Evaluation of the Software Program WindFarm and Comparisons with Measured Data from Alsvik

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Abstract

The use of wind power is steadily increasing around the world as a viable, environmentally sound complement and alternative to fossil fuels. For a number of reasons when building wind power plants, the turbines are often placed in groups, so-called wind farms. This method of placement results in the fact that turbines will sometimes be immersed in the disturbed flow, the wake, of other turbines. Today, there exist a number of software programs that have been designed for the purpose of creating, analysing and optimising wind farm layouts. Effective and reliable predictions of wind farm performance is of importance when planning and establishing wind farms, as this reduces the economic risks associated with them.

FFA acquired the wind farm analysis program WindFarm for trial purposes. The first part of this report deals with the evaluation and testing of WindFarm. Among the questions asked were; How sensitive is WindFarm to variations in the input parameters? How well does it predict the energy output of a wind farm? The idea was to get a clearer understanding of the program functions, calculation methods, efficiency and the calculation accuracy.

Several test cases were examined to gain a better knowledge of the operation of the program. Firstly, the program was tested to try and establish how deviations in input parameters affect the calculated results. WindFarm was also compared to FFA's own wind farm analysis program, FFA-MILLY. This was done by remaking a previous investigation performed with FFA-MILLY on a planned wind farm at Södra Kalmarsund. This site was run in WindFarm with exactly the same data as used with FFA-MILLY. Lastly WindFarm was compared to experimental measurements done at Vattenfalls experimental wind farm at Alsvik, Gotland. This was done to try and establish WindFarms ability to model and predict wind farm efficiency and energy yield.

WindFarm is a relatively new and untried software product, which naturally contains bugs and faults. In addition, there are a number of parameters, calculation options and wake modelling options that must be set and defined by the user, thus offering ample opportunity for mistakes and errors. Further it is concluded that there are some relatively large differences between the available modelling methods. However, determining which model is to be preferred cannot be done on the basis of investigations made in this report. To make an accurate and fair evaluation of wind farm modelling methods, accurate data from larger wind farms than Alsvik would be needed. However the results of this report should give a hint to which parameters dominate the calculation results and may help WindFarm users judge the validity of calculations and possibly how to improve them.

The second part of the report examines measured data from Vattenfalls experimental wind farm in Alsvik on the island of Gotland in the Baltic Sea. The focus of this part of the report was to try to determine the accuracy of these measurements. The data was treated with a focus on trying to eliminate, or compensate for, as many consistent errors as possible and to make estimates of the remaining uncertainties. This was done so that the models used in WindFarm could be compared to the measured data as accurately as possible.

The main sources of error that were examined were, yawed flow and uncertainties in the wind velocity- and wind direction measurements.

When the turbine is not aligned perfectly perpendicular to the wind it gives rise to so called yawed flow. This misalignment of the turbine clearly affects the power output, but by removing all data emanating from the most misaligned turbines it was possible to limit the deviations in the output power data. When studying the effects of yawed flow an interesting discovery was made; turbine misalignment need not necessarily lead to a lower energy production as expected. On the contrary, a couple of degrees of positive yaw angle might even increase turbine efficiancy.

When examining the wind direction measurements, the wind vane seemed to be offset 10-15 degrees from the expected value. This was dealt with using a correction equation originally created by Jan-Åke Dahlberg. Attempts were made to improve upon his original correction equation but the results were not good enough to justify discarding Dahlberg's original equation.

The wind velocity measured by the anemometers, mounted on booms stretching out from the measurement masts, is somewhat disturbed by the presence of the mast and boom itself. This gave rise to uncertainties when measuring the wind speed. Instead of using the anemometers, the possibility of using the turbines themselves to measure the wind velocity was examined. This turned out to be a better way of measuring the wind velocity since the turbine is not influenced by the measurement mast. The error due to the mast effects is thus eliminated.

The statistical uncertainties were assumed to be independent of the errors from the yawed flow and were then combined and error bars were added to the data.

The data were thereafter compared to calculations made by FFA-MILLY and WindFarm. The conclusions from the comparisons were that the models, in general, seem to underestimate the wake losses, and thereby over predict the total energy yield of the wind farm. This is not a very surprising result when considering the short distances involved in Alsvik. The models used start their calculations at a distance of about 4-5 diameters downstream of the turbine and this is the shortest distance involved in Alsvik. When the distance to the disturbing turbine increases, the accuracy of the models improves. It would therefore be interesting to see the effect of using the models on a larger wind farm.

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Preface

This report is the result of a thesis project conducted at the Aeronautical Research Institute, FFA, in Stockholm, Sweden. The thesis constitutes a mandatory part of the MSc degree at the Royal Institute of Technology in Stockholm. The actual work was carried out at the wind energy department at FFA.

The project supervisor was Sven-Erik Thor, FFA, and the academic examiner was Arthur Rizzi at the department of aeronautics at KTH.

Nomenclature

α	The measured wind direction
α_{corr}	Corrected wind direction using Dahlberg's equation
β	The direction of the nacelle position
γ	Yaw angle
C_T	Thrust coefficient
D	Rotor diameter [m]
v	Wind velocity in the free stream

1 Introduction

The use of wind power is steadily increasing around the world as a viable, environmentally sound complement and alternative to fossil fuels. For a number of reasons when building wind power plants, the turbines are often placed in groups, so-called wind farms. This method of placement results in the fact that turbines will sometimes be immersed in the disturbed wind flow, the wake, of other turbines. When standing in the wake of another, the energy yield of the turbine will be reduced. Several mathematical and empirical models have been developed to better be able to predict the power output when planning the construction of wind farms. Some of these models have recently been incorporated into commercial software packages, designed to plan and optimize the layout of projected wind farms. The programs include Windfarmer from GarradHassan, WindPRO from Energy and Environmental data in Denmark and the program evaluated in this study, WindFarm from ReSoft.

FFA acquired the wind farm analysis program WindFarm for trial purposes. The idea was to get a clearer understanding of the programs functions, calculation methods, efficiency and accuracy. Effective and reliable predictions of wind farm performance is of importance when planning and establishing wind farms, as this reduces the economic risks associated with them [1].

1.1 WindFarm

WindFarm is a software program for the analysis, design and optimisation of wind farm sites. It is mainly based on wake modelling theory previously developed by Ainslie [5]. The program mathematically simulates aerodynamic and meteorological occurrences for the purpose of predicting, among others things wind farm efficiency, energy production and optimal turbine layout.

The WindFarm program consists of a main program, acting as the project framework, and a number of modules that perform specific tasks. The modules included in the version acquired by FFA are listed below and a brief description of each module can be found in Appendix B.

- Data Conversion
- Digitisation
- Energy Yield
- Long Term Wind Analysis
- Noise Calculation
- Optimisation of layout
- Turbine Analysis
- Wind Flow (MS-Micro)

In the program mainframe, the user enters the information that applies to all of the design and analysis process. For each new project the following data is specified:

- The wind farm site region is defined by entering location and size of the wind farm site.
- For the purpose of wind flow calculations, terrain height and roughness data is specified.
- A background map, Windows bitmap, can be added as a visual aid. Furthermore, it is possible to add identifying features to the landscape, such as fence lines, landowner boundaries, roads, etc.

One of the more important variables for a wind farm analysis program like WindFarm, is wind data. In WindFarm wind data can be introduced either as a wind distribution file or a so-called wind stepping file. The purpose of the wind distribution file is to provide data describing the prevailing meteorological conditions at the planned site as accurately as possible. The file is specified with a vertical wind profile, reference height, the number of wind sectors used and a frequency table. The frequency table defines the amount of time and with what speed the wind blows in a specific direction.

For the purpose of more detailed studies a stepping data file can be used. This allows the creation of a series of points or steps at which the power is to be calculated. The wind step file consists of wind direction, wind speed, turbulence and wind profile. The benefit of the step file is that each of the previously mentioned parameters can be varied between steps.

One of the more important modules in WindFarm is the Energy yield module. This module calculates the wind farm energy production, whilst including the effects of topography and wakes on the energy content in the wind. The energy yield module requires a number of files and parameters to be set. These are comprised of:

- A file containing wind data
- A file containing wind flow data
- A File containing wind farm layout data
- Calculation options
- Wake and wake combination models

Changes to wind speed, wind direction and wind profile due to topography, is possible to calculate with WindFarm's Wind flow module. This module uses source code from the MS-Micro/3, a program developed by the Atmospheric Environment Service of Environment Canada and Zephyr North [5]. It should be observed though, that this method has limitations, especially in steep terrain (chapter 2).

2 Earlier investigations

The authors of this report have read two earlier studies of the WindFarm program, both performed and written by Alan Harris, [2] and [3], who is also the creator of the program. The first report '*A Sensitivity Analysis of WindFarm Energy Production*' is a study into "the effect on the energy yield of the various parameters and representations available within the program and possible errors induced by imperfect knowledge of turbine and wind data". In this report the percentage change in wind farm efficiency has been studied for changes in WindFarm input parameters. Results include the following table, which shows a ranking of the input variables for a 10% change. It should be noted that the tabulated values only apply for the conditions described in the above mentioned report.

Variable	Change in efficiency [%]
Mean wind speed	17.0
Wind profile	4.8
Wake combination	2.0
Weibull parameters	1.1
Turbine thrust	0.6
Wake starting level	0.5
Wake decay	0.5
Wake turbulence	0.5
Wake meandering	0.5
Wind rose alignment	0.4

Table 2.1: Influence on calculated efficiency for a 10% change of the input values.

Mr Harris concludes that a 10% error in wind speed measurements is quite realistic. He therefore states that "there would be a greater return on investment by improving wind measurement/estimation and correlation with meteorological stations than in refining the estimation of the effect on the energy yield of a wind farm of the other parameters in this study". The second report, '*The Assessment of Commercially Available Topographic and Wake Models of Wind Farm Output',* had two main objectives; firstly, to examine recorded energy output of individual turbines on two U.K. wind farms for various wind directions and speeds, thus providing specific test cases for energy prediction programs. Secondly, to evaluate the capability of Renewable Energy Systems (RES) wind farm energy prediction program WindFarm. Here Harris concludes that for relatively gentle terrain the theoretical results represent the measured reasonably well, with little

indication of error due to the wind flow calculations not representing the topographic effects properly. Further he notes that different wake modelling techniques did not suggest any significant improvements. However, where the terrain was more undulating and complex, the calculations exhibited significant differences to the measurements. Harris believes that the major part of the discrepancy is due to the wind flow modelling of the topographic effects.

3   Tests performed

One purpose of this report was to analyse WindFarm, to establish an understanding of its functions, strong points and weaknesses. To do this, four different tests were performed. To begin with, it was of interest to investigate how deviations in input parameters affected the calculated results. A similar investigation has been performed earlier by Harris, as mentioned in chapter 2, but it was concluded that Harris' results were only valid for a specific case and therefore a more general approach was needed.

The next point examined was the wake and wake interaction modelling methods. Questions to be answered were; how do the models differ from each other and what are their respective pros and cons? A better understanding of the different modelling methods should help, when performing energy yield calculations, in choosing a suitable model and evaluating the results.

FFA-MILLY is a wind farm analysis program that has been developed at FFA, based on the model MILLY. FFA-MILLY has been used to do calculations on a planned offshore wind farm in southern Kalmarsund, in the southeast part of Sweden. This set of calculations were repeated in WindFarm, thus enabling a brief study of how the results from WindFarm and FFA-MILLY compared to each other.

Finally, the question of the precision of the calculations done by WindFarm was examined. This was best done by comparing the calculated data from WindFarm to measurements performed on a real site. The field measurements that were to be used were obtained from FFA's experimental wind farm at Alsvik, situated on the island of Gotland in the Baltic Sea.

3.1   Deviation in input data

The energy yield module of WindFarm requires three or four data files for the calculation the energy yield of a wind farm. These files contain data defining the wind farm layout, wind distribution, turbine characteristics and wind flow with the latter being optional. The data in these files will naturally not be exact, but contain errors and deviations. It is therefore of interest to investigate how the energy yield calculations are affected by predictable deviations in the input data.

3.1.1   Turbulence

As mentioned in the literature study report by Djerf and Mattsson [4], shear turbulence, wind shear and turbulence in the atmospheric flow all play a more or less important role in making wakes diffuse and recover. In WindFarm shear turbulence and added turbulence (see Chapter 3.2) are represented in the mathematical model and can therefore not be adjusted by the user. On the other hand, turbulence in the atmospheric flow, measured or

estimated, is a variable input parameter. It is difficult to measure turbulence with any greater certainty and therefore it is of interest to see how the overall energy yield results are affected by uncertain data. Since atmospheric turbulence works to diffuse and recover velocity in wakes, it is only in wake interference situations its presence is of importance. Therefore it should be fair to say that the more inefficient a wind farm is, the more apparent are the effects of atmospheric turbulence.

3.1.2   Thrust coefficient

The thrust coefficient, C_t, defines the initial velocity deficit of the wake, as can be read about in more detail in [4], and is therefore an important parameter in WindFarm efficiency calculations. As with atmospheric turbulence, deviations in the thrust coefficient should get more prominent as wind farm efficiency declines. The thrust coefficient is a theoretical value determined by calculation or derived from turbine loading measurements. Since the thrust coefficient itself cannot be measured, it is difficult to define its uncertainties, but a qualified guess should put them below ten percent.

3.1.3   Wind speed and direction.

Important parameters in WindFarm efficiency yield calculations, are wind speed, direction and frequency for a designated location. Wind data for a chosen site can be obtained either by measurements done on the location, or by calculating/predicting expected values based on data from nearby meteorology stations. Whatever method is used, the wind data will inevitably deviate from the true values. Since the energy content in the wind increases with the cube of the wind speed, the effects of erroneous data should be appreciable as shown earlier by Harris (chapter 2). However, this report only briefly examines the effects of changes to wind direction.

3.2   WindFarm calculation methods.

To calculate the energy yield, WindFarm is equipped with a number of wake modelling parameters that can be set by the user. These modelling parameters are based on different modelling methods, which are described in more detail in the report by Djerf and Mattsson [4]. Listed below are the different modelling choices that are offered by WindFarm. It can be noted that the WindFarm user manual [5] recommends the use of the axisymmetric wake, energy balance and Garrad Hassan added turbulence. Wake velocity deficit model:

- Axisymmetric wake
- WASP/Park
- UPMPARK

Wake Meandering on/off

Wake combination method:
- Sum of squares of velocity deficits
- Energy balance
- Geometric sum
- Linear superposition

Wake added turbulence:
- None
- Garrad Hassan model
- RISØ model

Axisymmetric wake

This is a calculation method developed by Ainslie [6]. It is a 2-dimensional method assuming fully turbulent wake flow where the circumferential velocities are zero and the flowfield stationary with time. According to Harris [5] the wake development is a function of the wind turbine thrust coefficient, C_t, the ambient turbulence and the ratio of hub height to roughness length. To reduce calculation time, WindFarm uses a prefabricated look-up table. Covering 100 rotor diameters downstream in 1 diameter steps, the table lists the velocity deficit ratio for various values of thrust coefficient and ambient turbulence. The velocity deficit profile of the wake is assumed Gaussian everywhere.

WASP/Park

Park developed by Katic, Højstrup and Jensen is a model that is designed to require a modest computer capacity. The model is based on the description of a single wake in terms of the initial velocity deficit and a wake decay coefficient. The wind speed is said to be constant across the wake, thereby using a linear distribution for the velocity profile of the wake. The wake behind the turbine is assumed to spread out linearly as a function of downwind distance.

UPMPARK

This 3-Dimensional model by Crespo and Hernández calculates the flow magnitudes at every point of the flow field. The turbine is assumed to be immersed in a non-uniform basic flow corresponding to the atmospheric boundary layer. The wake is simulated by solving Navier-Stokes equations, using the turbulent kinetic energy and its dissipation rate for closure of the turbulent flow equations. However, in WindFarm, UPMPARK is represented as data in a predefined lookup table and is therefore not represented in its whole. Thus, it should be fair to say that WindFarm does not represent the original UPMPARK code.

Wake meandering

Wake meandering is a method of simulating the variation of wind direction, as function of turbulence, during a measurement period. According to the user manual [5], it makes little difference to energy yield calculations other than smearing out details in wake characteristics.

Added turbulence

The added turbulence is taken into account when the rotor disc is in the wake of upstream wind turbines, where it is calculated for the specified downstream distance and taken as constant over the full width of the wake.

Wake combination method

The above velocity deficit models are calculations of a single wake, which therefore require superposition assumptions for wind farm calculations. The interaction of wind turbine wakes is a complex process that is difficult to model. WindFarm therefore supplies 4 different wake combination methods to choose from. However, Harris [5] does not recommend the use of linear superposition or geometric superposition, as they tend to overestimate the velocity deficits.

3.3   Comparison with FFA-MILLY

As FFA has taken part in the development of the wind farm analysis program FFA-MILLY, There was an interest in how the program compares to WindFarm.

Originally Vermeulen and Builtjes incorporated experimental data to make corrections to Lissaman's original model, see [4], thus developing MILLY. Using experimental data from the wind farm at Alsvik, FFA further improved on this, resulting in the computer code FFA-MILLY. The programs modelling of interacting wakes was improved by adding the squares of the velocity deficits instead of, as in the original MILLY, adding them linearly. Another improvement was the introduction of added turbulence in the turbine wake. These alterations were assumed to give a better description of the interaction of multiple wakes. FFA-MILLY requires the following input data,

- The site, with the position of the turbines
- The turbine data used
- The wind speed
- The ambient turbulence

3.4   The Alsvik test case

When evaluating WindFarm it was desirable to be able to make comparisons to a real wind farm. For this purpose, measured data from the Alsvik wind farm was evaluated to be able to determine the accuracy of the data. This wind farm is operated by Vattenfall and monitored by FFA for the purpose of making experimental measurements and determining the effects on a turbine operating in the wake of another. The layout of the Alsvik wind farm is presented in Appendix A and chapter 4.3.1.

4 Test cases

Chapter 3 was an account of the calculation tests that were to be performed with WindFarm. Listed below, and described with more detail in this chapter, are the cases that were used to make these tests.

- The simple case; for the evaluation of deviations in input data (Chapter 3.1) and modelling methods (Chapter 3.2).
- The southern Kalmarsund project; for the comparison of FFA-MILLY and WindFarm (Chapter 3.3).
- Alsvik wind farm; for the comparison of field data with calculations made by WindFarm (Chapter 3.4).

4.1 A simple test case

To examine how deviations in turbulence and thrust coefficient, C_t, affect calculation results and to monitor the behaviour of WindFarm's different modelling methods, a simple test case was needed. This test case did not require any height or roughness data, neither was a wind profile necessary.

4.1.1 Row and box configuration

To examine the effects of deviations in the input data, two wind farm layout configurations were used (Figure 4.1), a row configuration (1xn), where each turbine stands in a row parallel to the wind vector, and a square configuration (nxn).

