribution predict the long term predicted wind speed of the wind farm gives much more satisfying results than looking at a short period with a specific wind distribution and supposedly good production data. This could be due to the fact that the measurements that are 35 km from site are allowing the wind field to rotate from the mast to the turbines. But it could also indicate that the wake models work better on an average non-extreme direction distribution than a very specific and irregular distribution.

A host of wake models have been tested and the best fitting model seem to be the original N.O. Jensen model. While the Silstrup scenario indicates that a Wake Decay Constant of 0.04 would be more appropriate for the back row, the normal scenario indicated that an intermediate WDC would fit better on the back rows and 0.075 would fit well on the front rows.

Compensating for the energy drain with an internal roughness improves the result, but is not as effective as on a smooth surface. Applying an internal roughness area of class 2.4 (0.174m) reduces the error on the prediction of the actual park efficiency to 0.3% of total production, which corresponds to an error of 2.7% on the wake loss parameter.

A significant uncertainty in this case study is the establishment of the actual wake loss. This is of a scale where it does not change the qualitative results of the study but may affect the error values.

Nevertheless the case indicates an error on the wake loss parameter in the scale of 10% if standard settings are used (N.O. Jensen, WDC = 0.075), while this can be reduced significantly if internal roughness is applied.

## 7. References

1. Thøgersen, Morten et.al., "Vindresourcekort for Danmark", Energi- og Miljødata and Risø National Laboratory, 2001.
2. Thøgersen, Morten, "WindPRO / PARK, Introduction to Wind Turbine Wake Modelling and Wake Generated Turbulence", EMD International A/S, 2008.
3. Frandsen, Sten et.al., "The necessary distance between large wind farms offshore – study", Risø National Laboratory, 2004

## Case study 2: Zafarana

### 1. Abstract

At the Zafarana site the combination of large array wind farm and uniform wind direction offer unique opportunities to investigate array loss models performance down through multiple rows of turbines.

Default modelling settings fails to predict sufficient array loss. At the last rows the deficit is in the range of 15% to 20%- on total AEP.

Alternative park models do not improve this result. On the contrary, some provide an even poorer result.

Attempts at covering up the energy deficit by introducing an energy drain in the form of an internal increased roughness are successful. A detailed combination of roughness zones can make a quite acceptable prediction of actual losses, while a simple uniform roughness zone seems sufficient to cover up the deficit.

### 2. Introduction

The Zafarana wind farm is located in Egypt on the western shore of the Bay of Suez (see Figure 26). The project has been established in several stages and has throughout received Danida support in the form of extensive study performed by Risø. In the course of this study several meteorological towers has been erected and data has been made available to EMD trough [1].

The wind farm consists of 11 rows of turbines with a total of 222 turbines (Figure 27). While some of the rows are quite regular others take a wavy shape, but remain in an east to west configuration. The turbines are Vestas V47 660kW at 45 m hub height and Nordex N43/600kW at 40 m hub height.

A unique property of the site is that the wind direction is almost uniformly from the north meaning that the rows are perpendicular to the wind direction almost all the time. Also the wind farm will in this way simulate a much larger windfarm.



Figure 26. Location of Zafarana wind farm.



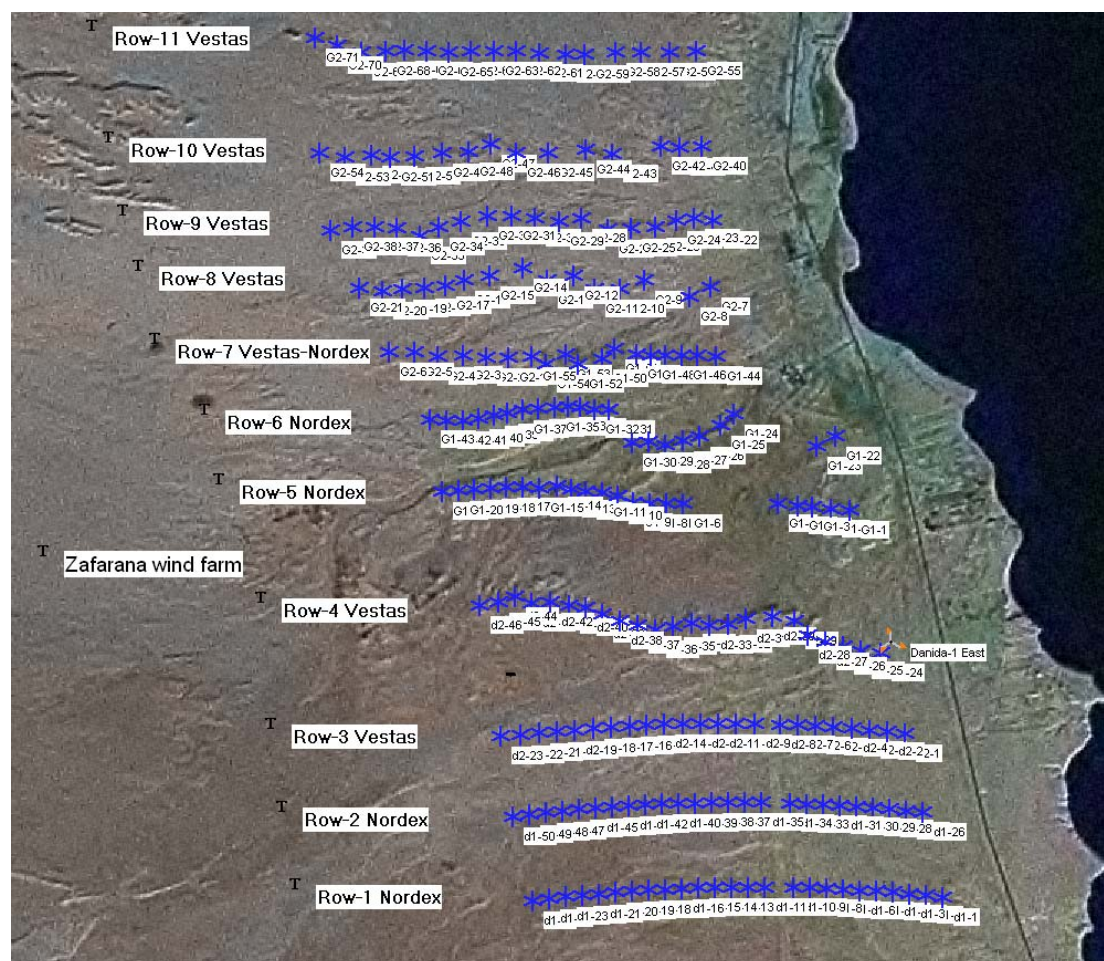


Figure 27. Detailed map of the Zafarana wind farm including the meteorological mast used in the present study.

### 3. Scope of study

The objective of studying the Zafarana project is to test if the wake loss calculation models (Park models) currently in use are able to predict the observed array losses in the wind farm. If they cannot predict the array losses sufficiently precise two methods will be tested to repair the calculation:

1. Adjustment of wake decay constant
2. Adjustment of internal roughness

### 4. Data background

While the project contains an overwhelming amount of data, only a limited amount is actually used for the study.

Measurements were made at numerous places around the wind farm, but the only place where measurements were made almost undisturbed from the wind farm at a time where the entire wind farm was in operation is the Danida East mast just east of row 4 (Figure 27). Here data from the period May 2004 to October 2004 have been extracted.

The anemometer used is placed at 42 m above ground and the logger provides 10 minutes mean wind speed. Through comparisons with other data in the area it was found that the wind directions are offset 33 degrees, which has been corrected.

Figure 28 shows wind direction rose for the corrected mast. Note that 36 sectors have been applied. This is done due to the very specific direction of the wind.

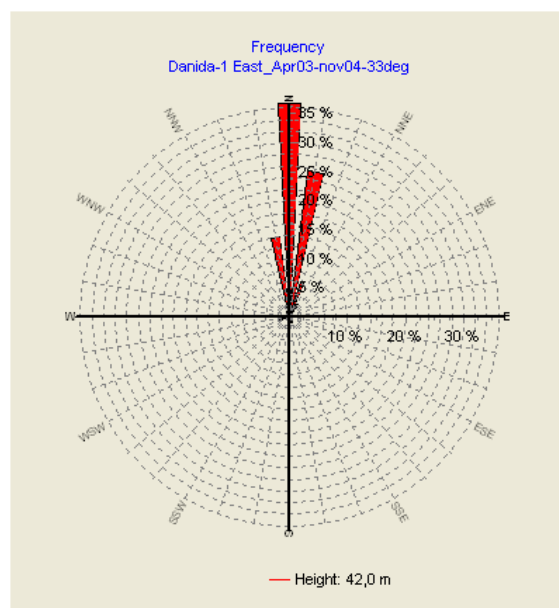


Figure 28. Directional distribution of the measurements at Danida-1 East.

The landscape model for the site is rather simple. The desert is almost uniformly smooth (roughness class 0.8, roughness length 0.011 m) bordered on the east by the sea (class 0, length 0.0001 m). Along the coast some construction areas are set to a higher roughness (class 2.5, 0.2 m), but these will only have small influence as the wind rarely comes from that direction. A map of the roughness is shown in Figure 29.

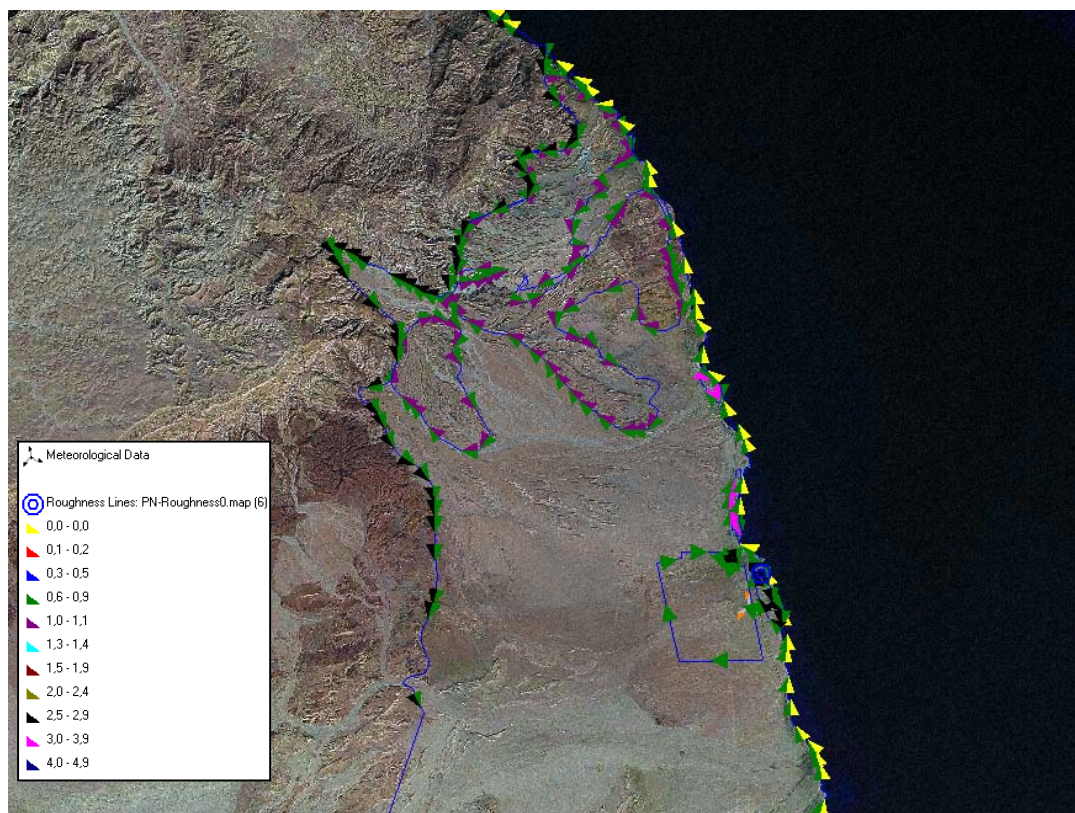


Figure 29. Map of the basic roughness description of the site. Note the frame around the wind farm, which is here set to roughness class 0.8 both inside and outside.



Detailed height contours are provided for the site, but the terrain is almost level and hill speedup will contribute very little to the production output. A map of height contours is shown as Figure 30.

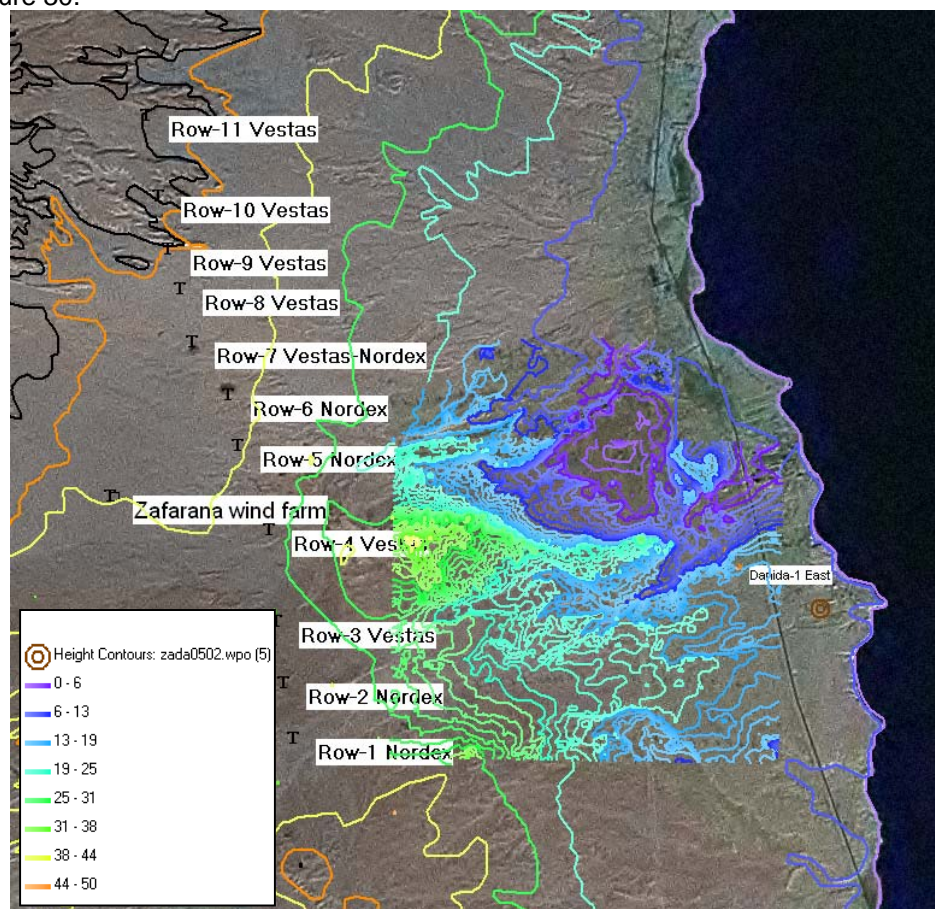


Figure 30. Height model used for the calculations. The closest region is described in higher detail than the remote region.

Production is known on a monthly level for every single turbine in the wind farm. For the calculation the mean annual production based on the 6 month concurrent with the wind measurements are found. In that way we know what the calculation result should be. The turbine productions are corrected to 100% availability by comparing neighbour turbines month-by-month and adjusting the ones clearly having availability losses.

The turbines themselves have power curves that seem reliable when comparing them to standard HP curves (Figure 31). At the relevant mean wind speed (8 to 9 m/s) the power curves deviate 1 to 2% from the HP standard values. However during the period a few of the turbines have produced poorer than expected due availability problems. While some work has been done to correct this problem these turbines will still stand out compared to the others.

#### HP curve comparison

Vmean	[m/s]	5	6	7	8	9	10
HP value	[MWh]	697	1.126	1.578	2.004	2.385	2.722
Dr. Frey, official from man., 11/96	[MWh]	707	1.139	1.600	2.043	2.440	2.775
Check value	[%]	-1	-1	-1	-2	-2	-2

#### HP curve comparison

Vmean	[m/s]	5	6	7	8	9	10
HP value	[MWh]	804	1.313	1.839	2.350	2.781	3.163
Level 0 - calculated -- 07-2001	[MWh]	847	1.361	1.885	2.372	2.800	3.156
Check value	[%]	-5	-4	-2	-1	-1	0



Figure 31. HP curve check of the Nordex (top) and Vestas (bottom) turbine types. Both power curves seem quite reliable.

The air-density of the air at hub height has been calculated from an average temperature of 25 degrees Celsius and an average height of 60 m above sea level (terrain + tower).

Due to blade contamination (sand) some reduction must be expected, especially for the stall regulated Nordex turbines, while the pitch regulated Vestas turbines do not seem to be reduced that much. This probably explains the generally better performance of the Vestas turbines relative to the Nordex turbines.

## 5. Calculation results

### 5.1. Principle

The wake-loss calculations are tested by letting a wind model created from the concurrent measurements predict the actual production of the turbines for the same period. While it is not possible through observation to separate out what is unobstructed production and what are array losses, we know that the compounded effect is what the turbine has produced. If we can predict the front row with a reasonable precision we know that deviations in the prediction of the following rows are due to deficiencies in the park model, since the landscape is simple and quite homogenous.

The model used is the WAsP model using standard parameter settings.

To measure the success of a calculation the ratio actual/calculated production is established, where actual is the realized production corrected to 100% availability during the 6 months measurement period.

### 5.2. Basic calculation

The first calculation is a basic setup using standard parameters for an onshore project in non complex terrain. That means:

Park model: N.O. Jensen

WDC: 0.075

Roughness: Standard roughness description.

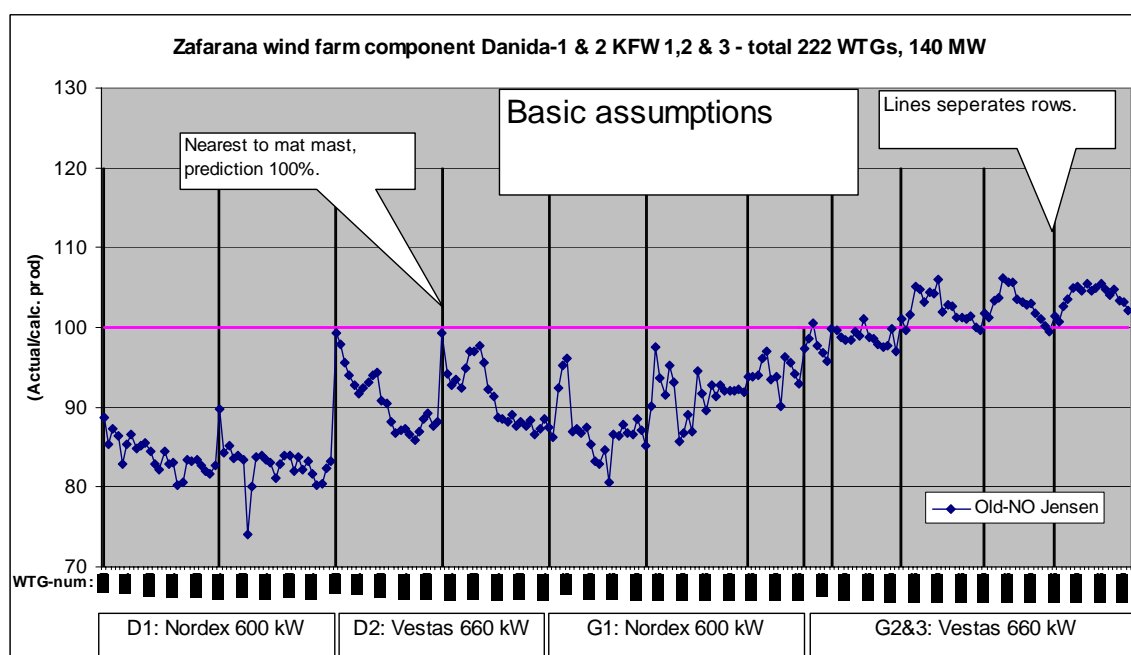


Figure 32. The basic calculation result.

The result of the graph is shown in Figure 32. Here each turbine is represented by a blue diamond symbol and the object is for each turbine to strike the 100% line, where actual production is fully predicted by calculated production.

Dark vertical lines separate each row out and in the bottom each turbine group is identified. These are the stages in which the turbines were erected – the letter D & G is for Danish and German which relate to the donor country.

A first observation is that the turbine right next to the mast is correctly calculated. This is a turbine, which is almost an undisturbed as the mast itself and it would be a minimum criteria for the model at least to be able to predict itself.

Secondly a gradual decrease can be observed down through the rows. The first rows seem to be under-predicted, while the back rows gets more and more over-predicted. The under prediction of the first rows could be due to some sheltering effect on the mast, but that only exaggerates the over prediction of the back rows.

### 5.3. Alternative models

The first test change is to try the different models EMD has implemented in WindPRO. These are all described by Thøgersen [2]. Here the following models have been tested, all using default WindPRO settings.

N.O.Jensen old  
 N.O.Jensen new  
 Eddy Viscosity (Ainsley)  $k=0.015$   
 Eddy Viscosity (Ainsley)  $k=0.025$   
 EWTS II (Larsen)

All other parameters are the same as in the basic calculation.

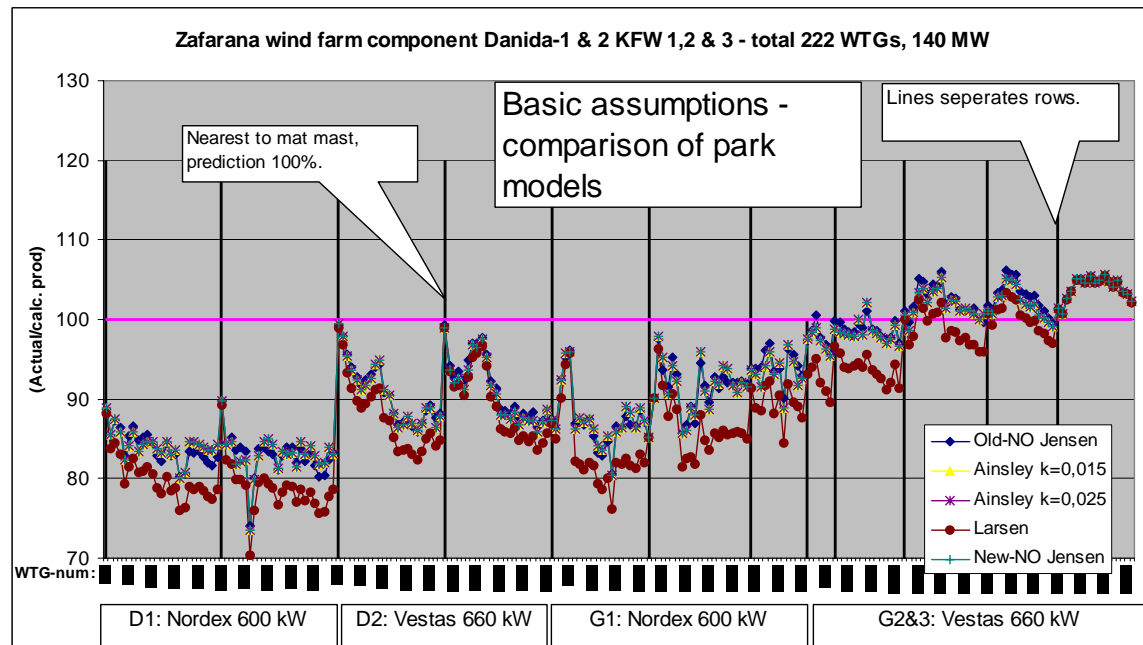


Figure 33. Attempts using different park models do not improve the result. Except for the Larsen model, the different models are quite consistent.

The result can be seen in Figure 33. Here it can be seen that regardless of  $k$  parameter setting the Ainsley model calculates a very similar result to the old N.O. Jensen model. The new N.O. Jensen model however is slightly poorer, particularly down wind in the wind farm. The Larsen model fares the worst over-predicting the production typically by 5%.

Regarding the gradual slide observed in the basic calculation no change in model seem able to correct that problem. For the following tests therefore only the old N.O. Jensen is used.

## 5.4 Adjustment of internal roughness

Since the majority of the turbines are over-predicted, especially in the back rows, it seems the model is lacking an energy drain. One of the suggestions regularly mentioned [3] is that large wind farms themselves are increasing the roughness of the surface they stand on, especially when that surface is very smooth.

Introducing an area of increased roughness inside the wind farm will indeed introduce an energy drain, which will impact the most on the back rows. After some experimentation the optimal roughness configuration was found to be:

Middle section: class 1.5, length 0.055 m

Southern section: class 1.8, length 0.079 m

Extreme south: class 2.4, length 0.174 m

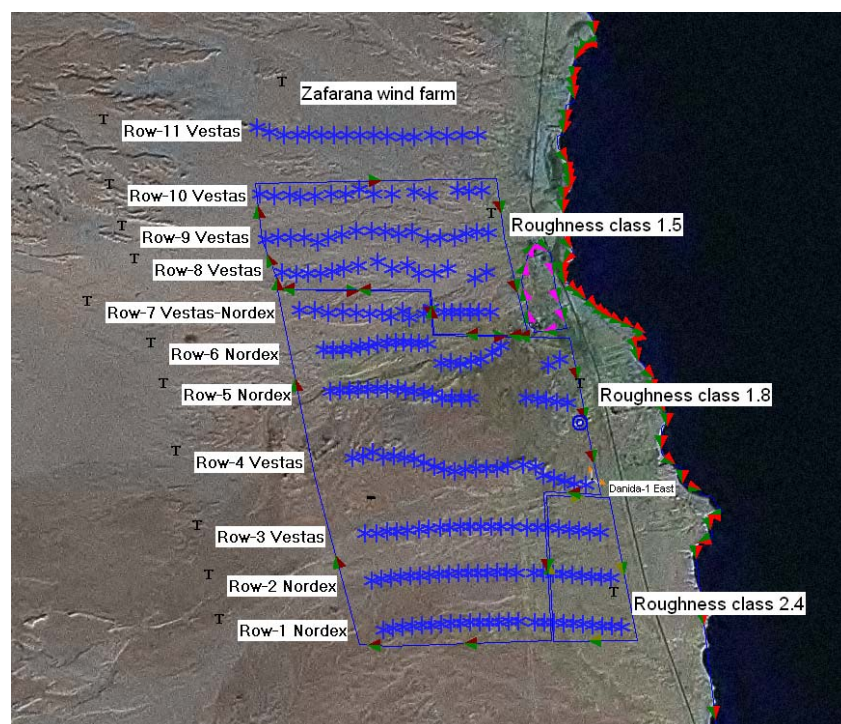


Figure 34. Optimized roughness description.

The resulting calculation can be seen in Figure 35.

This clearly changes the result into something very close to the correct result. In addition the deviations within each row are also smoothened out, giving a more homogenous expression.

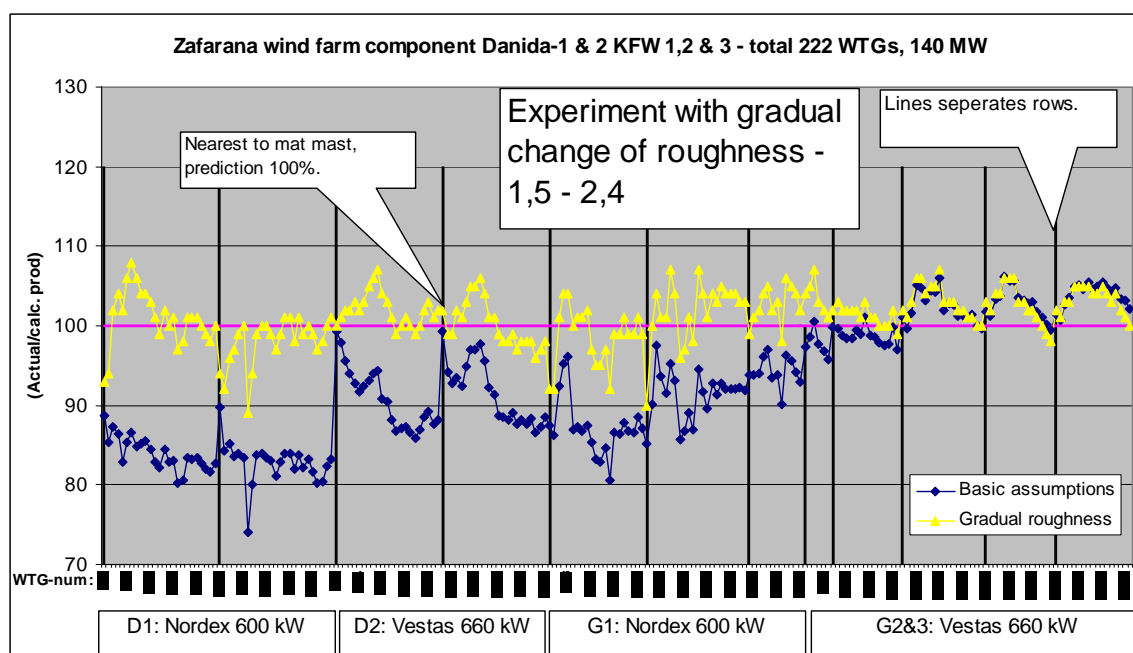


Figure 35. Introducing an energy drain in the form of an optimized roughness zone closes the gap to the actual production.

While this detailed added roughness model yield an acceptable result it would be desirable with a simpler roughness model that would be easier to apply when the result is not known in advance. For this purpose a simple roughness class 1.8 (0.079 m) is defined inside the wind farm (Figure 36). The result is shown in Figure 37. This is not nearly as homogenous as the detailed roughness, but still by and large cover the energy gap left by the basic calculation.

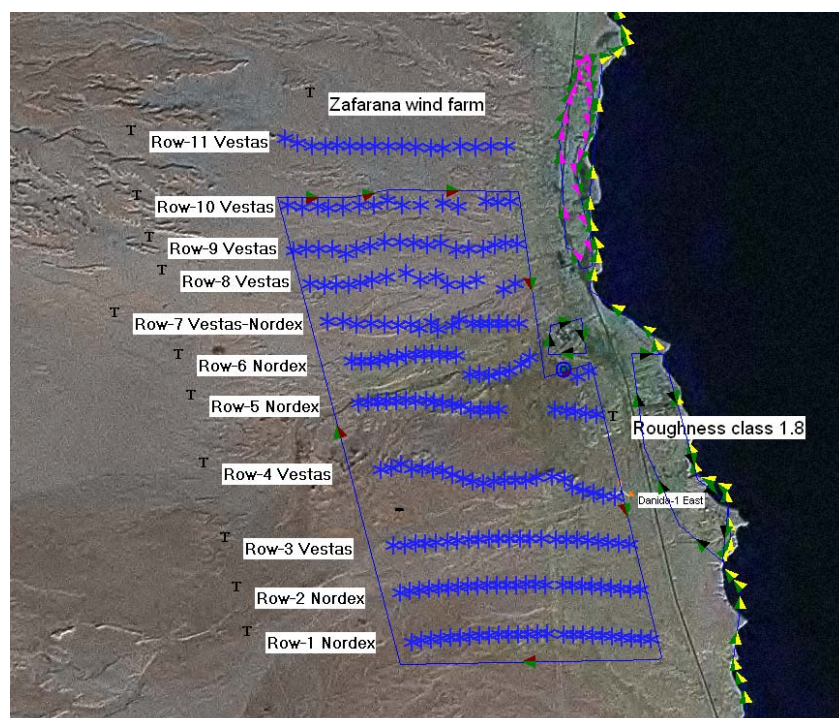


Figure 36. A uniform internal roughness zone of roughness class 1.8.