Wind farm efficiency is a function of the wind velocity deficit in the turbine wakes and the frequency of wake interference. By using the above-mentioned configurations with an increasing number of turbines, the effects of wakes and wake interference could be included as a variable. For all configurations the separation between the turbines, downstream and across, were 7 turbine diameters.
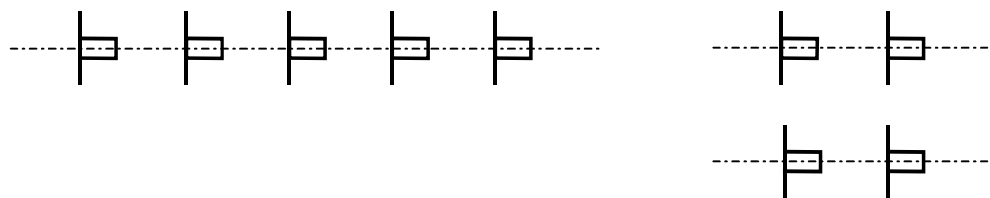
Number of turbines, n				
1xn 5	10	15	20	100
nxn 2x2	3x3	4x4	5x5	10x10

Figure 4.1 and Table 4.1: The row (1xn) and square (nxn) wind farm configuration.

4.1.2   The wind turbines

The turbine named N2, with geometrical and performance data based on the WEGA II turbine, is the same as was specified to be used in the southern Kalmarsund project (Chapter 4.2.2). The turbine has a hub height of 90 m and a rotor with an 80 m diameter, working at a constant rotational speed of 21 rpm. This turbine was chosen since it is large and with its high thrust coefficient values (Figure 4.3) develops an intense wake.

4.1.3   Wind data

For these calculations WindFarm's Step file function was used. This function allows the creation of a series of points or steps at which the wind farm power is calculated. The wind speed was set to 7 m/s with a 10% turbulence level. To catch the effects of the turbine wakes, the wind was assumed to blow from the head of the turbine row, within a forty-degree sector that in turn was divided into 200 steps or points.

4.2   Southern Kalmarsund

In a report from June 1990, Dahlberg and Meijer [7] account for prediction calculations of a planned wind farm in southern Kalmarsund, Sweden. The calculations were performed with FFA-MILLY, a wake modelling computer program originally called MILLY, developed at TNO in the Netherlands [4]. Drawing from experiences gained from the experimental wind farm at Alsvik, Dahlberg and Meijer modified MILLY to better simulate effects such as the increase of turbulence within wakes.

The report contains calculations of the wind farm efficiency for two different turbine placement configurations, using data for both the prevailing wind conditions, i.e. the wind rose, and an even wind distribution.

4.2.1   Wind data

Wind data for the region of southern Kalmarsund consisted of an 18-sector wind rose, 20° per sector, were each sector contained the frequency of 2 m/s wind bins, between 2 and 24 m/s. The wind data was also divided into three atmospheric stability classes, each class having a turbulence intensity of 3%, 7.5% and 15% (Figure 4.2). Since turbulence has a positive effect on wind farm efficiency, the frequency of each turbulence class needs to be accounted for in the calculations. The frequency for the three turbulence classes was 29.8%, 38.6% and 31.5% of 8760 hours respectively. All data was valid at the turbine hub height, 90 m.
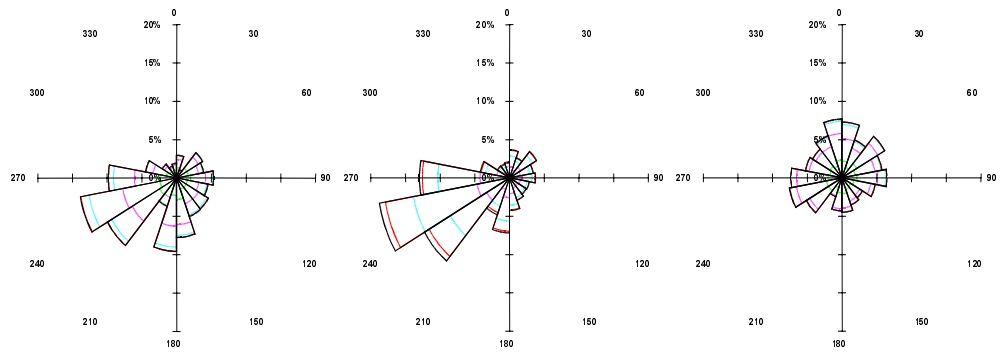
Figure 4.2: Wind roses for the three turbulence intensity classes; 3%, 7.5% and 15%. Note that the three wind roses represent one year each.

WindFarm can only calculate the energy yield for 8760 hours, one year, and one stability class per calculation. Therefore it was necessary to modify the wind data and results, to get the energy production for one year and still include the effects of the three stability classes. Each stability class with wind frequency was recalculated to represent one year of measurements. Thereafter the energy production for each stability class was calculated with WindFarm, thus producing a total of three years energy production. Therefore the results had to be transformed to represent one year's energy production. This data transform does not affect the final result since it is a mere manipulation of time.

4.2.2   The wind turbines

The southern Kalmarsund wind park was to be equipped with 98 identical turbines, named N2, with geometrical and performance data, based on the WEGA II turbine. The N2 turbine was specified to have a hub height of 90 m and to be equipped with an 80 m diameter rotor, working at a constant rotational speed of 21 rpm.
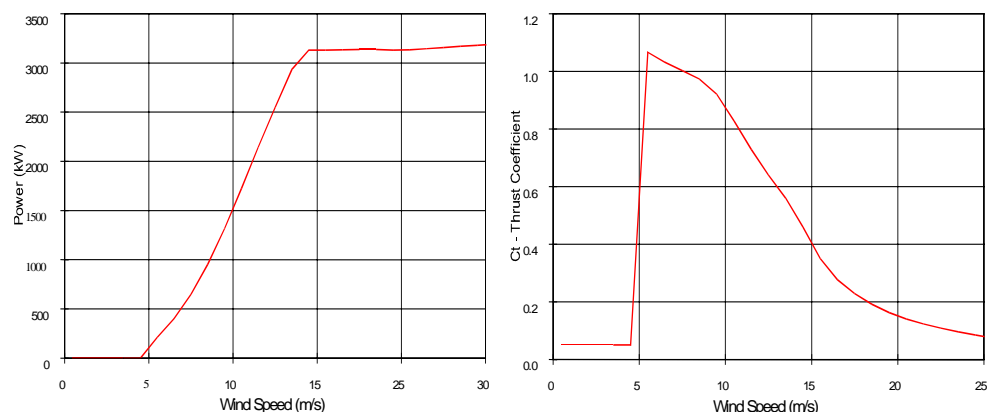

Figure 4.3: Power curve and thrust coefficient graphs for the N2 turbine. Observe that the thrust coefficient is greater than 1 for wind speeds between 6-8 m/s.

Dahlberg and Meijer calculated the performance data for the turbine with the help of WINRO [7]. The results of their calculations can be viewed above as graphs for the power curve and thrust coefficient (Figure 4.3).

4.2.3   Wind farm configuration

Calculations were made on two wind farm configurations (Figure 4.4), both made up of 98 turbines placed within a predefined area. The configuration named 14X7 consisted of fourteen groups of seven turbines, where each group of seven turbines was placed in the form of a hexagon with one turbine at its centre.

The minimum distance between two turbines in the wind farm was 10 rotor diameters. In the alternate configuration the turbines were placed in six rows, oriented square to the predominant wind direction thus called 6TR. Within each row the turbines had a separation of only 3.75 rotor diameters. In turn the rows were 31.75 rotor diameters apart, giving ample room for the wakes to dissipate in the predominant wind direction.
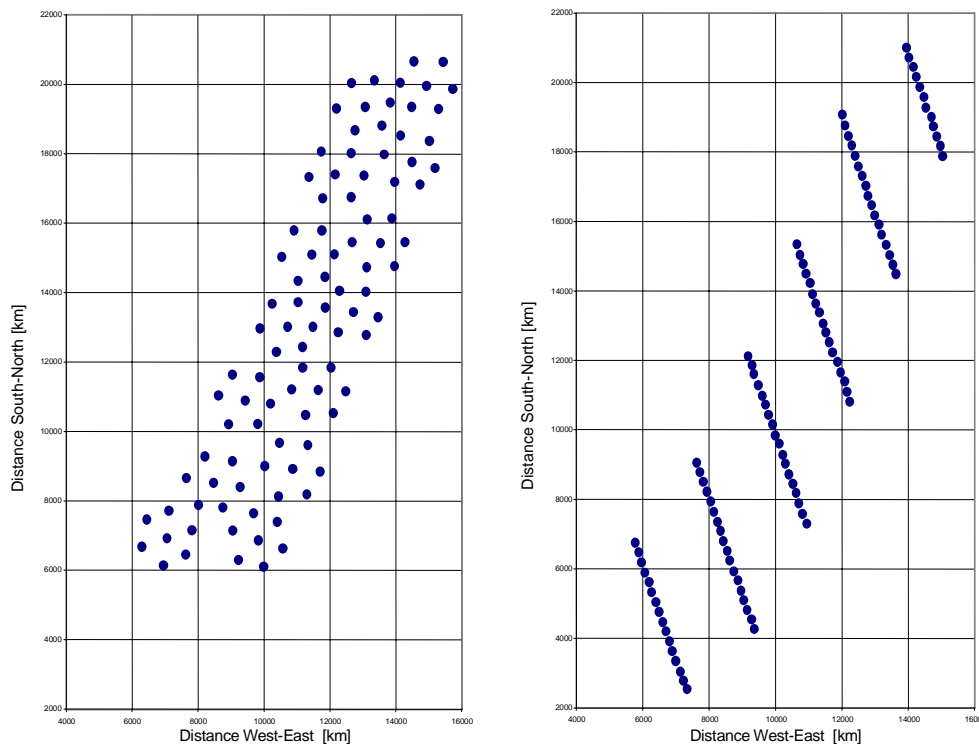

Figure 4.4: Wind farm configurations 14X7 and 6TR of 98 wind turbines.

4.3   Alsvik

In order to evaluate WindFarm's accuracy in predicting wind farm efficiency, comparisons with full-scale measurements were necessary. It was therefore of importance to acquire large quantities of reliable measurements, of meteorology and turbine performance. It was found that

the experimental wind farm at Alsvik, situated on west coast of the island of Gotland (Appendix A), could provide the required data for an initial investigation.

4.3.1   The location

The wind farm at Alsvik, specifically designed for the purpose of experimental measurements, consists of four strategically placed wind turbines (Figure 4.5). Three of the turbines stand on a line that runs along the shore in a NNW-SSE direction. The fourth turbine is located to the east of this row, thus deliberately subjecting it to wind turbine wakes during westerly winds. The land behind them, to the northeast, is low and flat consisting mainly of grazed grasslands and a low growing pine forest. Since the Alsvik wind farm was intended for experimental measurements, it was equipped with two meteorological masts, each being 52 m in height, that measure wind speed and direction on seven elevations above ground.
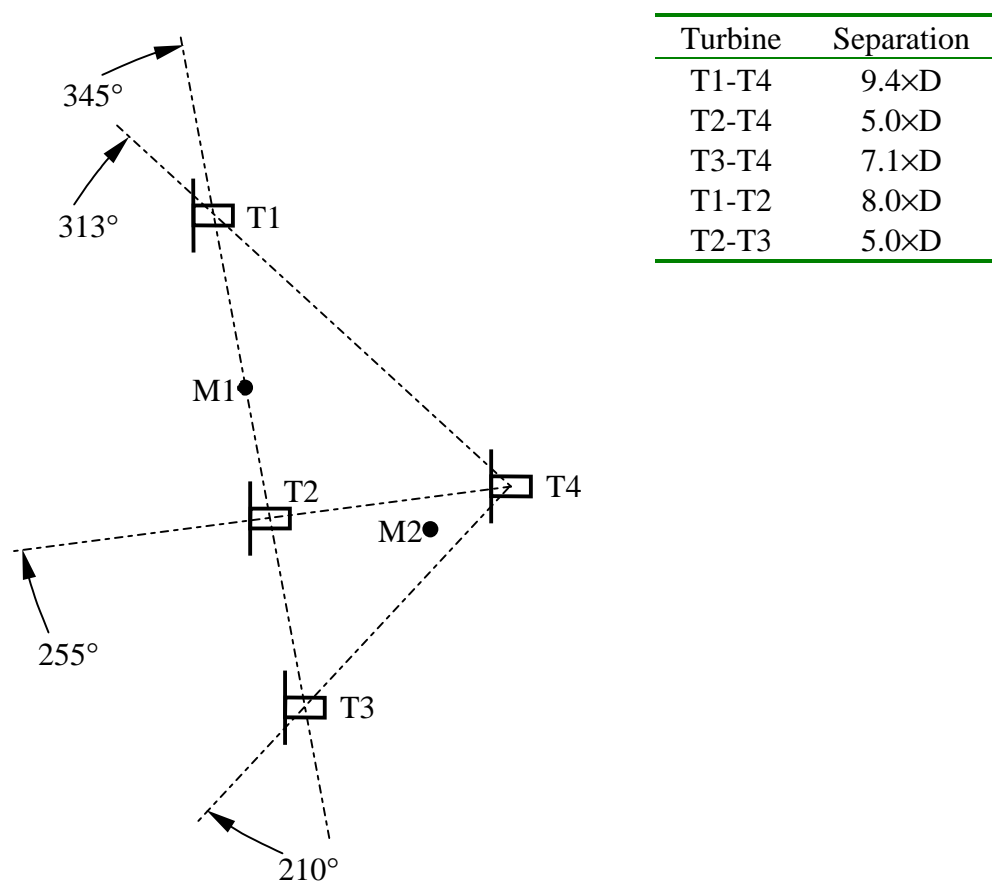
Turbine	Separation
T1-T4	9.4×D
T2-T4	5.0×D
T3-T4	7.1×D
T1-T2	8.0×D
T2-T3	5.0×D

Figure 4.5 and Table 4.2: Layout of the wind farm at Alsvik, with turbines T1-T4 and masts M1, M2.

4.3.2   The turbines

The four wind turbines at Alsvik are of a three-blade upwind rotor type, manufactured by DANWIN and have the following geometrical and performance data:

- Angular velocity 42 rpm
- Cut in/out speed 5 m/s, 25 m/s
- Hub height 35 m
- Rated power 180 kW
- Rated wind speed 12 m/s
- Rotor diameter 23.2 m
- Stall regulated

The power curve for the DANWIN turbines is based on measurements performed at Alsvik and compiled in chapter 5.3.4. The resulting power curve is presented below together with thrust coefficient curve. All turbine data, except the power curve, is presented courtesy of Dahlberg (Figure 4.6).
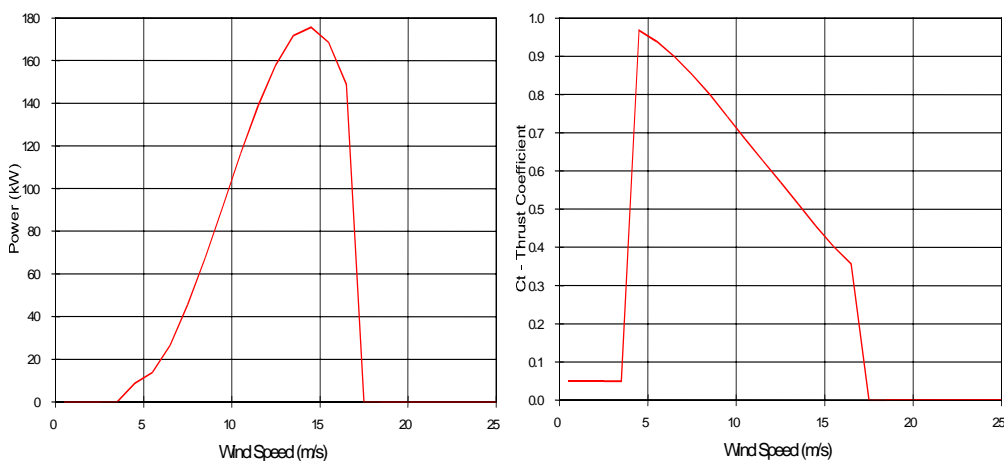

Figure 4.6: Power curve and wind-thrust coefficient graph for the
            DANWIN turbine. Observe that the cutout speed is 25 m/s. The
            discrepancy is due to lack of data.

4.3.3   Wind data

To be able to make predictions on the power output of the wind farm, the models used in WindFarm needed accurate wind data from the site. The measurements incorporate wind velocity measurements in all directions during the course of several years. The wind data was divided into three bins, each representing a turbulence level of 3, 7 and 15%. The data was used to create a wind rose in WindFarm, see Figure 4.7.
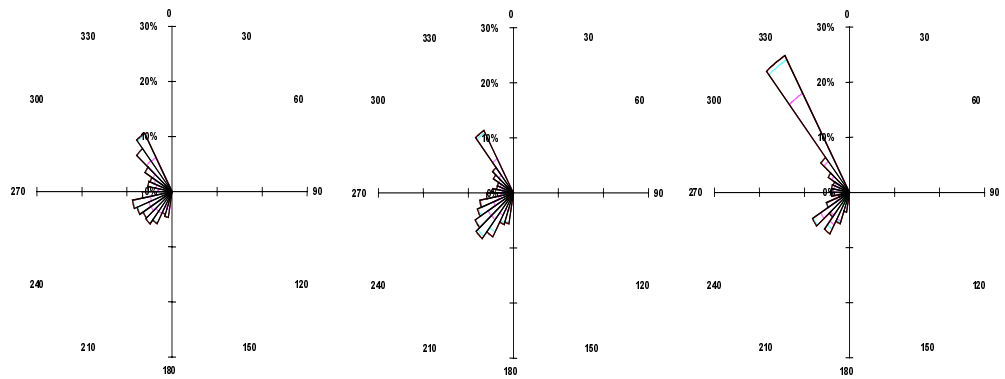
Figure 4.7: Wind rose, created in WindFarm using measured wind data from Alsvik. Observe that the wind data only represents a sector between 190° and 330°.

These turbulence levels were measured with the same sample rate as before, 2 Hz. The measured turbulence was taken as the standard deviation of the wind velocity divided by the wind velocity itself, giving the turbulence during the measurement minute in percent. The wind data was corrected for mast- and boom effects as will be described in chapter 5. However, to be able to measure turbulence, the anemometer had to be used since the turbine is incapable of doing this.

In essence, the turbulence is quick variations in the small-scale wind velocity, and the turbine does not react quickly enough to changes in the wind speed to be able to read these variations. To be able to divide the data into turbulence bins, the turbulence had to be calculated for each measured wind velocity and, since this was not possible using the turbines, the anemometer had to be used instead.

5   Evaluating the measured data from Alsvik

The different wind farm planning programs that exist all use models like the ones described earlier in the literature study by Djerf and Mattsson [4]. However, when using mathematical models to predict the power output of wind turbines, the accuracy of the models comes into question.