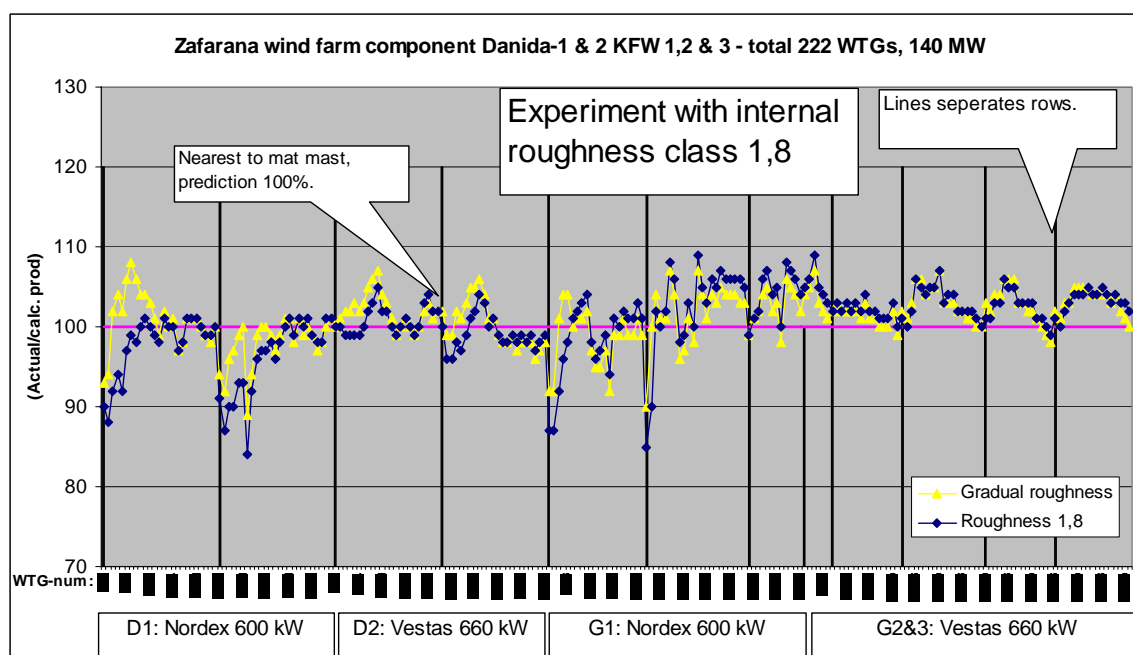


Figure 37. A uniform internal roughness of 1.8 is a good approximation to a detailed roughness description.

## 5.5. Adjustment of Wake Decay Constant.

Another strategy is to modify the Wake Decay Constant (WDC). As discussed in the main report the Wake Decay Constant is a property of the wind and as such a physical parameter linked to the turbulence intensity of the wind. In a low roughness environment like a desert one might theorize that the initial conditions are characterized by low turbulence and thus low WDC (Though due to large stability differences between day and night, the turbulence levels becomes very low at night and higher than normal for this roughness at day). The wind turbines adding turbulence to the wind increases the ambient turbulence level and thereby the WDC increases.

This is at odds with the function of the WDC as an energy drain handle. The lower the WDC the further downstream the wake will carry and the larger the cumulative impact of a large wind farm. Thus the WDC must be reduced inside the wind farm to make up for the energy drain.

An experiment was made where the WDC was reduced from the 0.075 of the basic calculation to 0.05 and 0.03, which are commonly recognised as being suitable for smooth surface conditions.

The results are shown in Figure 38. While WDC = 0.05 leads to a small improvement, 0.03 leads to a major change in the result. While the global average is now close to 100% the results are seriously skewed. Behind the first few rows the results are getting seriously under predicted, while the back rows are still significantly over predicted.

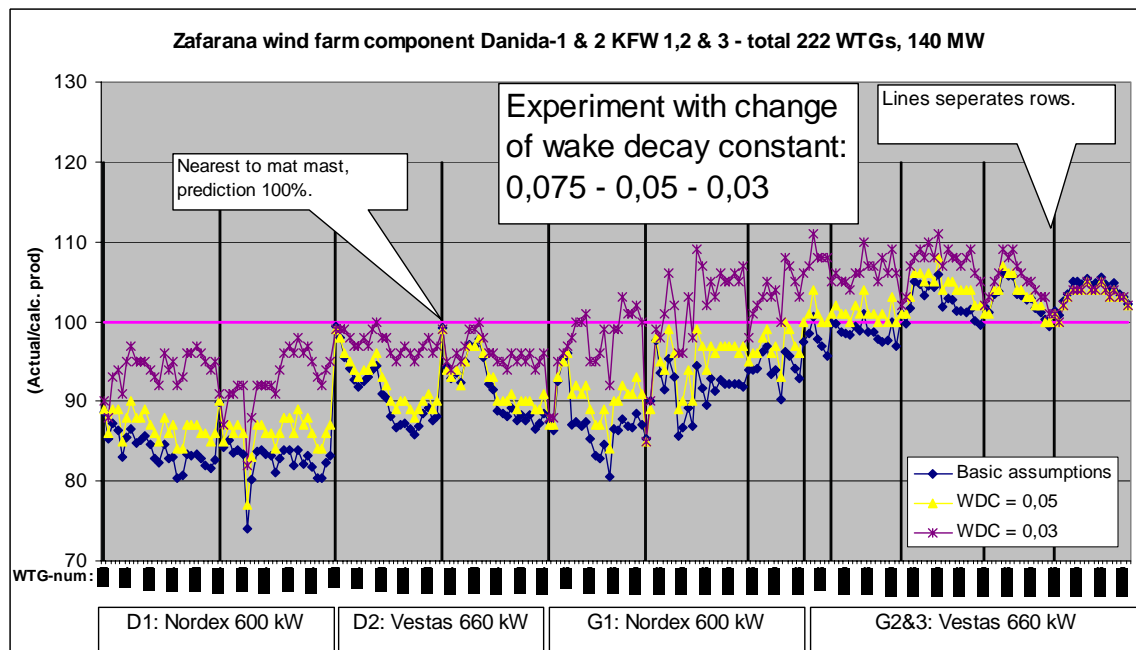


Figure 38. Results from test of 3 different wake decay constants.

## 6. Conclusion.

At the Zafarana site the combination of large array wind farm and uniform wind direction offer unique opportunities to investigate array loss models performance down through multiple rows of turbines.

Default modelling settings fails to predict sufficient array loss. At the last rows the deficit is in the range of 15% to 20%.

Alternative park models do not improve this result. On the contrary, some provide an even poorer result.

Attempts at covering up the energy deficit by introducing an energy drain in the form of an internal increased roughness are successful. A detailed combination roughness zone can make a quite acceptable prediction of actual losses, while a simple uniform roughness zone seem sufficient to cover up the deficit.

The range of validity of these particular values for the roughness zone in terms of row and column spacing has not been tested. Also it must be mentioned that the needed roughness change might depend on as well hub height as spacing and base roughness. Therefore the result cannot be generalised, but for sure recommended as a preliminary model fix.

## 7. References

1. Capacity credit analysis for wind farms in Egypt - Wind energy production analysis – Final report dec. 2004, Carl Bro and EMD.
2. Thøgersen, Morten, "WindPRO / PARK, Introduction to Wind Turbine Wake Modelling and Wake Generated Turbulence", EMD International A/S
3. Frandsen, Sten et.al., "The necessary distance between large wind farms offshore – study", Risø National Laboratory, 2004

## Case study 3: Horns Rev

### 1. Abstract

The Horns Rev offshore wind farm has been analyzed as a case study on wake loss calculation. Comparison of observed park efficiency data with model calculations reveal a minor error in calculation of the total park efficiency, but a major inability in calculating the park efficiency for the individual directional sectors. The different available wake models were tested and showed that the classic N.O. Jensen model with a proper choice of Wake Decay Coefficient would provide the most accurate total wake loss. Inclusion of an internal rough boundary layer seems to be unnecessary unless the wake model used is the EWTS or Eddy viscosity. Analysis of stability equivalent data showed a pronounced influence of stability on the observed park efficiency and a new method is suggested to adjust for stability influence.

### 2. Introduction

The Horns Rev offshore wind farm was erected end 2002 and consists of 80 Vestas V80-2.0MW wind turbines. The wind farm is located 13 km from the west coast of Jutland and the turbines are placed in a regular geometrical shape with a spacing of 7 rotor diameters (figure 1).

The first years of operation the turbines were suffering from poor availability, but this have been improved and for 2005 the availability was 95% according to the operator (Elsam) [1].

While Horns Rev was erected by the Danish utility Elsam, it is currently owned and operated jointly by the two utilities Vattenfall (60%) and DONG (40%).

DONG has kindly provided SCADA data on the wind farm performance together with information on stability conditions. These data are the basis for the analysis of wake prediction on the wind farm.

Analysis of the Horns Rev data was previously reported by EMD in 2006 [2]. Since then more data has been collected by DONG (formerly ELSAM) supplemented now by meteorological stability data. Also the data processing techniques have been revised and new ideas are incorporated.

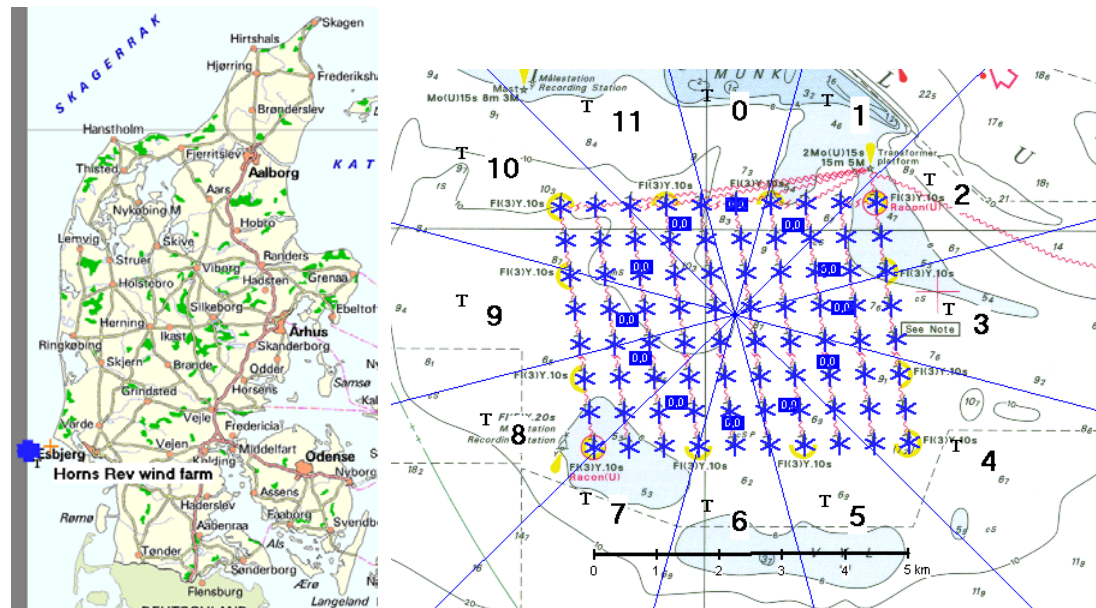


Figure 39. Map of the Horns Rev site and the layout. The numbering on the right indicates direction sectors. Maps courtesy of the National Survey and Cadastre (KMS).

### 3. Scope of study

The objective of using the Horns Rev case is to test the available wake models on a large offshore wind farm in a high wind speed environment. Horn Rev is a pioneering off shore wind farm and as such can serve as test bed for future offshore wind farms.

Two different methods for correction of wake models is tested: The addition of an energy drain in the form of an internal roughness zone as has been tested in other cases (Klim, Zafarana) and a methodology where different meteorological stability regimes are calculated independently with unique wake decay constants.

The nature of the data available sets the limits for the experimentation possible and, being congregated second hand data, the validity and uncertainties of the data cannot be examined by EMD. In this sense we rely on the provider of the data to ensure the health of the data.

### 4. Data background

The wind model used for the calculations on the Horns Rev wind farm is the standard Danish wind model DK'92.

DK'92 is based on old measurements from the site Beldringe on the island of Fyn, which has been calibrated with production data from local wind turbines providing regional correction factors. For the Horns Rev wind farm the correction factor on production output is on average 1.28. Since the direction distribution used is directly adopted from Beldringe, it is possible it will be slightly different for Horns Rev. The energy rose is displayed in Figure 2, and indicate a predominant wind direction from south-southwest to west, where the fetch consists of open sea.



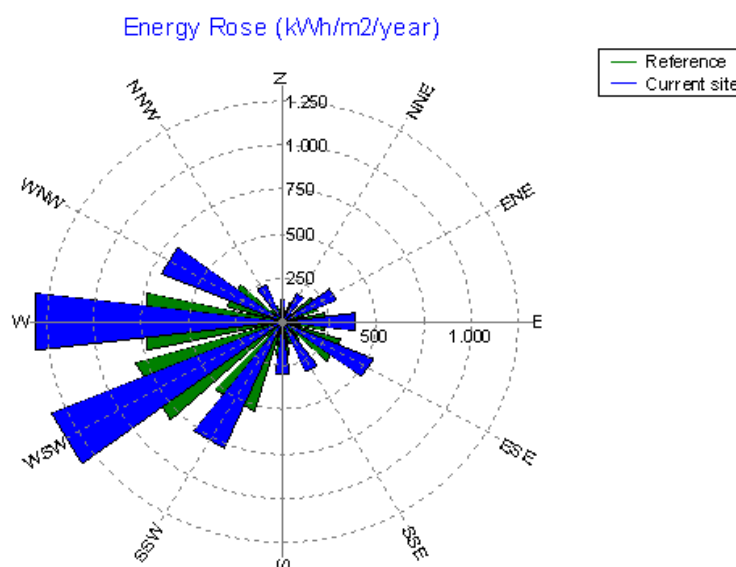


Figure 40. Energy rose for the DK92 wind statistic. The green rose is for a flat roughness class 1 site, while the blue rose is for the Horns Rev site.

The landscape texture in terms of roughness is fairly simple. The roughness is universally set to the offshore roughness of class 0 (0.0002 m) except on the eastern coastline where the roughness is obtained from the wind resource map for Denmark, an earlier project from EMD and Risø. Here the terrain is digitized in 1 by 1 km tiles based on the density of shelterbelts and villages, while major elements like forests, coastlines, towns and lakes are digitized separately. While the site is relatively compact and distant from the shore the experienced roughness is not expected to change much throughout the wind farm.

The site is entirely flat so no height model is used.

The turbines used on Horns Rev are Vestas V80-2MW turbines and the power curve used is the official power curve as informed by the manufacturer. However since the actual production is not a concern of the study the actual precision of the power curve is not important as long as it is of the correct type and scale.

The air-density of the air at hub height has been set to standard 1.225 kg/m<sup>3</sup> since this is the air density with which the DK'92 wind statistic is calibrated.

The operator, DONG, has provided SCADA data for the wind farm. These data contains two kinds of information of interest:

- The measured park efficiency (inverse wake loss) of the entire wind farm for each wind speed bin from 4 to 15 m/s in steps of 1 m/s and each of 12 direction sectors.
- The time distribution of meteorologically stable, neutral and unstable conditions for each speed and direction bin.

The measured park efficiency has been found by comparing the production output of the appropriate corner or mid-row turbine with that of the entire wind farm thus assuming that the reference turbine is not suffering any wake loss.

DONG has filtered the data so that the data from each turbine represent only valid operating data, so that the deficit registered can be fully ascribed to wake loss. This is particularly important for the reference turbines. However this may include readings from periods where other turbines have been out, for example an upwind turbine. While the wake loss for such situations would be less it is expected that this error is negligible due to the high availability during the measurement period [3]. This validation method has been confirmed by DONG.

The park efficiency data can be extracted as congregated data for the entire period, but not as a time series. This means that in order to use the data it must be assumed that the data is valid for an average period. The park efficiency data can however be specified for three different stability regimes [4].

An example of the extract is shown in Figure 41

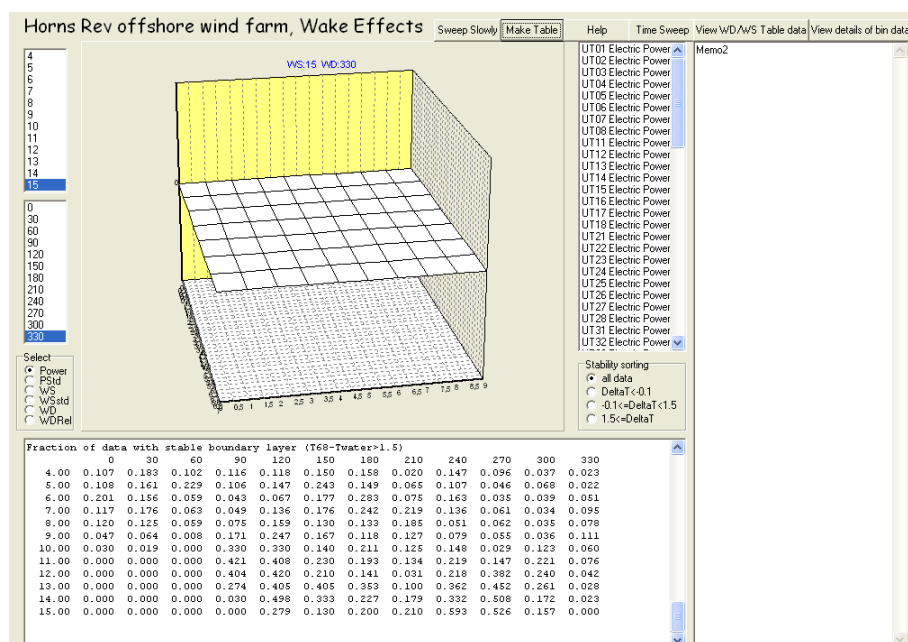


Figure 41. User interface of the SCADA VIEW tool from DONG.

The stability classes are selected as:

$T_{\text{air}} - T_{\text{water}} < -0.1^{\circ}$  : Unstable boundary layer.  
 $-0.1^{\circ} \leq T_{\text{air}} - T_{\text{water}} < 1.5^{\circ}$  : Neutral boundary layer.  
 $1.5^{\circ} \leq T_{\text{air}} - T_{\text{water}}$  : Stable boundary layer.

The SCADA extracts provide for each bin the fraction of the data belonging to each of the stability classes.

## 5. Calculation results

### 5.1. Principle

A method has been developed by EMD to compare park efficiency tables as those provided by the SCADA system to the park efficiency results from WindPRO.

A WindPRO PARK calculation result applies the wind atlas chosen on each turbine location so that sector-wise Weibull distributions for each turbine are obtained. These Weibull distributions are applied to the power curves (air-density adjusted) to obtain the freestanding turbine production.

The wake loss is calculated for each speed and direction bin and deducted from the freestanding production.

The PARK calculation can provide a PARK power curve for the entire wind farm, where the power output is specified as a total for each speed and direction bin and compared to the ideal freestanding output of the wind farm.

Taking the ratio of each bin to the freestanding park power curve give a bin-wise park efficiency directly comparable to the SCADA table.

In order to find the sector-wise or total park efficiency the following method is used.

The calculated Weibull distributions for the site at hub-height together with the frequency distribution give the number of hours of operation for each bin. Through lookup in the freestanding park power curve and the park efficiency table the production for the bin can be found. The production for the sector is the summation of all bins in the sector, while total production is the sum of all bins. The ratio of this to freestanding calculated production is the park efficiency, which can thus be found both sector-wise and for all sectors.

Based on this technique observed park efficiency can be compared to calculated park efficiency both for individual bins, sector-wise and as totals.

### 5.2. First calculation – sector wise park efficiency.

The first calculation is a basic setup using standard parameters for an offshore project in non-complex terrain. That means:

Park model: N.O. Jensen

WDC: 0.04

Roughness: Standard roughness description.

The results of this calculation can be used take a closer look at the wake losses inside the wind-farm and to what extend a standard model is able to predict it. Already Jensen [4] reported a systematic failure of the model in certain directions and this picture is confirmed by this calculation.

Measured wake loss (1-park efficiency) is plotted in Figure 42 against calculated wake loss together with the relative error.

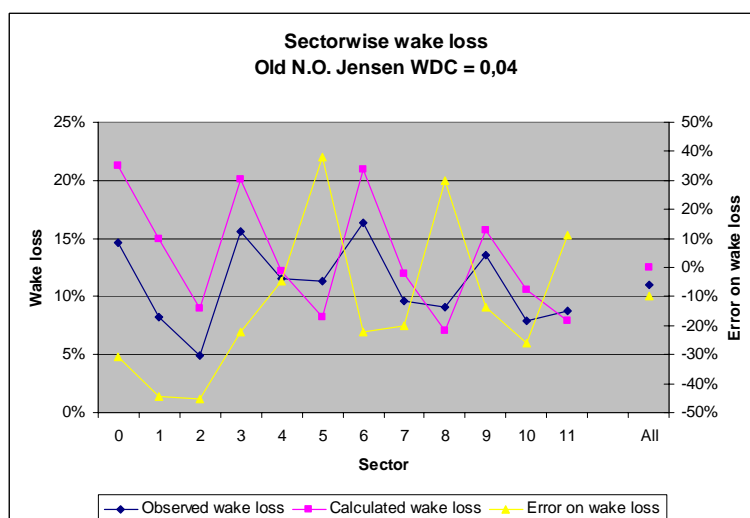


Figure 42. Observed versus calculated sector-wise wake loss. The calculation is based on the old N.O. Jensen model with a WDC of 0.04. The difference is 1.5% of production or 10% total wake loss.

In this figure it is clear that the prediction is quite far off in the individual sectors, but this error is sometimes positive and sometimes negative, resulting in a total error, which is relatively small (10% on wake loss). Especially those directions with a high observed wake loss tend to be over-predicted in wake loss.

We can get a more detailed look if we consider the individual bins. Figure 43 shows the park efficiency for each wind speed bin as a total for all sectors. Here we can see that the calculated park efficiency is not so far off the measured, but consistently lower at all wind speeds, especially at the lower wind speeds.

Individually from sector to sector the match is less good as can be seen in Figure 44 where sector 0 and sector 5 are presented. This is well in accordance with Figure 42.

All sectors are presented in appendix A.

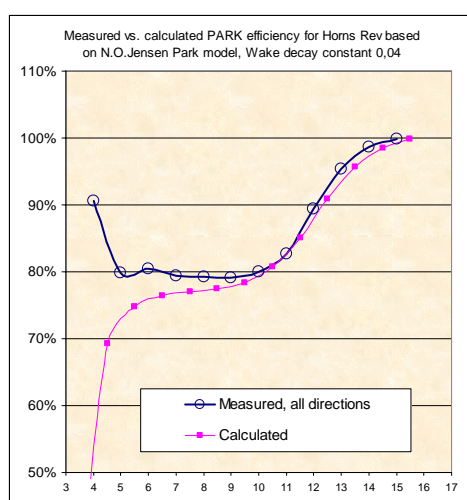


Figure 43. Observed versus calculated park efficiency. The wind speed bins represent all sectors.

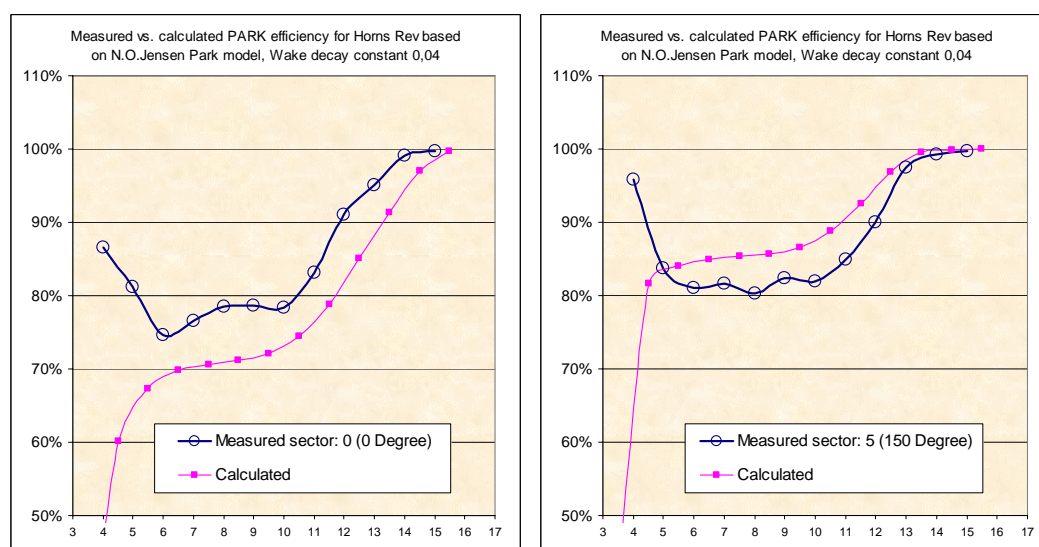


Figure 44. Observed versus calculated park efficiency. The left figure illustrate sector 0 (north), while the right figure shows sector 5 (south).

### 5.3. Test of methods.

Following the initial test using the standard procedure for calculating wake loss a number of alternative methods and choices of parameter settings have been tested. The intention is to find if a different method will improve the precision of the wake modelling.

The following models have been tested, all using default WindPRO settings where nothing else is stated.

N.O.Jensen old (WDC = 0.075)

N.O.Jensen new (WDC = 0.04)

Eddy viscosity (Ainslie), default settings

Eddy viscosity (Ainslie), axial grid size = 0.1 x rotor diameter

EWTS (1<sup>st</sup> order)

The parameter modified in the Ainslie calculation is the grid density which in the axial direction (away from the turbine) normally is 0.25 x rotor diameter, but here also has been tested for 0.1 x rotor diameter, the same grid size, as is used perpendicular to the axial direction.

The wake decay constant (WDC) is set to 0.04 in all calculations except for one calculation using the N.O. Jensen model where 0.075 is used. A WDC of 0.04 is the normally recommended WDC offshore and correspond to a turbulence intensity of 8% [5].

The results of the test are tabularized in Figure 45 and illustrated in Figure 46.

Normal wind model	Park efficiency %	Wake loss %	Difference from actual wake loss in percentage of production %	Difference from actual wake loss relative to actual wake loss %
Observed park efficiency	89,0%	11,0%		
N.O. Jensen WDC 0,04 (Standard)	87,5%	12,5%	1,5%	13,9%
N.O. Jensen WDC 0,075	91,6%	8,4%	-2,6%	-23,6%
N.O. Jensen 2005 WDC 0,04	89,3%	10,7%	-0,3%	-2,9%
Ainslie Standard settings	93,1%	6,9%	-4,0%	-36,8%
Ainslie (grid axial=0,1)	92,2%	7,8%	-3,2%	-29,1%
EWTS	93,7%	6,3%	-4,7%	-42,8%

Figure 45. Tabularized results of tests with a variety of park models to predict the observed park efficiency.

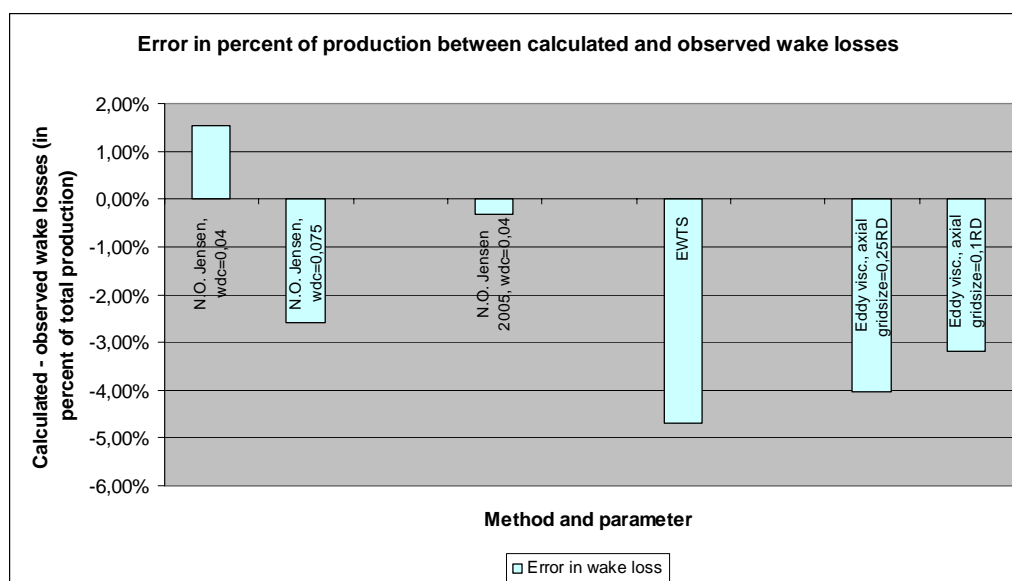


Figure 46. Difference in wake loss between calculated and observed wake loss. A positive figure results in the under-prediction of the production output.

While the results using the N.O. Jensen model cluster around the correct measured result it is clear that the standard WDC of 0.04 over-predicts the wake loss, while the onshore standard of 0.075 significantly under-predicts the wake loss. It is reasonable to believe that at least the total wake loss can be calculated correctly through an intelligent setting of the wake decay constant.

The new implementation of the N.O. Jensen model is rather close to the correct result, which is not surprising as experience (see Zafarana and Klim cases) has shown that for same WDC the new implementation calculates somewhat less wake loss than the old implementation. To simply rule that the new implementation is more correct to use in this environment is not justified.

Both EWTS and Eddy viscosity methods vastly under-predicts the wake loss. Using a smaller grid size for the eddy viscosity model improves the result, but it is still very far off the measured wake losses.

A major problem using the classic N.O. Jensen model is the large errors by sector. If this is due to the sharp edges of the wakes calculated by the N.O. Jensen model, which virtually switch the wake influence on and off along a sharp boundary, the more refined eddy viscosity model might address this problem.

However as can be seen in Figure 47 even disregarding the offset in calculated wake loss the error is not any more constant than for the N.O. Jensen model. The sector-wise error in wake loss is not simply due to errors along the edge of the wakes.



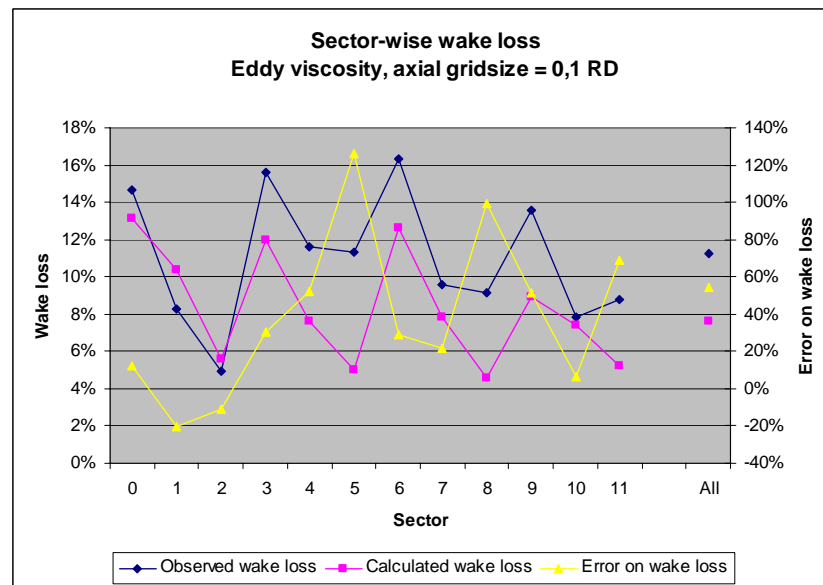


Figure 47. Sector-wise wake losses like figure 4, but this time compared to a calculation using the Eddy viscosity model with an axial grid size of 0.1 x RD.

## 5.4 Adjustment of internal roughness

In previous studies it has been suggested to add an energy drain to the wake loss calculation in the form of an internal roughness zone (Zafarana). This should especially be the case for wind farms in low roughness sites. Horns Rev is exactly that, so this site should be an obvious candidate for such an approach.

An internal roughness zone is added to the roughness map by drawing a roughness line along the boundary of the wind farm with roughness class 1.4 (0.05 m) on the inside (Figure 22).

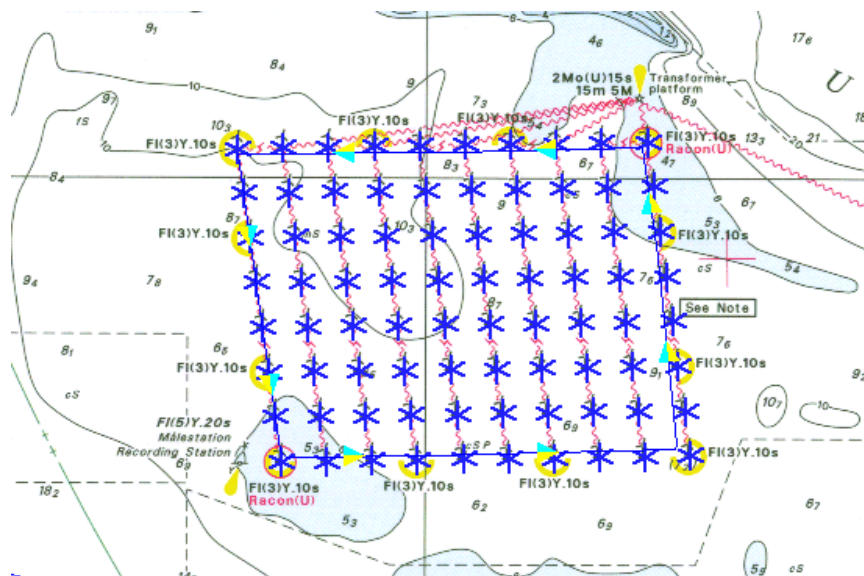


Figure 48. A revised roughness map including an internal roughness area. Maps courtesy of the National Survey and Cadastre (KMS)

The effective park efficiency is now calculated by comparing the resulting production with the freestanding calculated production from the previous calculation without internal roughness.

Figure 49 tabulates the results using internal roughness and Figure 50 adds the internal roughness results to results in figure 8.

Normal wind model	Park efficiency %	Wake loss %	Difference from actual wake loss in percentage of production %	Difference from actual wake loss relative to actual wake loss %
Observed park efficiency	89,0%	11,0%		
N.O. Jensen WDC 0,04 (Standard)	82,8%	17,2%	6,2%	56,9%
N.O. Jensen WDC 0,075	86,9%	13,1%	2,2%	19,7%
N.O. Jensen 2005 WDC 0,04	84,6%	15,4%	4,4%	40,3%
Ainslie Standard settings	88,2%	11,8%	0,9%	8,0%
Ainslie (grid axial=0,1)	87,4%	12,6%	1,7%	15,1%
EWTS	89,0%	11,0%	0,0%	0,4%

Figure 49. Tabularized results introducing an internal roughness in the wind farm.

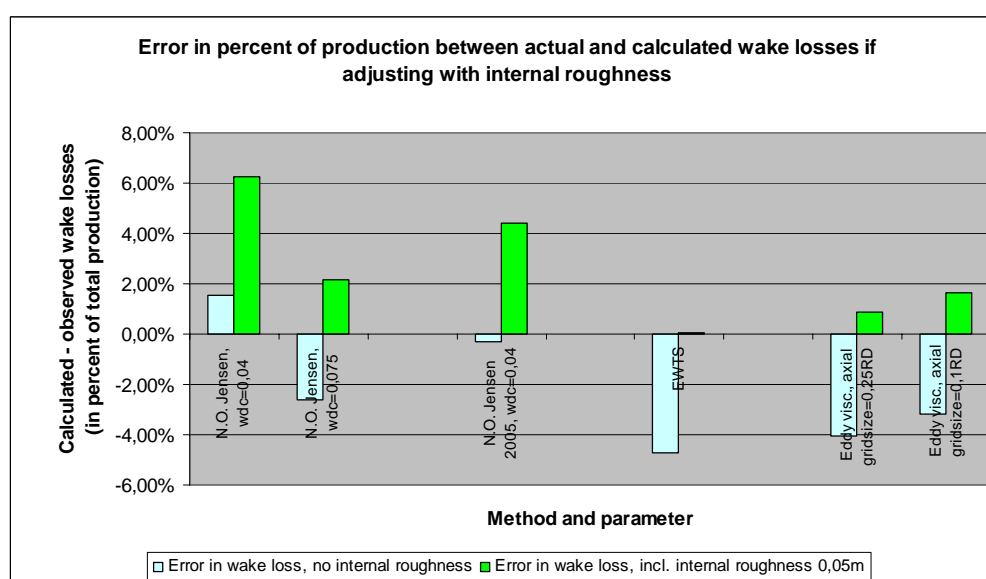


Figure 50. Results using an internal roughness added to figure 8.

The result of adding the energy drain is a simple offset of the production and thus the effective wake loss. Since the standard N.O. Jensen already over-predicted the wake loss, it is now even more over-predicted, to an extend where it is obviously wrong. Using the onshore WDC the result is now as over predicted as it was before under predicted and the new implementation of N.O. Jensen, which before fitted well is now obviously over predicted.

It is interesting however that including an internal roughness zone have solved the problem when using the EWTS and eddy viscosity wake model. This would explain why earlier studies [6] have found that eddy viscosity + internal roughness predicts well observed wake loss on Horns Rev.

## 5.5. Stability adjustment.

Since the data set from Horns Rev includes park efficiency for 3 different meteorological stability classes it is possible to take a look at this as well.

If we look at the bin-wise park efficiency for the three stability classes, in Figure 51 covering all sectors, it is clear that the park efficiency is high for unstable conditions, closer to calculated park efficiency for neutral conditions and lower for stable conditions.

This is a trend that is constant throughout all sectors as can be seen in appendix A.

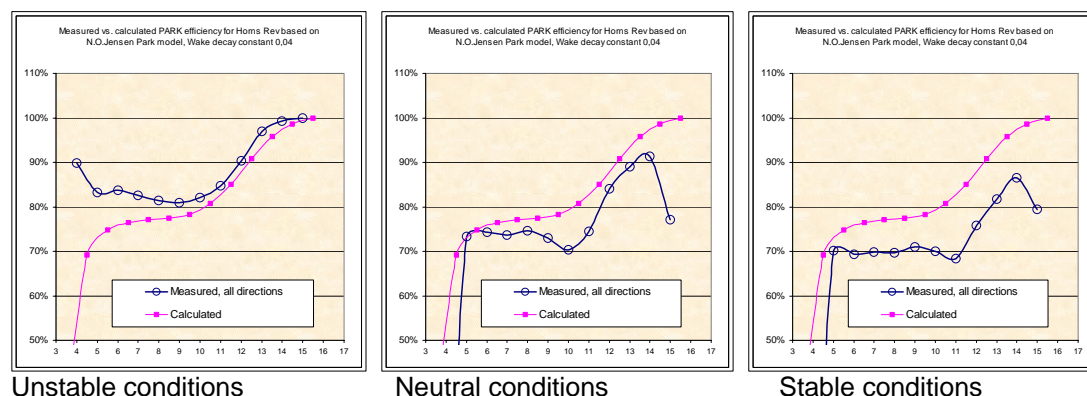


Figure 51. Observed versus calculated park efficiency for unstable conditions (left), neutral conditions (centre) and unstable conditions (right). For all charts a WDC of 0.04 has been used.

The thought is therefore close at hand that the meteorological stability has a significant influence on the wake loss and that the resulting wake loss is dependent on how often you have the different stability regimes.

We here suggest a method for adjusting for the stability influence.

The principle of the method is that we will find the observed park efficiency for each stability class and then test what wake decay constant will result in a good prediction of the observed park efficiency. Then the park efficiency will be weighted with the frequency of each stability class and the result will be the total park efficiency. This weighting can be done either sector-wise or for the total of all sectors.

From the SCADA results we are informed which ratio of each bin belong to which stability class. The distribution is shown in Figure 52. It can be seen that unstable data are dominating, but also that the ratios vary significantly from sector to sector. The sectors 0, 1 and 2 lack neutral and stable data even in some of the high wind speed bins also. This is a problem since this would result in an observed park efficiency of 0 or 1 in those bins and thus over- or under-predict the actual wake loss for the sector. Therefore; for the neutral and stable case only sector 3 to 11 are considered.

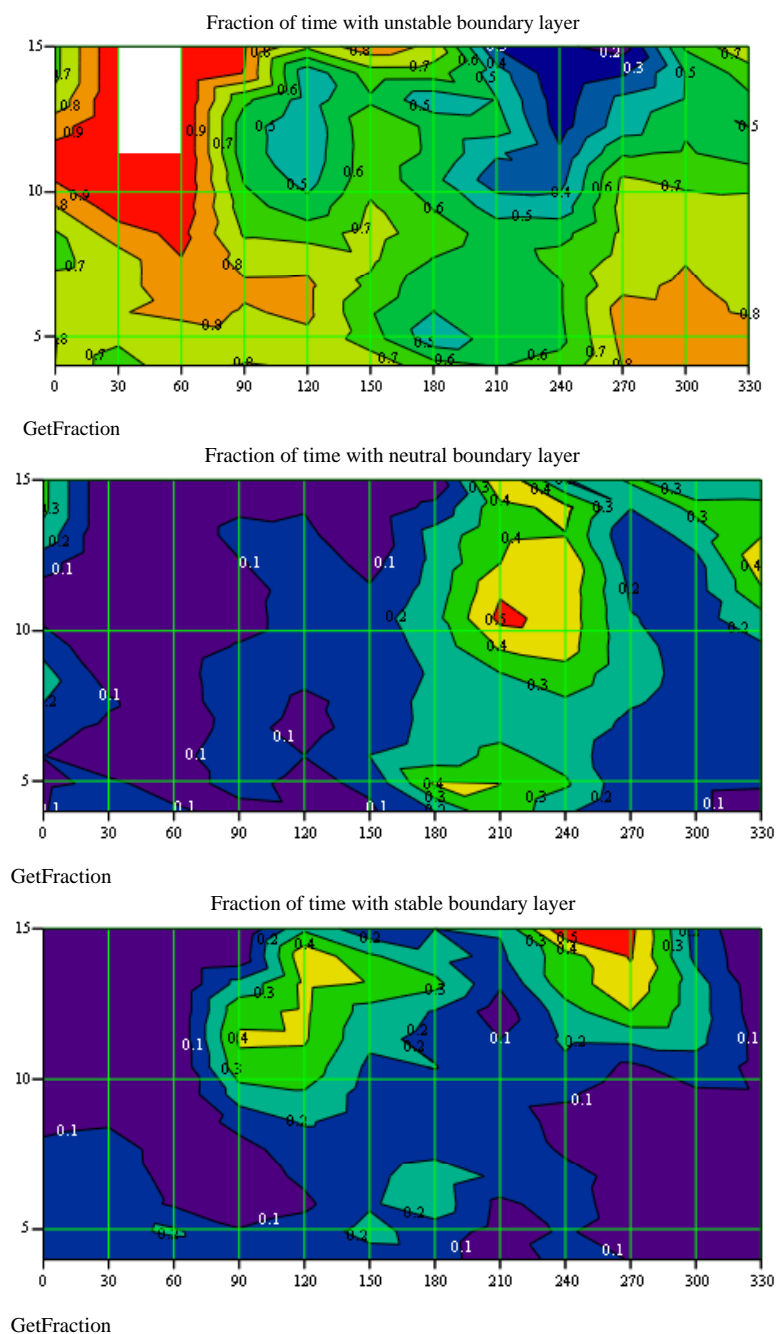


Figure 52. Fraction of each speed and direction bin that belong to a specific turbulence class. Courtesy of Leo E. Jensen, DONG [2].

By considering the valid sectors the observed park efficiency is found for each stability class. Then the appropriate wake decay constant is found that can predict the total park efficiency. As wake model is used the standard old N.O. Jensen model. The results are listed in Figure 53. For stable conditions the WDC of 0,025 fitted the best, while 0.06 gave the best fit with unstable data. Neutral data fitted best with the standard WDC = 0.04.

	Observed park efficiency	Calculated park efficiency	Wake Decay Constant
Unstable	90,2%	90,4%	0,06
Neutral	88,0%	87,6%	0,04
Stable	84,3%	84,4%	0,025

Figure 53. Observed and calculated park efficiencies using the selection of wake decay constants and old N.O. Jensen.

Assuming the calculated Weibull distributions for the wind farm, the number of hours the wind farm will be operating in each bin is found. Applying the frequency of each stability class we get the number of hours with each stability class in each sector. Since we only have stability ratios from 4 to 15 m/s the sector-wise ratios are normalised to 100% assuming an equal distribution from 4 to 25 m/s.

Normalised time weight

Sector	0	1	2	3	4	5	6	7	8	9	10	11
Neutral	13%	6%	4%	12%	11%	12%	23%	37%	37%	19%	17%	19%
Unstable	78%	84%	90%	71%	62%	69%	57%	50%	42%	61%	71%	75%
Stable	9%	10%	6%	18%	27%	20%	20%	13%	21%	20%	12%	6%

Figure 54. Normalised time weight of the stability classes in each sector.

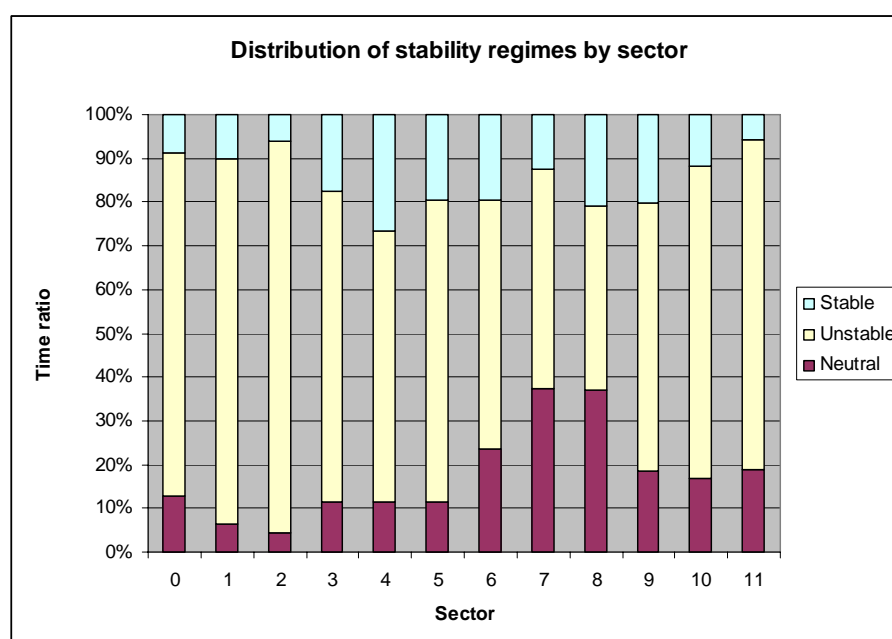


Figure 55. Time weight of stability regimes by sector.

Each sectors park efficiency is now weighted with frequency resulting in a total park efficiency by sector. This is in turn collected to a total all-sector park efficiency by calculating the absolute wake loss and compare it to freestanding production. The result is shown in Figure 56 and Figure 57. It can be seen that the total park efficiency has gone up from 87.5% to 88.6%, which is much closer to the observed park efficiency of 89.0%. Sector-wise there is still some difference between observed and measured park efficiency, but the gap is significantly smaller.

An alternative approach is to calculate the all-sector park efficiency for the three WDC's and weight them according to their total frequency. In this case we would be disregarding that the weighting could be quite different from sector to sector, but the result is quite similar at a park efficiency at 88.7%.

Sector	0	1	2	3	4	5	6	7	8	9	10	11	All
Observed park efficiency	85.3%	91.7%	95.1%	84.4%	88.4%	88.7%	83.7%	90.4%	90.9%	86.5%	92.1%	91.2%	89.0%
Standard calculated park efficiency	78.8%	85.1%	91.0%	79.9%	87.8%	91.8%	79.0%	88.0%	93.0%	84.3%	89.4%	92.1%	87.5%
Stability adjusted park efficiency	81.5%	87.7%	92.4%	81.9%	88.7%	92.3%	80.5%	89.1%	93.1%	85.6%	91.0%	92.9%	88.6%

Figure 56. Table giving the observed park efficiency, a standard N.O. Jensen calculation with WDC = 0.04 and the stability adjusted result.

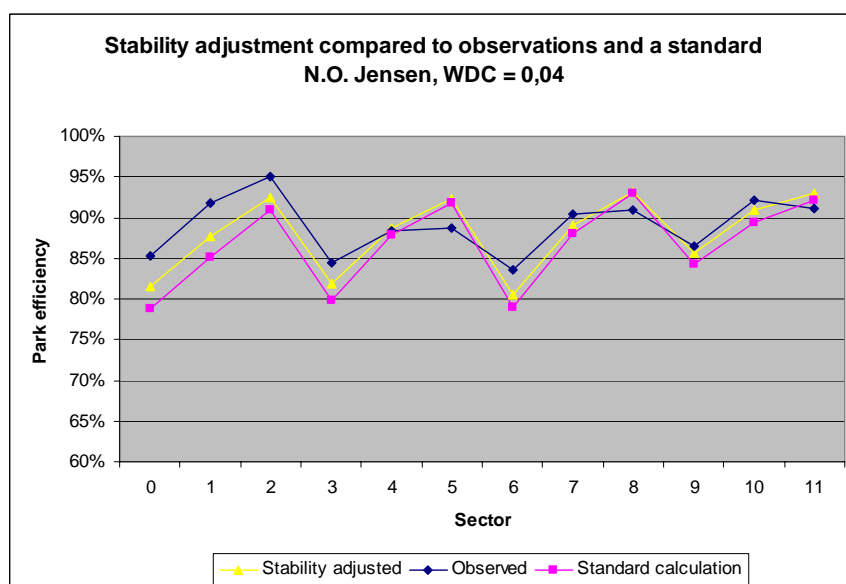


Figure 57. Observed park efficiency against the stability adjusted data and a standard N.O. Jensen, WDC = 0,04 calculation.

A method has thus been constructed for adjusting park efficiency with meteorological stability. The operator will have to go through the following steps.

- Gather temperature measurements from approximately 70 m above sea level and just below sea level.
- Distribute the temperature measurements into the three above mentioned stability classes and calculate the frequency of these in each sector.
- Perform three park calculations using the old N.O. Jensen calculation with WDC of 0.025; 0.04 and 0.06.
- Weight the park efficiency of each sector by the frequency of the stability class to get a total park efficiency for each sector
- Apply each sector's park efficiency on the freestanding production in that sector and add these together to get the total production. The ratio to freestanding production is the park efficiency.

The method needs to be tested on other sites before it can claim to be generally applicable. Also it is important to note that there are large sector-wise errors that the stability correction does not sufficiently address. The method only solves part of the problem.

It is possible that a more refined model that takes into account that the stability regimes are also a function of wind speed will improve the result of the adjustment. Also the model could be refined by a more direct measurement of the stability condition, for example in the form of a stability length directly from the wind flow. This could in turn lead to a direct relationship between ambient turbulence parameters (being a function of stability) and Wake Decay Constant.

However the method presented here is fundamentally crude and refinements may be overshadowed by uncertainties. Also it is the idea that the method should be easy to apply and replicate on other offshore wind farm sites.

## 6. Conclusion.

The Horns Rev wind farm is a large offshore wind farm and as such the focus of this entire project.



Based on the data available it has been possible to test observed versus calculated park efficiency (wake loss).

Tests of standard methods and simple adjustments to methods have shown that the default offshore method (old N.O. Jensen, WDC = 0.04) calculates too low park efficiency (too high wake loss), which is contrary to experiences from other sites where this particular model calculated too low wake losses. Other standard methods typically calculate the park efficiency of Horns Rev too low.

In other studies the introduction of an internal roughness zone (internal boundary layer) were needed to correct the park efficiency calculation. On Horns Rev the introduction of the internal roughness zone only exaggerate the park efficiency of the standard model and make it even more conservative. An otherwise very optimistic model like the Eddy viscosity model however is corrected to a result very close to the observed park efficiency.

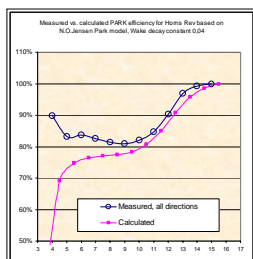
A new type of adjustment is suggested based on recordings of vertical temperature difference (equivalent to meteorological stability) and a differentiation of observed park efficiency between three stability classes. The adjustment has been calibrated using these observations and is in the present case able to narrow the park efficiency error down to 0.4% of total production (4% error on the wake loss parameter).

The stability adjustment is relatively easy to apply on other offshore wind farms, but will need to be verified before it can be pronounced universally valid.

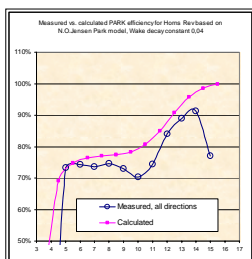
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4. Jensen, Leo E., "Analysis of array efficiency at Horns Rev and the effect of atmospheric stability, EWEC proceedings, 2006.
5. Thøgersen, Morten, "WindPRO / PARK, Introduction to Wind Turbine Wake Modelling and Wake Generated Turbulence", EMD International A/S
6. Schlez, Wolfgang et.al., "New Developments in Precision Wind Farm Modelling", DEWEK, 2006

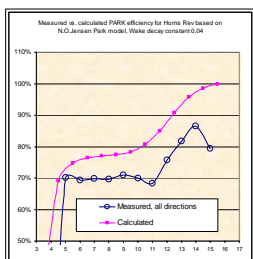
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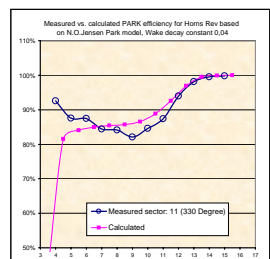
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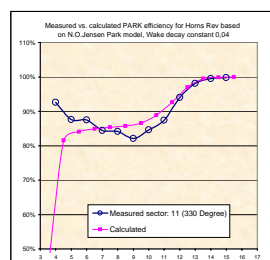
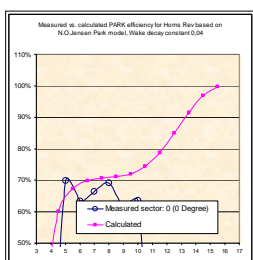
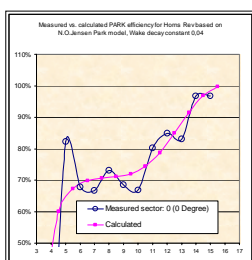
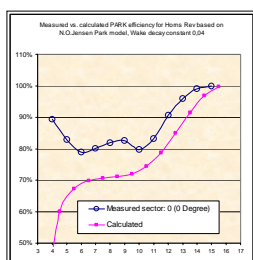
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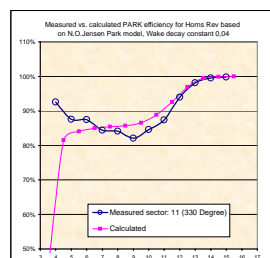
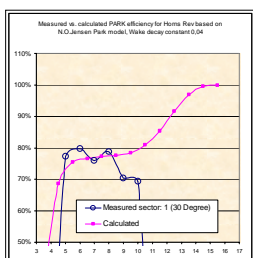
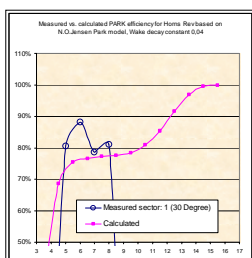
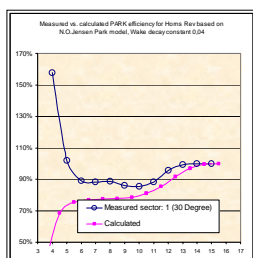
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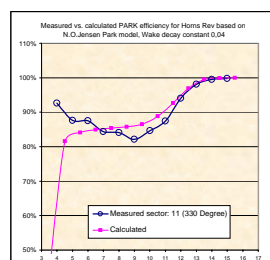
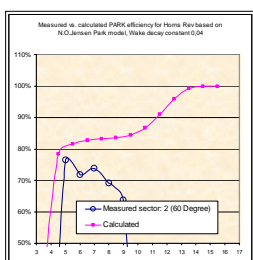
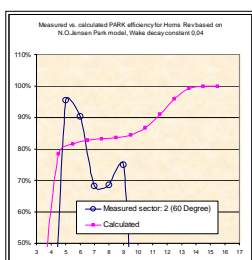
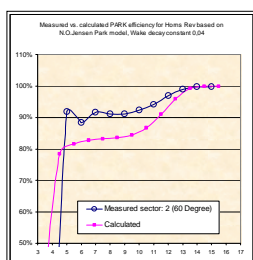
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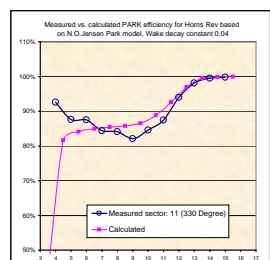
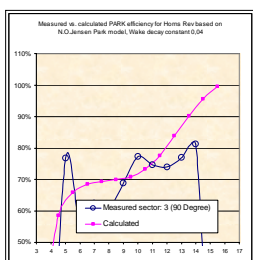
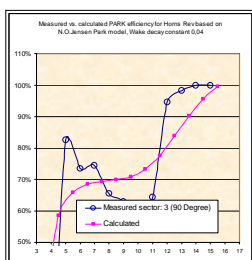
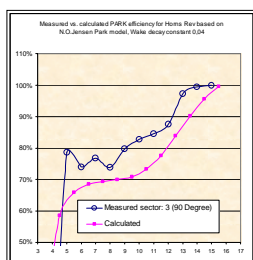
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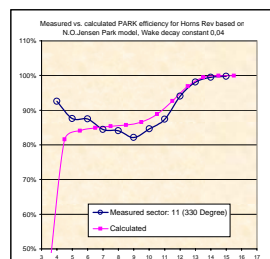
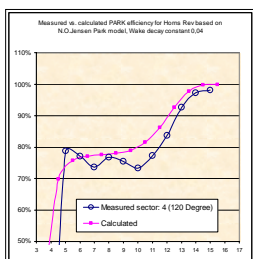
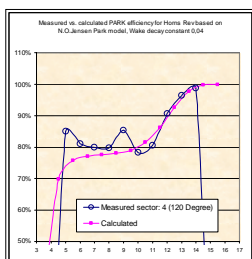
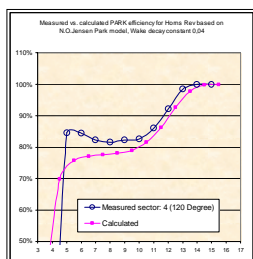
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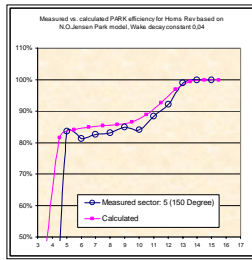
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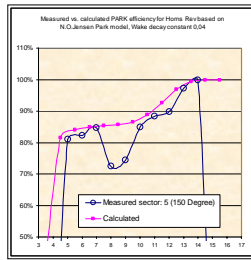
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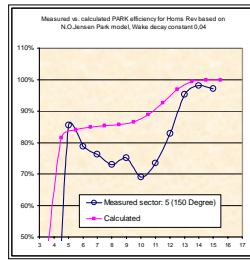
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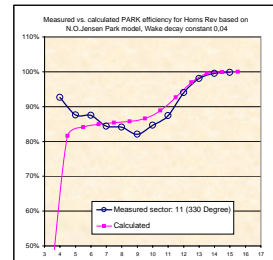
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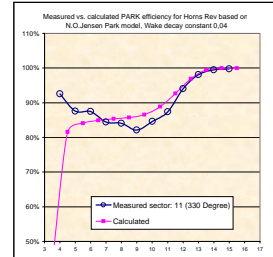
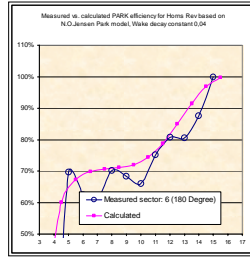
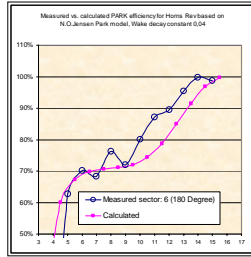
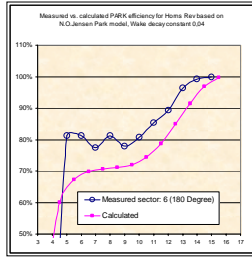
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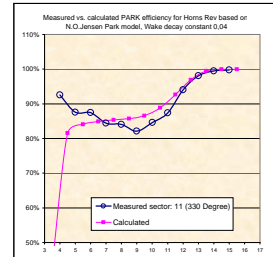
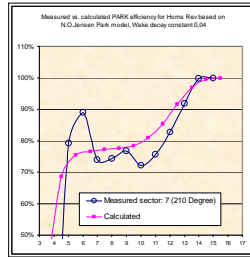
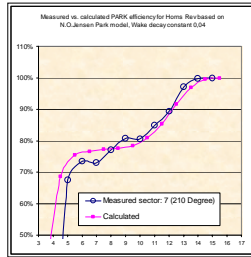
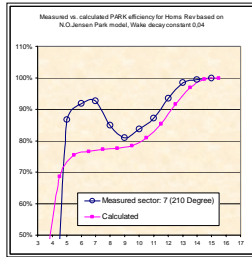
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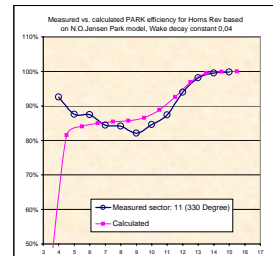
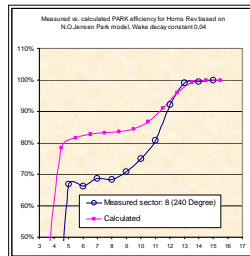
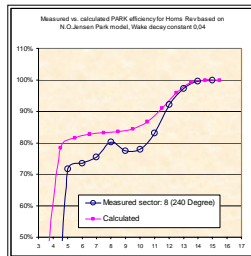
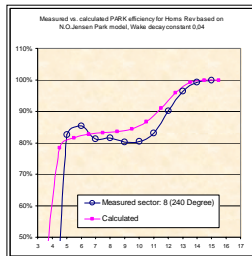
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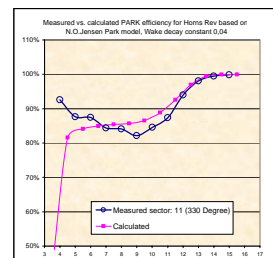
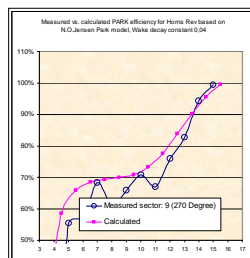
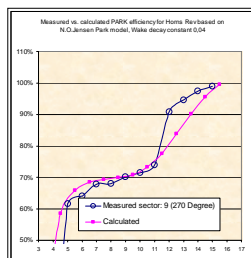
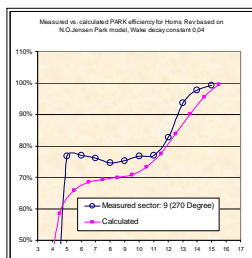
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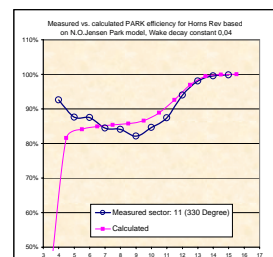
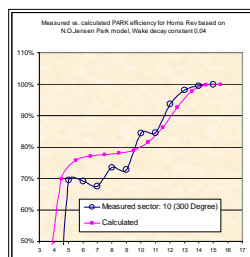
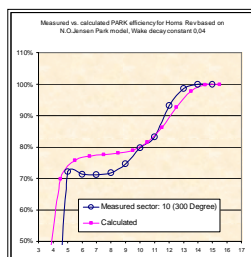
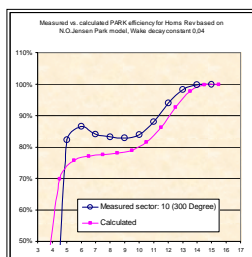
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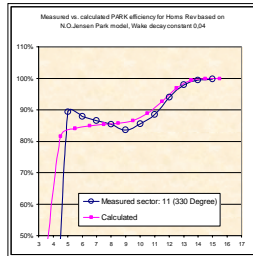
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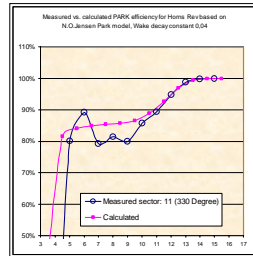
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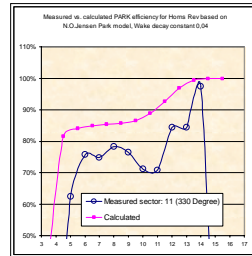
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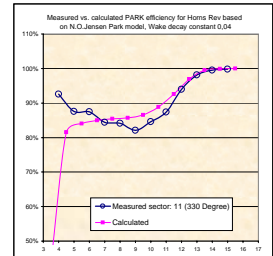
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**Stable conditions**



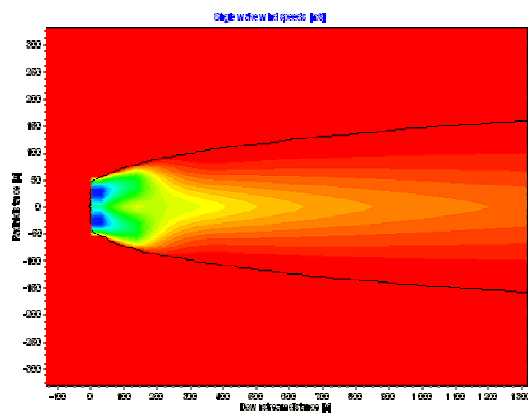
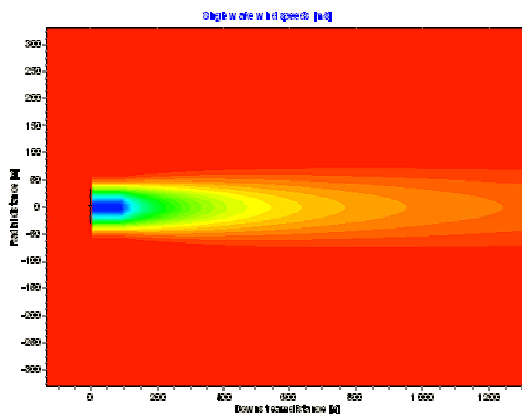
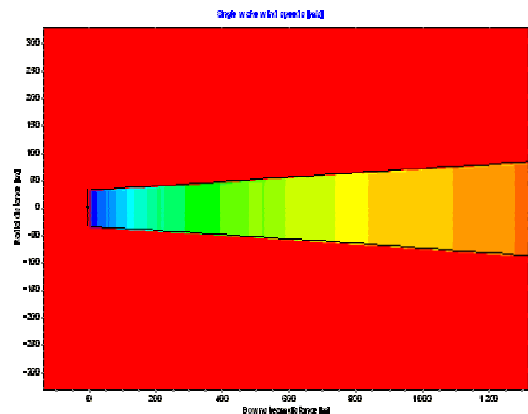
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# APPENDIX A

# WindPRO / PARK

## Introduction to Wind Turbine Wake Modelling and Wake Generated Turbulence



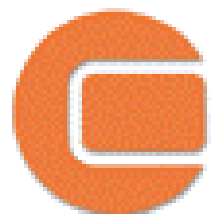
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01-04-05 – 1<sup>st</sup> edition completed  
14-12-05 – User guide added – Thomas Sørensen  
27-10-06 – Additions to chapters: 1 - Introduction, 3 – Eddy Viscosity and 6 – Wake Modelling (MLT)  
Added annex B and C, based on papers presented at the EWEA conference 2006  
06-02-07 – Clarified some equations in the G.C.Larsen model (Chapter 5) – MLT  
13-08-07 – Corrected equation in documentation for the Frandsen Model  
17-01-08 – Removed annex A. Annex B and C are now A and B

**Front cover**

The front cover shows a wake development behind a single turbine. The wake velocities are calculated using the N.O. Jensen PARK model, the Ainslie model (eddy viscosity) and the G.C. Larsen model.