When the models were developed the results obtained from them were compared to different sets of measured data, gathered both from wind tunnel and full-scale experiments. This data was assembled, put in a graph and compared to the predictions made by the model. Conclusions were then made as to how accurate the model was and whether refinements were necessary. But how accurate was the measured data? What was the margin of error in the measurements, and is it possible to measure the power output accurately enough to be able to make detailed refinements in the models? The focus of this report was to try to determine how accurately it is possible to measure the power output of individual turbines within a specific wind farm. The data available was measurements made at the Alsvik wind farm on the island of Gotland in the Baltic Sea. The data was treated with a concentration on trying to eliminate, or compensate for, as many errors in the measurements as possible. Also, to make estimates of the remaining uncertainties in the rest of the measurement points and explaining the reasons for them.

The measured values, which were used in this study, were output power, wind direction, wind velocity at hub height and nacelle direction. The wind velocity and direction was measured using anemometers mounted on two masts at seven different heights. The layout of the farm and the position of the measurement masts are shown in Appendix A.

The measurements of interest to this study have been conducted in the predominant wind direction, 190-330 degrees. It would also have been interesting to look at the case when the wind is blowing from the direction of 150-200 degrees. However, in this region there was not enough measurement data of good quality available to be able to make a thorough study. Therefore, chapters 5, 6, 8 and 9 of the report focuses on the region of 190-330 degrees and specifically the power output of turbine #4 when it is operating in the wakes of the other three. If not otherwise stated, the value of the measured power output refers to the power of turbine #4. All of the measurements have inherent errors affixed to them and the task at hand involved identifying the sources of these and, as far as possible, compensating for them or introducing error bars in the graphs. The major sources of error that have been identified in this study, and that will be considered in this report, are:

- Errors due to the misalignment of the turbine into the wind (chapter 5.1)
- Uncertainties in the wind direction measurements (chapter 5.2)
- Uncertain wind speed measurements (chapter 5.3)

When the measurements were made a huge amount of data was collected. Each batch of measured data consisted of one-minute measurements made over a period of three hours. In turn, each data file consisted of several of these three-hour measurement periods. In these batches there were measurements made in all wind directions and wind speeds up to about 18 m/s.

The next step was to put these data in bins, sorted after wind speed, so that the output power could be plotted against the wind direction.
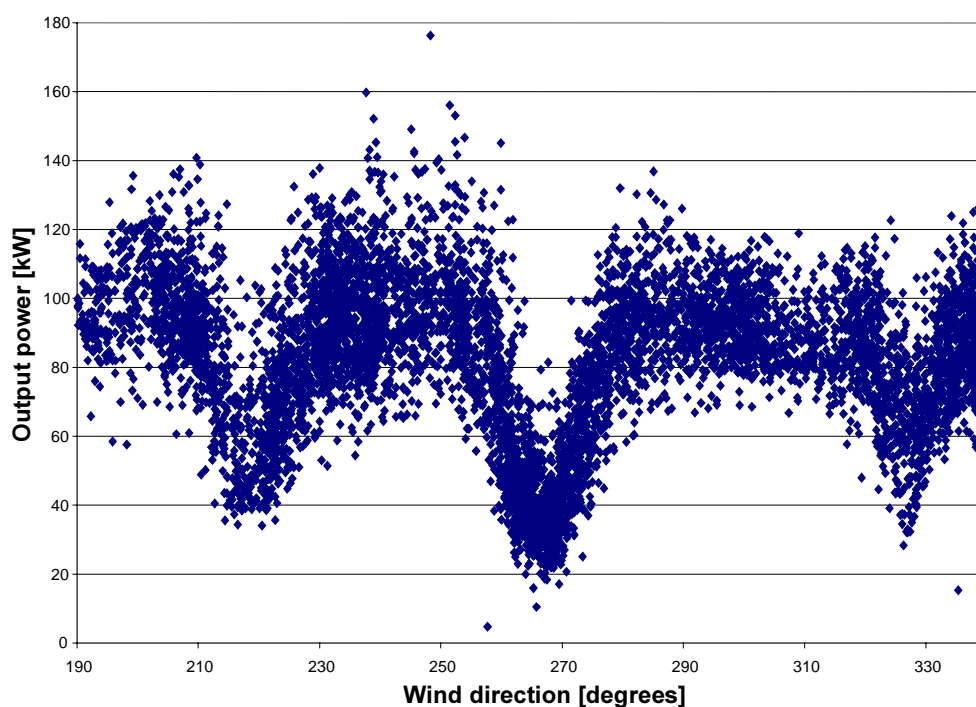
Figure 5.1: Binned, uncorrected data for a wind speed of 9-10 m/s.

The dips in Figure 5.1 correspond to the wind directions where turbine 4 is operating in the wake of one of the other turbines. As the turbine spacing varies between 7, 5 and 9.5 rotor diameters, left to right, the energy deficits in the wakes can clearly be seen. The largest power deficit occurs in the 250 to 280 degree interval, which represents the case when turbine 4 is immersed in the flow of turbine 2 which stands closest, at a distance of 5 rotor diameters. The deficit in 210 to 235 degrees represents the wake of turbine number 3 at a distance of 7 diameters, and the last interval, 320 through 330 degrees, representing the wake of turbine number 1, which is placed at a distance of 9.5 diameters from turbine 4.

5.1   Yawed flow

When the turbine is operating and producing power, field measurements have shown that it is not uncommon for the nacelle to be slightly misaligned with respect to the wind direction. This give rise to so-called yawed flow as shown in Figure 5.2.
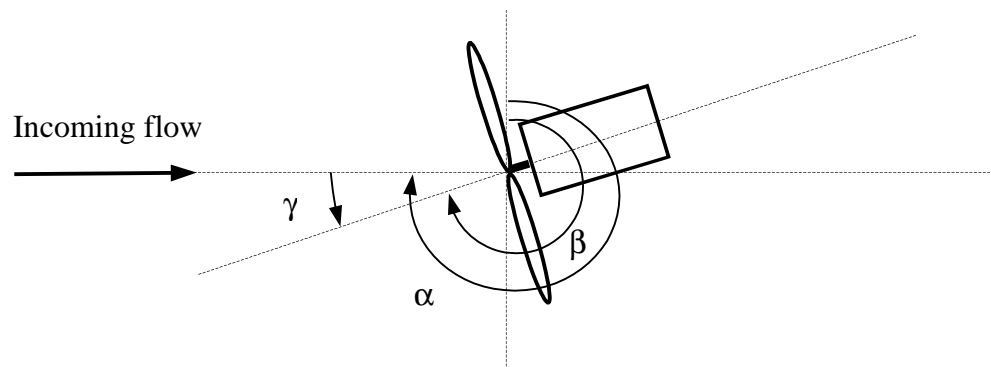
Figure 5.2: Yawed flow, the turbine is seen from above.

When the wind hits the turbine at an angle that is not perpendicular to the blades, it could be expected that less force would be created to produce power, which would mean that the power output by the turbine would differ from the expected value. However, experiments conducted by Dahlberg [8], on a 3 MW turbine, have indicated that when the yaw angle, γ, was positive, the power output could actually increase compared to the expected value. The yaw angle is defined as positive when the situation is such that the blade that is pointing upwards has a slight tail wind.
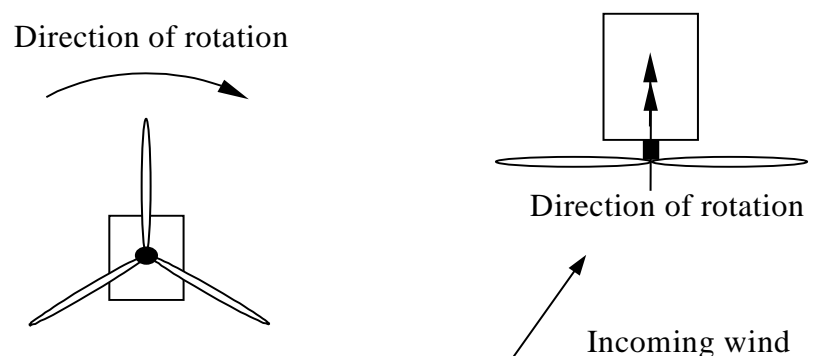
Figure 5.3: Definition of positive yaw angle.

This behavior was studied using the measured data available for the Alsvik wind farm to see if the result could be seen here.

The direction of the nacelle, β, has been measured over an extended period of time along with the direction of the wind, α. The position of the nacelle was subtracted from the wind direction (eq 5.1) to produce the yaw angle for the turbine

$$\gamma = \alpha - \beta \qquad (5.1)$$

The measured wind directions used in this calculation were corrected according to the findings in chapter 5.2. When evaluating the data, bins that were based on fewer that 10 readings were ignored as this was regarded as too few values on which to base a judgement on [9].

The power output was normalized with the expected undisturbed output at the wind speed in question, taken from the power curve (Figure 5.16), and plotted against the yaw angle. The results produced tended to confirm the findings of Dahlberg [8] as the output power seemed to increase for a positive yaw angle, γ, of approximately 5 degrees (Figure 5.4).
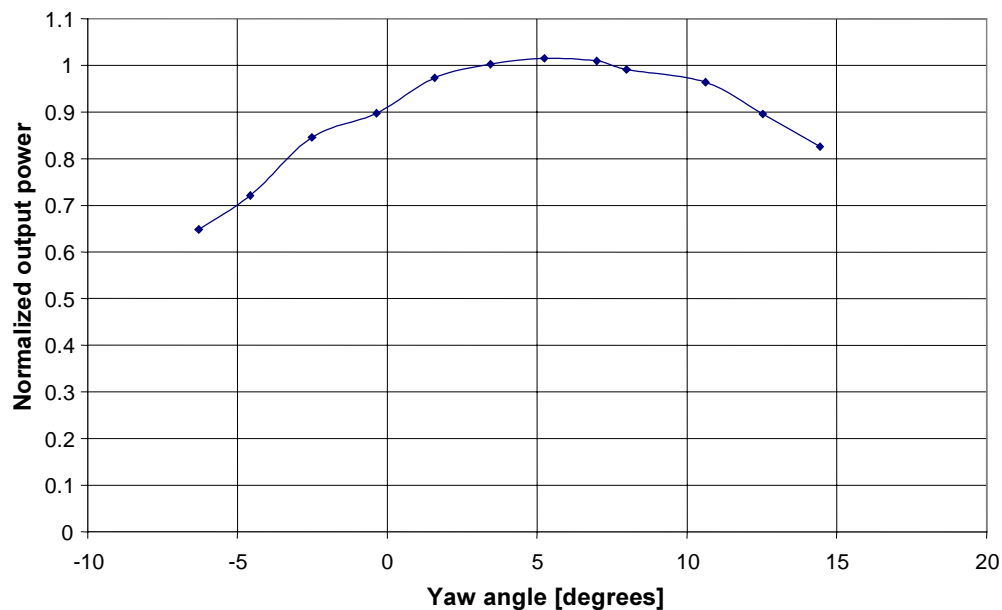

Figure 5.4: Power output at different yaw angles.

By choosing the interval in which to accept data from the graph in Figure 5.4, it seemed possible to limit the error due to the misalignment of the turbine by choosing to ignore measurements that has a yaw angle outside the interval $0 < \gamma < 10$. This would limit the measurement error due to the yaw angle to +2 and -10 %. These limits would, of course, be the outer limits of the error. Furthermore, this would not be a measurement error in the sense of the wind direction and velocity measurements, but would

instead be a deviation from the expected value. It would, however, be the actual power produced by the turbine, which means that it should not be corrected for but would have to be dealt with by introducing larger uncertainties. The other conclusion that could be drawn from these results is that the power output appeared to increase when the yaw angle was positive approximately 5 degrees. This would indicate that it is actually beneficial to strive for a couple of degrees positive yaw angle. However, theoretical calculations as well as more measurements are necessary to confirm this phenomenon, before any definite conclusions can be drawn.

5.2   Wind direction measurements

When evaluating the measured data and comparing it to the calculated values obtained from FFA-Milly and WindFarm, a slight discrepancy was noticed in the measured wind direction. It seemed as if the wind vane used in the measurements was constantly adding 10-15 degrees to the value that would be expected when examining the directions in which turbine 4 should be disturbed by the other turbines. Also, predictions by FFA-Milly displayed a wind direction for the disturbances that was different from the measurements, see Figure 5.5.
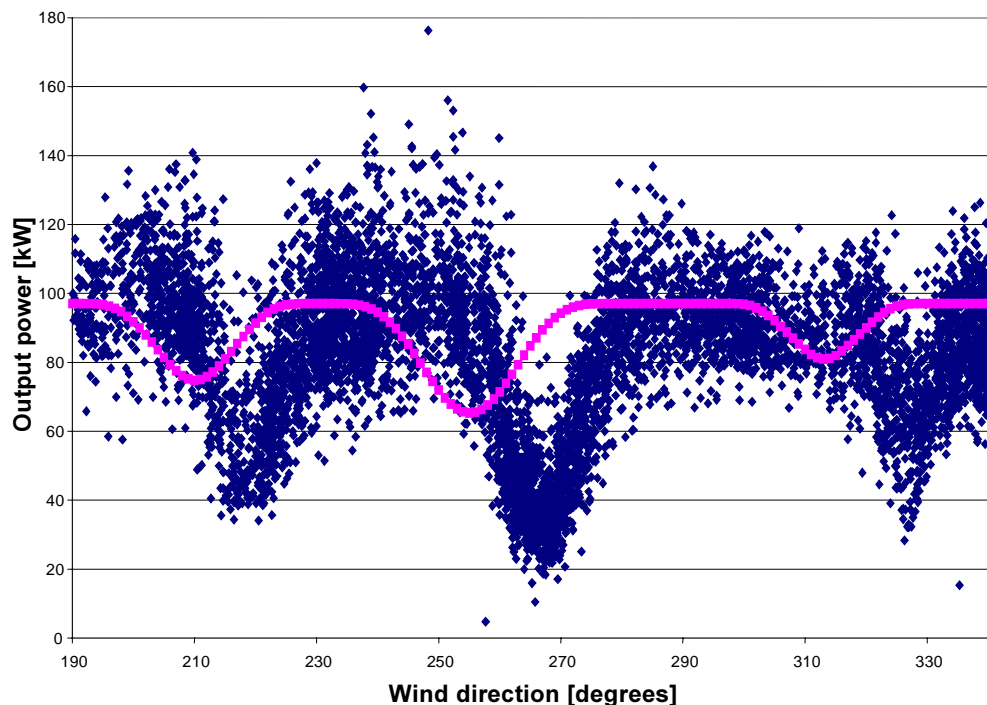

Figure 5.5: Measured, uncorrected wind directions compared to predictions made by FFA-Milly.

The vane is placed directly below the anemometer on a boom stretching out 1.2 m from the mast itself, see Figure 5.6

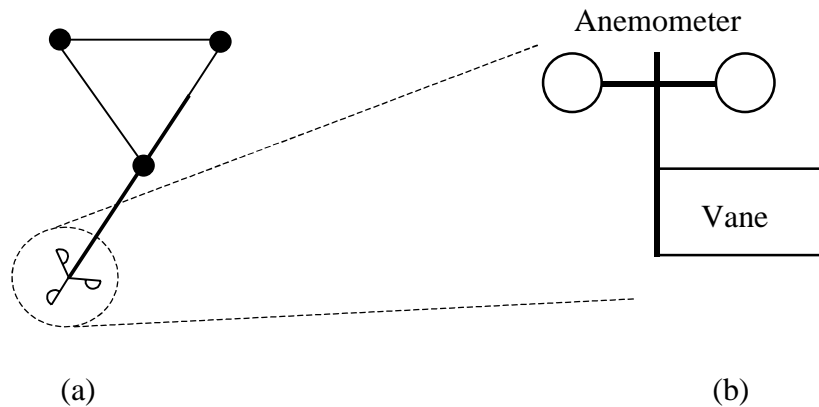<div style="text-align:center">(a)   (b)</div>

Figure 5.6: The mounting of the anemometer and wind vane on mast 1, (a) from above (b) from the side.

One reason for this deviation could be that the potentiometer connected to the vane was offset in the measurements. The vane had been calibrated in a wind tunnel and then shipped out to the site. The assumption that the conditions in the wind tunnel were the same as on the actual site could be somewhat incorrect. There are also corrections made when the data was converted from electrical signals to a format that could be read by the computer. These corrections could be erroneous, resulting in an error in the measured wind direction. This does seem to be a consistent error though, which would mean that it could be compensated for.

To be able to make corrections for the error in wind direction measurements, the directions where turbulence could be expected were looked at. Turbulence could be expected to occur where the anemometer was in the wake of another object or where the wind had traveled across rough terrain. Therefore, to be able to predict where the turbulence should be the highest, these directions on the map were examined (Figure 5.7).

The turbulence experienced by the measurement masts should be especially prominent when the mast is standing in the wake of the turbines or when the boom on which the wind vane is mounted is downwind of the mast itself. These directions were then compared to turbulence measurements. The direction in which the turbulence could be seen to increase was compared to the expected direction taken from Figure 5.7. The turbulence for the entire 360°, measured in mast 2 is shown in Figure 5.8. The turbulence was calculated as the standard deviation during the measurement minute divided by the measured wind velocity itself,

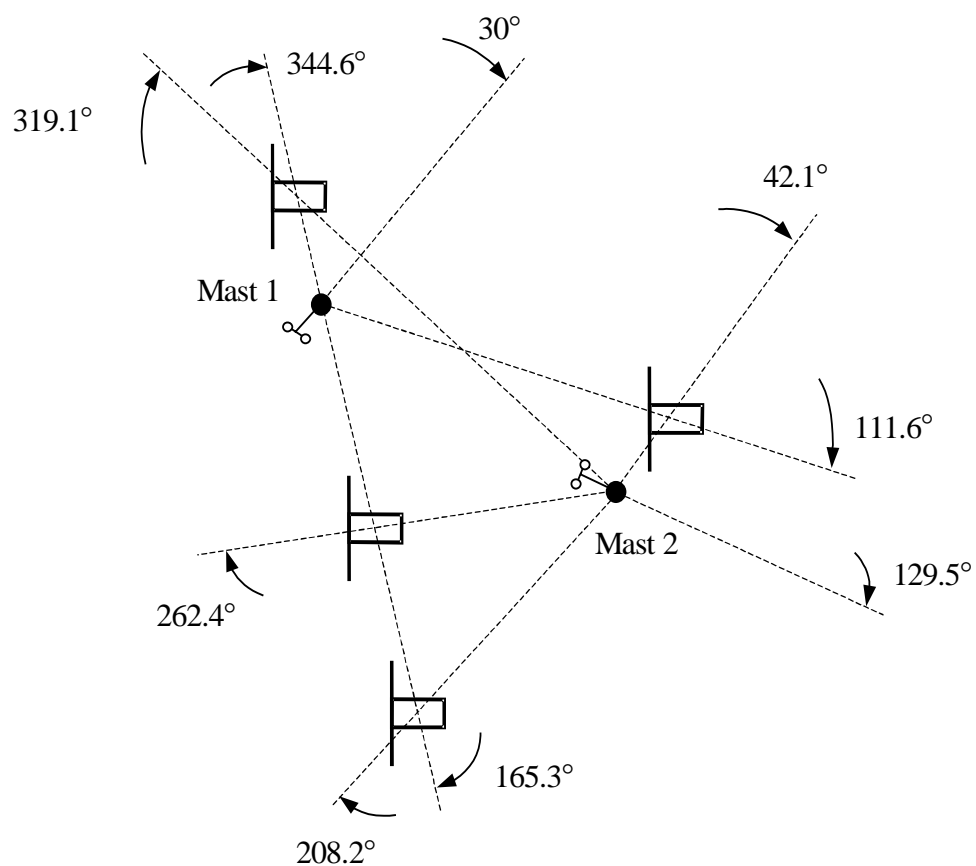$$turbulence = \frac{std(v)}{v} \cdot 100 \qquad (5.2)$$
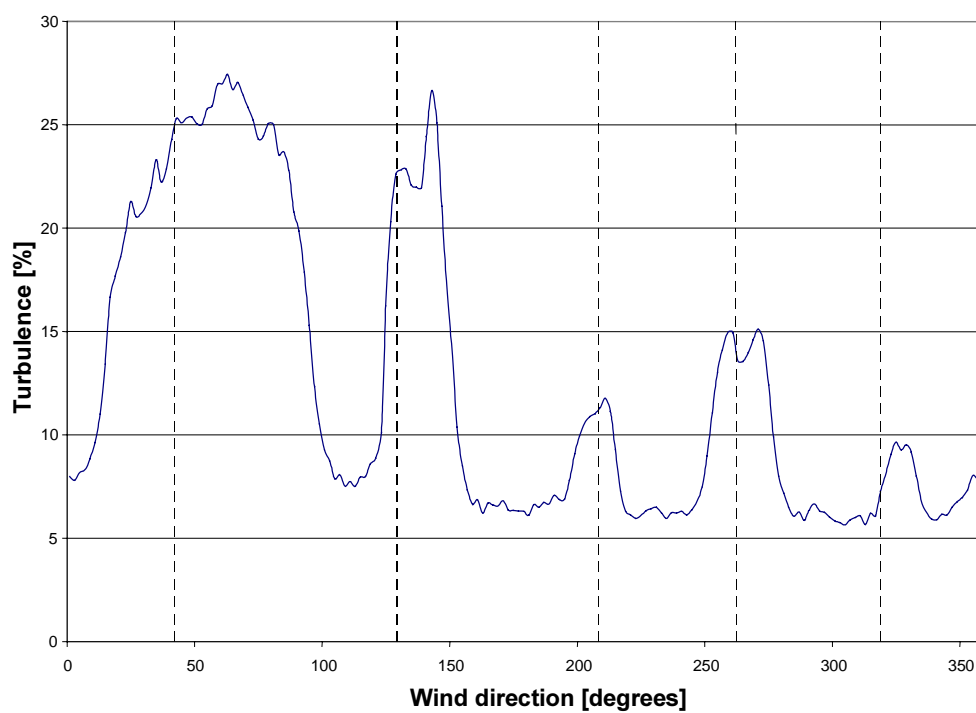
Figure 5.7: Map (compass) directions.

Figure 5.8: Turbulence measured in mast 2.

The dashed lines in Figure 5.8 represents the directions in which the peaks of the turbulence were to be expected according to the map directions in Figure 5.7. I.e. where the turbines were located with respect to mast 2 and the directions could be seen to correspond to the directions for mast 2. A similar curve was produced for mast 1 and the directions could then be compared to the ones from the map. The peaks of the data points represent the direction where the turbulence is at its highest, i.e. in the middle of the wakes. This has been done by Dahlberg and resulted in

$$\alpha_{corr} = 0.94 \cdot \alpha + 5.21 \qquad (5.3)$$

When correcting for the error in mast 2, the value is first transferred to mast 1 and then eq 5.3 is applied as in eq 5.4.

$$\alpha_{corr} = 0.94 \cdot (0.97 \cdot \alpha + 17.9) + 5.21 \qquad (5.4)$$

In Figure 5.9 it can be seen that when the wind direction is corrected with eq 5.3 the dips in the measured values correspond well to the predictions made by FFA-Milly and the directions given by the map in Figure 5.7.
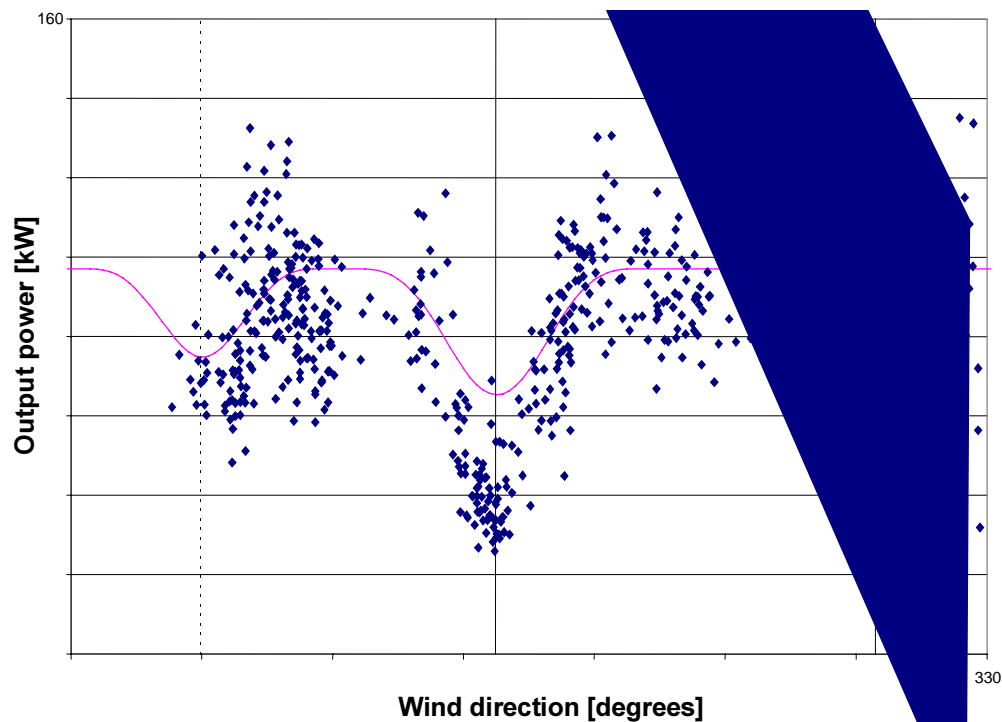

Figure 5.9: Wind direction vs. output power for Alsvik, compared to predictions made with FFA-Milly. The wind speed is 9-10 m/s and measured in mast 1.

Attempts were made to improve on these equations, using both second and third degree equations but the equations obtained did not produce results good enough to justify discarding Dahlberg's original correction equation.

The energy deficit calculated by FFA-MILLY in Figure 5.9 is preliminary and is at this stage to be taken as a comparison of wind directions only, not the deficit itself. A more thorough investigation and comparison of FFA-MILLY with the measured data is done later in this report. The raw data was extracted by using measurements filtered according to the findings in chapter 5.1, where the yawed flow was examined.

5.3   Wind speed measurements

The wind velocity was measured with anemometers positioned in the two different masts located as shown in Appendix A. The measurements that were used were made in mast 1 with anemometers mounted at 7 different heights, of which only the measurements from hub height were used when plotting the power output.

5.3.1   The effect of deflected flow

When passing the measurement mast, the flow is deflected around the mast (see Figure 5.10) and this will produce an error in the velocity measurements. The wind speed would therefore, when the wind direction is as in Figure 5.10 (a), increase, or stagnate when the wind is flowing straight into the boom. This can be seen as an apparent drop in the averaged power output as the wind direction goes from 180 to 360 degrees, see Figure 5.11.

(a)   (b)
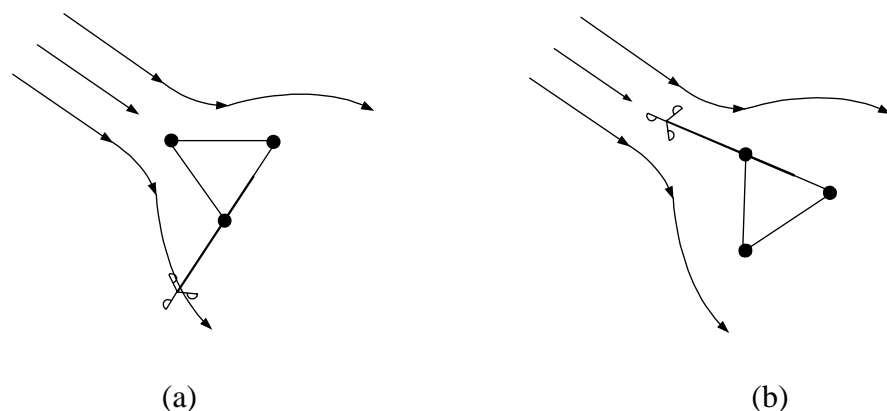
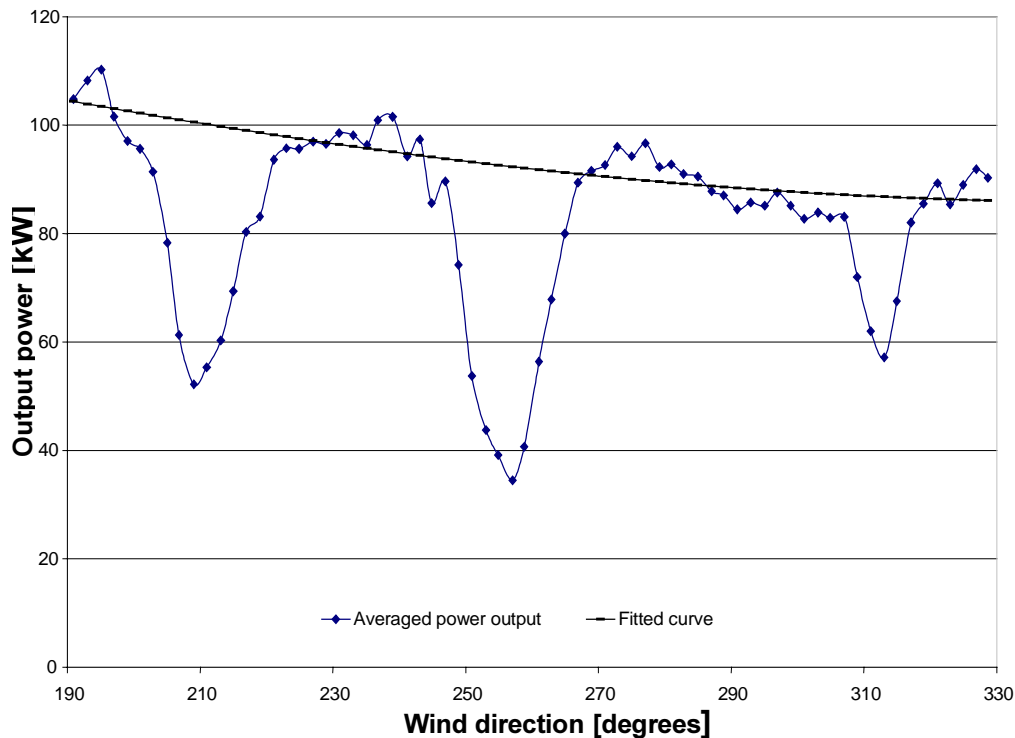Figure 5.10: The wind velocity increases in (a) and decreases in (b).

Figure 5.11: Averaged power output at wind speed 9-10 m/s, power drops as the wind direction increases.

The expected power output at 9-10 m/s for this type of turbine is around 95-100 kW taken from the power curve of the turbine. It is possible that the increased output around 200°–260° is caused by the error in wind speed measurements. When the wind speed measured is lower than the true value, it will give an apparent higher output at that velocity. These effects have been seen in wind tunnel tests and calculations conducted by Dahlberg [10] with anemometers of the same type as those used in Alsvik. The conclusion reached in those experiments was that the wind speed increases with a maximum of 1.3% when the boom is perpendicular to the wind, and decreases with a maximum of 2.7% when it is pointing straight into the wind as shown in Figure 5.10.

5.3.2   Wind gradients

When comparing the velocity measurements from the two masts, it could be seen in the power curve (Figure 5.12) that mast 2 seemed to be measuring a lower wind speed than mast 1.
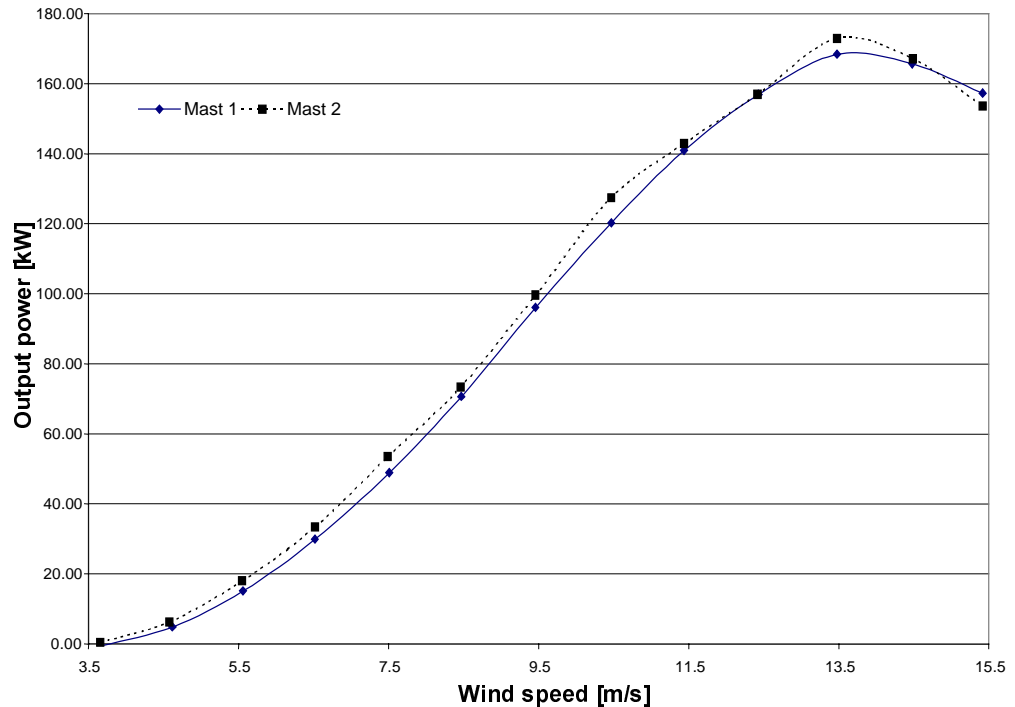

Figure 5.12: Power curves when the wind speed is measured in different measurement masts.

This was examined for different heights of the measurement masts and it seemed to hold true for the entire curve. The lower wind velocities measured by mast 2 could be due to the fact that it is placed further inland than mast 1, which is placed right by the water. Since the roughness height will increase over land the wind gradient, at the heights involved, might have changed when it reaches mast 2 compared to mast 1. The wind gradient for mast 2 might therefore be different than for mast 1 as shown in Figure 5.13.
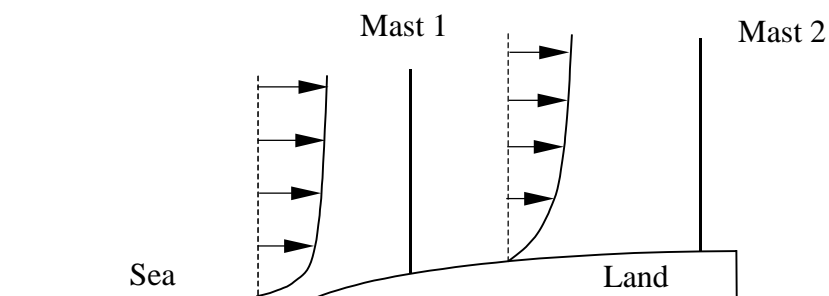
Figure 5.13: Different wind gradients for mast 1 and mast 2.

This hypothesis appeared to be confirmed when the measured wind gradients were plotted together in the same graph. Magnusson also mentioned this phenomenon for the Alsvik wind farm in [11]. The gradients shown in Figure 5.14 are measured at a wind speed of 6-8 m/s and 8-10 m/s at hub height, when the wind direction is in an interval of 285–295 degrees.
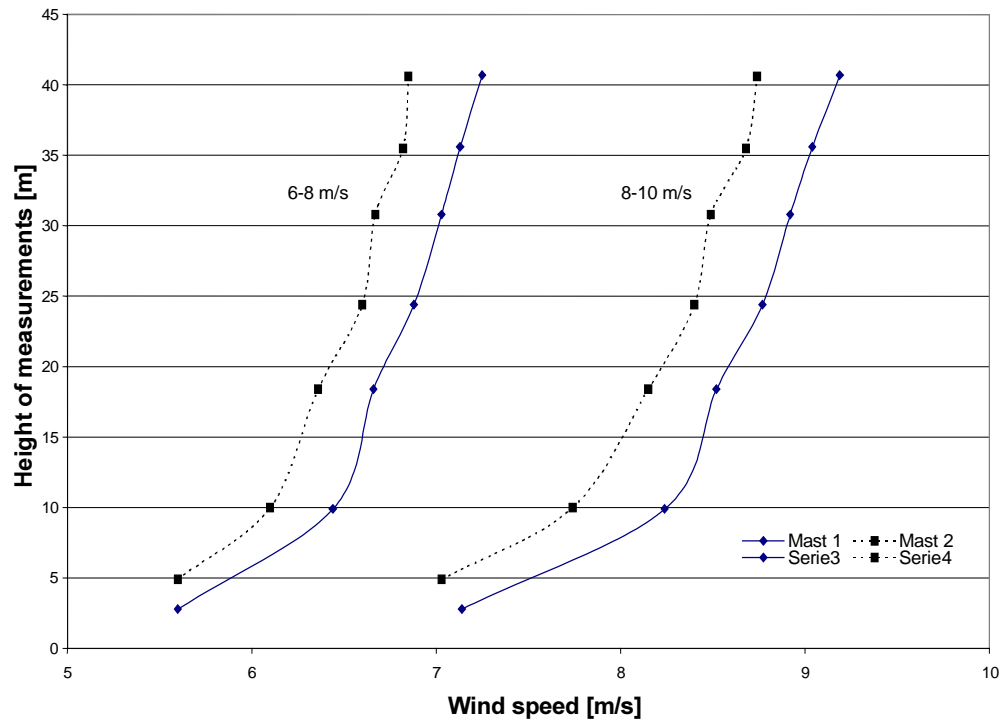

Figure 5.14: Different wind gradients for the two measurement masts taken at two different wind speeds.