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## 1. Introduction to Wake Modelling

This paper gives a brief introduction to the concept of wake modelling for arrays of wind turbines. While WindPRO offers the opportunity to calculate the wind farm wakes with a number of different wake models, the user must choose and configure the model that fits the best into the area of application. This report gives selected background theory of single and multiple wake modelling and also on the implementation of the specific wake models. Descriptions of the different wake models are found in the succeeding chapters.



Figure 1: A cluster of four >2 MW semi-offshore turbines in Frederikshavn, Denmark.

### Introduction

When the turbine extracts power from the wind, a wake evolves downstream of the turbine. If another nearby turbine is operating within this wake, the power output for this downstream turbine is reduced when comparing to the turbine operating in the free wind. This reduction of power output is – on an annual basis – typically in the range of approximately 2% - 20%, depended on the wind distribution, the wind turbine characteristics and the wind farm (array) geometry.

The turbines operating in the wake are not only subjected to a decreased wind speed but also increased dynamic loading – arising from the increased turbulence induced by the upstream turbines. This increased turbulence must be accounted, when selecting a turbine suitable class of turbines. This is typically done though the specifications in the international codes – e.g. the IEC-61400-1 code for wind turbine structures.

The models available in WindPRO are currently all single wake models, i.e. models capable describing the flow downstream of one turbine. When having multiple turbines, the results from the single wake models are aggregated into a combined result by using empirical combination rules.

### The Wake after an Idealized Turbine

Assuming an idealized turbine – where flow around and behind the turbine is without rotation and friction - it is possible to derive some general and important equations describing the wake wind speeds. For further details please consult the publication by Andersen et al. [1]. The derivation is based on the simplified Bernoulli equation, stating that the mechanical energy per unit mass – along a streamline - is conserved:

$$\frac{\rho V^2}{2} + p = H \quad (1)$$

where  $\delta$  is the air density  
 $V$  is the wind speed  
 $p$  is the pressure  
 $H$  is the total energy (constant along any streamline)

The Bernoulli equation gives the relation between pressure and wind speed, as the total pressure is constant along a streamline (streamline = a line which is drawn, such as it is always tangent to the velocity vector). Using the Bernoulli equation just before and after the rotor gives us two equations:

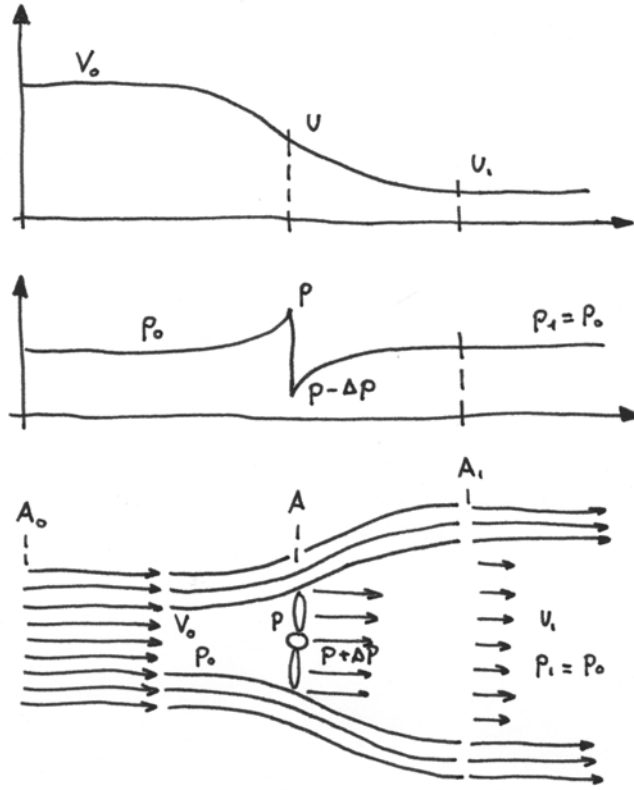


Figure 2: Flow near an idealized turbine: velocity and pressure.

$$\begin{aligned} p_0 + \frac{1}{2}\rho V_0^2 &= p + \frac{1}{2}\rho u^2 \quad \text{and} \\ p - \Delta p + \frac{1}{2}\rho u^2 &= p_0 + \frac{1}{2}\rho u_1^2 \end{aligned} \quad (2)$$

These two equations are then subtracted to yield the drop in pressure over the rotor plane

$$\Delta p = \frac{1}{2}\rho(V_0^2 - u_1^2) \quad (3)$$

Another method for calculating the drop in pressure,  $\Delta p$ , is expressing the drop as the change in momentum of the mass of air passing through one square meter of the rotor area per second (actually by considering the second law of Newton). This yield

$$\Delta p = \rho u(V_0 - u_1) \quad (4)$$

Now equating the equations (3) and (4) gives an expression for the wind speed in the rotor plane:

$$u = \frac{1}{2}(V_0 + u_1) \quad (5)$$

i.e. the velocity in the rotor plane is exactly the average of the far upstream and the far downstream wind speed.

## 1. Introduction to Wake Modelling

The axial thrust force – i.e. the force acting in the direction of the wind – which is denoted,  $T$ , is calculated from knowledge of the pressure difference:

$$T = \Delta p \cdot A \quad (6)$$

where  $T$  is the thrust force  
 $\Delta p$  is the difference force  
 $A$  is the rotor area

Now defining a ‘axial interference factor’ –  $a$ , which is

$$u = (1 - a) V_0 \quad \text{and thus} \quad u_1 = (1 - 2a) V_0 \quad (7)$$

Inserting the equation (7) and equation (3) into the thrust definition equation (6) yields

$$T = 2\rho a(1 - a)V_0^2 A \quad (8)$$

Now defining a thrust coefficient,  $C_T = 4a(1 - a) \Rightarrow a = 1/2 \pm 1/2 \sqrt{1 - C_T}$ , gives

$$T = (1/2) \cdot \rho \cdot V_0^2 A \cdot C_T \quad (9)$$

Inserting the expression for  $a$  (and  $C_T$ ) into the equation (7), this yield

$$u_1 / V_0 = (1 - 2a) = \sqrt{1 - C_T} \quad (10)$$

With the equation (10) we now have a relation established between downstream wake wind velocity –  $u_1$ , the turbine thrust coefficient –  $C_T$  – and the free wind speed –  $V_0$ . This relation is - using an assumption of the downstream wake expansion – used for making simple and computationally very efficient turbine wake models – like the N.O. Jensen PARK model.

Wake Expansion: When applying the continuity equation in relation with the equation (6) and (10) which are expressions for the wind speed in the rotor plane ( $u$ ) and far downstream of the turbine ( $u_1$ ), then an expression for the so-called expanded diameter can be derived [2]:

$$D_{\text{exp}} = RD\sqrt{(1 - a)/(1 - 2a)} \quad (11)$$

Turbulent mixing makes the wind speeds recover to the free wind speeds at some downstream distance, but the equations (10) and (11) can be used to gain insight in the wake expansion rate.

### Important Wake Model Parameters

The wake models require different internal wake model parameters as input - as well as a varying number of additional parameters describing the terrain and/or wind climate conditions. Input parameters to a wake model can be turbulence intensity and roughness length. Typically, one would assume that such parameters are depended on the roughness class (or roughness length). In the lack of the preferred measured data, the table below suggests corresponding estimated wake model parameters.



## 1. Introduction to Wake Modelling

Terrain classification	Roughness Class	Roughness Length	Wake Decay Constant	Ambient Turbulence at 50 m* $A_x = 1.8$	Ambient Turbulence at 50 m** $A_x = 2.5$	Additional detailed description
Offshore. Water areas	0.0	0.0002	0.040	0.06	0.08	Water areas, oceans and large lakes. General water bodies.
Mixed water and land	0.5	0.0024	0.052	0.07	0.10	Mixed water and land. Also applies to the very smooth terrain
Very open farmland	1.0	0.0300	0.063	0.10	0.13	No crossing hedges. Scattered buildings. Smooth hills.
Open farmland	1.5	0.0550	0.075	0.11	0.15	Some buildings. Crossing hedges with 8 m height with distance 1250 m apart.
Mixed farmland.	2.0	0.1000	0.083	0.12	0.16	Some buildings. Crossing hedges 8 m high with distance 800 m apart.
Trees and farmland	2.5	0.2000	0.092	0.13	0.18	Closed appearance. Dense vegetation. 8 m hedges 250 m apart.
Forests and villages	3.0	0.4000	0.100	0.15	0.21	Villages, small towns and much closed farmland. Many high hedges. Forests.
Large towns and cities	3.5	0.8000	0.108	0.17	0.24	Large towns, cities with extended build up areas.
Large build up cities	4.0	1.6000	0.117	0.21	0.29	Large cities with build up areas and high buildings.

\* The turbulence intensity is actually calculated based on the assumption of homogeneous terrain with a surface roughness equal to the roughness length. Input to the calculation is also the turbulence measurement height – see the equation below (here based on  $A_x = 1.8$ , see the equation below).

\*\* Calculated using  $A_x = 2.5$ , see the equation below.

WindPRO 2.5 assumes that  $A_x = 2.5$ . Please note that if - during the automated conversions in WindPRO - a terrain classification is exceeding the limits in the table (either the 'Offshore' or the 'Large build up cities') then the nearest tabular value is chosen.

### Estimating the Turbulence Intensity

The turbulence intensity on a specific site can be estimated from the roughness rose or directly (in a more raw manner) from the surface roughness in the considered point. The relation between the turbulence and the surface roughness can – in the case of homogeneous terrain - be derived from boundary layer theory to, see Guidelines for the Design of Wind Turbines [3, section 3.1.2]:

$$E[\sigma_u] = U_{10} A_x \kappa [1 / \ln[z / z_0]] \Leftrightarrow I_T = \frac{E[\sigma_u]}{U_{10}} = A_x \kappa \left[ \frac{1}{\ln[z / z_0]} \right]$$

The value of A is reported to vary approximately between 2.5 to 1.8.  $\kappa$  is the Von Karman constant, which is equal to 0.4. In DS 472 the product between  $A_x$  and  $\kappa$  is (conservatively) set to 1.0. The estimated turbulence levels from the equation above give a mean level of turbulence. However in relation to IEC, the characteristic data needed is actually a mean value plus one standard deviation.

### Wake Model Limitations – Large Wind Farms and Thrust Coefficient

The wake models are calibrated and tested in small to medium sized wind farms – i.e. wind farms with up to approximately 50-75 turbines. For very large wind farms – 75 turbines or more – the turbines may

influence the surrounding upper air wind climate (Geostrophic winds). In that case, special modelling should be applied – e.g. by ‘artificially’ increasing the roughness within the wind farm.

An important parameter for most models is the thrust coefficient,  $C_t$ . The thrust coefficient is used to relate the free wind speed to the downstream wake wind speed through the equation  $u_1/V_0=(1-C_t)^{0.5}$ . Since the square root is taken, it might be a requirement – depended on the wake model - that the value of  $C_t$  is less than 1.0.

## Calculating the Annual Energy Production (AEP)

Below is a short description of the algorithm used for calculating the AEP. The wake calculations and the annual energy production (AEP) calculation are actually integrated within the same calculation loop. It is calculated according to the algorithm as outlined in the pseudo code below. Note, that the algorithm assumes that the free wind distribution is based on a modeled Weibull distribution. If measured data is used instead, then the joint distribution table data is used.

---

```
for iTurbine = 1: N

    Select i Turbine

    Wake Combination for iTurbine calculated (looking at all upstream turbines) /
    Inflow conditions calculated (turbulence and velocity deficits) /
    looping turbines 1 :( iTurbine-1)

    save iTurbine_ThisLoopWakeWSP

    Wake Model for iTurbine:
        - Velocity deficit caused by iTurbine on all downstream turbines
          calculated and stored (from iTurbine+1 to N)

    Incremental AEP calculation (assuming here 12 wind-sectors):
        Find Sector from SectorAngle
        Lookup in weibull table: BinProb=frequency(sector)*AngleStep/30*
        ( F(ThisLoop_WSP)-F(LastLoop_WSP) );
        // F is the cummulative weibull distribution
        AvgPowerInBin:=(Power(iTurbine_ThisLoopWakeWSP)-
                        Power(iTurbine_LastLoopWSP)) / 2;
        AEP_iTurbine:=AEP_iTurbine+AvgPowerInBin*8760*IncProb;

    save iTurbine_LastLoopWakeWSP=iTurbine_ThisLoopWakeWSP

end for
```

---

## References

- [1] P.S. Andersen, U. Krabbe, P. Lundsager, H. Petersen, *Basismateriale for Beregning af Propelvindmøller*, Risø-M-2153(rev.), Forsøgsanlæg Risø, Januar 1980.
- [2] J.G. Schepers: ENDOW: *Validation and improvement of ECN's wakemodel*, ECN-C-03-037, March 2003.
- [3] *Guidelines for Design of Wind Turbines*, DNV/Risø, Second edition, Risø National Laboratory

## 2. Introduction to the N.O. Jensen Wake Model

The N.O. Jensen wake model is a simple single wake model. The model is documented in the paper ‘A Simple Model for Cluster Efficiency’ by I. Katić et al [1] and is based on the assumption of a linearly expanding wake diameter. This note gives an introduction to the N.O. Jensen wake model and how it is implemented in WindPRO.

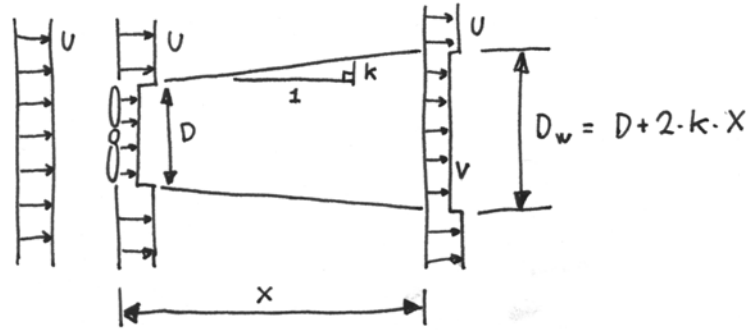


Figure 1: The N.O. Jensen wake model - overview.

### Single Wake Calculation

When calculating the velocity deficit, the reduced wind speed,  $V$ , downwind of the turbine is derived from:

$$1 - V/U = \left(1 - \sqrt{1 - C_T}\right) / (1 + 2kx/D)^2 \quad (1)$$

Comparing this equation with the previously derived equation for the wind speed just downwind of the turbine (2), it is obvious that the assumption is a linearly expanding wake width.

$$V_0/U = \sqrt{1 - C_T} \quad (2)$$

where

$V_0$  is the wind speed directly after the turbine of consideration

However it is noticed, that it is not the actual wake wind velocity that is subject for this expansion assumption, but rather the velocity deficit  $\delta V_i = (1 - V_i/U)$ . Note, that the velocity deficit is defined through the free wind speed,  $U$ .

A plot from a calculation in WindPRO is shown in Figure 2. Note, that the wake velocity deficit is uniform given a certain downstream position.

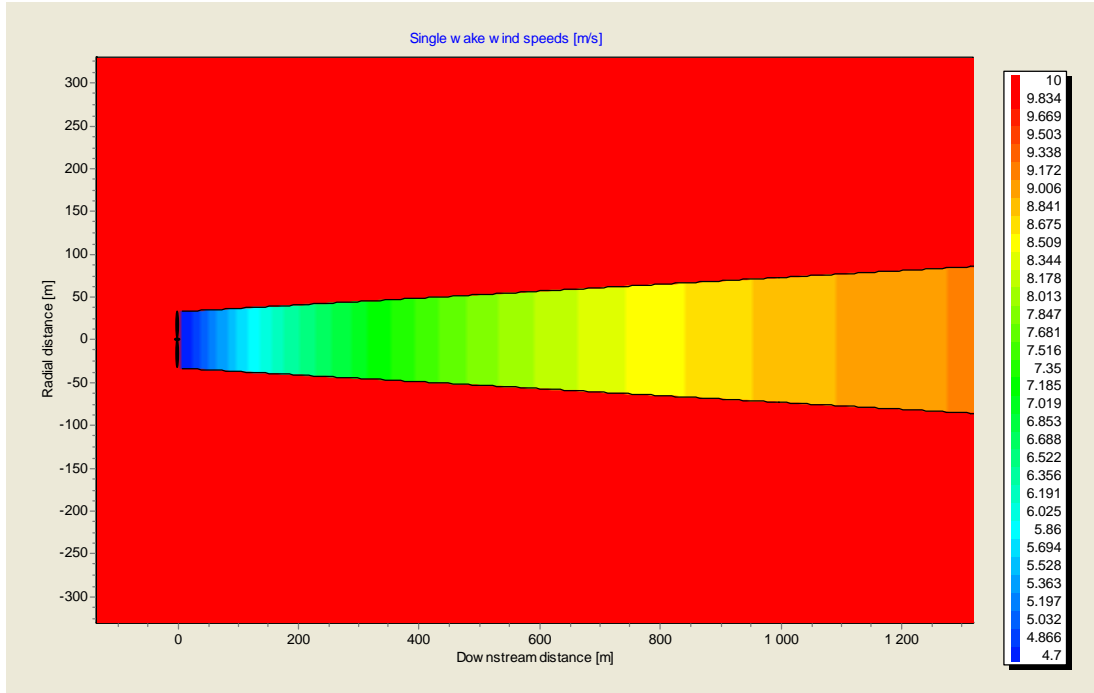


Figure 2: N.O. Jensen wake model - wake development after a single turbine.

## Multiple Wake Calculation

Katic et al. [1] suggests, that multiple wakes are calculated through the ‘sum of squares of velocity deficits’ wake combination model. Thus, the N.O. Jensen model initially implemented in the WindPRO PARK module as well as the WAsP / Park module uses the sum of squares of velocity deficit to calculate a combined wake contribution. The combined effects of multiple wakes are found as:

$$\delta V_n = \sqrt{\sum_{k=1}^{n-1} (\delta V_{kn})^2}$$

This model is treated in a succeeding chapter.

## References

- [1] I. Katić, J. Højstrup & N.O. Jensen, *A Simple Model for Cluster Efficiency*, European Wind Energy Association, Conference and Exhibition, 7-9 October 1986, Rome, Italy.

### 3. Introduction to the Ainslie Wake Model (Eddy Viscosity Model)

#### Introduction

The wind turbine wake application of an axi-symmetric formulation of the time averaged Navier Stokes equations with an eddy viscosity closure was initially made by Ainsley [3]. The application uses cylindrical coordinates and an assumption of incompressible fluid. A graphical overview of the model setup is shown in Figure 1.

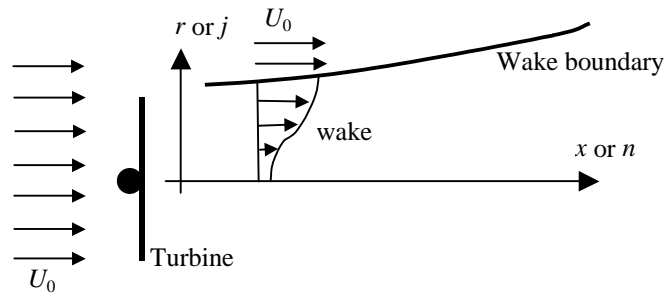


Figure 1: Flow around the turbine.

A result from an implementation of the model is shown in Figure 2, where the wake development behind a turbine with a 50 meters rotor is shown. The calculation is initiated at distance two-rotor diameters downstream (100 meters). Note, that the model calculates the flow through half of the rotor as indicated on Figure 1); this is due to the symmetry assumption used within the model. The free stream velocity is 8.0 m/s (as shown in the legend to the left), while the minimum velocity behind the turbine is 6.5 m/s. The trust coefficient – for this sample calculation – was set to 0.7.

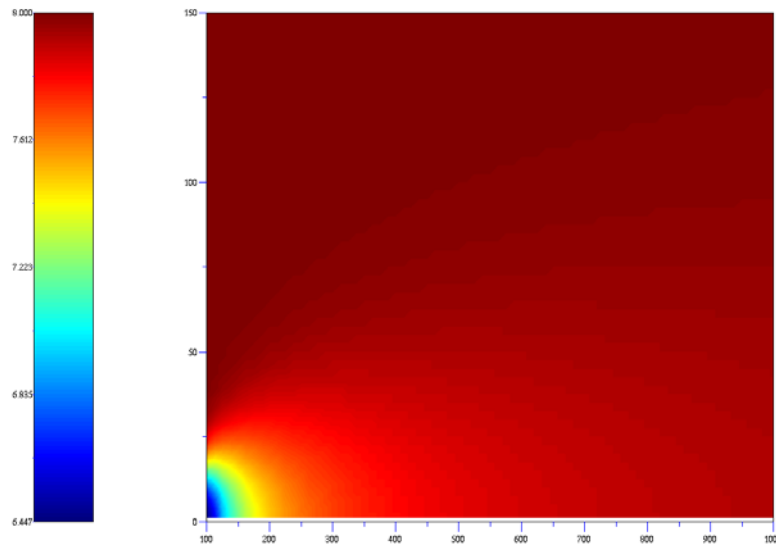


Figure 2: Wake development behind a turbine with a 50-meter rotor. Note that the calculation is initiated at 2 RD downstream.

#### Nomenclature

$I_T$	turbulence intensity
$v$	mean (averaged) velocity in radial direction
$u$	mean (averaged) velocity in axial direction
$U_0$	mean (averaged) velocity in free flow

$\sigma_u$	standard deviation of wind speed process
$\overline{uv}$	Reynolds stress
$\varepsilon(x)$	eddy viscosity

### Continuity Equation (axisymmetric case: $\partial/\partial\phi=0$ )

The continuity equation in cylindrical coordinates is (Shames [1]):

$$\frac{1}{r} \frac{\partial rv}{\partial r} + \frac{\partial u}{\partial x} = 0$$

### Navier Stokes Equation

In the thin layer approximation and using cylindrical coordinates, the Navier Stokes equations are:

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial r} = -\frac{1}{r} \frac{\partial(r\overline{uv})}{\partial r}$$

The last part of the equation above refers to the change in acceleration and thereby momentum. It is not possible to describe this contribution using the velocities in the averaged flow. The part is due to the change in momentum caused by the turbulent fluctuations.

### Eddy viscosity (or turbulent exchange coefficient for momentum)

The eddy viscosity is defined in Tennekes and Lumley [2], and is used for establishing an interaction between mean flow and turbulent eddies.

$$-\overline{uv} = \varepsilon(x) \frac{\partial u}{\partial r}$$

According to Ainslie [3], the eddy viscosity,  $\varepsilon(x)$ , is adequately described by a length scale  $L(x)$  and a velocity scale  $U(x)$ .

$$\varepsilon(x) = L(x) \cdot U(x) + \varepsilon_a$$

The length and velocity scales are taken to be proportional to the wake width  $b$  and the velocity difference across the wake shear layer (i.e. independent of  $r$ ).  $\varepsilon_a$  is the contribution from ambient turbulence to the eddy viscosity. The length scales are determined by:

$$L(x) \cdot U(x) = k_1 \cdot b \cdot (U_0 - u_0(x))$$

3 case studies showed  $k_1 = 0.015$ .

### Boundary conditions

Ainsley [3] gives the boundary conditions at two rotor diameters downstream of the turbine. The BC at this section is given as a Gaussian velocity profile with the input of initial velocity deficit  $D_M$  and wake width  $b$ :

$$1 - \frac{U}{U_0} = D_M \exp\left[-3.56 \cdot \left(\frac{r}{b}\right)^2\right]$$

Empirical data (wind tunnel studies) showed the following equations may be used for determining the velocity deficit and the wake width ( $A$  is ambient turbulence intensity in percent):



$$D_M = C_T - 0.05 - (16C_T - 0.5)A / 1000$$

$$b = \frac{3.56C_T}{8D_M(1 - 0.5)D_M}$$

Other authors specify a boundary condition where the initiation position (downwind position) varies. In Lange et al [4] reference to a study made by Vermeulen [5] is made. Vermeulen suggests that the near wake length is modeled through contributions from ambient turbulence, rotor generated turbulence and shear generated turbulence. The near wake length is divided into two regions; the first  $x_h$  is modeled as:

$$x_h = r_0 \left[ \left( \frac{dr}{dx} \right)_a^2 + \left( \frac{dr}{dx} \right)_\lambda^2 + \left( \frac{dr}{dx} \right)_m^2 \right]^{-0.5}$$

where  $r_0$  is an 'effective' radius of an expanded rotor disc,  $r_0 = [D / 2] \sqrt{(m+1) / 2}$  and  $m = 1 / \sqrt{1 - C_t}$   
 $D$  is the rotor diameter  
 $C_t$  the thrust coefficient

The different contributions in the equation above are calculated as:

$$\begin{aligned} \left( \frac{dr}{dx} \right)_a^2 &= \begin{cases} 2.5I + 0.05 & \text{for } I \geq 0.02 \\ 5I & \text{for } I < 0.02 \end{cases} & \text{ambient turbulence} \\ \left( \frac{dr}{dx} \right)_\lambda^2 &= 0.012B\lambda & \text{rotor generated turbulence} \\ \left( \frac{dr}{dx} \right)_m^2 &= [(1-m)\sqrt{1.49+m}] / (9.76(1+m)) & \text{shear - generated turbulence} \end{aligned}$$

where  $I$  is the ambient turbulence intensity  
 $B$  is the number of rotor blades  
 $\lambda$  is the tip speed ratio

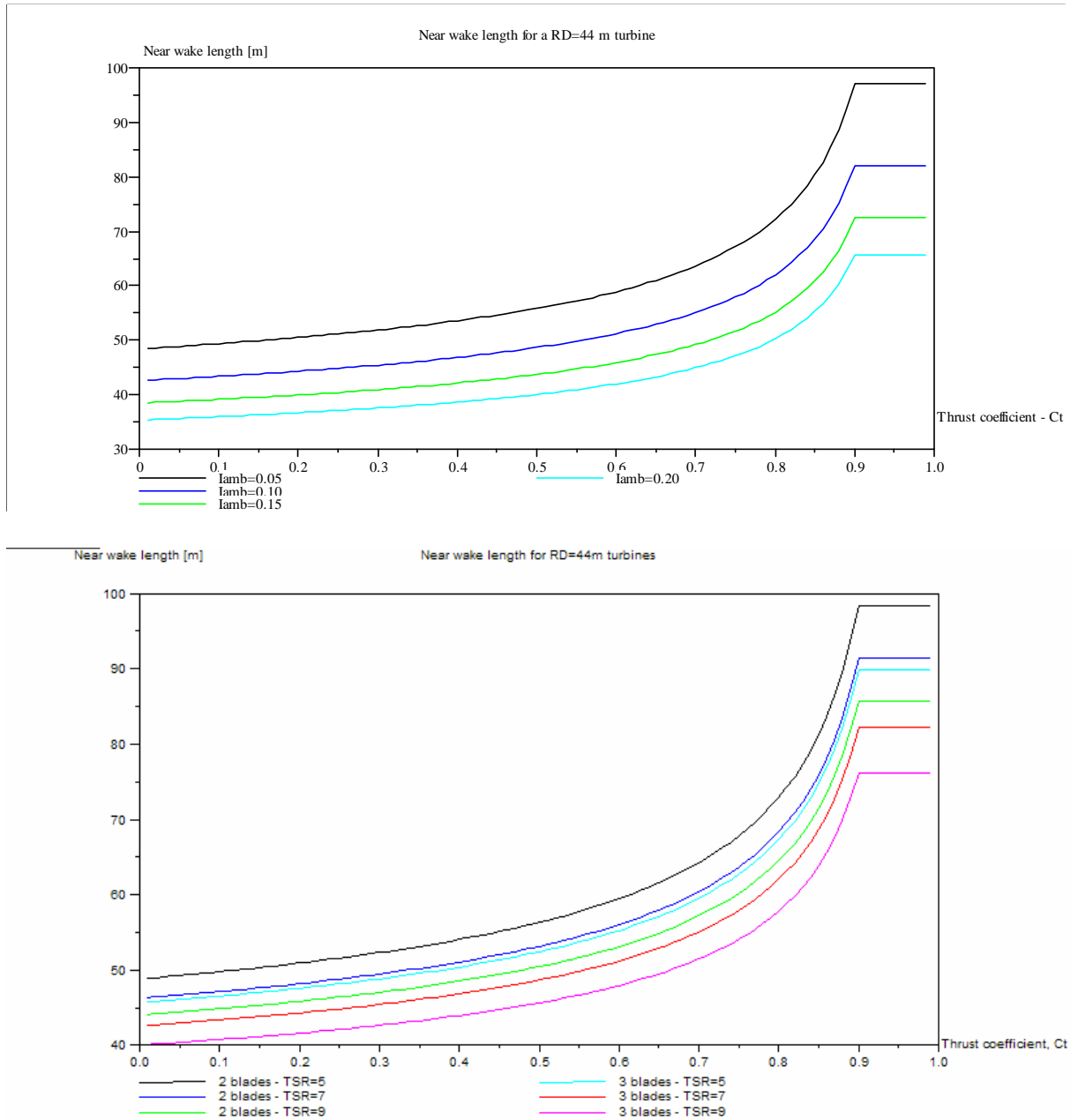


Figure 3: Near Wake Length for a 44 meter Rotor-Diameter Turbine using the Vermeulen Equations. Top: Sensitivity to ambient turbulence. Bottom: Sensitivity to type of turbine and tip speed ratio. Note, that the near wake length is decreasing with increasing ambient turbulence levels.