According to Figure 5.14, the wind speed at mast 2 was clearly lower than the one from mast 1. However, this might not hold true if the mast- and boom effects due to the deflected flow, discussed earlier, are taken into consideration. The booms on which the anemometers are mounted are aligned differently with respect to the wind. The boom mounted on mast 1 points in the direction of 210° while the boom on mast 2 is aligned in the direction of 303.5°. For the case when the wind was blowing in the direction of 285-295 degrees, as is the case in Figure 5.14, this would mean that the boom on mast 1 is perpendicular to the wind, while the one on mast 2 is pointing straight into the wind. Looking at Figure 5.10 this would represent case (a) and (b) respectively.

As has been discussed before, it has been shown that the wind velocity increases on the side of the mast while it is reduced in front of it due to stagnation. In this case the anemometer in mast 1 would be subjected to accelerated flow while the anemometer mounted on mast 2 should feel stagnation due to this effect. If this behaviour was taken into consideration

and the velocities corrected, the difference between the two wind gradients was no longer very large (Figure 5.15).
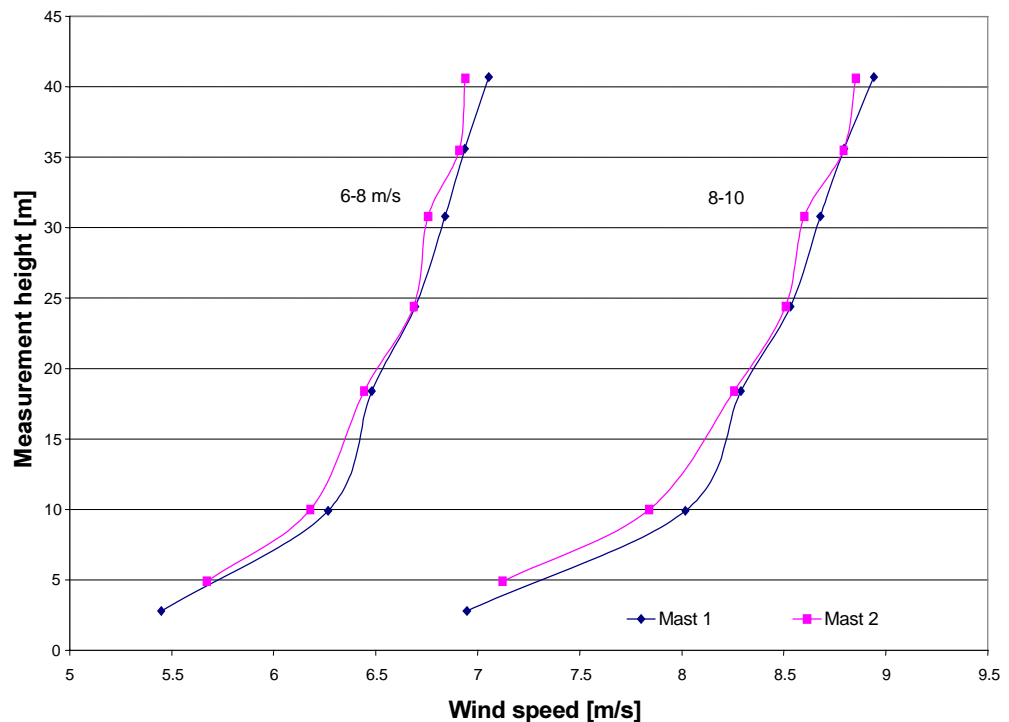

Figure 5.15: Wind gradients at two different wind velocities. The values have been corrected for mast- and boom effects.

It seems as if there still remains a difference between the two gradients. Calculating the difference in percent, the wind speed has been reduced about 1% when it reaches mast 2 compared to mast 1. This, however, is such a small error that it can not really be measured. It will therefore not be taken into account when producing error bars.

5.3.3   Using the turbines to measure the wind speed

The apparent difficulties of the anemometers to make accurate measurements introduced the need for and alternative way of getting the velocity at the site. A different way of measuring the wind speed is to use the wind turbines themselves as anemometers. The wind turbines might even be better measuring devices for wind velocity than the anemometer in this case since they measure the actual velocity felt by the rotor swept area when the turbines are producing power. If the power curve were to be used, the measured output power could be used to determine what the wind speed should be in that instance. For example, if the output power is measured to be 95 kW in one instant, the power curve would give the wind speed to be around 9.5 m/s, see Figure 5.16.
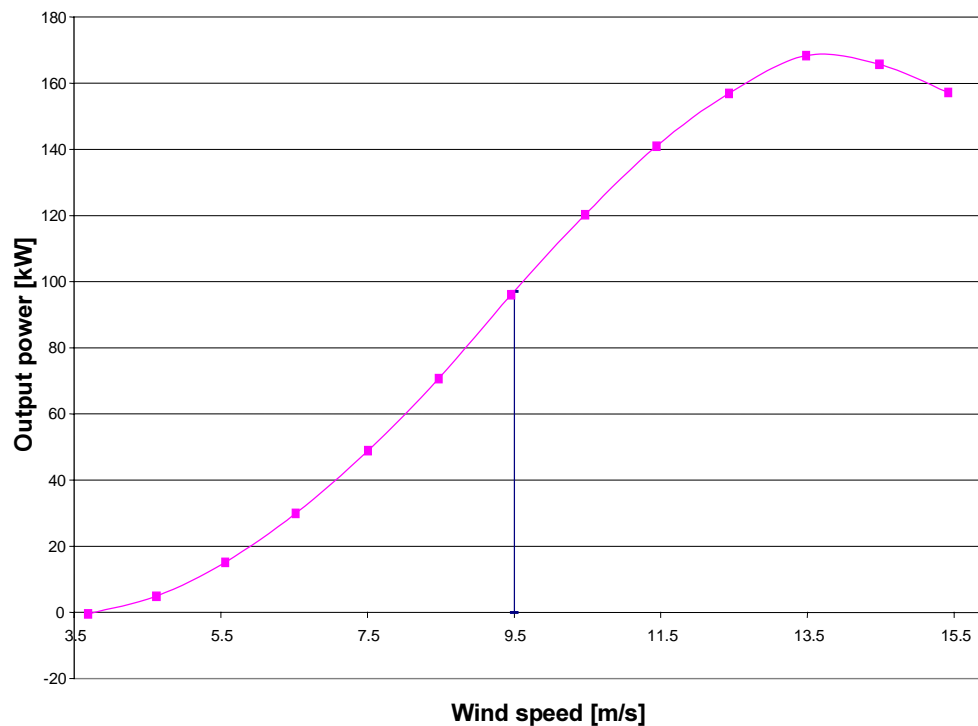
Figure 5.16: Wind speed taken from power curve with the aid of measured output power.

This value would of course be acquired by interpolation to achieve greater accuracy. When using this method, the drop in power output noticed in Figure 5.11 should be eliminated. The wind speed measurements made by the turbines themselves are insensitive to the effects that disturb the measurements made by the mast-mounted anemometers, such as boom- and mast effects (Figure 5.10).

The output power was taken as an average between turbines 1 through 3 when the wind was blowing from the sea, i.e. the interval of 190-330 degrees. This was when the three turbines were undisturbed and also the interval where there existed a lot of good wind data. These two approaches to measuring the wind speed are compared in Figure 5.17.
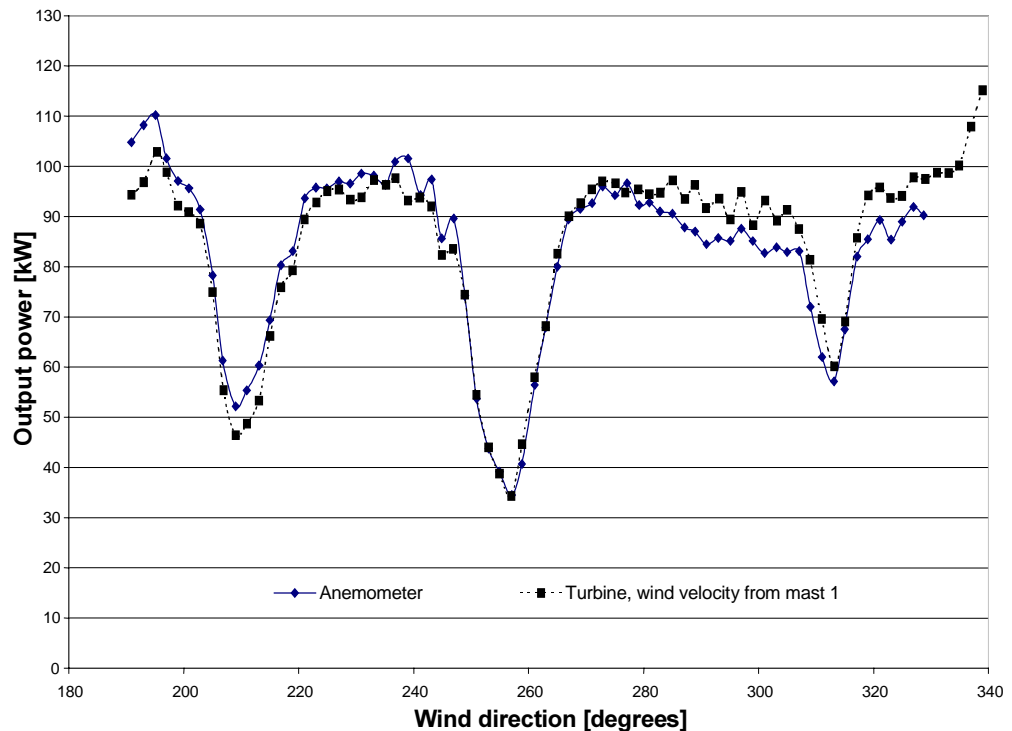
Figure 5.17: Comparison between the power when the wind speed is measured by the turbines and by the anemometer at a wind speed of 9-10 m/s.

It can be seen in this figure that when the anemometer in mast 1 measures the wind speed in the region of 180–250 degrees the values of the power output are higher than when the speed is measured by the turbines. Also in the region of 270-310 degrees the power output can be seen to be lower. This could be due to the mast and boom effects mentioned earlier, which the turbines do not feel. This means that the tendency of the average power output to drop in the undisturbed regions is eliminated when the turbines are used for wind velocity measurements, and the error due to the mast- and boom effects discussed earlier is removed. This together with the comparison made in Figure 5.17 leads to the conclusion that using this method for wind speed measurement is actually more accurate than using the anemometer.

5.3.4   The effect of using different power curves
When using the turbine to measure the wind speed, the results are heavily dependent on which power curve is used. In this case two different curves were compared to evaluate which to use when determining the wind speed.

- Power curve produced using measured data from Alsvik
- Calculated wind-power curve for the Danwin 23/180 turbine using the software WINRO [12]
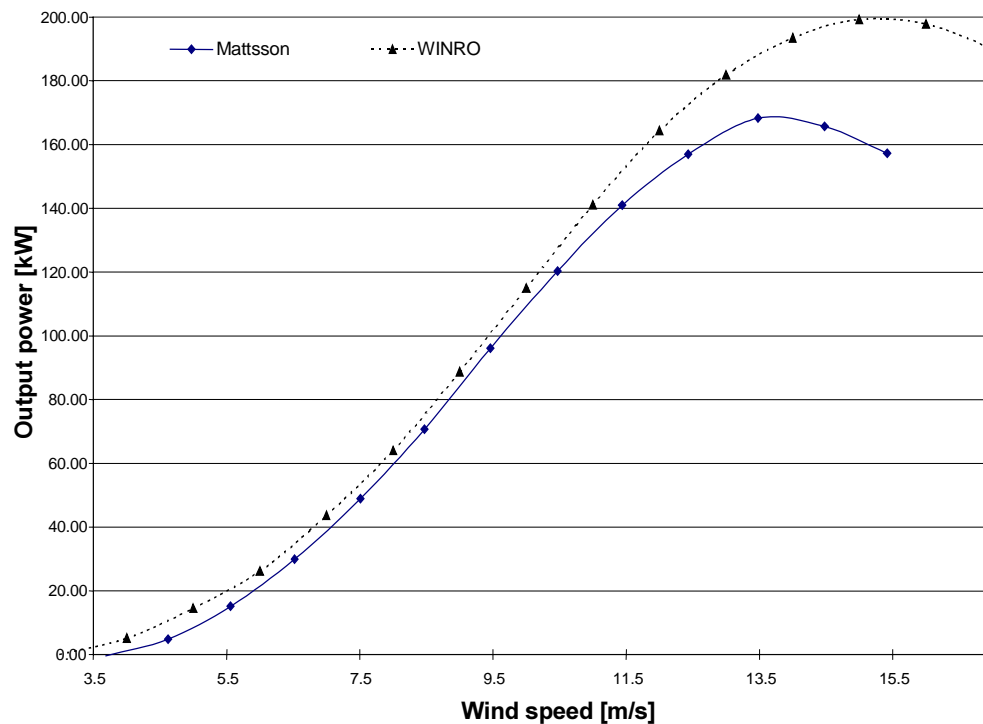
Figure 5.18: Power curves using different methods.

When looking at these different curves the problem is to choose the one that is closest to the truth. The difference between the one calculated by Dahlberg using WINRO [12] and the measured, uncorrected one is relatively large, especially when the wind velocity increases over 10 m/s. When producing output power curves using the graphs in Figure 5.18 the results between the two differ quite a lot, around 10%, especially in the region above 12 m/s, see Figure 5.19. It should be mentioned that the power curve given by WINRO is the shaft power, while the measured power curve is the electrical power given by the generator. This means that to be able to use the one from WINRO some corrections have to be applied to account for this.
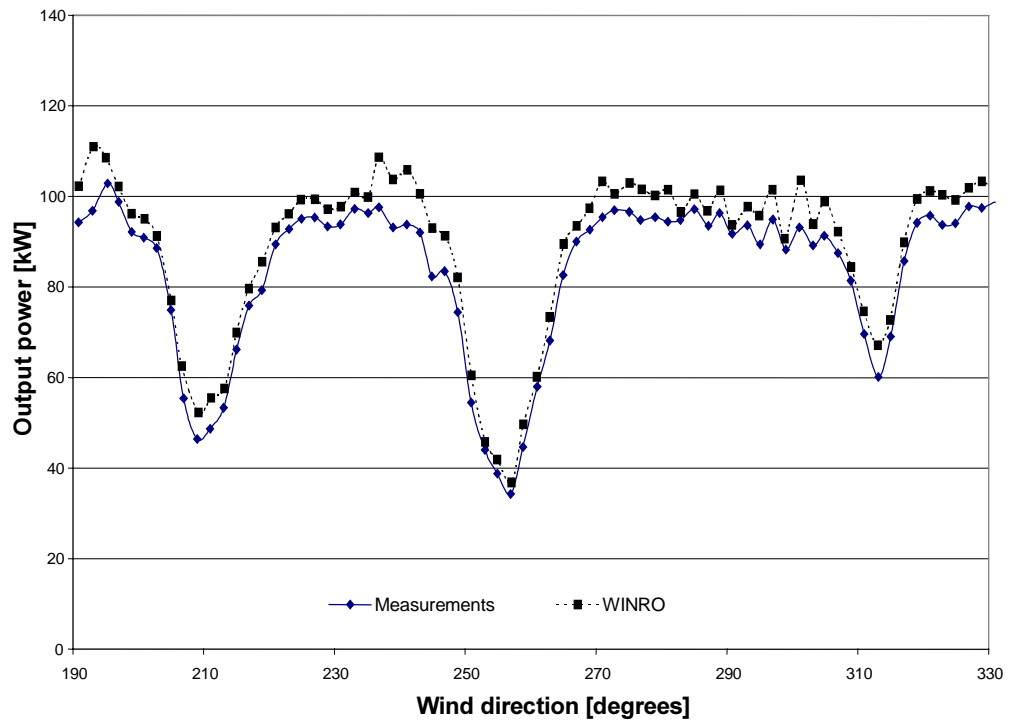
Figure 5.19: Wind direction - output power produced using different power curves in Figure 5.18.

The reason that the two curves in Figure 5.19 do not differ more is that they are produced in the wind speed range 9-10 m/s. In this region the differences between the two power curves are small and the differences will not be that great. The conclusion from comparing these two methods of obtaining the power curve is that the measurements should give a more accurate representation of the actual situation at the site.

6 Comparison with previous study of Alsvik

Jan-Åke Dahlberg at FFA has extensively studied the measured data from the Alsvik wind farm. One main difference between those studies and this one is that the data has been collected in smaller wind velocity bins. Dahlberg used wind velocity bins of 2 m/s while the ones made in this study was 1 m/s. This was done partly in an attempt to lower the standard deviation of the measured output power within the bins. As the wind velocity interval over which the bin was created increase, the standard deviation within the bin can also be expected to increase, since the spread between the largest and smallest values would increase. When comparing the standard deviations it can be seen that the new, smaller bins have a smaller deviation than the old one, as could be expected due to the smaller spread between the values.

(a)   (b)
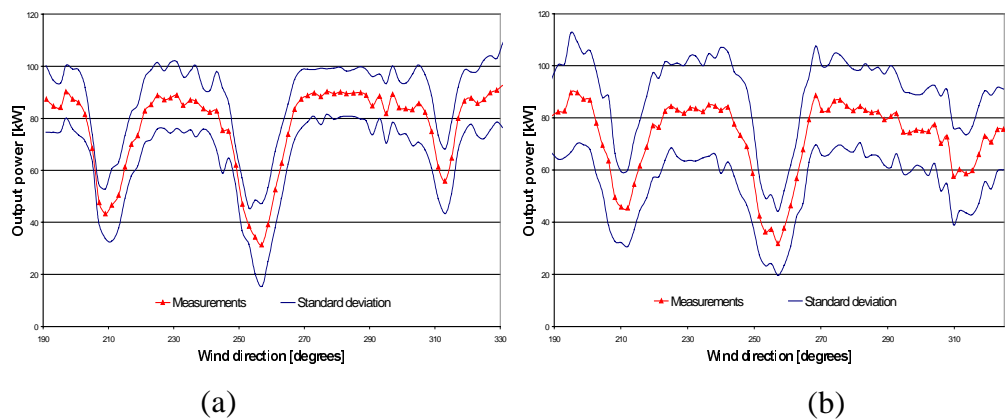
Figure 6.1: Comparing the standard deviations between the evaluation made in this report (a) and the one made by Dahlberg [12] (b).

The outer, dashed lines in Figure 6.1 represents the standard deviation of the bins for each point. It can be clearly seen that (a) has a significantly smaller standard deviation than (b). If the standard deviations are compared numerically, the average difference between the two is close to 55 %. To better be able to compare these two graphs the measured data in Figure 6.1, (a) has been corrected for mast- and boom effects. This means that the whole curve is somewhat lowered so that it is on the same level as the one produced by Dahlberg. This is not done later in the report since it is considered in this report to be preferable to try and show the uncertainties instead of correcting for them.