When the first near wake region,  $x_h$ , have been calculated, one can calculate the full near wake length,  $x_n$ , by:

$$x_n = \frac{\sqrt{0.212 + 0.145m}}{1 - \sqrt{0.212 + 0.145m}} \frac{1 - \sqrt{0.134 + 0.124m}}{\sqrt{0.134 + 0.124m}} x_h$$

Lange [4] reports that the equations save a singularity at about  $C_t = 0.97$ , so it is suggested that for  $C_t$ 's larger than 0.9, then the value for  $C_t$  equal to 0.9 is used. A sample calculation for a 44-meter rotor diameter turbine is shown in

## Numerical solution method

The differential equation is solved using a finite difference method using a generalized Crank-Nicholson scheme. The solution procedure followed is outlined in Wendt [6]. The numerical solution method used for solving the Navier Stokes equation is made by replaced the differential equation with the finite difference approximations. This approximation introduces truncation errors into the equation.

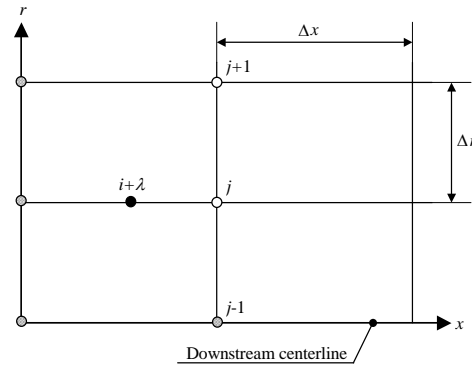


Figure 4: Grid for the generalized implicit method.

## Outline of the Solution Procedure

The solution of the partial differential equations invokes an iterative solution procedure. From the boundary condition, the continuity equation is solved. Then the downstream momentum equation is solved in order to get the next downstream velocities. This solution is obtained through an iterative process – the iteration is stopped when convergences is achieved.

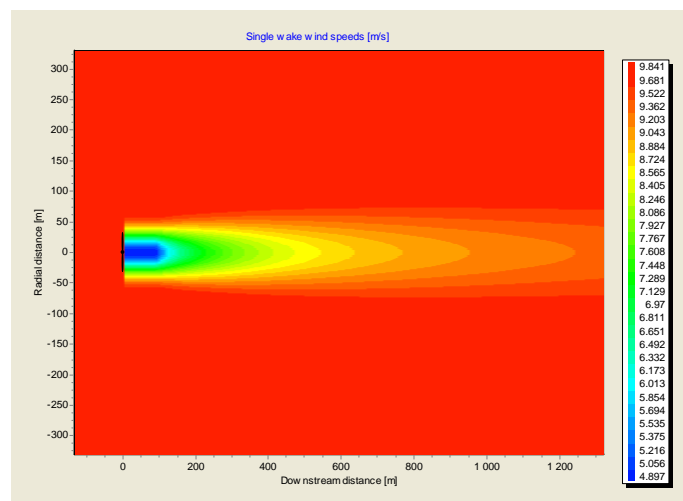


Figure 5: Eddy viscosity model – calculation from WindPRO.

A plot from WindPRO is shown in Figure 5. Note, that wind speeds within the near wake zone are approximated through the solution at the near wake distance.

## References

- [1] Shames, Irving H.: *Mechanics of Fluids*, McGraw-Hill International Editions, 1992
- [2] Tennekes, H. & J.L. Lumley, *A First Course in Turbulence*, The MIT Press, 1972

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- [3] Ainslie, J.F: *Calculating the flowfield in the wake of wind turbines*, Journal of Wind Engineering and Industrial Aerodynamics, 27 (1988), 213-224.
- [4] Lange, Bernard; H.P. Waldl; A.G. Guerrero; D. Heinemann & R.J. Barthelmie: *Modelling of Offshore Wind Turbine Wakes with the Wind Farm Program FLaP*, Wind Energy, 2003 6:87-104.
- [5] Vermeulen, P.E.J: *An experimental analysis of wind turbine wakes*, Proceedings of the International Symposium on Wind Energy Systems, Lyngby, 1980.
- [6] Wendt, John F. (Ed.): *Computational Fluid Dynamics – An introduction*, 2<sup>nd</sup> Edition, Springer-Verlag, 1996.

## 4. Introduction to the G.C. Larsen Model (EWTS II)

### Introduction

This model is a semi analytical model – derived from asymptotic expressions from Prandtl’s rotational symmetric turbulent boundary layer equations. Because of the asymptotic expressions, the model might be somewhat conservative for close spacings. The model is reported in [1] and is also the recommended wake model – for use with wake loading - in the project report from the European Wind Turbine Standards II Project, an EU-funded project finalized in 1999 [2]. This introduction is based on the EWTS-report [2]. A online introduction of the model can be found in the Risø report ‘A simple wake model’ [3] – this report is available online.

### Model Equations

Assuming that similarity exist between deficits at different downstream positions and only moderate velocity deficits, then the wake radius can be described by:

$$R_w = \left[ \frac{35}{2\pi} \right]^{1/5} \left[ 3c_1^2 \right]^{1/5} [C_T Ax]^{1/3} \quad (1)$$

where

$c_1$  is a non-dimensional mixing length, described by  $c_1 = l(C_T Ax)^{-1/3}$   
 $l$  is Prandtl’s mixing length

The  $c_1$  parameter does – according to reference [2] – to some degree separate the rotor drag dependence and thus the  $c_1$  is expected to be relative insensitive to the design and size of the rotor. An alternative and approximated specification of the  $c_1$  parameter is found in section 5.1 of the EWTS II report [2], where the parameter is estimated as seen below in equation (2). This specification is adopted in WindPRO.

$$c_1 = \left[ \frac{D}{2} \right]^{-1/2} (C_T Ax_0)^{-5/6} \quad (2)$$

where

$C_T$  is the thrust coefficient  
 $A$  is the rotor area  
 $D$  is the diameter of the upstream rotor  
 $x_0$  is an approximation parameter, determined by the equation (3) below

$$x_0 = 9.5D \left/ \left( \frac{2R_{9.5}}{D} \right)^3 \right. - 1 \quad (3)$$

In the equation above the  $R_{9.5}$  parameter is determined as:

$$\begin{aligned} R_{9.5} &= 0.5[R_{nb} + \min(h, R_{nb})] \\ R_{nb} &= \max(1.08D, 1.08D + 21.7D(I_a - 0.05)) \end{aligned} \quad (4)$$

where

$I_a$  is the ambient turbulence intensity at hub height

The wake boundary condition is satisfied, so that the wake radius at the rotor position equals the rotor diameter. Furthermore, empirical boundary condition is applied at 9.5 rotor diameters downstream, where the wake radius is determined from the equation (4). The equation ensures that the minimum turbulence intensity equal to 5% is used, and it essentially states that the wake expansion is dominated by ambient turbulence. The blocking effect of the ground is taken into account by using the design wake radius  $R_{9.5}$  in eq. (4) – including the mean of  $R_{nb}$  and the minimum of the hub height and  $R_{nb}$ .

Mean Wind Velocity Deficit: The mean wind deficit is determined from the expression (5),

$$\Delta V = -\frac{V_a}{9} (C_T A x^{-2})^{1/3} \left\{ r^{3/2} (3c_1^2 C_T A x)^{-1/2} - \left( \frac{35}{2\pi} \right)^{3/10} (3c_1^2)^{-1/5} \right\}^2 \quad (5)$$

where

$V_a$  is the ambient mean wind velocity at hub height

## Modified Near Wake Description

The G.C.Larsen wake model includes the option of having a semi-empirical near wake description (second order approach) – enabling the user to model the near wake with a ‘double peak’ velocity profile. This approach is described in detailed in reference [1]. Using the second order option may give a more precise near wake description, especially for densely space turbines. The far wake is not modified.

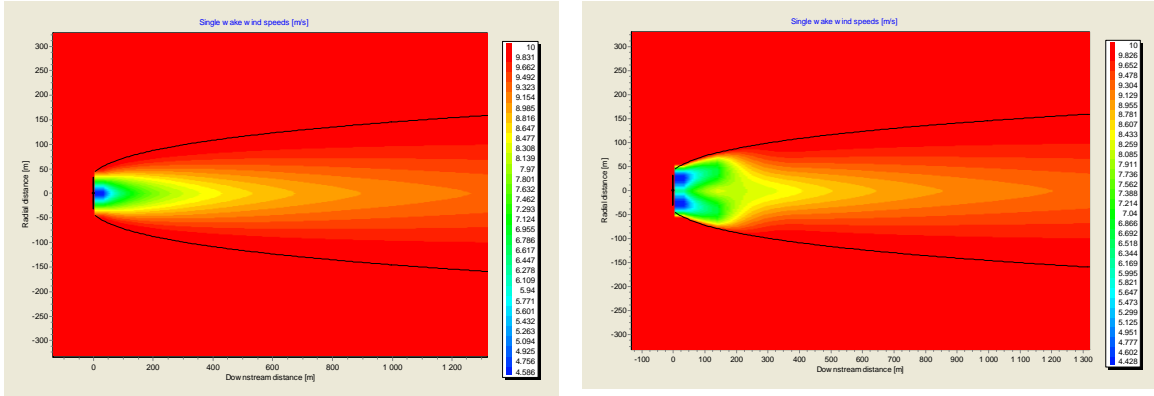


Figure 1: G.C.Larsen wake model (left: First order approach, right: second order approach)

## References

- [1] G.C.Larsen, J. Højstrup, H.A. Madsen, *Wind Fields in Wakes*, EUWEC '96, Gothenburg, 1996.
- [2] *European Wind Turbine Standards II*, ECN-C-99-073, 1999
- [3] Larsen, G.C, *A simple wake calculation procedure*, RISØ-M—2760, Risø National Lab., Roskilde (Denmark), (online: <http://www.risoe.dk/risepubl/VEA/veapdf/ris-m-2760.pdf>)



## 5. Wake Combination Models

Today (2005), most wake models are still single wake models. Thus, in order to obtain a usable result for wind farms with many turbines, these single wakes must be combined into a combined effect. This is done by purely empirical means, using different wake combination models.

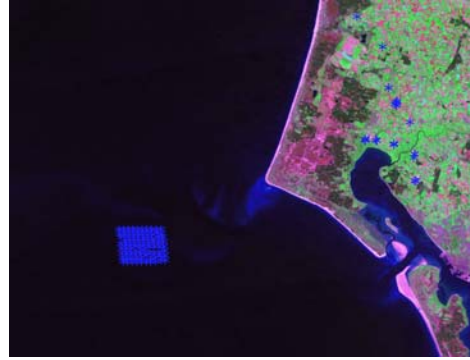


Figure 1: Horns Rev offshore wind farm.

### Introduction

Two problems occur when trying to combine the results from a several single wake model into one single downwind wind speed:

1. Since the results from many of the single wake models are non-uniform distributed velocities or velocity deficits, these results must be averaged or combined into an efficient (uniform) wind speed. This is necessary, because the wind turbine power output is to be estimated from the available power curves.
2. When the downwind velocities are determined through one single wake calculation for each turbine, the single wake results must be added into a combined effect.

### Ad. 1: Averaging of the Single Wake results

The output from many wake calculations is a non-uniform velocity field. However in order to calculate the power output from a measured power curve, the velocity field must be averaged over the rotor area. In WindPRO, a squared momentum deficit approach is used to calculate this reduction. This approach is similar to the one reported by Lange et. al [1].

$$(u_0 - u_{rotor})^2 = \frac{1}{A} \int_{rotor} (u_0 - u_w)^2 dA \quad (1)$$

where  $u_0$  is the free stream velocity  
 $u_{rotor}$  is the averaged velocity at the rotor  
 $u_w$  is the non-uniform wake velocity (i.e. a function of the distance and direction from the hub)

Investigations made in connection to the validation of the wake models implemented showed, that using linear combination of wind speeds or using exponents of order 3 only gave marginal differences on the averaged wind speed. The integration in (1) is done by numerical means.

### Ad. 2: Wake Combination Models

This averaging may be done in a variety of combinations. Djerf [2] states on option of four different wake combination methods: 1) Sum of squares of velocity deficits, 2) Energy balance, 3) Geometric sum, 4) Linear superposition. According to Djerf it is not recommend using methods (3) and (4). Schepers [3] suggests another approach. Schepers first calculates the wake from the upstream turbine. Then this wake is used for calculating the axial force coefficient on the second turbine downstream. The initial velocity deficit behind the second turbine is then calculated from the axial force.

In WindPRO, the ‘Sum of squares of velocity deficit’ methodology is used.

## Sum of Squares of Velocity Deficits

The N.O. Jensen model initially implemented in the WindPRO Park module as well as the WAsP / Park module uses the sum of squares of velocity deficit to calculate a combined wake contribution.

$$\delta V_n = \sqrt{\sum_{k=1}^{n-1} (\delta V_{kn})^2} \quad (2)$$

where  $\delta V$  is the velocity deficit defined as  $(1-V/U)$  – where  $U$  is the free wind speed  
 $n$  is the number of upstream turbines

Lange et. al [1] uses a slightly different formulation of the sum of the squares of velocity deficits approach. This equation is used in conjunction with equation (1) to calculate the deficit.

$$(u_0 - u_c)^2 = u_0^2 \left( 1 - \frac{u_c}{u_0} \right)^2 = \frac{1}{A} \int_{rotor} \sum_{i, allwakes} (u_{rotor(i)} - u_{w(i)})^2 dA \quad (3)$$

## Outline of the calculation procedure

An overview of the calculation procedure is as follows:

1. The calculation is initiated with the turbine positioned at the most upstream position (lup turbine)
2. Find (calculate) the wind speed directly upstream of the turbine
3. Calculate the wind speeds downstream of this turbine, i.e. for all downwind turbine positions
4. Calculate the deficits for all downstream turbine positions, i.e. relating to the free wind speed
5. If the downstream turbine is in a partial wake, then reduce the velocity deficit with the fraction of the overlap area to the rotor area of the downstream turbine.
6. Calculate the square of the velocity deficits
7. Continue with the next turbine (using step 1), by summing the squares of the velocity deficits.

## References

- [1] Lange, Bernard et al: *Modelling of Offshore Wind Turbine Wakes with the Wind Farm Program FLaP*, Wind Energy 2003; 6: 87-104
- [2] Djerf, E. & Mattson, H.: *Evaluation of the Software program WindFarm and Comparisons with Measured Data from Alsvik*, FFA TN-2000-30,  
[http://www.vindenergi.foi.se/Rapporter/TN2000\\_30\\_WindFarm.pdf](http://www.vindenergi.foi.se/Rapporter/TN2000_30_WindFarm.pdf)
- [3] Schepers, *ENDOW: Validation and Improvement of ECN's wake model*, ECN-C-03-034.

## 6. Introduction to Turbulence and Wakes

Wind turbines operating in wakes are subjected to higher turbulence levels than turbines operating in the free wind, thus appropriate turbulence calculations should be made before selecting the proper turbine design class when having clusters of turbines. This is due to the fact that the fatigue loads and possibly also the extreme loads are higher when the turbulence levels increases.

The wake added turbulence may be calculated using different wake or turbulence models. These models are typically very different in detailing level – and possibly also in accuracy. The models range is from simple engineering models to the more advanced computational fluid dynamic (CFD) models. The CFD-models are typically also very demanding in terms of calculation time.



This chapter gives an introduction to the calculations and operations performed on the measured ambient turbulence data, and how the turbulence data from single wake models is merged. We also give a brief introduction to the turbulence calculation required by the IEC 61400-1 structural code.

Figure 1: Part of a Flash Animation Created using WindPRO.

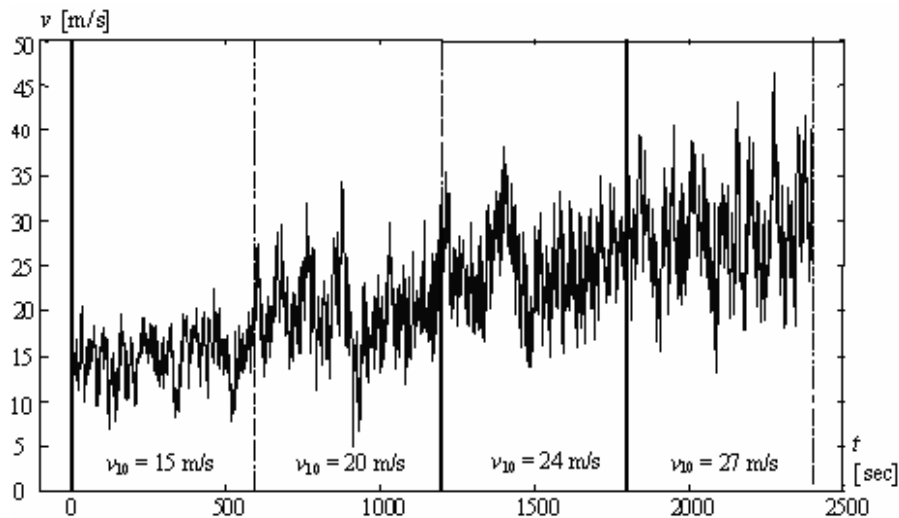


Figure 2: Turbulent winds – simulated at different mean wind speeds, from [1].

WindPRO contains several models for calculating the wake added turbulence. The ambient turbulence level must be user specified, e.g. through measured data or alternatively through the roughness classification.

### The Turbulence Calculation

When estimating the design, lifetime and fatigue on wind turbines, the turbulence levels are of outmost importance. The turbulent winds arise from several sources:

1. Orography induced turbulence, i.e. flow over hills and mountains
2. Roughness induced turbulence, i.e. flow generated by objects within the landscape
3. Turbine generated turbulence, i.e. turbulence in the wake of the turbines
4. Obstacle induced turbulence, i.e. turbulence generated in the wake of large nearby obstacles

The turbulence intensity is defined as the ratio between the standard deviation of the wind speed,  $\sigma_u$ , and the 10-minute mean wind speed,  $U_{10}$ . When dealing with wind turbine wakes, it is tradition to relate the 10-minute mean wind speed to the free wind speed, i.e. the wind speed outside the wake.

$$I_T = \frac{\sigma_u}{U_{10}} \quad (1)$$

The current edition of WindPRO – version 2.5 – deals primarily with the turbine generated turbulence. Orography and roughness generated turbulences are included only through the on-site meteorological measurements – or alternatively through user-defined turbulence input levels.

## Estimating the Ambient Turbulence Level

When doing the wake calculations then the ambient turbulence level must be estimated either through on-site meteorological measurements, through simple roughness classifications or using numerical flow models. Even if the definition of the ambient turbulence seems reasonable simple (see equation 1), then the estimation of this turbulence intensity is quite difficult due to the stochastic nature of the turbulence, i.e. for a given wind speed then measurements of turbulence intensity will show significant scatter. This scatter can be modelled only accurately as a random variable; so as a minimum requirement it is recommended not only to calculate the mean turbulence level, but also the standard deviation of the turbulence intensity. Actually, this is done automatically when you load meteorological measurements in a meteo-object in WindPRO.

In WindPRO three different measures of the ambient turbulence is used and calculated in each bin (wind speed and sector):

1. Mean (average) turbulence
2. Standard deviation of turbulence
3. Representative (characteristic) turbulence

The first two measures are purely statistical estimators, used in order to describe the turbulence distribution. The last issue (3) is included as the structural codes typically require that a design value of turbulence is used; i.e. the representative turbulence is some function of the mean and standard deviation of the turbulence. Actually, this definition of the representative ambient turbulence levels varies also with different structural codes, e.g. the IEC 61400-1 second and third editions [2, 3] have different definitions of this parameter, see below.

### Ambient Turbulence Level According to the IEC 61400-1 second edition

When estimating the wind condition to check if an IEC class turbine is suitable for a particular site, then the IEC 61400-1 second editions calls for calculating an  $I_{15}$  parameter which is a characteristic value of hub height turbulence intensity at 10 min average wind speed of 15 m/s. The characteristic value is calculated by adding the measured standard deviation of the turbulence intensity to the measured or estimated mean value (only considering the 15 m/s bin values) , i.e.

$$I_{15} = \mu_{I|15m/s} + 1.0 * \sigma_{I|15m/s} \quad (2)$$

The IEC 61400-1 ed. 2 requires the  $I_{15}$  parameter to be estimated using statistical techniques applied to wind speeds and turbulence measurements above 10 m/s. It specifies also, that the influence of the wakes should be accounted for.

### Ambient Turbulence Level According to the IEC 61400-1 third edition

IEC 61400-1 ed. 3 has a slightly different approach to turbulence modelling as it focuses on the standard deviation,  $\sigma_u$ , rather than the turbulence intensity. The IEC 61400-1 ed. 3 requirement is that the following equation is fulfilled for all wind speeds from 0.6 times the rated wind speed to the cut-out wind speed:

$$\sigma_1 \geq I_{eff} \cdot V_{hub} + 1.28 \cdot \hat{\sigma}_\sigma \quad (3)$$

where  $\sigma_1$  is the turbulence standard deviation from the normal turbulence model as specified in the IEC code  
 $I_{eff}$  is the total turbulence (ambient and wake)  
 $V_{hub}$  is the wind speed at hub height level  
 $\sigma_\sigma$  is the measured standard deviation of the turbulence standard deviation

The factor 1.28 is applied because a 90% percentile is sought.

### Calculating the Ambient Turbulence from Measurements

When on site measurements are available then WindPRO is able to calculate the mean turbulence intensity table as well as the standard deviation of the turbulence intensity and a user defined representative turbulence level.

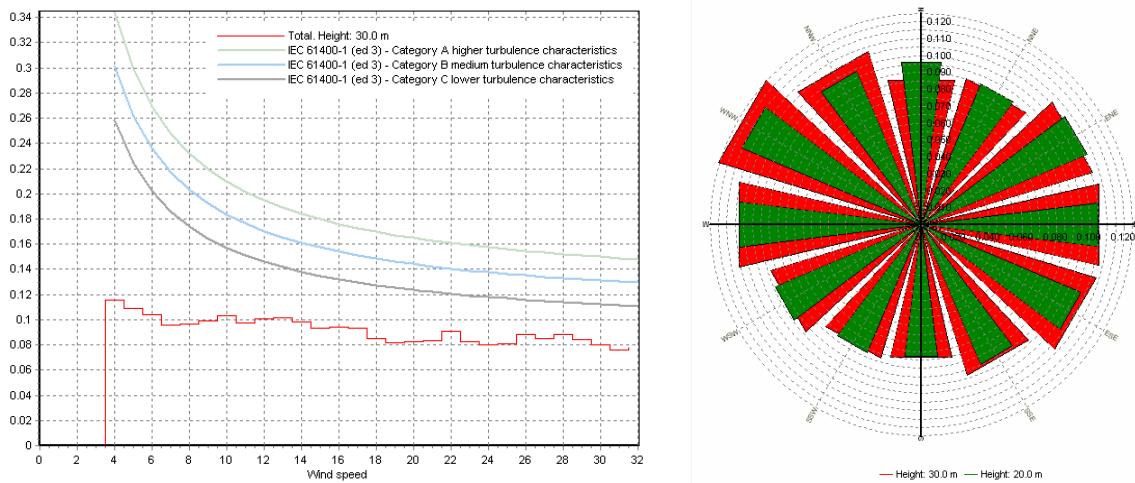


Figure 3: Measured Ambient Turbulence Levels.

### Calculating Turbulence Intensity from Roughness Data and/or Roughness Maps

The turbulence intensity on a specific site can be estimated from the roughness rose or directly (in a more raw manner) from the surface roughness in the considered point. The relation between the turbulence and the surface roughness can – in the case of homogeneous terrain - be derived from boundary layer theory to, see Guidelines for the Design of Wind Turbines [4]:

$$E[\sigma_u] = U_{10} A_x \kappa [1 / \ln[z / z_0]] \Leftrightarrow I_T = \frac{E[\sigma_u]}{U_{10}} = A_x \kappa \left[ \frac{1}{\ln[z / z_0]} \right] \quad (4)$$

The value of A is reported to vary approximately between 2.5 to 1.8.  $\kappa$  is the Von Karman constant, which is equal to 0.4. In DS 472 [5] the product between  $A_x$  and  $\kappa$  is (conservatively) set to 1.0. The estimated turbulence levels from the equation above give a mean level of turbulence. However in relation to IEC 61400-2, the characteristic data needed is actually a mean value plus one standard deviation, so some estimate of the standard deviation of the turbulence is needed.

### A Rule of Thumb to Estimate the Standard Deviation of the Turbulence

This standard deviation may be estimated – from a rule of thumb widely used in Germany. In the general case, the coefficient of variation ( $COV = \sigma / \mu$ ) is set to 20%. Only for forest sites and for extreme hill tops, this value is not sufficient but must be replaced by measurements.

### Vertical Scaling of the Ambient Turbulence Level

Often, when turbulence measurements are available from the site, the measurements are not taken at hub-height level. This calls for a vertical scaling of the ambient turbulence, which is done by assuming homogeneous terrain (an approximation to the real nature). Preferably, the turbulence should be taken from hub-height measurements.

Assuming that the wind flow is a horizontally homogeneous (i.e. the properties of the flow do not change in the horizontal direction), then the standard deviation of the wind speed process is only depended of the height above the terrain,  $z$ .

The turbulence intensity in the height  $x$  meters is defined as:

$$IT(x) = \frac{\sigma_U(x)}{U_{10}(x)} \quad (5)$$

Where

$IT$  is the turbulence intensity

$\sigma_U$  is the standard deviation of the wind speed

$U_{10}$  is the mean wind speed averaged over 10 minutes

Experimental data has shown that the standard deviation of the wind speed only decreases very slowly. In Armit [6] & Dyrbye & Hansen [7], it is said, that it is reasonable to use constant standard deviations up to about the half-height of the internal boundary layer. This assumption is also used in WAsP and in most structural codes.

Using this assumption, the vertical scaling of turbulence intensity between two heights is simply calculated by assuming the same standard deviations in the two heights ( $x$  and  $y$  meters or feet).

$$\begin{aligned} \sigma_U(x) &= \sigma_U(y) && \Leftrightarrow \\ IT(x) \cdot U_{10}(x) &= IT(y) \cdot U_{10}(y) && \Leftrightarrow \\ IT(y) &= \frac{U_{10}(x)}{U_{10}(y)} IT(x) \end{aligned} \quad (6)$$

So now the problem is reduced into calculating the mean wind speed in the new height. The vertical scaling of wind speeds may be done using the power law vertical wind profile a purely empirical equation. The power law wind profiles also require quite homogenous terrain.

$$U_{10}(y) = U_{10}(x) \cdot \left[ \frac{y}{x} \right]^\gamma \quad (7)$$

where

$\gamma$  is the wind gradient exponent

The wind gradient exponent is known to be very depended on the roughness length or the roughness class. The table below gives guidelines for selecting the wind gradient exponent – if no measured data is available:

Roughness Class	Roughness Length	Wind Gradient Exponent
0	0.0002	0.1
1	0.03	0.15
2	0.1	0.2
3	0.4	0.3

Inserting the equation (4) into (3) we obtain the turbulence scaling law, valid for homogeneous terrain:

$$IT(y) = \frac{U_{10}(x)}{U_{10}(y)} IT(x) = IT(x) \cdot \left[ \frac{y}{x} \right]^{-\gamma} \quad (8)$$

## Turbulence from Wind Turbine Wakes

The wake added turbulence is either derived from the (single) wake models that include turbulence modelling or from dedicated (empirical) turbulence models. The turbulence calculated from the different models may be parameterized in numerous ways, see e.g. Figure 4 which holds output from the eddy Viscosity wake model. Using the EV-model one may relate the eddy viscosity to the turbulence intensity or alternative use empirical values. Again, other models have wake turbulence included in a purely empirical manner. The turbulence model must be used in connection with a wake model – in order to take the reduced wind speeds in the wind farm into account.

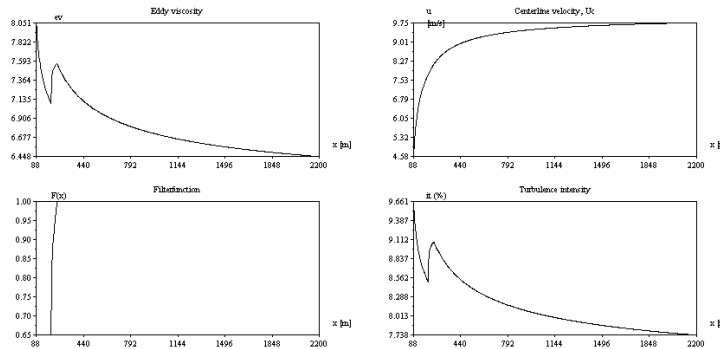


Figure 4: Single Wake Turbulence Modelling using the Eddy Viscosity Model.

The results from the turbulence models – may typically come within one of four categories:

1. Added turbulence model – calculated for the wake after a single turbulence
2. Added turbulence model – calculated for all surrounding turbines
3. Total turbulence model - calculated for the wake after a single turbulence
4. Total turbulence model – calculated for all surrounding turbines

Models (1) and (2) give the wake added turbulence contribution. This should be added to the ambient turbulence level. The model type (3) gives the total turbulence level for a given wake at a given position (ambient and wake added), and this must be summed into a combined effect considering all upstream



turbines. The model type (4) gives the total turbulence level in an integrated manner, thus no single wake adding is needed.

All of the turbulence models implemented in WindPRO belong to any of these four types.

### **Calculating the wake added turbulence intensity**

The turbulence intensity is defined as the ratio of standard deviation to the mean wind speed. It is common practice to relate the turbulence intensity – also within the wake – to the ambient free wind speed. Also, it is practice to assume that the added turbulence level may be added as independent stochastic variables.

In the Danish Recommendation [6] the total turbulence intensity is actually calculated from

$$I_{total} = \sqrt{I_{ambient}^2 + I_{park}^2} \quad (9)$$

### **Partial Wakes - Turbulence**

When the turbine operates in a partial wake, we use the equation (6) to calculate the added turbulence level – considering the rotor area with ambient turbulence only. A linear weighting with rotor areas is assumed.

### **Converting From Time Series Turbulence to Turbulence Tables**

From WindPRO 2.5, the meteo object is the container for three different turbulence tables: The representative or characteristic turbulence table, the mean turbulence table and the standard deviation turbulence table. Each of these tables is used to store the turbulence intensities.

Each table with turbulence intensities is typically binned with an angular interval equal to 30 degrees and a wind speed interval equal to 1.0 m/s. In each bin the sample statistics are then calculated (mean and standard deviation), see also [8]:

$$\overline{X} = \frac{X_1 + X_2 + \dots + X_n}{n} \quad (10)$$

$$S = \sqrt{\sum_{i=1}^n \frac{(X_i - \overline{X})^2}{n-1}} \quad (11)$$

where  $\overline{X}$  is the sample mean  
 $S$  is the sample standard deviation

These two sample statistics are stored in the mean and standard deviation tables respectively. The representative turbulence table values is calculated using the IEC code relations (or user defined relations) as indicated earlier in this chapter. Not only are the binned statistics stored and presented but actually also omni-directional statistics and the sector-wise results. All of these statistics are – as a default setting – derived directly from the time series data.

### **Manual Editing of the Mean and Standard Deviation Turbulence Tables**

When you choose to manually edit the turbulence tables (mean + standard deviation tables), then the omni-directional and sector-wise means are calculated using the assumption that the binned sample distributions are independent Gaussian distributions.

By using this model to calculate statistics you will typically have results that is only differing a few per mille when compared to statistics based on the measured time series data. This is due to the fact that the samples may not fit perfectly to the Gaussian distribution.

Note: Only the mean + standard deviation tables may be edited. The representative turbulence is calculated automatically based on this table.

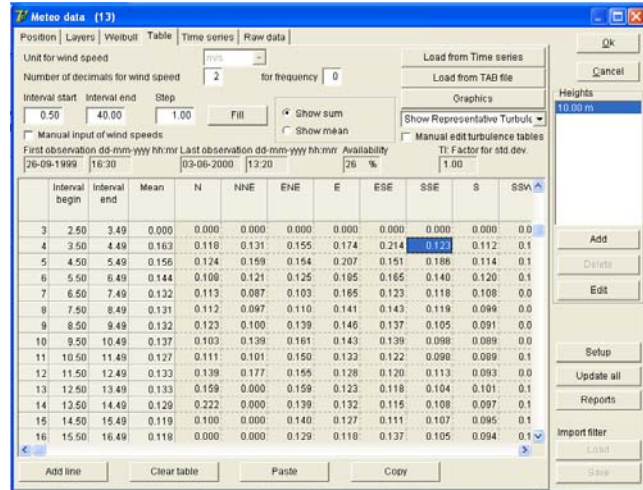


Figure 5: Screen Shot of Meteo Object Turbulence Table in WindPRO 2.5.

If you wish to reset your manual edits, then you must reload tables from the time series data.

We calculate the statistics using a Monte Carlo simulation approach. This approach requires both lookup in the frequency table (to get the number of actual samples in each bin) and lookup in the binned turbulence sample statistics (mean and standard deviation). The approach follows the following procedure, as outlined in this pseudo code algorithm:

---

```

for each sector-bin (typically 1 - 12) do
  Get mean and standard deviation of selected sector-bin
  Make Gaussian distribution using the mean and standard deviation
  Lookup in frequency table to find number of occurrences (cnt) in this bin
  If wind speed is less than the 'include turbulence wind speed' then cnt = 1
  If cnt = 0 then we assume that cnt = 1
  Use Gaussian distribution to simulate 'count' new occurrences
  Update omni-directional Statistics using the simulated data
end

```

Calculate the omni-directional mean and standard deviations

---

Wind Speed Interval [m/s]		Omni-directional Turbulence Intensity		
From	To	Time series	Gaussian model	Difference
6.5	7.5	0.132	0.132	0.000
7.5	8.5	0.131	0.132	0.001
8.5	9.5	0.132	0.132	0.000
9.5	10.5	0.137	0.137	0.000
10.5	11.5	0.127	0.127	0.000
11.5	12.5	0.133	0.133	0.000
20.50	21.50	0.099	0.099	0.000
21.50	22.50	0.114	0.114	0.000
22.50	23.50	0.097	0.098	0.001
23.50	24.50	0.093	0.093	0.001
24.50	25.50	0.092	0.097	0.005
25.50	26.50	0.099	0.097	0.002

Table 1: Comparing Selected Results from Turbulence Table Calculations.

A sample calculation – where the representative turbulence has been extracted using a factor on the standard deviation equal to 1.00 - is shown in the Table 1. Please note, that the difference between representative turbulence calculated using the time series data and the Gaussian model data increases when the frequency decreases (typically at very rare bins in the upper tail of the distribution).

## **References**

- [1] Misfeldt & Thøgersen, *Reliability Analysis of Wood Structures*, Aalborg University, 1997 (unpublished)
- [2] IEC 61400-1:1998 (2<sup>nd</sup> edition)
- [3] IEC 61400-1 (3<sup>rd</sup> edition)
- [4] DNV & Risø: *Guidelines for the Design of Wind Turbines*, Risø National Laboratory
- [5] DS472, Danish Code of Standards for Wind Turbine Structures
- [6] Armit, *Wind Structures*, Lecture Series, Von Karman Institute for Fluid Dynamics, 1976.
- [7] Dyrbye & Hansen, *Wind Loads on Structures*, John Wiley and Sons, 1996
- [8] Sheldon M. Ross: *Introduction to Probability and Statistics for Engineers and Scientists*, Wiley Series in Probability and Mathematical Statistics, John Wiley & Sons, 1987

## 7. Danish Recommendation – Turbulence Model

The Danish Recommendation [1] from 1992 specifies a quite simple wake added turbulence model. If the turbines are erected in a cluster with a minimum distance between the turbines of 5 times the rotor diameter – or in a row with the distance 3 times the rotor diameter – then a added turbulence intensity of  $I_{\text{park}} = 0.15$  can be used. An alternative is to use the a mean-contribution, which varies by the mean wind speed and the distance between the turbines:

$$I_{\text{park}} = \beta_v \cdot \beta_l \cdot 0.15 \quad (1)$$

where  $\beta_v$  is a parameter taking the mean wind speed into account (see the Figure 1)  
 $\beta_l$  is a parameter taking the distance between the turbines into account (Figure 2 and 3).

The  $\beta_l$  parameters are dependend on the geometrical configuration of the wind farm, i.e. if the wind farm is erected in a cluster (Figure 2 ) or in a row (Figure 3).

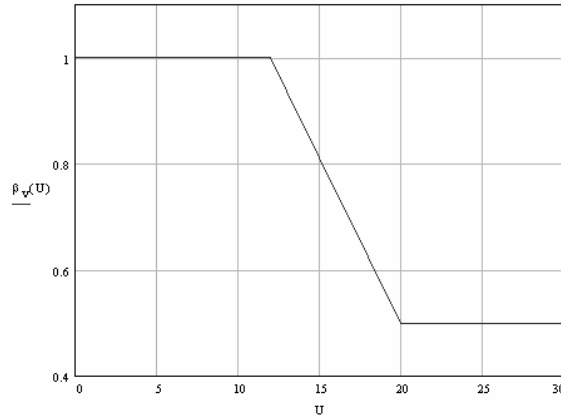


Figure 1: Factor taking wind velocity into account,  $\beta_v$ .

The  $\beta_l$  factor is determined from the Figures 2 and 3.

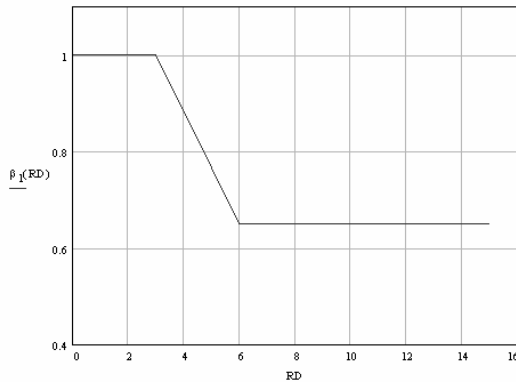


Figure 2:  $\beta_l$  for turbines in a row.

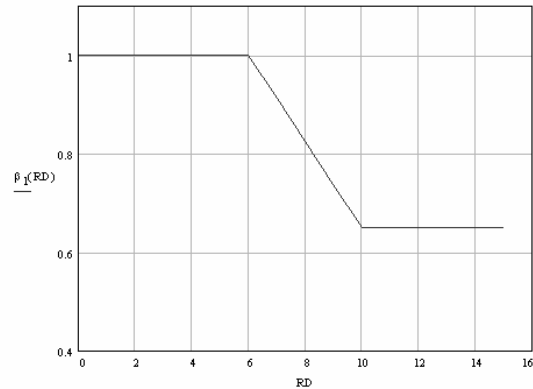


Figure 3:  $\beta_l$  for turbines in a cluster.

## **The Wake Added Turbulence**

The total turbulence intensity is calculated from

$$I_{total} = \sqrt{I_{ambient}^2 + I_{park}^2} \quad (2)$$

## **References**

[1] *Recommendation for the fulfillment of the requirements found in the technical criteria*, Danish Energy Agency, 1992

## 8. Turbulence Model – Frandsen & DIBt

S. Frandsen and M.L. Thøgersen [1] report an empirical turbulence model for calculating the integrated wake effect of turbines. This model takes into account the different structural fatigue responses of the structural materials considered, e.g. steel in the towers and hub extenders and glass fibre reinforced polyester (GRP) or glass fibre reinforced epoxy (GRE) in the blades. The equations below assume that the wind direction is approximately uniform distributed. Reference is made to Frandsen & Thøgersen [1] and Guidelines for the Design of Wind Turbines [2].

This model is included as a recommended model in the German DIBt Richtlinie [3].

### Determining the Total Turbulence Intensity

The total turbulence intensity is determined from:

$$I_{T,total} = \left[ (1 - N \cdot p_w) I_T^m + p_w \sum_{i=1}^N I_{T,w}^m(s_i) \right]^{1/m} \quad (1)$$

$$I_{T,w} = \sqrt{\frac{1}{[1.5 + 0.3 \cdot s_i \cdot \sqrt{v}]^2} + I_T^2} \quad (2)$$

where  $p_w = 0.06$  (probability of wake condition)

$s_i = x_i / RD$

$N$  is the number of closest neighboring wind turbines

$m$  is the Wöhler curve exponent of the considered material

$v$  is the free flow mean wind speed at hub height

$x_i$  is the distance to the  $i$ -th turbine

$RD$  is the rotor diameter

$I_T$  is the ambient turbulence intensity (free flow)

$I_{T,w}$  is the maximum turbulence intensity at hub height in the center of the wake

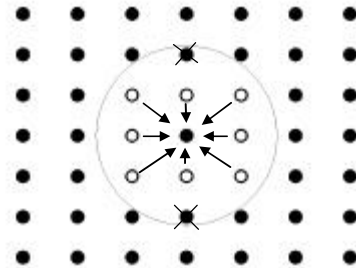
The number of closest neighboring turbines is determined as follows  
– see also the figure to the right.

$N=1$  : 2 wind turbines

$N=2$  : 1 row

$N=5$  : 2 rows

$N=8$  : Wind farms with more than two rows



### Increased Turbulence in Very Large Wind Farms

If the wind farm has more than five rows, the wind farm itself heavily influences the ambient wind climate. Also – if the distance between turbines in rows perpendicular to the predominant wind direction is less than 3 times the rotor diameter, an increase in mean turbulence level must be taken into account. This is done by substituting the ambient turbulence levels in (1) and (2) with the turbulence calculated from the equations (3) and (4).

$$I_T^* = 0.50 \cdot \sqrt{I_w^2 + I_T^2} + I_T \quad (3)$$

$$I_w = \frac{0.36}{1 + 0.08\sqrt{s_r s_f} v} \quad (4)$$

where  $s_r = x_r / RD$   
 $s_f = x_f / RD$   
 $s_r$  is the distance *within* the row  
 $s_f$  is the distance between rows

## References

- [1] S. Frandsen & M.L. Thøgersen, *Integrated Fatigue Loading for Wind Turbines in Wind Farms by Combining Ambient Turbulence and Wakes*, Wind Engineering, Volume 23, No. 6, 1999.
- [2] *Guidelines for Design of Wind Turbines*, DNV/Risø, Second edition.
- [3] Deutsches Institut für Bautechnik – DIBt, *Richtlinie für Windenergieanlagen, Einwirkungen und Standsicherheitsnachweise für Turm und Gründung*, Fassung März 2004.
- [4] S.T.Frandsen, *Turbulence and turbulence generated structural loading in wind turbine clusters*, Risø National Laboratory, January 2007.



## 9. Turbulence Model – D.C. Quarton & TNO Laboratory

A simple equation to determine the wake added turbulence has been proposed by D.C. Quarton and J.F. Ainslie [1]. The parameters in the equation have been re-calibrated by Quarton and Ainslie (the modified values) and also the Dutch TNO laboratory [2].

The main form of the equation is

$$I_{add} = K_I \cdot C_T^{\alpha_1} \cdot I_{amb}^{\alpha_2} \cdot (X / X_n)^{\alpha_3} \quad (1)$$

where  $K_I$  is a proportionality constant  
 $\alpha_1, \alpha_2, \alpha_3$  are exponents  
 $X$  is the downstream distance (in meters)  
 $X_n$  is a characteristic wake length (either denoted near wake or far wake)  
 $I_{amb}$  is the ambient turbulence

The near wake length ( $X_n$ ) is determined as described in the chapter dealing with the eddy viscosity wake model. In case of the TNO model, then the near wake length is replaced with a slightly different expression for the far wake length, see [2].

The proportionally constant and exponents are determined from the table below

Reference	$K_I$ -Constant	$\alpha_1$ -exponent	$\alpha_2$ -exponent	$\alpha_3$ -exponent
Quarton and Ainslie (original)	4.800	0.700	0.680	-0.570
Quarton and Ainslie (modified)	5.700	0.700	0.680	-0.960
Dutch TNO laboratory	1.310	0.700	0.680	-0.960

Note, that the ambient turbulence must be entered in percent (i.e. 10) when using the Quarton-Ainslie constants, while the TNO-constants are with ambient turbulence as decimal number (i.e. 0.10).

At the Figure 1 it is also easily seen, that the two models (Ainslie (modified) and TNO) actually are the same.

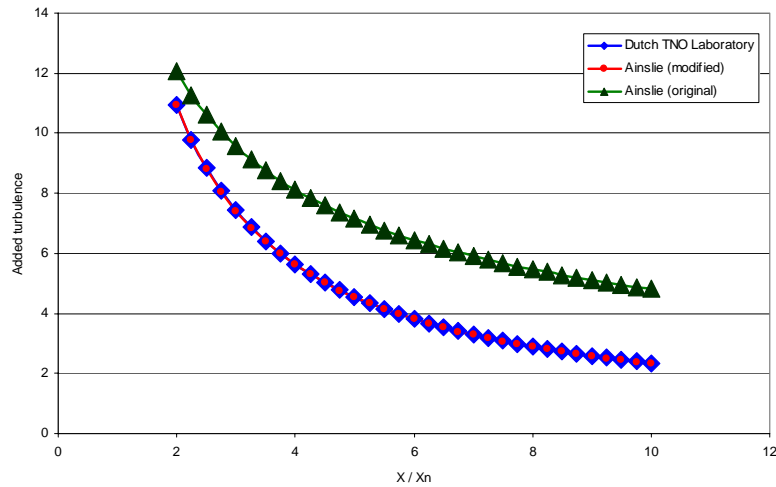


Figure 1: Wake Added Turbulence from the Three Models.

## References

- [1] Quarton and Ainslie, *Turbulence in Wind Turbine Wakes*, Wind Engineering Vol 14 No 1
- [2] *European Wind Turbine Standards II*, ECN-C--98-096, December 1998.

## 10. Turbulence Model – B. Lange

The B. Lange turbulence model can only be used with the eddy viscosity wake model, because the turbulence parameters are derived directly from the eddy viscosity.

### Turbulence within the Wake

The turbulence intensity,  $I_T$ , is defined as the standard deviation of the wind speed process divided by the mean wind speed, i.e.

$$I_T = \sigma_u / u_0$$

It is possible to relate the eddy viscosity to the turbulence intensity. According to Lange et al [1], the turbulence intensity within the wake can be calculated using the following relation below. Please note that the equation relates to the free wind speed,  $U_0$ :

$$I_T = \varepsilon \frac{2.4}{\kappa \cdot U_0 \cdot z_h}$$

### Alternative Empirical Approach

Another alternative empirical characterization of the wake turbulence was proposed by Quarton and Ainslie [2]. Their equation is based on a parameterization on the near wake length – which is primarily used in relation with the Eddy Viscosity model. They report, that the empirical turbulence decay is somewhat higher than other model predictions. The equation is:

$$I_{add} = 4.8 C_T^{0.7} I_{amb}^{0.68} [X / X_n]^{-0.57}$$

where  $I_{add}$  is the added turbulence intensity from the wind turbine wake  
 $I_{amb}$  is the ambient wind speed  
 $X$  is the downstream distance  
 $X_n$  is the near wake length

This alternative approach can also be used with other wake modes, as the near wake length is easily determined through empirical equations. For further details on the near wake length – please see the chapter on the Eddy viscosity wake model.

### References

- [1] Lange, Bernard; H.P. Waldl; A.G. Guerrero; D. Heinemann & R.J. Barthelmie: *Modelling of Offshore Wind Turbine Wakes with the Wind Farm Program FLaP*, Wind Energy, 2003 6:87-104.
- [2] Quarton & Ainslie: *Turbulence in Wind Turbine Wakes*, Wind Engineering, Volume 14, No. 1.

## **11. Turbulence Model – G.C. Larsen**

The G.C. Larsen is a simple empirical equation to determine the turbulence level within the wake. Reference is made to the paper '*Wind Field in Wakes*' [1] and the European Research Project – European Wind Turbine Standards - EWTS II [2].

### **Turbulence Intensity**

At positions downstream of the turbine, the wake added turbulence intensity can be determined from the equation:

$$I_w = 0.29S^{-1/3} \sqrt{1 - \sqrt{1 - C_T}} \quad (1)$$

where  $S$  is spacing expressed in rotor diameters  
 $C_T$  is the thrust coefficient

The expression for turbulence intensity is only valid for distances larger than two rotor diameters downstream.

### **References**

- [1] G.C.Larsen, J. Højstrup, H.A. Madsen, *Wind Fields in Wakes*, EUWEC '96, Gothenburg, 1996.
- [2] *European Wind Turbine Standards II*, ECN-C-99-073, 1999

## 12. User guide to wake modeling and turbulence calculation

The new wake models are operated from the PARK calculation exactly like previous versions of WindPRO. It is possible to operate the PARK calculation with exactly the same wake model as before. The new models offer alternatives to the standard N.O. Jensen model and provide the possibility to calculate the wake-induced turbulence in the wind farm. EMD recommends using the N.O. Jensen model as the standard model unless special needs require the use of the alternative models.

### PARK default settings

When the PARK calculation option is started WindPRO default settings applies. These make the calculation identical to previous versions of WindPRO (WindPRO 2.4 mode). The settings are as shown below.

The screenshot shows the WindPRO software interface with the following settings:

- Main** tab selected.
- Name:** As a new wind farm with local data
- Air density varies at WTGs (here: 395,0 m):** 1,199
- Hub height for key results:** 50,0 m
- Report:** Additionally to result also reduce energy with: 10 % (e.g. uncertainty and/or loss reduction)
- Calculate:**
  - ☒ Energy reductions due to wakes
  - ☐ Wake added turbulence
  - ☐ RIX (Ruggedness Index)
  - ☐ Reduced wind speeds inside wind farm
  - ☐ Park power curve based on PPV model
- Wake model:**
  - ☒ No model
  - ☒ N.O. Jensen (RISØ/EMD)
  - ☐ N.O. Jensen (EMD) : 2005
  - ☐ Eddy Viscosity Model (J.F. Ainslie) : 1986
  - ☐ EWTS II (G.C.Larsen) : 1999
- Turbulence model:**
  - ☒ No model (ambient turbulence only)
  - ☐ B.Lange: 2002 - Eddy viscosity turbulence
  - ☐ Danish Recommendation: 1992
  - ☐ G.C.Larsen / EWTS II : 1999
  - ☐ S. Frandsen: 1999 - Effective turbulence mod
  - ☐ Quarton/Ainslie: 1989 - Empirical turbulence
  - ☐ Empirical turbulence - Dutch TNO laboratory
- Sector wise Parameters:**
  - Terrain: User defined, Tt: 14,7 %, WDC: 0,075, sectors: 1.

The N.O. Jensen (RISØ/EMD) model is selected with a Wake Decay Constant of 0,075 uniformly for all sectors. This is the wake model used in WindPRO 2.4. It does not allow calculation of wake-induced turbulence, but it ensures that the PARK result is identical to earlier calculations.

The only options available are the Wake calculation settings and the Sector wise parameters.

The Wake calculation settings allow the user to modify the basic parameters of the wake calculation. They are common to the other models. The start, end and step of wind speed and angle are set to cover the full range at a reasonable level of detail and should preferably not be changed.

General calculation settings	
Description	Value
Start wind speed [m/s]	0,50
End wind speed [m/s]	30,50
Step in wind speed [m/s]	1,00
Start angle [deg]	0,5
End angle [deg]	360,0
Step in angle [deg]	1,0

Ok Cancel

The sector wise parameters are covered in a separate section.

## N.O. Jensen (EMD) : 2005

As described in theory this model is identical to the old N. O. Jensen model except that it allows the calculation of wake induced turbulence, reduced wind speeds inside wind farm and a park power curve based on the PPV model

Main | WTGs | Wind distribution | Description

Name: As a new wind farm with local data

Air density varies at WTGs (here: 395,0 m): 1,199 Edit/View ☒ Auto / Individual

Hub height for key results: 50,0 m 50 meters recommended

Report: Additionally to result also reduce energy with: 10 % (e.g. uncertainty and/or loss reduction)

Report: Label for reduced energy result: Result Label: Result-10,0%

Calculate: ☒ Energy reductions due to wakes

☐ Wake added turbulence

☐ RIX (Ruggedness Index)

☐ Reduced wind speeds inside wind farm

☐ Park power curve based on PPV model

Wake model

- ☐ No model
- ☐ N.O. Jensen (RISØ/EMD)
- ☒ N.O. Jensen (EMD) : 2005
- ☐ Eddy Viscosity Model (J.F. Ainslie) : 1986
- ☐ EWTS II (G.C.Larsen) : 1999

Turbulence model

- ☒ B.Lange: 2002 - Eddy viscosity turbulence
- ☐ Danish Recommendation: 1992
- ☐ G.C.Larsen / EWTS II : 1999
- ☐ S. Frandsen: 1999 - Effective turbulence model
- ☐ Quarton/Ainslie: 1989 - Empirical turbulence model
- ☒ Empirical turbulence - Dutch TNO laboratory : 2004
- ☐ DIBt: 2004 - Added Turbulence Model

Advanced model parameters Wake calculation settings Turbulence model parameters

Sector wise Parameters

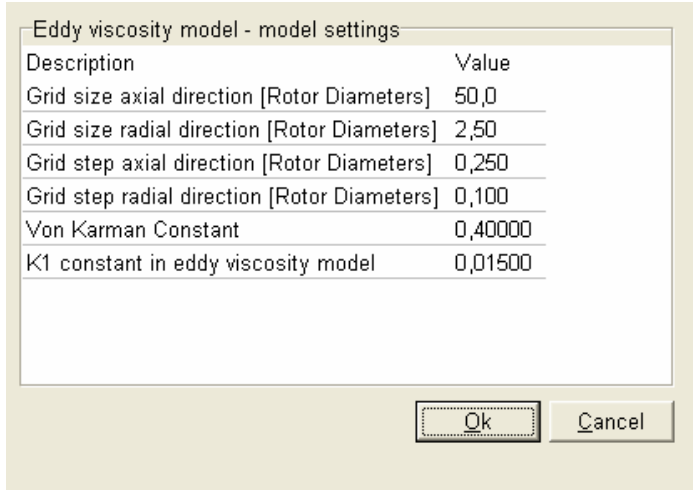
Terrain: User defined, TI: 14,7 %, WDC: 0,075, sectors: 1. Edit Edit WAsP parameters

Ok Cancel

EMD recommends using the Empirical turbulence – Dutch TNO laboratory turbulence model together with N. O. Jensen, but it can be combined with the others except for B. Lange: 2002.

## Eddy viscosity model

Selecting the eddy viscosity model by Ainslie 1986 enables the same options as N. O. Jensen except that it is now possible to use the B. Lange turbulence model and that a set of advanced model parameters can be selected.



Description	Value
Grid size axial direction [Rotor Diameters]	50,0
Grid size radial direction [Rotor Diameters]	2,50
Grid step axial direction [Rotor Diameters]	0,250
Grid step radial direction [Rotor Diameters]	0,100
Von Karman Constant	0,40000
K1 constant in eddy viscosity model	0,01500

Ok Cancel

The parameters have primarily to do with the grid size of the calculation. Smaller grid size means a slower calculation and since it is already a slow calculation we recommend that these be not reduced any further unless a special need requires this.

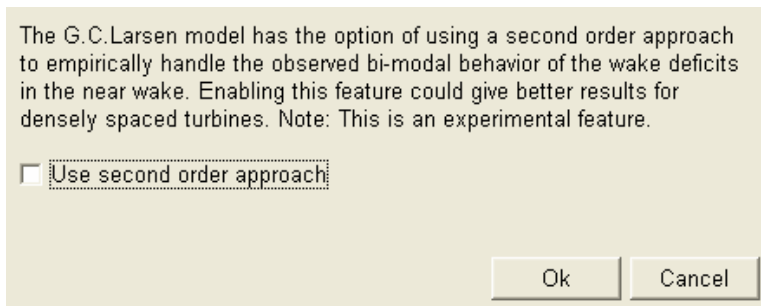
Von Karmans constant is a well-described constant and should not be changed.  
For the K1 constant please refer to the theoretical section.

## EWTS II

The EWTS II model allows the same turbulence options as the N. O. Jensen model but the recommended turbulence model is the G. C. Larsen/EWTS II model.

A special “Advanced model parameter” with this model gives the possibility to use a second order approach.

As it is an experimental feature it should be used with caution. Please refer to the theoretical section.



The G.C.Larsen model has the option of using a second order approach to empirically handle the observed bi-modal behavior of the wake deficits in the near wake. Enabling this feature could give better results for densely spaced turbines. Note: This is an experimental feature.

☐ Use second order approach

Ok Cancel

## Sector wise parameters

These are the parameters defining the ambient turbulence. As mentioned above the default setting will just give a uniform wake decay constant of 0,075 which is suited for most sites (see below).

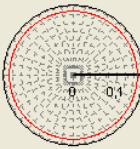
Grey columns are needed parameters for the selected wake model. Ambient turbulence is scaled in height according to description in the WindPRO manual.

Height for turbulence specification [m]


Number of wake sectors

From [deg]	To [deg]	Terrain type and class	Turbulence intensity	Roughness length [m]	Wake decay constant
-180	180	User defined	0,1468	0,055	0,075

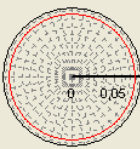
Turbulence Intensity



Roughness Length



Wake decay constant



Turbulence, roughness length and wake decay constant are all linked. The roughness length is (part of) what causes the turbulence and it is the turbulence that gives the wake decay constant.

These three parameters can be changed individually or set altogether by selecting a terrain type.

A more detailed definition of the ambient turbulence can be defined by adding sectors. The three circle diagrams on the right will then show the directional distribution of the turbulence, roughness and wake decay constant.

Another option is to load turbulence data from the Meteo object. This requires a meteo object with a time series of turbulence intensity (typically generated from standard deviations of 10-minute readings).

Pressing the “Load from Meteo Data” button opens a selection tool where the proper meteo object and height can be selected. The user can then select only to include turbulence for specific wind speeds or simply import turbulence for the full range of wind speeds. If more wind speeds are selected WindPRO will make an average of the turbulence intensity to calculate the appropriate roughness lengths and wake decay constants.

With Ok the data are loaded and presented as shown below.




Grey columns are needed parameters for the selected wake model. Ambient turbulence is scaled in height according to description in the WindPRO manual.

Height for turbulence specification [m]

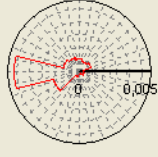
Number of wake sectors

From [deg]	To [deg]	Terrain type and class	Turbulence intensity	Roughness length [m]	Wake decay constant
-15	15	User defined	0,0925	0,001	0,0444
15	45	User defined	0,0908	0,0008	0,0434
45	75	User defined	0,0923	0,001	0,0443
75	105	User defined	0,0828	0,0003	0,0405
105	135	User defined	0,0849	0,0004	0,041
135	165	User defined	0,0748	0,0002	0,04
165	195	User defined	0,0709	0,0002	0,04
195	225	User defined	0,0856	0,0004	0,0412
225	255	User defined	0,0995	0,0022	0,0507
255	285	User defined	0,1091	0,0052	0,0531
285	315	User defined	0,0949	0,0013	0,0462
315	345	User defined	0,0938	0,0012	0,0453

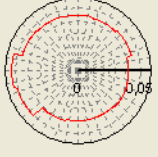
Turbulence Intensity



Roughness Length



Wake decay constant



The window also has a calculator that can be used to calculate the turbulence intensity based on the surface roughness.

**Ambient turbulence estimation**

The relation between the turbulence and surface roughness can - in the case of homogeneous terrain - be derived from boundary layer theory. Note that the relation is a very rough idealization of the true stochastic nature of turbulence. Experiments have shown that the value of A varies between 1.8 and 2.5. The von Karman constant has the value of 0.4.

$$I_T = \frac{E[\sigma_u]}{U_{10}} = A_x \kappa \left[ \frac{1}{\ln[z/z_0]} \right]$$

Ax:

kappa:

z:

z0:

Result:

With this tool it is possible to calculate “manually” the relation between roughness length and turbulence intensity. Please note that the parameter A is an empirical size, which is not exact.

## The turbulence models

The turbulence models are described in detail in the theoretical section. The operation of them in WindPRO is almost identical, the only difference is some special parameter settings that some of them facilitates and the time it takes to calculate them. The choice of model does not influence the format of the printout beyond the result they provide and the mentioning of the model and parameters used.

The following is a summary of the possible parameter settings.

## B. Lange

There are no special parameters for this model. The input data comes from the Eddy viscosity wake model.

## Danish Recommendation

The options available for this model are shown below. Please refer to the theoretical section for an explanation of the parameters.

Model settings

☐ Use constant added turbulence (do not take row configuration into account)

☐ Turbines are in a row configuration

☒ Turbines are in a gridded (cluster) configuration

Ok Cancel

## G. C. Larsen / EWTS II

There are no special options for this model.

## S. Frandsen, 1999

For this model there are a number of options. These are all explained in the theoretical part. A special feature is the geometrical section. WindPRO should in normal cases be able to figure this out by it self, but with random layout wind farms, this may not be done correctly.

Wöhler curve data and wake probability

Wöhler curve exponent

The effective turbulence model is a design turbulence model, taking into account the structural fatigue resistance of the material considered. Typical values of the Wöhler curve exponent (fatigue property) are: Steel=3, Glass Fibre Reinforced Polyester = 9 (GRP), Glass Fibre Reinforced Epoxy = 12 (GRE).