Further attempts were made to lower the standard deviation of the data by decreasing the bins even more. Both wind velocity bins of 0.5 m/s and direction bins of 1° were tried but that did not lower the deviation enough to

justify the smaller bins, with correspondingly fewer values in them. The amount of measured data points in each bin simply became too small to be able to draw any conclusions from.

7   Results

In this analysis of WindFarm, four tests were performed on three wind farm test cases. The Simple case (Chapter 4.1) was used to investigate how the energy yield calculations are affected by deviations in input data (Chapter 3.1). The Simple case was also used to analyse the difference between the wake and wake interference modelling methods available to the WindFarm user (Chapter 3.2).

A previous investigation into the wake interference effects of a planned wind farm in southern Kalmarsund was used to make the comparison of FFA-MILLY and WindFarm (Chapter 3.3 and 4.2). By running the same input data through both programs, a simple comparison could be made.

In the final test, WindFarm calculation results were compared to energy yield measurements previously carried out on an experimental wind farm. The energy yield of the Alsvik wind farm was calculated using wind data measured at the site (Chapter 3.4 and 4.3). The results of the calculations were thereafter compared with energy yield measurements for the corresponding wind data.

Having made a successful energy yield calculation, WindFarm presents the results either in the form of a graph or as a data list. Furthermore, the data list can be exported, in ASCII format, to a file. Each list features six columns containing wind direction [°], wind speed [m/s], base power [kW], topographic effects [%], wake losses [%], and total power [kW]. For the purpose of presenting multiple calculations in one graph, the results were exported with the energy yield for each calculation point of the wind direction. The data lists were thereafter imported to MS-Excel to simplify data handling and to produce graphic presentations. Since absolute figures were not of interest here, the energy yield results were presented in the form of wind farm or turbine efficiency,

$$Efficiency = \frac{Total \quad power}{Base \quad power} \cdot 100 \qquad (7.1)$$

It is important to note that the results presented in the following graphs only apply for the specified input data given in Chapter 4. The graphs should only be viewed as illustrations of how the change of an input parameter can affect the final result.

7.1   Input data

7.1.1   Turbulence

The simulated influence of atmospheric turbulence on the dissipation rate of wakes was analysed using only two turbines, one placed dead centre in the wake of the other. By measuring the energy production of the leeward turbine, for turbulence levels between 2 and 16%, the relation between turbulence and wake recovery could be illustrated (Figure 7.1). The graph shows the expected positive effects of atmospheric turbulence. Furthermore, the calculation was made for two instances of turbine separation, 5 and 11 rotor diameters. This produced an interesting result; the turbulence-efficiency curve for a turbine separation of 5 rotor diameters. Here WindFarm predicts a local efficiency maximum for 8% turbulence and a local minimum in the vicinity of 12% turbulence. As the distance between the turbines increases the curve straightens out until it shows an almost constant efficiency increase at 11 rotor diameters. The reason for this has not been established, but would require further investigation.

The influence of wind speed, in conjunction with turbulence, was also briefly investigated. An increase in wind speed, from 8 to 10 m/s, gave an increase in turbine efficiency (Figure 7.2), as could be expected if the thrust coefficient curve (Figure 4.3) is accounted for. However, there is a slight difference between the two curves for turbulence levels above 12%, suggesting that the positive effects of turbulence increases with the wind speed. Is this reasonable, is this a deliberate result or a side effect? Further investigation would be needed. On the other hand, the differences are so small they can probably be neglected.
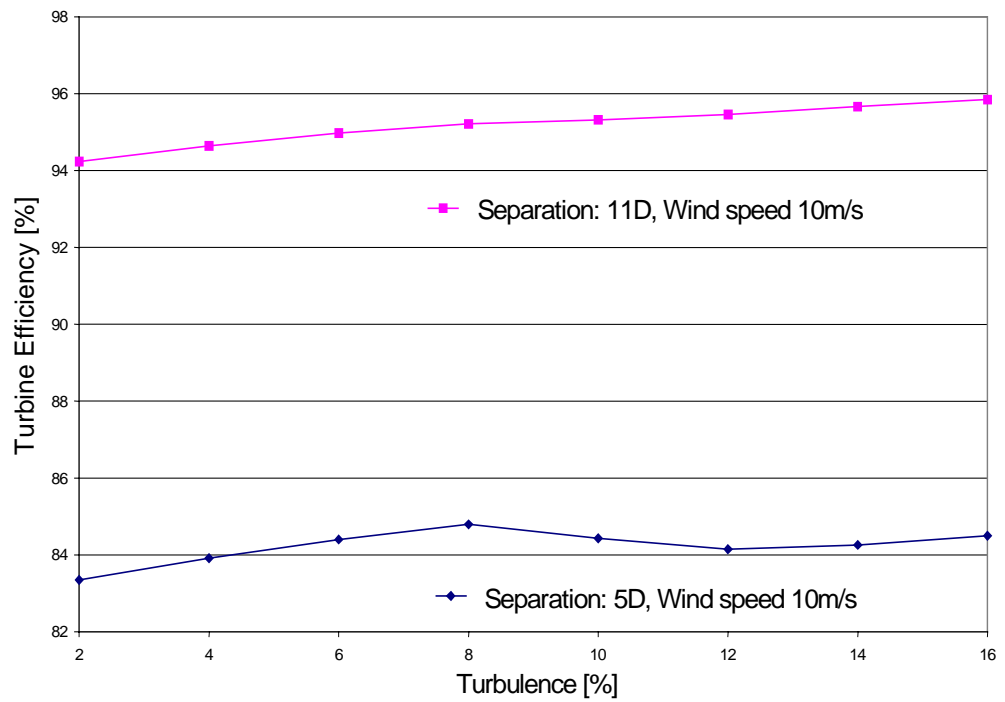
Figure 7.1: Turbine efficiency as a function of turbulence with curves representing two instances of turbine separation, 5D and 11D.
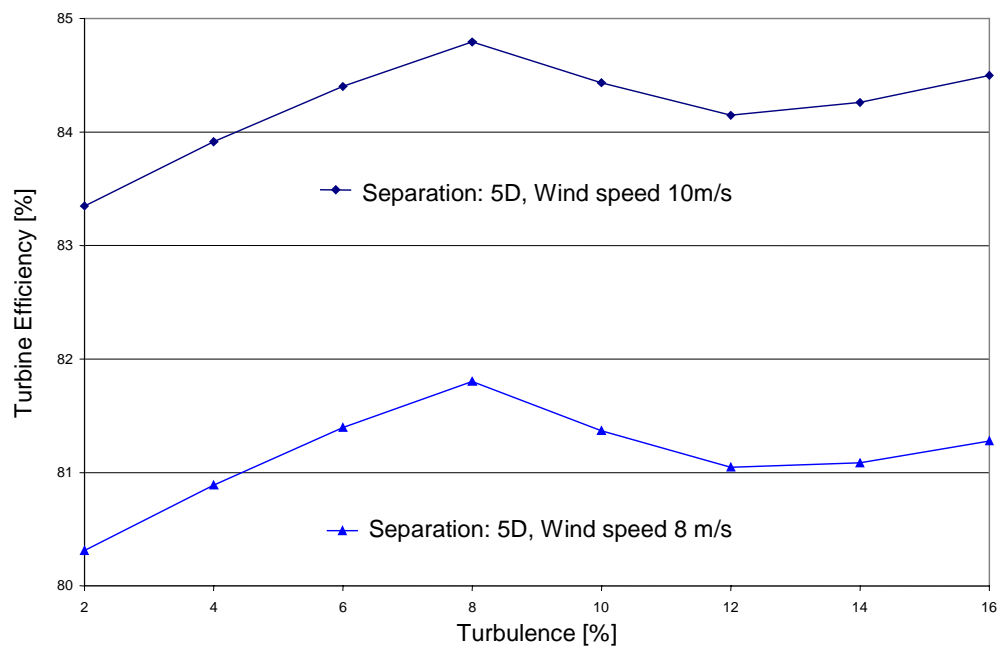

Figure 7.2: Turbine efficiency as a function of atmospheric turbulence. The curves represent the wind velocities 8 and 10 m/s.

7.1.2 Thrustcoefficient

Presented below (Figure 7.3) is a graph showing how a ten-percent deviation in thrust coefficient affects the calculated wind farm efficiency. The graph shows the efficiency for two different wind farm layouts, with the turbines placed in a row (*1xn*) or configured as a square (*nxn*), with an increasing number of turbines in the wind farm. The spacing between the turbines is 7 rotor diameters everywhere.

With the turbines placed in a row configuration the wind farm efficiency appears to converge towards a minimum value, whilst a square configuration rapidly loses efficiency as the wind farm size increases. A closer look at the graph reveals that the three curves, in each set, slowly diverge. The interpretation of this is that the effects of a deviation in thrust coefficient are a function of wake interference.

For a turbine working in the wake of another, the distance between them is an important factor affecting the efficiency of the leeward turbine.

In Figure 7.4 each curve represents the efficiency of a turbine, working at a specific distance from an upwind turbine, as the thrust coefficient is decreased. The graph implies that the wind speed deficit in the wake is a linear function of the thrust coefficient.
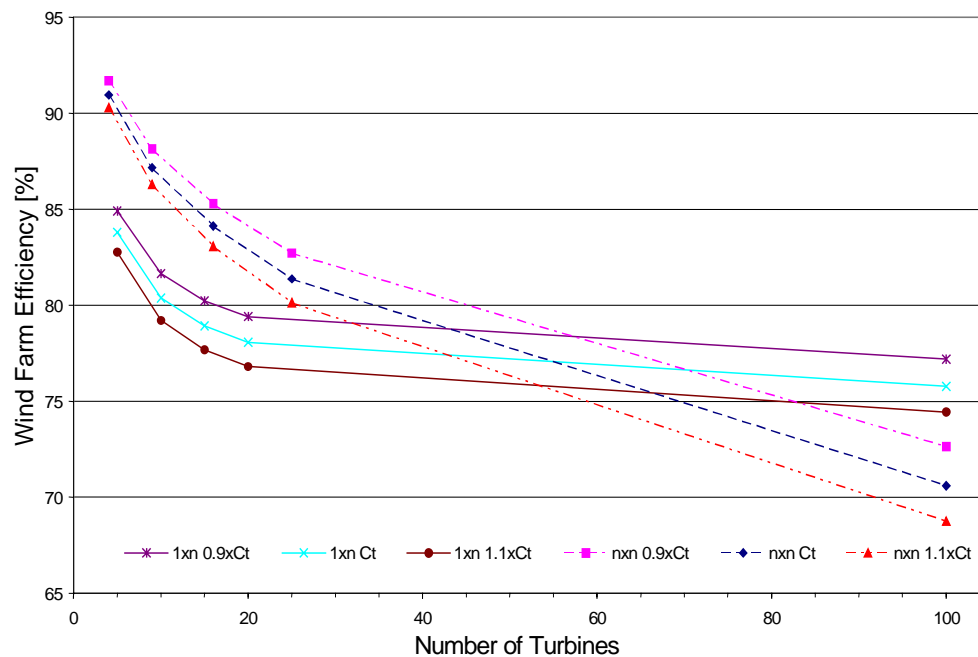
Figure 7.3: The effects of a 10% change in Ct on wind farm efficiency. The graph shows the results for a row (1xn) and a square (nxn) layout, containing between 5 and 100 turbines. The spacing between the turbines is 7 rotor diameters.
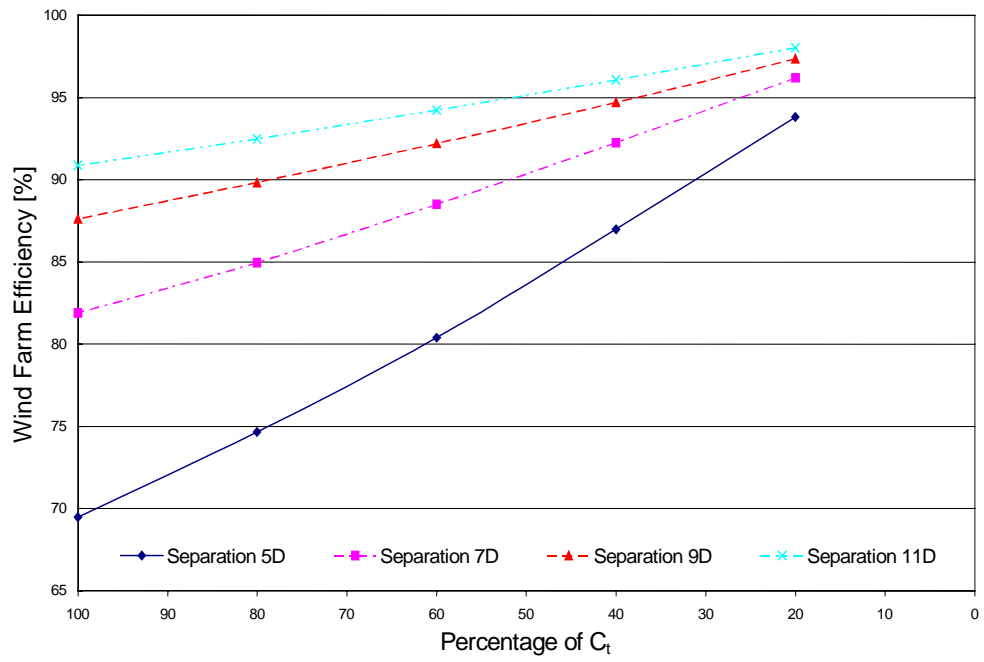
Figure 7.4: Efficiency for one turbine working in the wake of another,
whilst the thrust coefficient is reduced. The graph features four
different turbine separation distances.

7.2   Modeling

7.2.1   Wake model

The Axisymmetric and UPMPARK models give approximately the same results, differing with only 1 to 2 % seemingly independently of the number of turbines in the wind farm (Figure 7.5). The Park model on the other hand, calculates a wind farm efficiency that is initially 10 % lower, than the previously mentioned models, with the difference getting larger as wake interference increases. This is clearly seen in the case of the square configuration.
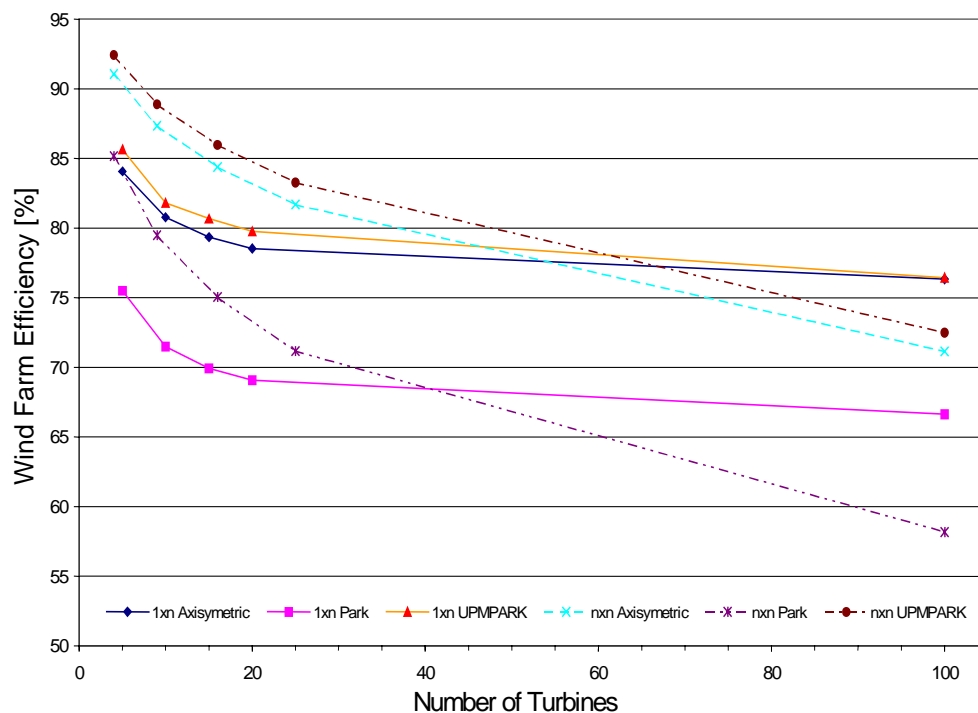
Figure 7.5: Difference between the three available wake models. The
            spacing between the turbines is 7 rotor diameters.

Here it is important to note that the Park model can not handle turbine thrust coefficients that equal or exceed the value of one. Since the N2 turbine used for these calculations did have $C_t>1$, the initial Park calculations failed. To remove this problem the C_t curve was 'trimmed' to make a wake model comparison possible. The effects of this measure are small, but it should be said that the curves in the graph above show slightly, less than a percent, higher values than otherwise.

7.2.2   Wake combination model

As expected the differences between the wake combination models become more apparent as the wake interference increases (Figure 7.6). The WindFarm users guide [5] recommends that the models Geometric superposition and Linear superposition not be used. Even so, the Energy balance and Sum of squares methods demonstrate quite large differences that would clearly be noticeable when doing calculations on large wind farms with intense wake interference.

7.2.3   Added turbulence model

Turbulence introduced by the turbine rotor works to diffuse the wake and, through dilution, reenergize the air behind a turbine. The graph below (Figure 7.7) illustrates how WindFarm models added turbulence. As with the other wake related models, the effects of added turbulence become more noticeable as wake interference increases. The difference between no added turbulence and the models, Garrad Hassan and Risø, appears to be constant.
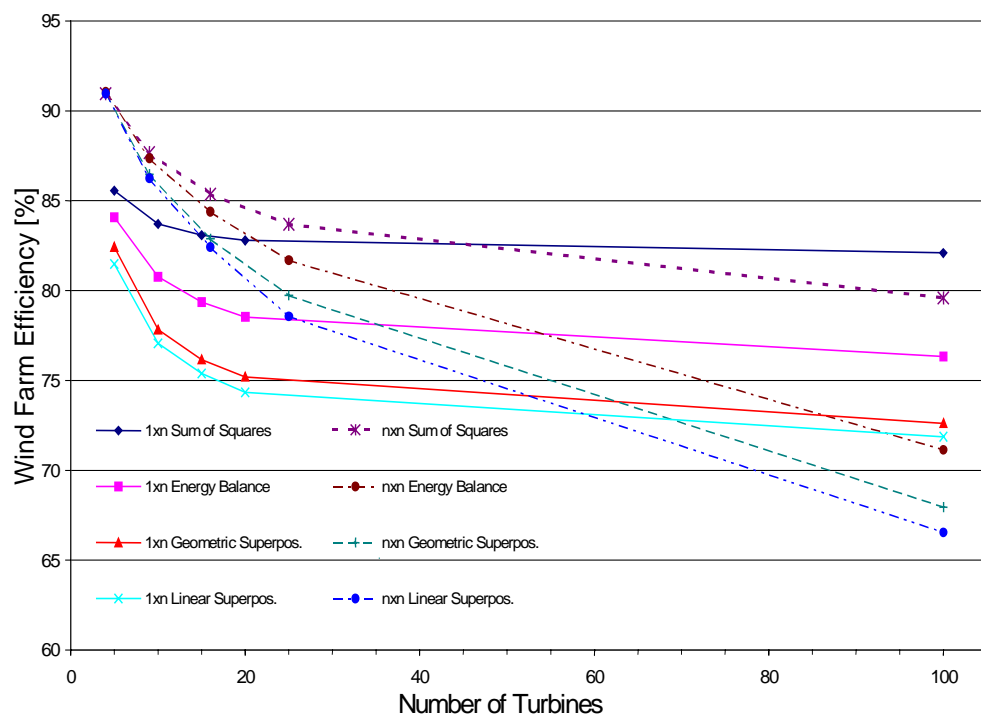
Figure 7.6: How the choice of wake combination model affects the calculations. The spacing between the turbines is 7 rotor diameters.
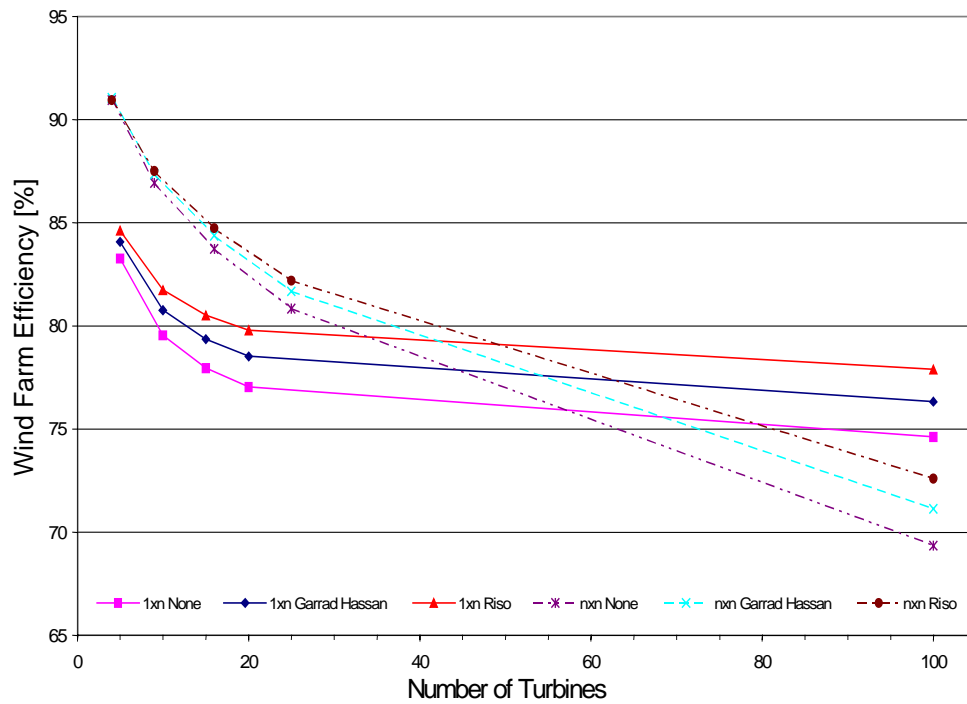
Figure 7.7: Turbulence introduced by the turbine rotor works to diffuse the wake. In the figure the difference between neglecting this effect and two methods of modelling it is shown. The spacing between the turbines is 7 rotor diameters.

7.3   Kalmarsund

When Dahlberg and Meijer [7] examined the offshore wind farm at southern Kalmarsund, they used two possible turbine layout configurations, the 14x7 and the 6TR, which were described earlier in chapter 4.2.3. Calculations were made using both a wind rose, describing the prevailing wind conditions, and a so-called step file with a uniform wind around the compass. These calculations, previously made with FFA-MILLY, were replicated as closely as possible using WindFarm.

The results listed in the table below (Table 7.1) clearly show that the wind farm efficiency for southern Kalmarsund is high. Thus it can be concluded that the effects of wake interference are small for both layout configurations, 14x7 and 6TR. This means that parameters such as turbulence, thrustcoefficient, and wake modelling methods would have had a lesser importance to the final results, as was seen in the previous tests (Chapter 7.1 and 7.2).

To put the results, the differences between the two programs and the two layout configurations, into perspective a few extra calculations were made. First an examination of how a 10% deviation in thrust coefficient changes the wind farm efficiency and thereafter three calculations showing the influence of a rotation of the wind rose. The extra calculations were only performed on the 6TR layout configuration.

		WindFarm		FFA-MILLY	
Layout		Efficiency	Total Yield	Efficiency	Total Yield
		[%]	[GWh]	[%]	[GWh]
14X7	Wind Rose	93.88	1040.75	93.6	1030.7
6TR	Wind Rose	94.04	1042.55	94.7	1042.6
14X7	Uniform wind	94.40	1046.45	93.6	1030.1
6TR	Uniform wind	93.05	1031.56	93.4	1028.5
6TR	Wind Rose, 110%Ct	94.13	1043.45		
6TR	Wind Rose, 90%Ct	95.02	1053.31		
6TR	Wind Rose -10 deg	94.08	1042.97		
6TR	Wind Rose -20 deg	93.21	1033.35		
6TR	Wind Rose +40 deg	95.15	1054.82		

Table 7.1: Total wind farm yield and efficiency for southern Kalmarsund as calculated by WindFarm and FFA-MILLY.

7.3.1   Wind rose

The graph below (Figure 7.8) shows the results of energy yield calculations, performed with WindFarm and FFA-MILLY, using the 6TR configuration and a wind rose as input data. As could be seen in Table 7.1 the differences in results between the two programs are small. However, the graph does indicate a possibility of increasing the wind farms efficiency. By rotating the wind farm approximately 40° anticlockwise, the region of intense wake interference should coincide with a wind sector of lower energy content. Rotating the wind rose 40° clockwise, thus simulating the rotation of the wind farm 40° anticlockwise, resulted in an improvement of the wind farm efficiency with approximately 1% (Table 7.1). This, however, is theoretical improvement, as it requires the wind rose to constantly mirror the conditions at the wind farm site.

7.3.2   Uniform wind

The use of a stepping wind file, uniform wind, has produced the energy production graph below (Figure 7.9). At a quick glance it appears as though the difference between the two models, WindFarm and FFA-MILLY, is constant but a closer look reveals some interesting details. It appears as if WindFarm predicts a higher energy production everywhere (1) except in the intense wake caused by the tightly spaced row of turbines (2) in the 6TR layout. Another interesting point of difference appears as the wind sweeps past 10 and 200 degrees. Here FFA-MILLY predicts the turbines to be undisturbed (3), whilst WindFarm shows some sort of wake interference.

The power production curves produced by FFA-MILLY appear to contain more detail than those done by WindFarm. This is most probably a consequence of using the wake meandering function in the WindFarm calculations. As mentioned earlier in chapter 3.2, wake meandering smears out the details as it simulates a wandering movement of the wake caused by turbulence.
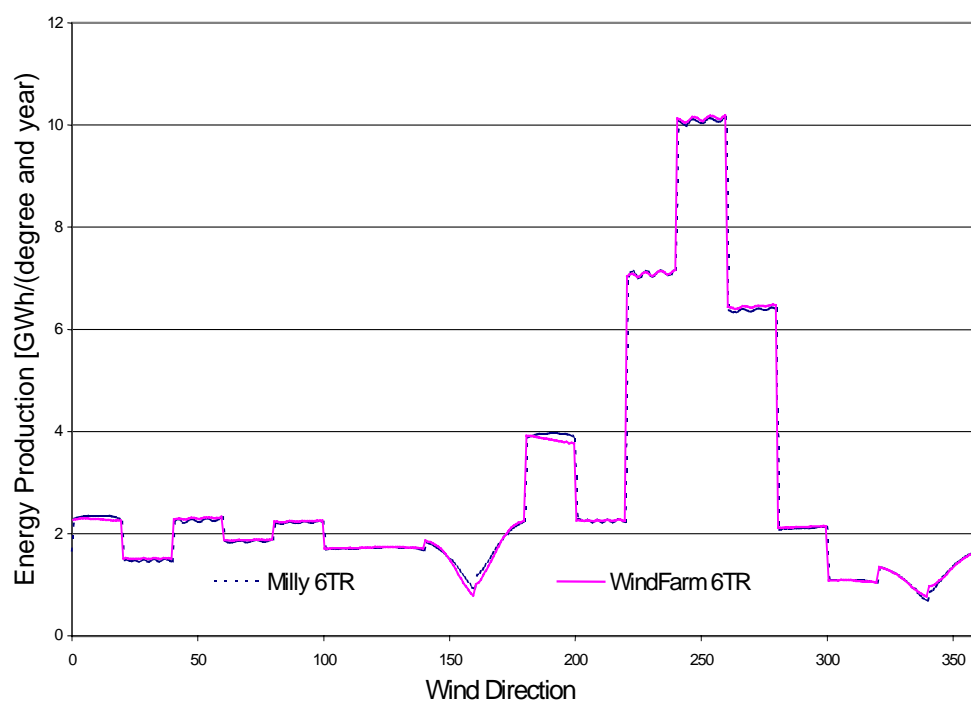
Figure 7.8: Energy production as calculated by WindFarm and FFA-MILLY for the southern Kalmarsund case using an 18-sector wind rose.
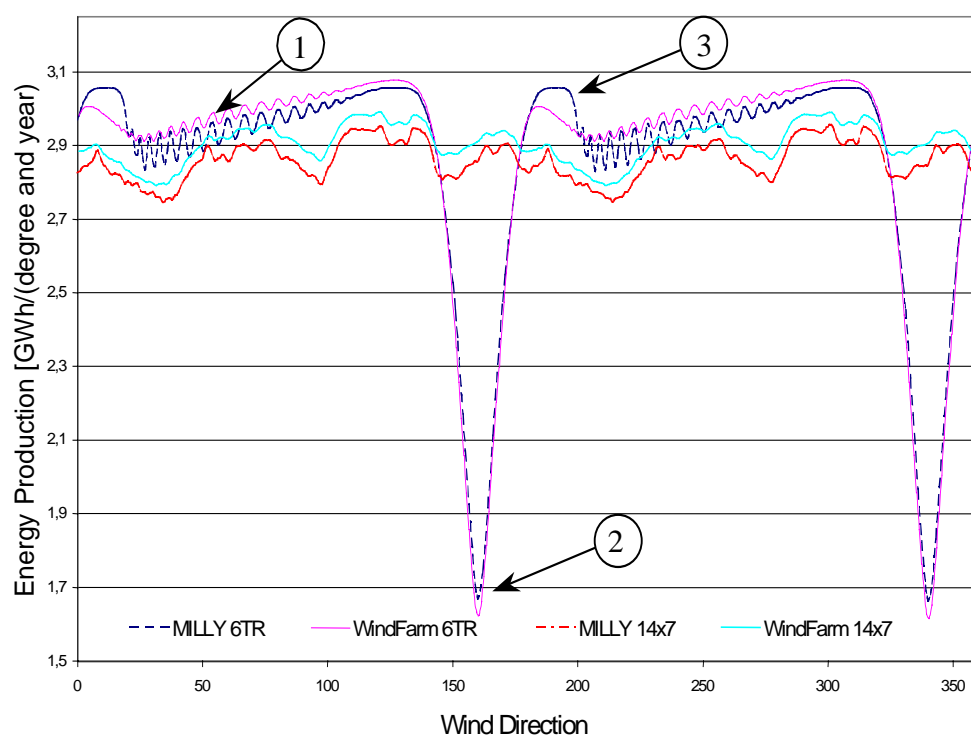

Figure 7.9: Energy production at the southern Kalmarsund wind farm, calculated by WindFarm and FFA-MILLY using a uniform wind.

8   Gathering the data from Alsvik

The objective of this study was to be able to quantify the uncertainties appearing in the graphs of the measured values so that they could be compared to the models. The most difficult part was to be able to quantify an uncertainty with a good, solid motivation. This is what has been attempted in the previous chapters and what remains now are to show the uncertainties graphically.

To better be able to compare the data with the models, the measured data should be presented on the same form as the calculated data given by WindFarm. This means that all the measurements for all the wind speeds would have to be gathered in the same graph and normalised with the expected power output at that particular wind speed. The bins will now contain all the data that has been extracted from the data files. The y-axis will therefore no longer display the actual power output, but instead the wake losses compared to undisturbed output, which is equal to 1.0. (Figure 8.1).

The data was weighted together depending on the amount of time each wind velocity appeared, meaning that the wind velocities that contained more measurement data was given a larger impact on the normalised curve. When trying to evaluate the data the most graphical way of doing it is to calculate an average value of the data and put error bars on it. The standard uncertainties for the data were calculated by taking the standard deviation for the bins and dividing it with the root of the number of values in the bin. This was weighed in the same way as the data itself. This was then added to the uncertainties from the yawed flow, discussed earlier. This uncertainty was considered being independent of each other making it possible to add the squares of the uncertainties. The result was a curve with normalised values with error bars.

The large uncertainties in the downward direction are due to the error of the yawed flow. Again it should be mentioned that these are extreme values of the error, i.e. the maximum error.
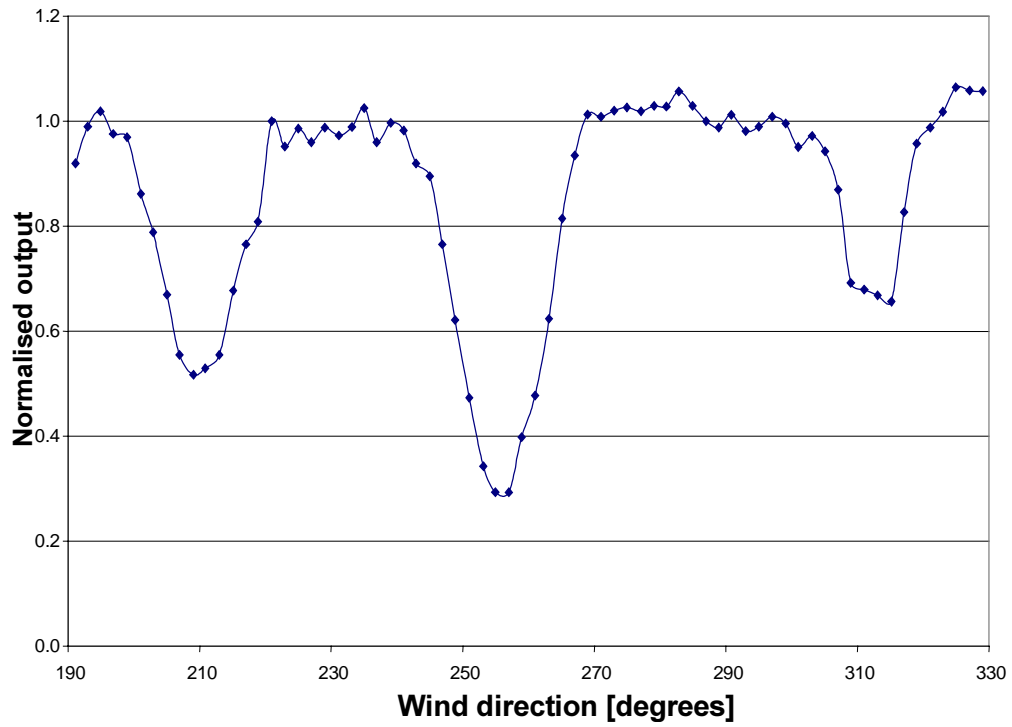
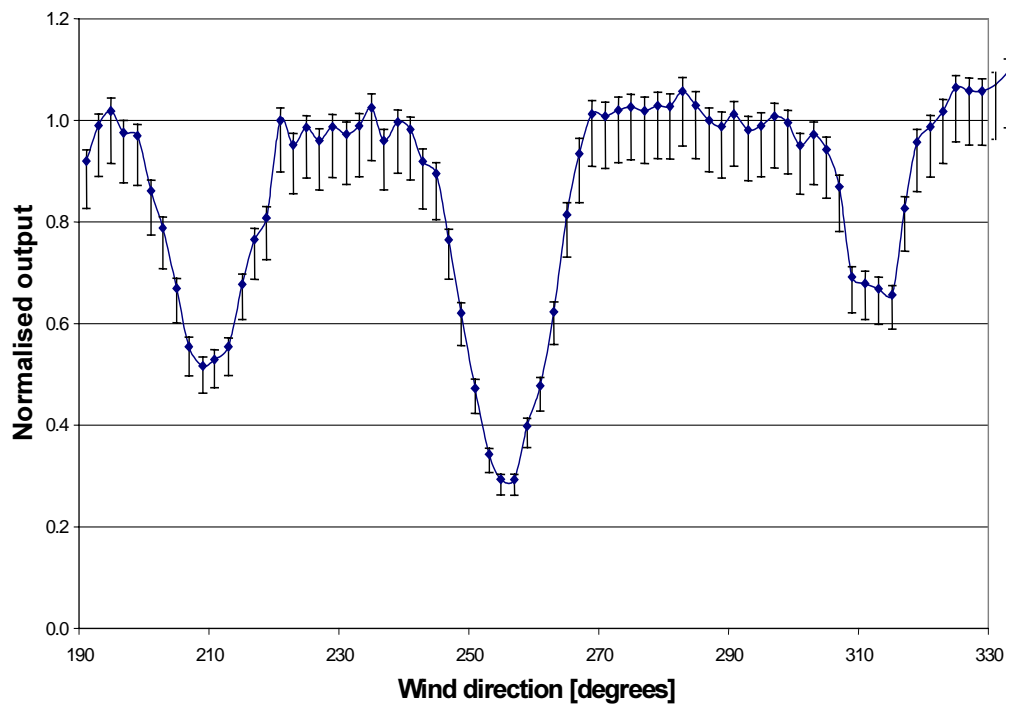Figure 8.1: Wake losses for turbine 4 for all the measured wind speeds

Figure 8.2: Normalised values with uncertainties.

9 Comparing the measured data with the models

The models that were compared with the measured data was the PARK/Wasp model, Ainsle's eddy viscosity model, a version of UPMPARK used in WindFarm and finally FFA-MILLY. All of them except FFA-MILLY are incorporated in to the software package WindFarm by ReSoft. The data for the Alsvik wind farm has been entered into these programs to be able to see how well the models predict the power output of the farm in general and turbine 4 in particular. The models have also been compared to the measurements in trying to calculate the total energy yield of the farm over the course of one year.