Wake probability  (0.06 is recommended)

Very large wind farm (increased ambient turbulence)

☐ Large wind farms: Increased ambient turbulence

The model may take an increased ambient turbulence level into account, if the site has many turbines. The effective turbulence model suggest that increased turbulence should be taken into account if there are more than five rows of turbines with more than five turbines in each row.

Geometry settings

☒ WindPRO calculates geometric settings in model

Neighbor turbines

Distance between wind turbines within a row [m]

Distance between wind turbine rows [m]

WindPRO may calculate the number of neighboring turbines. However, when the wind farm has complex geometry, this estimation may fail. Alternative, you may manually specify the number of neighboring turbines (model parameter <= 8).

Cancel Ok

## Quarton / Ainslie

For this model there are two suggestions for the parameter setting including the option to user-define them. These options and the parameters are explained in the theoretical section.

Model: Empirical wake added turbulence model proposed by Quarton and Ainslie  
Reference: D.C.Quarton and J.F. Ainslie: Turbulence in Wind Turbine Wakes, Wind Engineering - Vol. 14 - No. 1 - pp. 15-23

Description	Value
Global proportional constant (default 4.80)	4,800
Ct exponent (default 0.70)	0,700
lamb exponent (default 0.68)	0,680
Distance ratio exponent (default -0.57)	-0,570

Original constants (table read-only) Ok Cancel

With the lower menu box it is possible to change between parameter settings.

## Empirical turbulence – Dutch TNO laboratory.

Here the following parameters are available. They are explained in theory.

Model: Empirical added turbulence model proposed by the Dutch TNO laboratory  
Reference: European Wind Turbine Standards II, ECN-C--99-073, 1999

Description	Value
Global proportional constant (default 1.31)	1,310
Ct exponent (default 0.70)	0,700
lamb exponent (default 0.68)	0,680
Distance ratio exponent (default -0.96)	-0,960

Ok Cancel

## DIBt 2004

The parameters available for this German standard are identical to the Sten Frandsen model.

## Wake added turbulence

The Wake added turbulence calculation is included in the PARK calculation if the check box with the same name is hatched in the Main tab sheet of the PARK calculation.

The calculation will result in a report page for the entire wind farm and a sheet for each of the turbines.

The common page gives the general calculation parameters and the below table which presents the maximum turbine intensity at 15 m/s and the associated wind direction. This turbulence intensity is a combination of the ambient turbulence and the wake induced turbulence.

Free Wsp: 15,0 m/s							
Manufact.	Type	Power [kW]	Diam. [m]	Height [m]	Dir [deg]	W/sp [m/s]	It [%]
1	VESTAS	V39	600	39,0	40,5	277	15,0 13,1
2	VESTAS	V39	600	39,0	40,5	261	15,0 13,1
3	VESTAS	V39	600	39,0	40,5	258	15,0 13,1
4	VESTAS	V39	600	39,0	40,5	309	15,0 11,9
5	VESTAS	V39	600	39,0	40,5	283	15,0 12,4
6	VESTAS	V47	660	47,0	40,0	308	15,0 11,8
7	VESTAS	V47	660	47,0	40,0	255	15,0 11,3
8	VESTAS	V47	660	47,0	40,0	255	15,0 11,3

For the individual turbine pages the page can be designed from the Report setup window to contain a number of different results.

The screenshot shows the 'Reports' and 'Pages' sections on the left, and the 'Turbulence' section on the right. The 'Reports' section lists various report components with checkboxes and page numbers. The 'Pages' section shows the page numbers for each component. The 'Turbulence' section has three sub-sections: 'Include these wind speeds in the report', 'Include these graphs in the report', and 'Wind Speed Reduction: Graph type'.

Reports	Pages
<input checked="" type="checkbox"/> Main Result	1
<input type="checkbox"/> Reference WTGs	(1)
<input checked="" type="checkbox"/> Production Analysis	2
<input checked="" type="checkbox"/> Power Curve Analysis	1
<input checked="" type="checkbox"/> Terrain	1
<input checked="" type="checkbox"/> Wind Data Analysis	1
<input checked="" type="checkbox"/> Park power curve	1
<input checked="" type="checkbox"/> WTG distances	1
<input checked="" type="checkbox"/> WTG Turbulence: Main Result	1
<input checked="" type="checkbox"/> WTG Turbulence: Main Result	1
<input checked="" type="checkbox"/> Map	1
	11

Result to file:

Report language:

☐ Use for all calculations

☐ Use selected as default

☐ Clear default

**Turbulence**

Include these wind speeds in the report

- ☐ 0,5 m/s
- ☐ 1 m/s
- ☐ 1,5 m/s
- ☐ 2 m/s
- ☐ 2,5 m/s
- ☐ 3 m/s
- ☐ 3,5 m/s
- ☐ 4 m/s
- ☐ 4,5 m/s
- ☐ 5 m/s

Include these graphs in the report

- ☐ Maximal ambient turbulence intensity
- ☒ Mean ambient turbulence intensity
- ☒ Maximal total turbulence intensity
- ☒ Mean total turbulence intensity
- ☒ IEC 61400-1:1999 turbulence classes A+B

Wind Speed Reduction: Graph type

- ☒ Show as wind rose (at mean wind speed)
- ☐ Show as polar line graph (at winds chosen above)

The turbulence can be calculated for a number of different wind speeds where 15 m/s is the default selection.

Then the graphs and tables can show mean and/or maximal ambient and/or total turbulence. Also the requirements for IEC 61400-1 turbulence classes can be included and thus compared to the calculated turbulence.

Finally the wind speed reduction can be shown as either a wind rose or as polar line graphs.

The wind speed, turbulence, A and k parameters are presented for each direction on the report page as shown below. The turbulence data is presented also in the form of a diagram. The maximum turbulence,

average direction weighted turbulence and the average ambient turbulence is compared to the IEC 61400-1 codes

WindPRO version 2.5.0.60 Dec 2005

**Project:**

**Cronalaght demonstration - Energy calculation**

**Description:**

This project primarily illustrates how to calculate energy production, based on either EU-Wind Atlas data, or on local measurements. Also ATLAS contra WASP is illustrated, as well as the powerful VISUAL module for exact positioning of the WTGs, metering masts etc.

**Printed/Page:**

13-12-2005 15:21 / 10

**Licensed user:**

**EMD International A/S**  
Niels Jernesvej 10  
DK-9220 Aalborg Ø  
+45 9635 4444  
Thomas Sørensen  
Calculated:  
13-12-2005 14:58/2.5.0.60

**PARK - WTG Turbulence: Main Result for One WTG**  
**Calculation:** As a new wind farm with local data **WTG:** 1 - VESTAS V39 600 39.0 I/OI Manufacturer 05-03-2000 1.225 30.00 0.00, Hub height: 40.5 m

**Turbulence Model**  
DIBT 2004 - Added Turbulence Model

**Wake Model**  
N.O. Jensen (EMD) : 2005

**Calculation Settings**

Air density calculation mode	Individual per WTG
Result for WTG at hub altitude	1,200 kg/m <sup>3</sup> to 1,207 kg/m <sup>3</sup>
Hub altitude above sea level (asl)	327,6 m to 385,4 m
Annual mean temperature at hub alt.	7,6 °C to 8,0 °C
Pressure at WTGs	967,0 hPa to 973,8 hPa
Wind speed: start - end	0,50 m/s - 30,50 m/s
Step in wind speed	0,50 m/s
Angle: start - end	0,50° - 360,00°
Step in angle	1,00°
Turbulence measure-height	50,00 m
Ambient turbulence level	7,1 % - 10,9 %
Number of WTGs	8

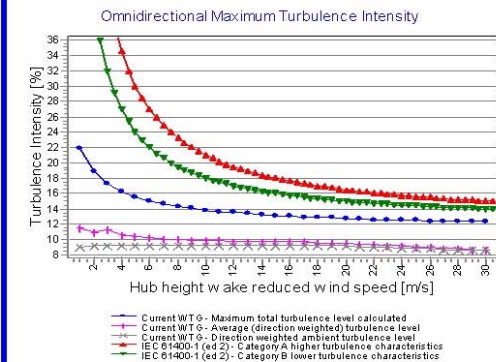
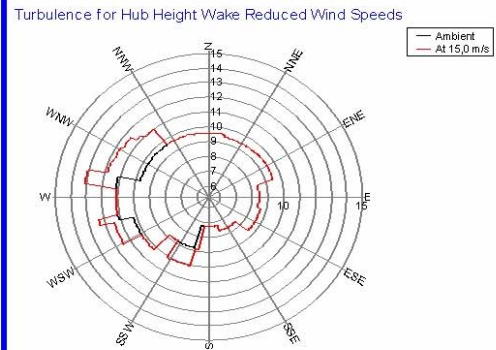
Scale 1:21,000

New WTG Site Data

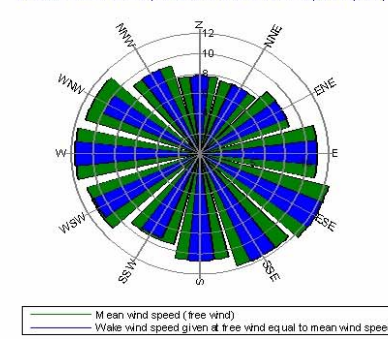
**Wind and Turbulence at Hub Height 40,50 m**

Weibull Wind Distribution					Max. Turbulence Given at WTG WS		
Sector	A	Mean	k	Freq. [%]	Ambient [%]	15,0 m/s [%]	
0 N	8,74	7,75	2,471	4,7	9,6	9,6	
1 NNE	8,46	7,50	2,428	4,8	9,4	9,5	
2 ENE	9,88	8,76	2,447	4,9	9,5	9,5	
3 E	12,31	10,80	2,135	6,4	8,5	8,6	
4 ESE	13,95	12,38	1,908	12,6	8,6	8,6	
5 SSE	13,17	11,66	2,123	8,8	7,6	7,6	
6 S	11,98	10,61	2,338	8,1	7,3	10,1	
7 SSW	10,55	9,37	2,557	9,9	8,8	10,2	
8 WSW	12,38	10,98	2,533	11,0	10,2	12,4	
9 W	13,03	11,57	2,521	11,5	11,1	13,1	
10 WNW	12,65	11,21	2,205	10,9	9,7	11,9	
11 NNW	10,35	9,16	2,123	6,1	9,7	11,0	
All	11,94	10,58	2,104	100,0	11,1	13,1	

The turbulence calculated is reported as total turbulence levels, i.e. the sum of assumed ambient turbulence at hub height and calculated wake turbulence at hub height. The ambient turbulence data is given at a certain h.a.g.l. - then recalculated to hub height. Please note, that the ambient turbulence level is assumed independent of the wind speed level - but dependent on the wind direction.



Undisturbed Wind Speed and Wake Wind Speed (m/s)



## Reduced wind speeds inside wind farm

Checking the check box of the same name include the “Reduced wind speeds inside wind farm” calculation.

The only option to choose from the report setup page is the free wind speed at which the wind speed reductions should be calculated.

The report page is shown below and illustrates the wind speed reductions as vectors giving the direction for maximum wind speed reduction and the magnitude of this reduction.

The wind speed reductions can also be printed to a text file or copied to clipboard from the report setup. This is done through this window.

The screenshot shows a software window with a light beige background. It contains two columns of checkboxes for selecting parameters. The first column is titled "Wind speed [m/s]" and lists values from 0,5 to 3,5. The second column is titled "Angle (Clock wise from north) [°]" and lists values from 0,50 to 7,50. Below these columns is a section titled "WTGs" with a list of turbine IDs: 9850, 9852, 9853, 9851, 9854, 11054, 11055, and 11056. At the bottom of the window are three buttons: "Copy to clipboard", "Select all", and "Close".

Wind speed [m/s]	Angle (Clock wise from north) [°]
<input type="checkbox"/> 0,5	<input type="checkbox"/> 0,50
<input type="checkbox"/> 1,0	<input type="checkbox"/> 1,50
<input type="checkbox"/> 1,5	<input type="checkbox"/> 2,50
<input type="checkbox"/> 2,0	<input type="checkbox"/> 3,50
<input type="checkbox"/> 2,5	<input type="checkbox"/> 4,50
<input type="checkbox"/> 3,0	<input type="checkbox"/> 5,50
<input type="checkbox"/> 3,5	<input type="checkbox"/> 6,50
<input type="checkbox"/> 4,0	<input type="checkbox"/> 7,50

WTGs

- ☐ 9850
- ☐ 9852
- ☐ 9853
- ☐ 9851
- ☐ 9854
- ☐ 11054
- ☐ 11055
- ☐ 11056

Copy to clipboard    Select all    Close

In this way the wind speed reduction can be analyzed for particular wind speeds wind directions and turbines.

Project:

**Cronalaght demonstration - Energy calculation**

Description:

This project primarily illustrates how to calculate energy production, based on either EU-Wind Atlas data, or on local measurements. Also ATLAS contra WASP is illustrated, as well as the powerful VISUAL module for exact positioning of the WTGs, metering masts etc.

Printed/Page

13-12-2005 15:41 / 1

Licensed user:

**EMD International A/S**

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DK-9220 Aalborg Ø

+45 9635 4444

Thomas Sørensen

Calculated:

13-12-2005 15:33/2.5.0.60

## PARK - Wind Speeds Inside Wind Farm: Main Result

Calculation: As a new wind farm with local data

### Wake Model

N.O. Jensen (EMD) : 2005

#### Calculation Settings

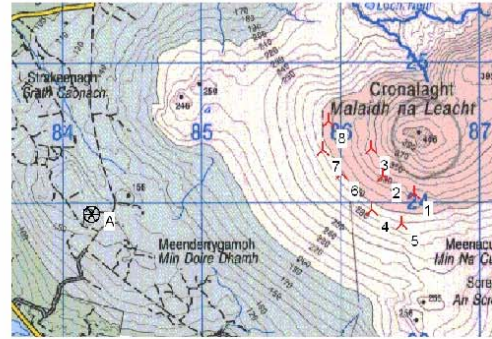
Air density calculation mode Individual per WTG  
Result for WTG at hub altitude 1,200 kg/m<sup>3</sup> to 1,207 kg/m<sup>3</sup>  
Hub altitude above sea level (asl) 327,8 m to 385,4 m  
Annual mean temperature at hub alt. 7,6 °C to 8,0 °C  
Pressure at WTGs 967,0 hPa to 973,8 hPa

#### Wake Model Parameters

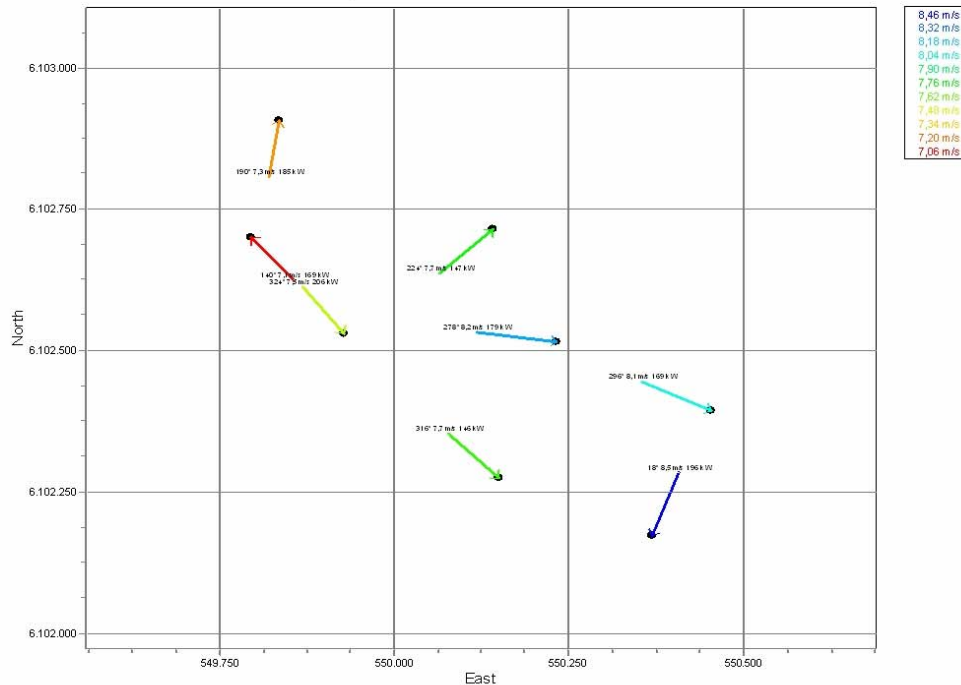
From angle [°] 345,0 15,0 45,0 75,0 105,0 135,0 165,0 195,0 225,0 255,0 285,0 315,0 Other  
To angle [°] 15,0 45,0 75,0 105,0 135,0 165,0 195,0 225,0 255,0 285,0 315,0 345,0  
Wake Decay Constant 0,044 0,045 0,044 0,040 0,041 0,040 0,040 0,041 0,051 0,053 0,046 0,045 0,040

#### Wind statistics

IE 30,0 m Cronalaght met mast.vvws



Free Wind Speed: 10,0 m/s  
Maximum Reduced Wind Speed Inside Wind Farm and the Concurrent Direction





## Park power curve based on PPV model

The Park Performance Verification model is a way to verify the performance of a wind farm by comparing it with concurrent measurements at a nearby meteorological station.

The PPV model establishes the connection there is between wind speed and wind direction at the mast with production output of the wind farm. The result of the PPV calculation is a table like below with production as function of speed and direction

Wind speed [m/s]	Park WTG: N [kW]	NNE [kW]	ENE [kW]	E [kW]	ESE [kW]	SSE [kW]	S [kW]	SSW [kW]
0,5	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
1,5	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
2,5	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
3,5	8	25	9	0	0	4	25	6
4	65	104	57	14	31	108	113	63
4,5	185	231	154	94	183	268	271	158
5	348	408	308	244	353	457	457	319
5,5	541	621	486	411	548	676	681	507
6	760	864	687	598	766	929	934	722
6,5	1.015	1.138	928	816	1.022	1.223	1.227	966
7	1.298	1.439	1.192	1.057	1.304	1.557	1.557	1.238
7,5	1.616	1.773	1.487	1.328	1.627	1.926	1.922	1.546
8	1.959	2.127	1.805	1.627	1.973	2.321	2.315	1.878
8,5	2.318	2.485	2.141	1.950	2.342	2.728	2.715	2.224
9	2.683	2.843	2.484	2.290	2.720	3.134	3.114	2.582
9,5	3.049	3.196	2.830	2.642	3.100	3.527	3.492	2.942
10	3.399	3.514	3.166	2.992	3.468	3.882	3.840	3.292
10,5	3.722	3.814	3.483	3.334	3.805	4.185	4.135	3.617
11	4.008	4.069	3.769	3.654	4.106	4.430	4.385	3.907
11,5	4.249	4.289	4.024	3.948	4.347	4.616	4.575	4.158
12	4.446	4.465	4.242	4.195	4.544	4.749	4.720	4.362

In order to make a PPV model in WindPRO there must be a site data object for WasP calculation on the location of the meteo mast. It is not necessary that this site data object hold a relevant wind statistic as the site data object for the PARK calculation will be used.

The site data object and the hub height is chosen in the PARK calculation set up (below)

The result is obtained through “Result to file” in the Report setup where “Park power curve” is chosen.

## Annex A: Case Study – Horns Rev Offshore Wind Farm

This annex is mainly based on a paper presented at the EWEA 2006 conference in Athens, Greece.

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### Recalibrating Wind Turbine Wake Model Parameters

#### – Validating the Wake Model Performance for Large Offshore Wind Farms

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#### Summary

As part of the Danish PSO sponsored project '*The Necessary Distance between Large Wind Farms at Sea*' EMD International A/S has implemented a number of wake models in the WindPRO software. In this paper we report the preliminary results of a case study on Horns Rev offshore wind farm, where the actual observed wake losses are compared with calculations using the implemented wake models. The wake loss can be analyzed by sector and wind speed, which in the future allow for improved parameterization of the models. This case study indicated that the traditional N.O. Jensen wake model is more precise at predicting the observed wake loss than the other tested wake models, at least when the current default parameters are used.

#### Introduction

The aim of the analysis is to verify/improve existing wind turbine wake models through model parameter adjustments, so that they can be utilized in large offshore wind farms. The analysis includes parameter sensitivity studies on three different wake models, the N.O. Jensen model [1], the Ainslie model (Eddy Viscosity) [2] and the G.C.Larsen model (Prandtl BL-equations) [3]. The performance of each of the models is compared to data based on the performance of offshore wind farms. The focus of the analysis is – primarily – to predict energy output for the wind farm as well as for single wind turbines in the farm. The secondary objective is to predict the mean wind speeds and turbulence in the wakes.

#### Motivation

Most wind turbine wake models - used in wind farm evaluations today - are based on the single wake flow downstream of a wind turbine. The flow from each of the single wakes is then added into a combined effect – using a simple empiric combination model. This model is normally a 'quadratic wind speed-deficit model'. In connection to the Danish research project, '*The Necessary Distance between Large Wind Farms at Sea*', EMD has implemented two alternative wake models as alternative to the widely used N.O. Jensen model [4]. All three wake models can be used for energy calculations, mean wind field calculations and with turbulence-calculations. The models are varying in complexity from a simple empiric engineering model to an axi-symmetric CFD-model. All the models still lack a structured validation and calibration for use on large offshore farms, just as the used wake combination model is not necessarily applicable for this purpose.

#### Current Progress (February 2005)

A preliminary wake study has been completed for one offshore site and a number of other wind farms are being prepared for study. Model parameters have through previous studies and literature been suggested and these are tested against this first case. The study will proceed with parameter adjustments on this first site and other wind farms in order to align these models to a correct prediction.

#### Expected results

The offshore measurements at the demonstration wind farms located in Danish waters contain a powerful potential for improving the existing wake models. The use of validated wake models gives a high degree of certainty for project developers running analyzes on large offshore wind farms. As the project is based on re-calibration of offshore specific

parameters for existing and already validated models the results will - on a fairly short term - be able to improve the estimates and decrease the uncertainties for these models.

### The project

The project has partly been funded by a grant from the Danish public service obligation (PSO) R&D program. The project runs from primo 2005 to ultimo 2006.

### Test case Horns Rev.

The Horns Rev offshore wind farm was erected end 2002 and consist of 80 Vestas V80-2.0MW wind turbines. The wind farm is located 13 km from the west coast and the turbines are placed with a spacing of 7 rotor diameters. The first years of operation the turbines were suffering from poor availability, but this have been improved and for 2005 the availability was 95% according to the operator (Elsam) [5].

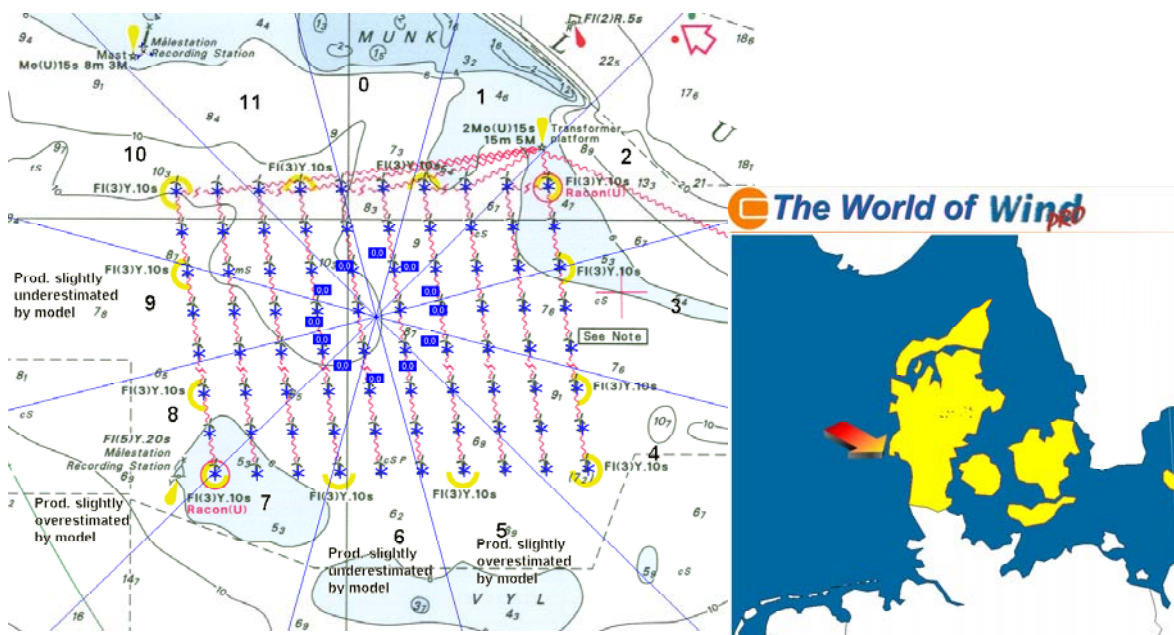


Figure 1. Map of the Horns Rev wind farm with sector numbering, showing the 12 direction sectors in which data are grouped in the analyses.

### Measured wake loss.

The operator Elsam has (through Elsam Engineering) developed a SCADAVIEW system [5] that is able to produce the deficiency in production for the wind farm compared to a free standing turbine as a function of wind speed and wind direction. The free standing turbine is the corner turbine which is most exposed to the wind direction in question. In so far as that turbine is operating correctly this system provides measurements of actual wake losses.

### Test environment.

EMD has created a test system where the measured wake loss can be compared to the calculated wake loss. Park production calculations are run in WindPRO with the model and parameter settings wanted and the result is exported as a Park power curve (PPC). The PPC tells what the cumulative effective power curve has been for the wind farm as a whole. The difference from a simple multiplication of the power curve with the number of turbines and the PPC is the wake loss. In this way measured and calculated wake loss can be compared as a function of wind speed and direction. In addition by employing a representative Weibull distribution these individual wake losses can be converted to the combined wake loss. The total measured park efficiency is 87,6%, which corresponds to a wake loss of 12,4%.

### Preliminary test runs

The wake models mentioned in the introduction and further described in the WindPRO manual [4] have been tested in this environment with a few tests of different parameter settings. The test settings were:

N.O. Jensen (old) [1]: This is the standard model used in previous versions of WindPRO and by WAsP's Park model. The only parameter which can be adjusted is the Wake Decay Constant (WDC), which has been tested for WDC = 0.04 and 0.075, which are recommended settings for offshore and onshore conditions respectively.

N.O. Jensen (2005): This is a modification of the old N.O. Jensen model to accommodate a new system for addition of wakes and includes optionally wake induced turbulence calculation [4]. Only WDC = 0,04 is tested.

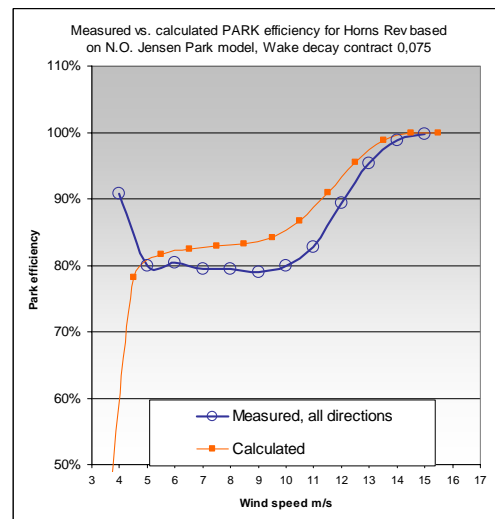
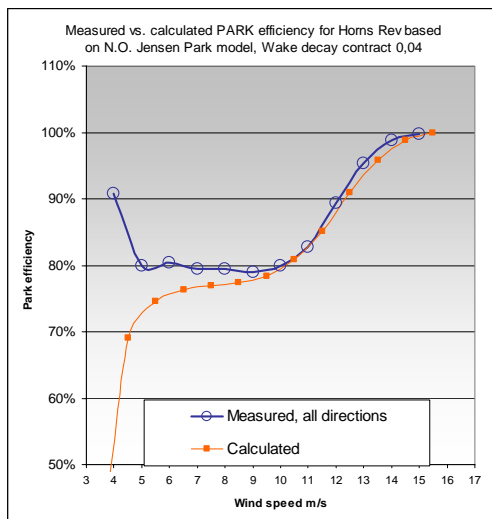
EWTS II (1999): This is a new model in WindPRO suggested by G.C.Larsen (1999) [3]. WDC = 0,04 is tested. Standard parameters as described in the WindPRO manual are used for a first order calculation.

Eddy Viscosity model (1986): This model was suggested by J.F. Ainslie (1986) [2] and is new in WindPRO. This one has several parameters to adjust. In this test standard settings for WindPRO as described in the manual are used except for the constant K1, which is tested for the values 0,015 (standard) and 0,025.

As a special test suggested by some researchers the roughness inside the wind farm has been increased to  $z_0=0,05\text{m}$  to reflect the roughness change induced by the wind farm itself.

### Results

As the below figures show, the N.O. Jensen with offshore WDC = 0.04 is the most accurate model to predict the wake losses. The old version is slightly tighter to the measured values than the new version (N.O.Jensen 2005 as implemented in WindPRO 2.5 in addition to the old to make Wake turbulence calculation optional). Increasing the WDC to 0,075 seems to be a poor idea. Both EWTS II and the Eddy Viscosity model seem to under predict the wake loss and therefore over predict the production.



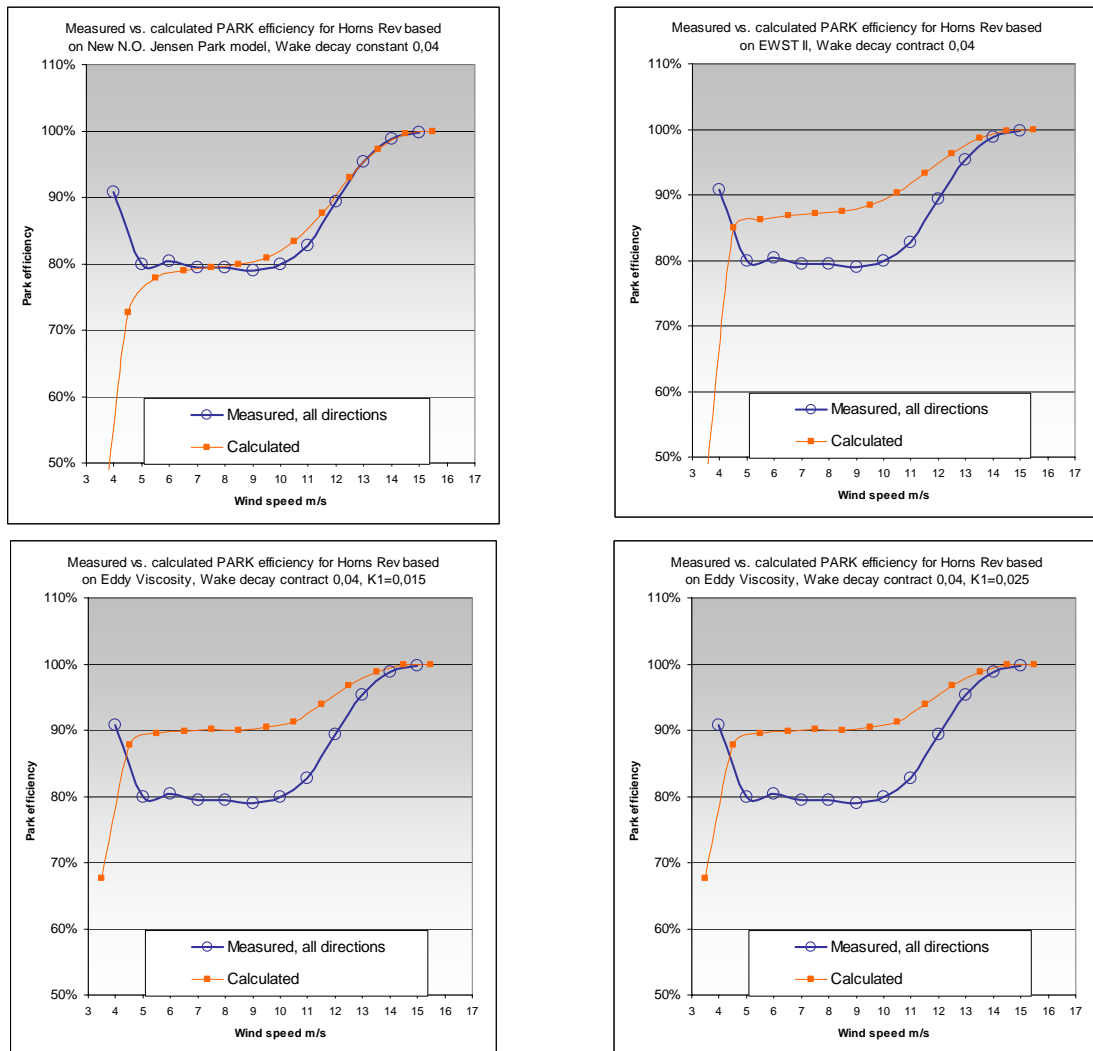


Figure 2. Preliminary tests of four available methods with standard conditions or limited parameter variation. The graphs plot the measured and calculated park efficiency for all sectors as a function of wind speed.

Even for the best predicting model there is variation as to how well each direction is predicted. Below are shown two examples of a good and less good prediction at two different sectors.

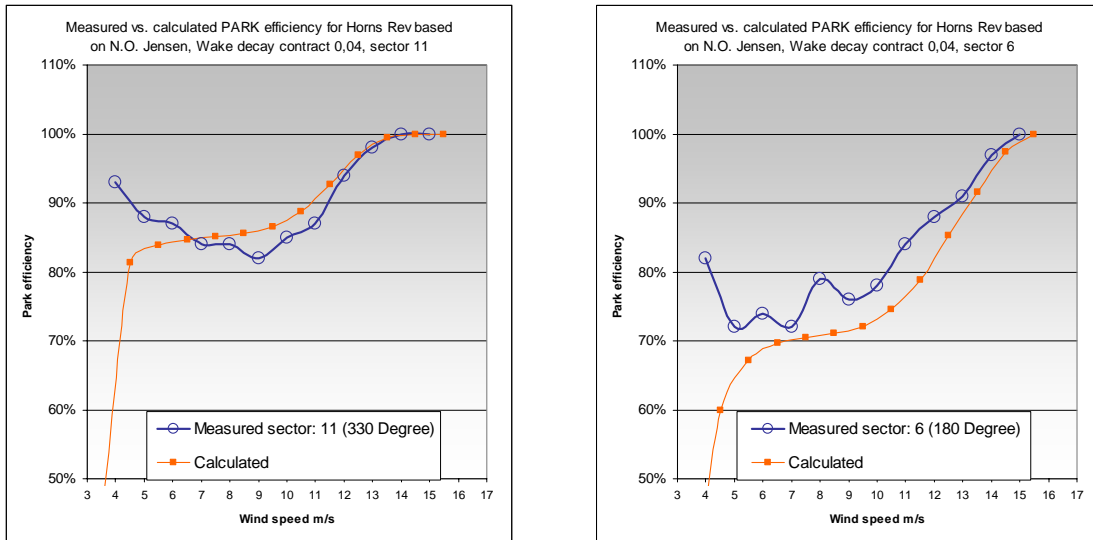


Figure 3. Even though the total fit between measured and calculated park efficiency of the old N.O. Jensen model is good, the individual sector fits can be less accurate as the two examples above illustrate.

The total difference in measured and calculated wake losses is illustrated in figure 4. Negative values are due to models that under predict the wake loss and therefore calculate too high a production. It is clear that the old N.O. Jensen for this case seems superior as long as a reasonable WDC is used.

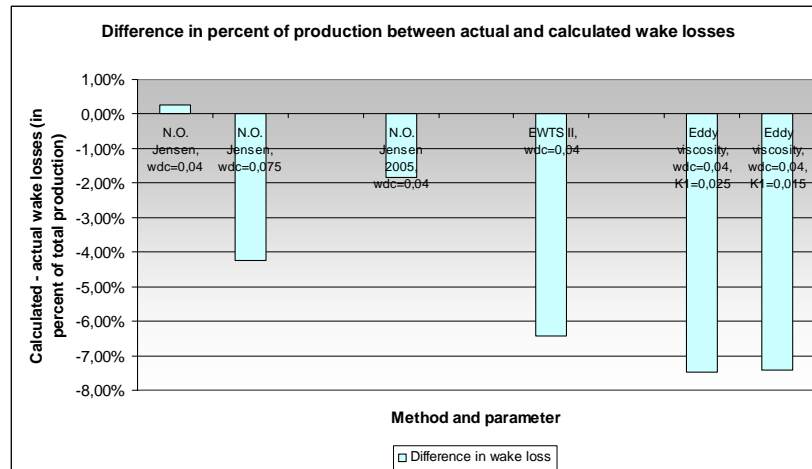


Figure 4. The ability of the models to accurately predict the measured wake loss is illustrated by this figure. A negative value of e.g. 2% means that the calculation model calculate the wake loss 2% of total production less than actually observed and therefore total production 2% higher. Most of the models under predict the wake loss, except for the old standard N.O. Jensen model that apparently is able to accurately predict the wake losses.

If an internal roughness of 0,05m is introduced inside the wind farm, the wake losses remain the same but since the base calculated production is reduced the wake loss deficit can be attenuated. This is illustrated in figure 5, which apparently

improves the performance of the poorly performing EWTs II and eddy Viscosity, but offsets the otherwise well performing N.O. Jensen model. While an internal roughness seems to be a good idea at other locations it is apparently not appropriate on this location.

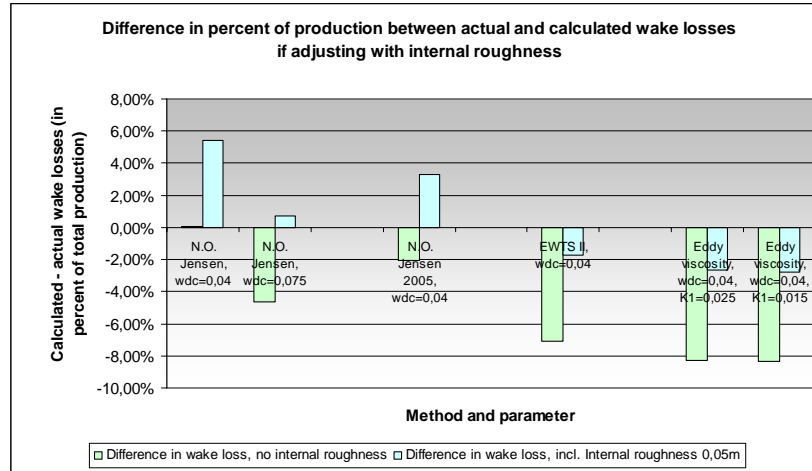


Figure 5. Introducing an internal roughness area of  $z_0=0,05\text{m}$  inside the wind farm lower production and can thus compensate for the lack of predicted wake loss. However for well predicting models like N.O. Jensen this does not necessarily improve the prediction.

## Conclusion

The N.O.Jensen model with  $WDC=0.04$  seem to predict the measured array losses for the Horns Rev wind farm very accurate. Other models under predict losses typically around 6 to 8% of total production and thereby overestimate production. For other large wind farms tested, but not reported in this paper, it seems that even the most conservative of the models, the old N.O.Jensen, under predict array losses. The reason for correct prediction of Horns Rev might be the very open offshore location with high mean wind speed and real open sea stability conditions.

## Future work

The plan is to set up a few other cases in order to be able to calibrate the different models and define the proper procedures and parameters choice for the models used.

## References

- [1] Katić, Højstrup J, & Jensen N.O. A Simple Model for Cluster Efficiency, *European Wind Energy Association, Conference and Exhibition*, 7-9 October 1986, Rome, Italy.
- [2] Ainslie, J.F: Calculating the flowfield in the wake of wind turbines, *Journal of Wind Engineering and Industrial Aerodynamics* 1988, **27**: 213-224.
- [3] Larsen G.C, Højstrup J, Madsen HA. Wind Fields in Wakes, *EUWEC '96*, Gothenburg, 1996.
- [4] Nielsen P, et.al., *The WindPRO manual edition 2.5*, EMD International A/S, 2006.
- [5] Leo E. Jensen, Personal communication on the SCADA results from Horns Rev Wind farm, Elsam Engineering 2006.

## **Annex B: Case Study – Wake Added Turbulence at Nørrekær Enge**

This annex is mainly based on a paper presented at the EWEA 2006 conference in Athens, Greece.

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### **Evaluating Models for Wind Turbine Wake Added Turbulence – Sensitivity Study of the Models and Case Study**

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### **Summary**

A range of turbulence models for wake added turbulence has been implemented in the WindPRO software. These models have been parameterized according to recommendations from the researchers who published or revised the models or the guidelines from which the model originate. The authors of this paper are in the process of validating these turbulence models by use of case studies. This paper presents the preliminary results from one such case study: The Nørrekær Enge wind farm in Denmark. Using two meteorological masts in and on the perimeter of the wind farm the ambient turbulence at both places has been measured. The difference is the wake added turbulence. An initial setup of 13 different combinations of turbulence and wake models has been tested against these measurements. The tests reveal a varying degree of success, both among the model configurations, but also among the direction sectors investigated. They highlight the importance of choosing a proper set of parameters, but also that test cases a highly sensitive to error.

### **Introduction**

Turbines operating in wakes are subjected to significant higher structural loading than turbines operating in the free wind. Appropriate turbulence calculations should be made before selecting the proper turbine design class when having clusters of turbines. In this study, the wake added turbulence has been calculated using three different wake models and seven different turbulence models. These models are typically very different in detailing level – and possible also in accuracy. The models range is from simple engineering models to the more advanced computational fluid dynamic (CFD) models. The CFD-models are typically also very demanding in terms of calculation time.

### **Turbulence Models and Wake Models Included in the Analysis**

In the analysis the following wake added turbulence models have been implemented and tested: Danish Recommendation: 1992, Eddy Viscosity: 2003 (B. Lange), Quarton:1996 (D.C. Quarton & J.F. Ainslie), Dutch TNO Laboratory, G.C.Larsen: 1998 (EWTS II), S. Frandsen: 1999 (Efficient turbulence model) and the DIBt Richtlinie: 2004. The turbulence model must be used in connection with a wake (wind field) model. In the analysis, the following wake models are included: PARK model: 1996 (N.O. Jensen), Eddy viscosity model: 1988 (J.F. Ainslie), G.C. Larsen: 1998 (European Wind Turbine Standards II). A description of these models including references can be found in the WindPRO manual [1].

### **Sensitivity Studies**

The turbulence model parameters will be subjected to a sensitivity analysis to test the performance of the models under various environmental conditions. The performance of the models will then be compared.



## Case Studies

The ambient turbulence level from measurements in a number of international wind farms will be compared with calculated predictions of ambient + wake added turbulence. The performance of the models will be compared.

### Progress (February 2006)

The combinations of wake and turbulence models have been tested on the wind farm Nørrekær Enge in Denmark. At this stage the models have been using standard settings with the intention of fine tuning these with a sensitivity study. The preliminary results are reported below.

### The case: Nørrekær Enge

Nørrekær Enge is a wind farm in the Northern part of Denmark that was erected in 1988-90. When it was erected it was one of the largest of its kind with 36 130 kW and 42 300 kW Nordtank wind turbines. The utility Elsam operates the wind farm and the production is well documented. The turbines are located as illustrated in figure 1 in two groups with an internal spacing of 6-7 times rotor diameter. From 1991 to 1993 two metering masts have collected wind speed and turbulence readings at hub height (31 m). Their location is shown in figure 1. One is located on the southern edge of the wind farm and is thus undisturbed from sector 4 to 8. The second is located inside the wind farm near the east end and is influenced from all directions. With a distance of only 1800 m between the masts in a non complex landscape it is reasonable to assume that the ambient turbulence for the concurrent period is similar. Any additional turbulence at mast 2 from sector 4 to 8 will be wake added turbulence.

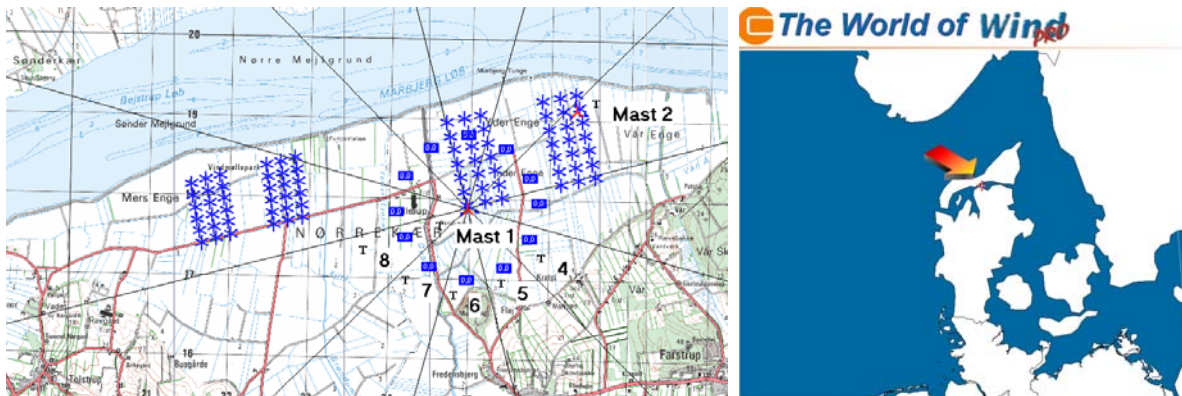


Figure 1. Outline of the test case Nørrekær Enge. The blue symbols are the wind farm, while the red symbols mark the two metering masts. Sector 4-8 are outlined at mast 1.

### The measurements

A section of the measurements is isolated where 1) there are concurrent healthy data on both masts and 2) all turbines are in operation. This leaves 24000 measurement points. Turbulence intensity (TI) is calculated from 10 minute mean wind speed readings and standard deviation on same. The TI readings are grouped so mean wind speed and standard deviation is obtained for every 1 m/s wind speed bin and 12 direction bins. From this, representative turbulence is calculated as recommended in IEC 61400 vs. 2 and vs. 3, that is respectively as  $\text{mean} + 1 \cdot \text{std.dev of TI}$  and as  $\text{mean} + 1.28 \cdot \text{std.dev of TI}$ .

Observations from sector 4 to 8 are extracted for the typical wind speeds of 9.5, 14.5 and 19.5 m/s.

### Calculation of turbulence

The calculation of wake added turbulence is an integral part of a standard energy production calculation using the WindPRO module PARK. A standard setup for an energy calculation is made using an orographic and roughness description and the wind atlas Danmark 92, which has in previous studies been shown to predict the wind farm production

well. Wake models and turbulence models from the list mentioned above is chosen with the appropriate parameter settings. As for ambient turbulence, the readings from mast 1, which is undisturbed in the investigated sectors is imported and used for each sector. This is also used to calculate the wake decay constant for the wake models. The turbulence is calculated for a virtual turbine at the location of mast 2.

The following combinations and parameter settings were tested. “0” means no parameter setting available. Standard parameters are the default parameters used in WindPRO.

Configuration	turbulence model	Parameters	Wake model	Parameters
1	EWTS II	0	N.O. Jensen	0
2	EWTS II	0	EWTS II	1.order
3	EWTS II	0	Eddy vis.	Standard
4	Danish recommendations	Gridded layout	N.O. Jensen, 2005	0
5	Steen Frandsen	Wohler =3, wake prop.=0,06	N.O. Jensen, 2005	0
6	Steen Frandsen	Wohler =9, wake prop.=0,06	N.O. Jensen, 2005	0
7	Steen Frandsen	Wohler =12, wake prop.=0,06	N.O. Jensen, 2005	0
8	Steen Frandsen	Wohl =9, wake prop=0,06, large w	N.O. Jensen, 2005	0
9	Quarton	Standard	Eddy Viscosity	Standard
10	B Lange	Standard	Eddy Viscosity	Standard
11	Dutch TNO	Standard	N.O. Jensen, 2005	Standard
12	Dutch TNO	Standard	EWTS II	Standard
13	DIBT	Wohler =3, wake prop.=0,06	N.O. Jensen, 2005	Standard

## Results

The observed representative (vs.2) TI for mast 1 and mast 2 is shown in figure 2. In some sectors there are no measurements of the higher wind speeds at the mast. Turbulence is higher at mast 2 due to turbulence from the wakes.

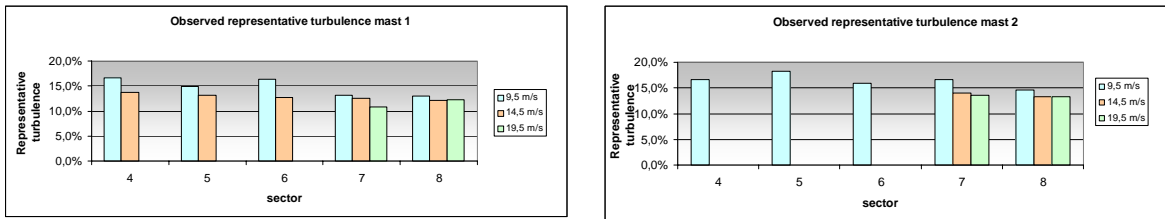
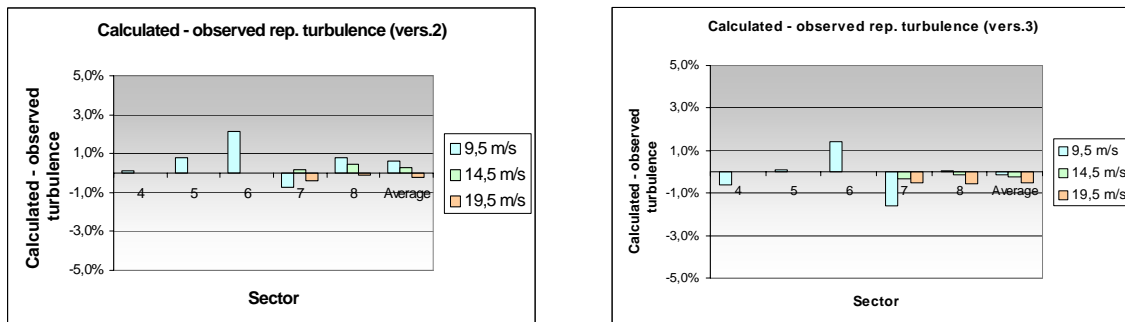


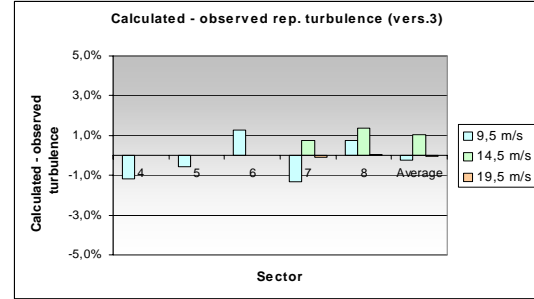
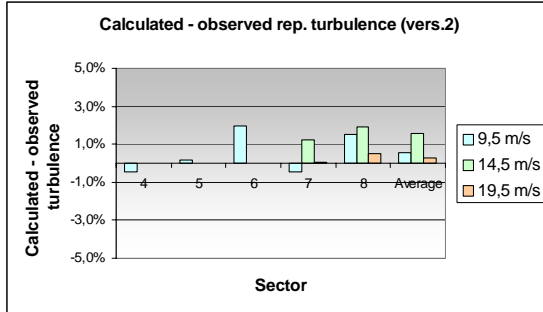
Figure 2. Observed representative (vs.2) turbulence intensity at mast 1 (reference) and mast 2 for three wind speeds and five sectors.

For each of the calculations the difference in calculated TI to the observed TI is plotted for a few representative configurations below. For sector 4 to 6 this is only possible for wind speed at 9.5 m/s. A positive difference of 1% means that the calculation model predicts a turbulence intensity that is 1% higher than observed at mast 2 (eg. 15% vs. 14%).

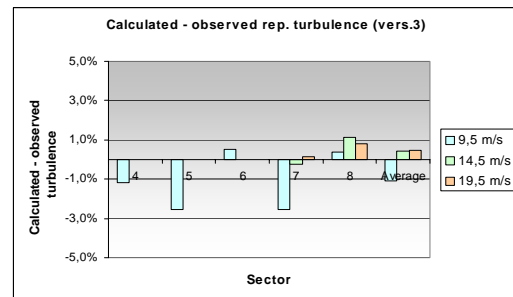
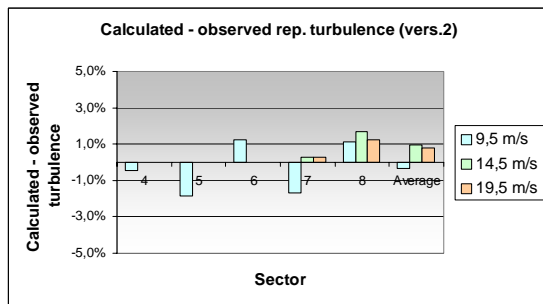


Configuration	turbulence model	Parameters	Wake model	Parameters
2	EWTS II	0	EWTS II	1.order

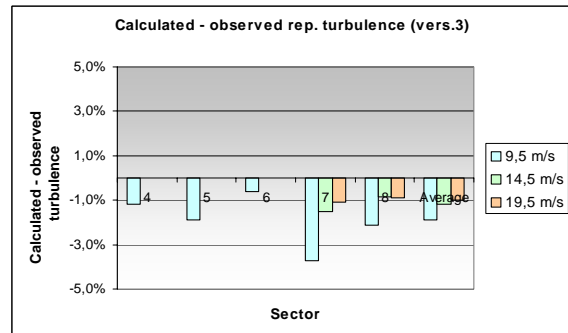
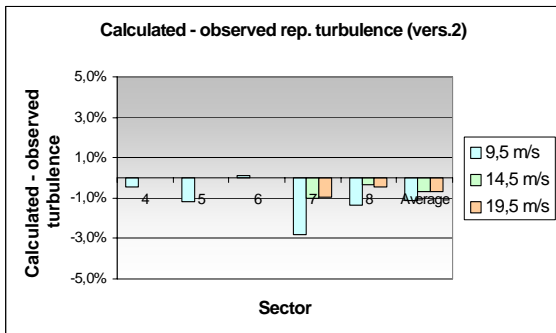
Case Study – Wake Added Turbulence at Nørrekær Enge



Configuration	turbulence model	Parameters	Wake model	Parameters
4	Danish recommendations	Gridded layout	N.O. Jensen, 2005	0



Configuration	turbulence model	Parameters	Wake model	Parameters
5	Steen Frandsen	Wohler =3, wake prop.=0,06	N.O. Jensen, 2005	0



Configuration	turbulence model	Parameters	Wake model	Parameters
9	Quarton	Standard	Eddy Viscosity	Standard

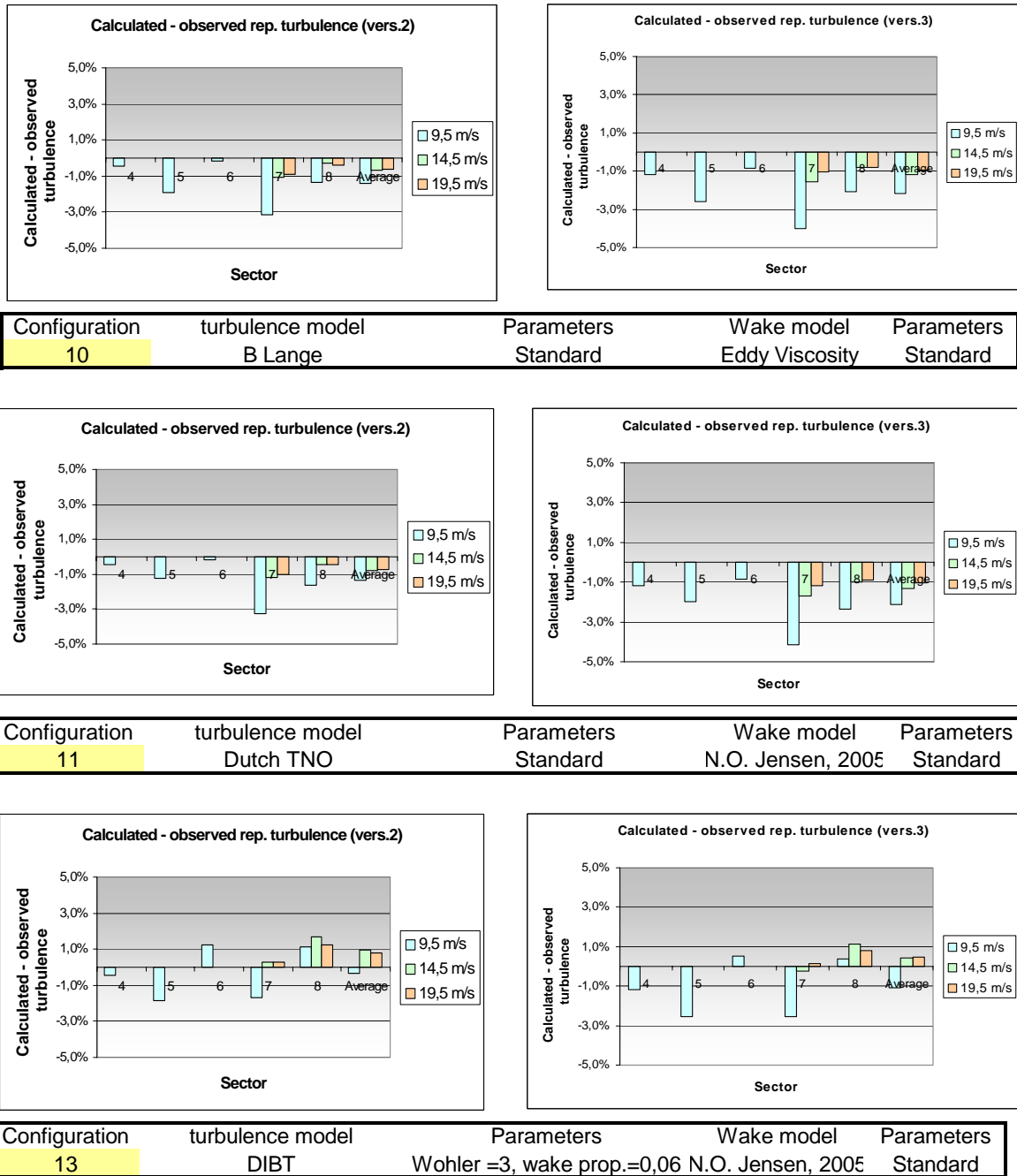


Figure 3. Difference in calculated TI to the observed TI for some of the calculation configurations.

For some of the configurations the calculated wake added turbulence is closer to the observed representative turbulence as calculated according to version 2, while others are closer with version 3. It can also be seen that the precision varies from sector to sector.

The calculated – observed turbulence results at 9.5 m/s in each sector are illustrated in figure 4 for each of the 13 tested configurations. The number in x axis refers to a turbulence model configuration from the table above. The average figure is an average of all three wind speeds and all sectors.

Where all the models agree in sector 4 where there is no significant wake influence at mast 2, the variation from model to model gets quite significant in the more disturbed sectors. Sector 8 most notably is calculated very differently with the Steen Frandsen turbulence model with a Wöhler curve exponent of 12 (config. nr.7), than with the Dutch TNO turbulence model (config. nr.11 and 12).

The parallel shifts between the sectors could indicate systematic errors in the observed turbulence intensity.

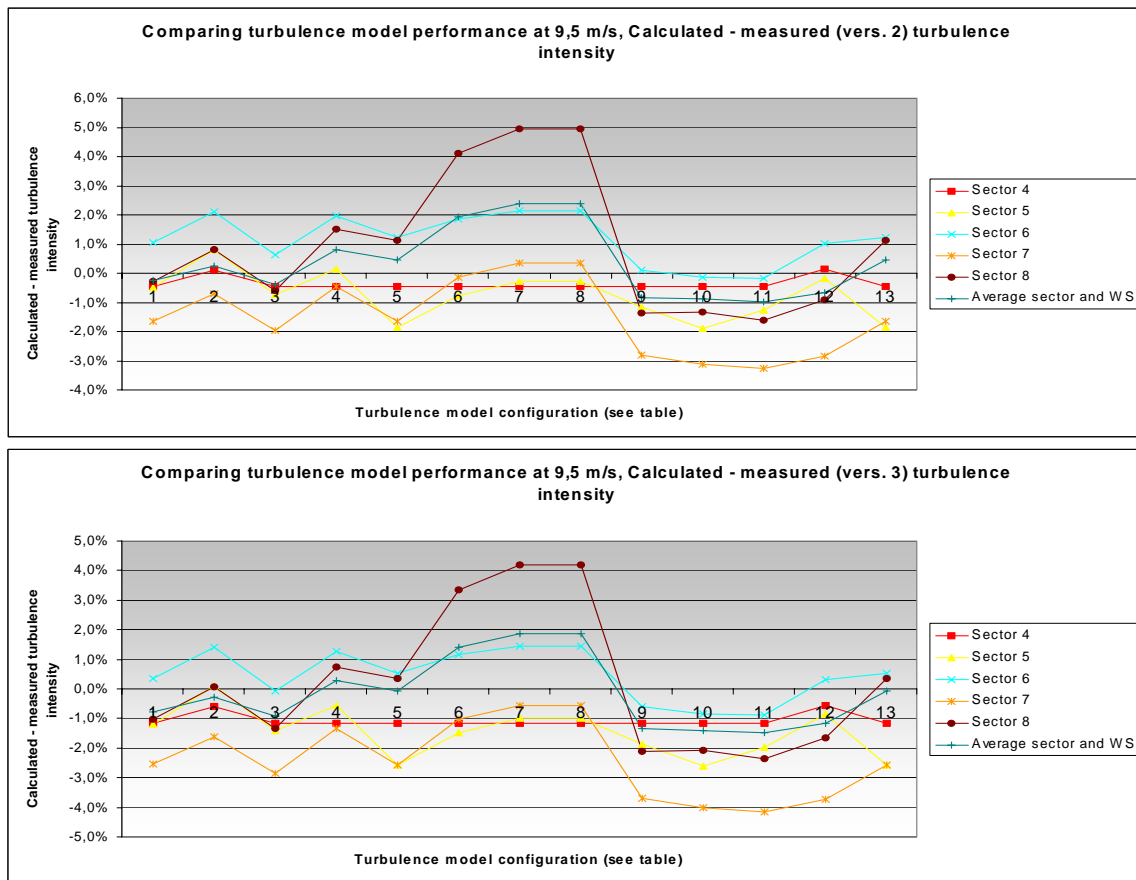


Figure 4. Difference in calculated TI to the observed TI across the configurations tested (please refer to the table) for each sector. The average is an average of all sectors and all three wind speeds.

## Conclusion

Testing the different wake added turbulence models and comparing the results with measured data, gives an overview of the model performance in various conditions. This case study begins this work. So far, the following observations based on this example can be made:

Some turbulence models clearly need a parameter calibration, or the user must at least be careful with the parameter settings. The precision varies from model to model, not necessarily with the most advanced being the most precise models. A case study is very sensitive to the precision of measured turbulence. If the ambient turbulence at the test site is different

from the reference site it offsets the results. If a model should be pointed out from this preliminary study then the EWTS II seem to perform better than average.

#### **References**

1. Nielsen P, et.al., *The WindPRO manual edition 2.5*, EMD International A/S, 2006.