9.1 Predicting the energy deficit in the wakes

When comparing the models with the measured data, the focus is on trying to determine how well the models can predict the power loss of the turbine when it is standing in the wake of the others. One way of looking at this is to simply compare the graphs and see how well the model follows the measured value and see if it falls within the limits set by the error bars. The other method that will be used is to calculate the area in the dip representing the power loss, instead of merely looking at the "depth" of the dips in the graph. This would give a good representation of the entire power loss of the turbine when it is situated in the wake of the others.
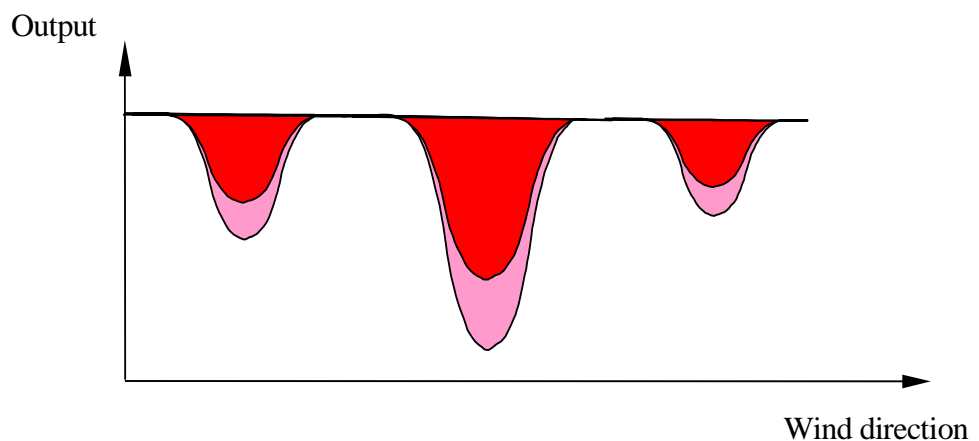
Figure 9.1: Looking at the area under the dips will give a good
representation of the velocity deficit in the wakes

The area is calculated using rectangular approximations of the dips. This method is not very exact, but in this case that is not necessary since we are only interested in the relationships between the areas, not the actual numerical size. This means that the scale on the y-axis of these graphs is a reference area and is only used for comparing the areas.

9.1.1   FFA-MILLY

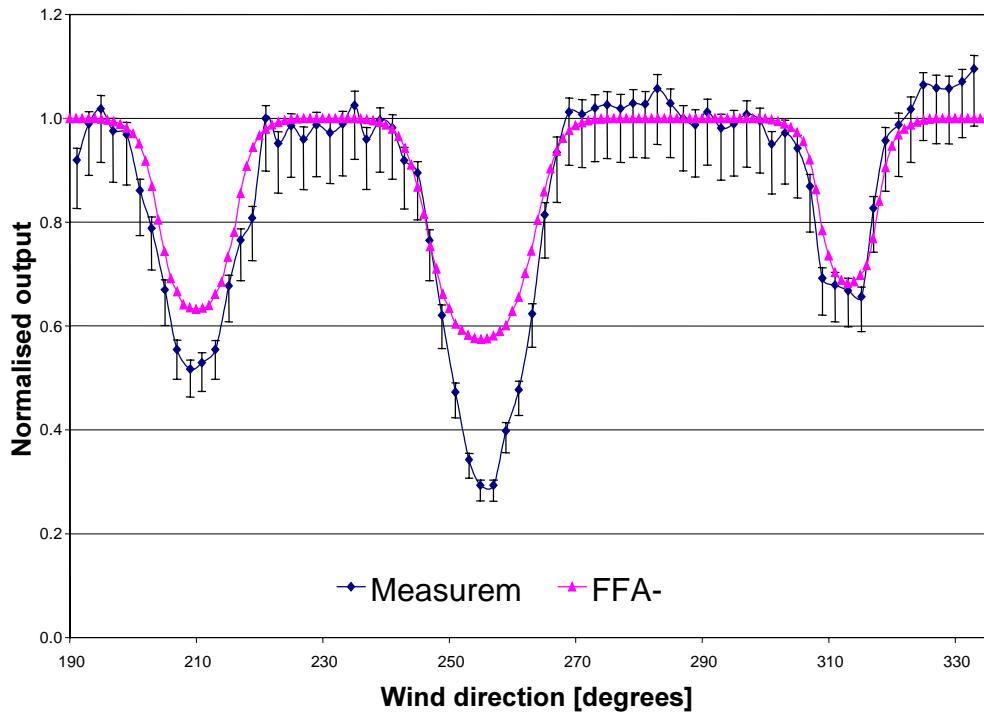The first model to be compared to the measurements is FFA-MILLY, developed at FFA based on the MILLY model described in [4].

Figure 9.2: Measured data compared to calculations by FFA-MILLY

When comparing the calculations made by FFA-MILLY to the measured data it can clearly be seen that the program tends to underestimate the velocity deficit in the wake of the closest turbine. When the spacing increase the program becomes better at predicting the deficit, and when the distance to the upwind turbine is 9.5D the estimation is very good. These results should be compared with the conclusions made in chapter 7.3, where the comparison with southern Kalmarsund is discussed. When comparing the area of the dips, the program shows a pretty good correlation with the measurements when the disturbing turbine is at a distance of 9.5 D while it becomes less accurate when the distance between turbine 4 and the disturbing turbine is smaller.
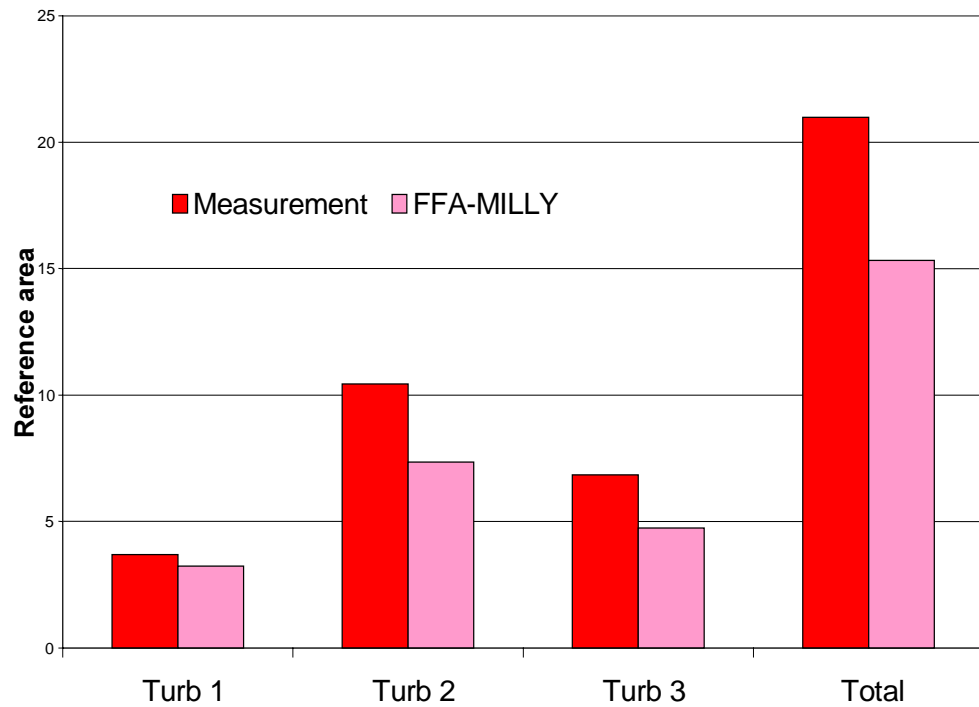
	FFA-MILLY Area	Measurements Area	Difference [%]
Turbine 1	3.23	3.30	12.25
Turbine 2	7.35	9.25	29.61
Turbine 3	4.74	6.18	30.77
Total	15.32	18.72	26.94

Figure 9.3 and Table 9.1: Comparison between the areas of FFA-MILLY and the measurements

The model seems to be able to predict the deficit in the wake of turbine 1 pretty well, with the result falling within 12% of the measured value. The difference in the other two wakes, where the disturbing turbine is closer, is larger as can be seen in Figure 9.3 and Table 9.1.

9.1.2 Ainslie

As with FFA-MILLY, Ainslie's eddy viscosity model can be seen to under estimate the wake deficits when the distance to the disturbing turbine is at a distance of 5 turbine diameters. For larger distances, when the separation is greater, the model becomes better at predicting the deficit in the wake.
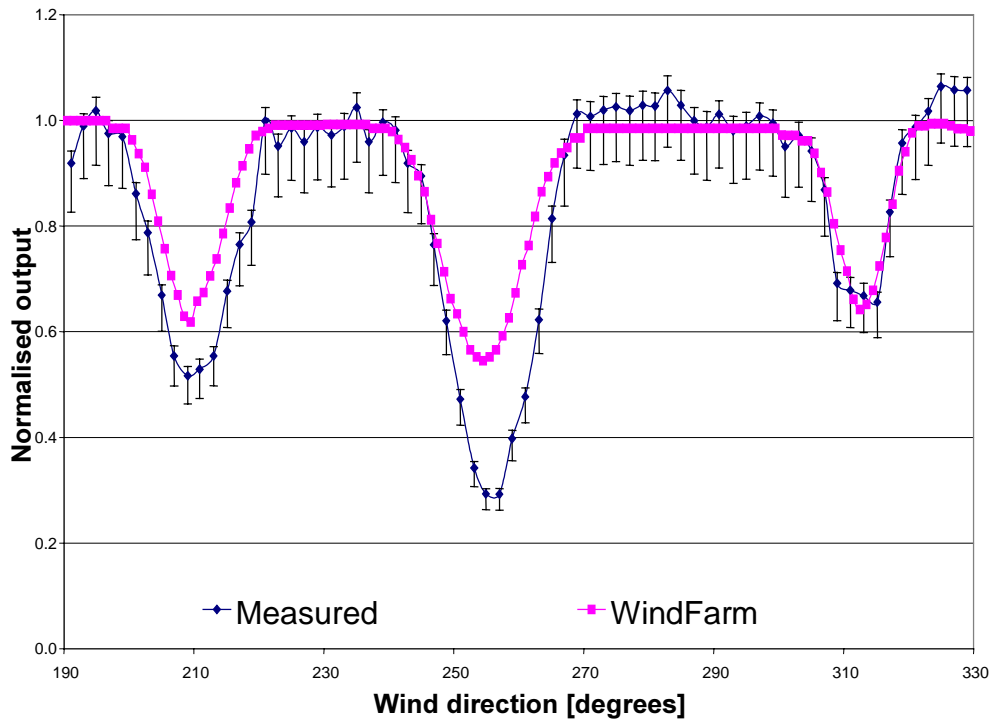
Figure 9.4: Comparison of Ainslie's model with the measured values with the error bars attached.

However, it is not until the distance to the upstream turbine increases to 9.5D that Ainslie's model starts to fall within the error bars.
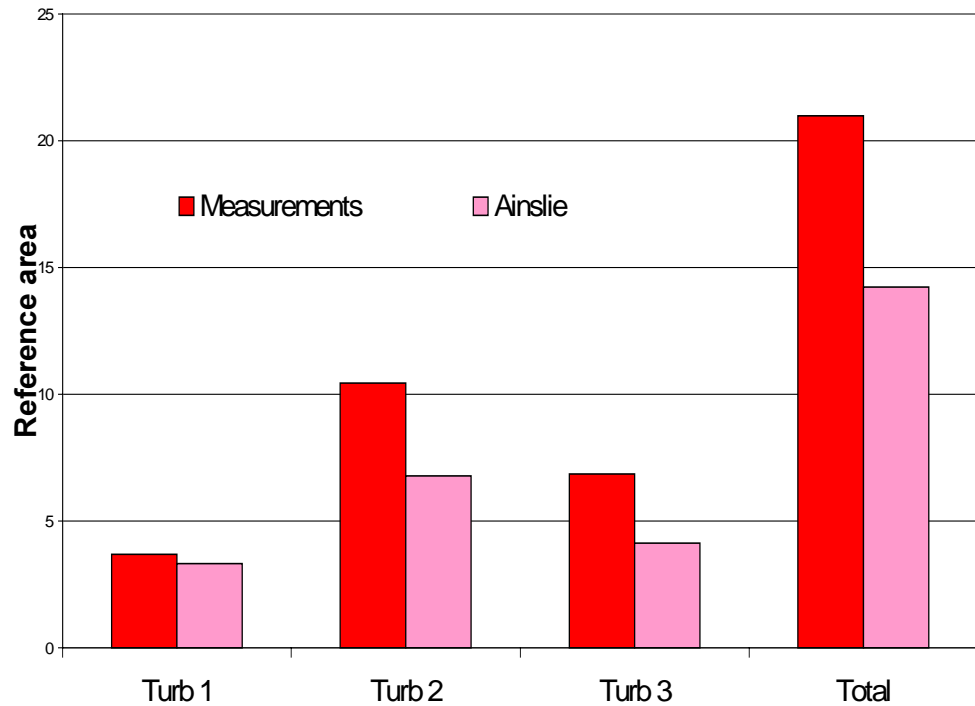
	Ainslie Area	Diff from measurements [%]
Turbine 1	3.32	9.82
Turbine 2	6.77	35.10
Turbine 3	4.12	39.84
Total	14.22	32.21

Figure 9.5 and Table 9.2: Comparisons between Ainslie's model, using windrose and step file as input data, and the measurements.

The eddy viscosity model does predict the deficit in the wake better than FFA-MILLY in the wake of turbine 1, but apart from that FFA-MILLY generally makes a better prediction.

9.1.3 UPMPARK

WindFarm does not solve the equations of UPMPARK every time the calculations are performed. Instead Harris [5] has solved UPMPARK for a number of test cases, and from those results created a straight look-up table which is utilised when the model is to be used. See chapter 3.2**.**
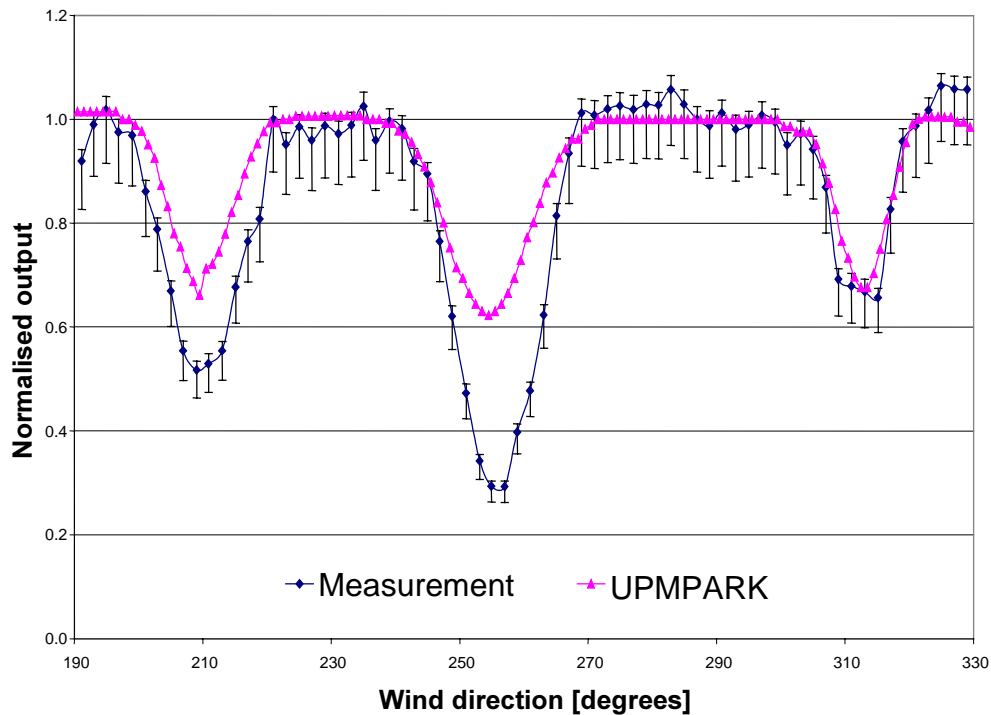
Figure 9.6: Measured data with errors compared to calculations by
         UPMPARK

The UPMPARK model seems to seriously underestimate the velocity deficits in the wakes. However, it too seems to make better predictions as the distance to the disturbing turbine increases.
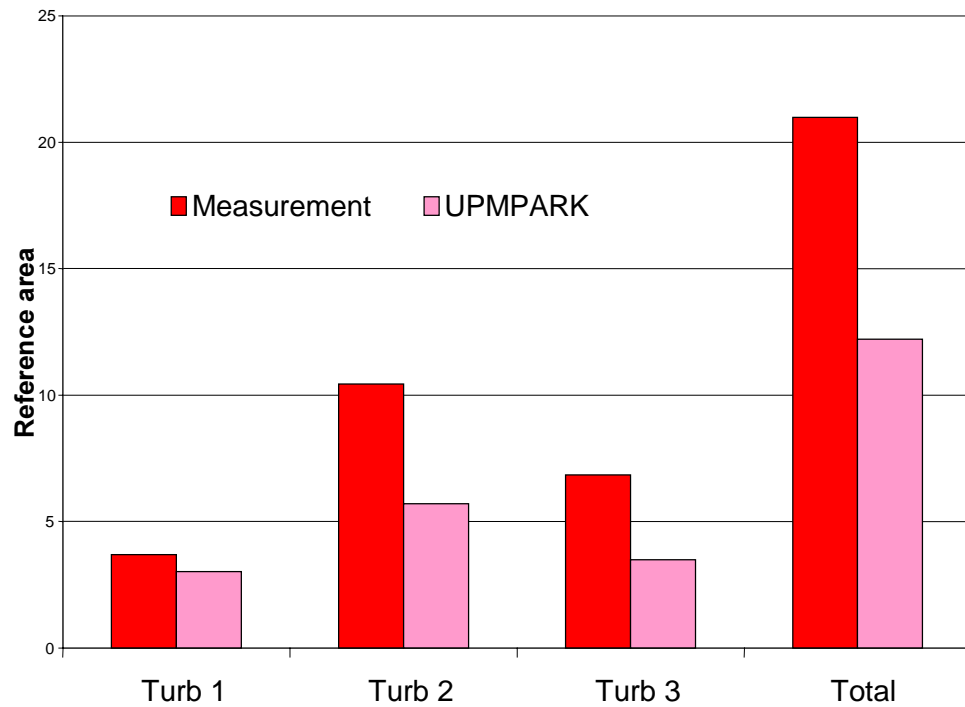
	UPMPARK Area	Measurements Area	Difference [%]
Turbine 1	3.01	3.30	18.17
Turbine 2	5.70	9.25	45.39
Turbine 3	3.48	6.18	49.09
Total	12.20	18.72	41.82

Figure 9.7 and Table 9.3: The area calculated by UPMPARK compared to measurements

UPMPARK does not predict the wake losses very well in this case. This is a somewhat surprising result, since the model is regarded as being quite accurate, as it is based on fundamental fluid dynamics equations [4]. One reason for the poor performance of UPMPARK in this case could be that it is not the model itself making the calculations, but rather the look up table in WindFarm mentioned earlier, using results from UPMPARK, again see chapter 3.2

9.1.4   PARK

The linear PARK model by Katic was then used in WindFarm to make calculations on the Alsvik case.
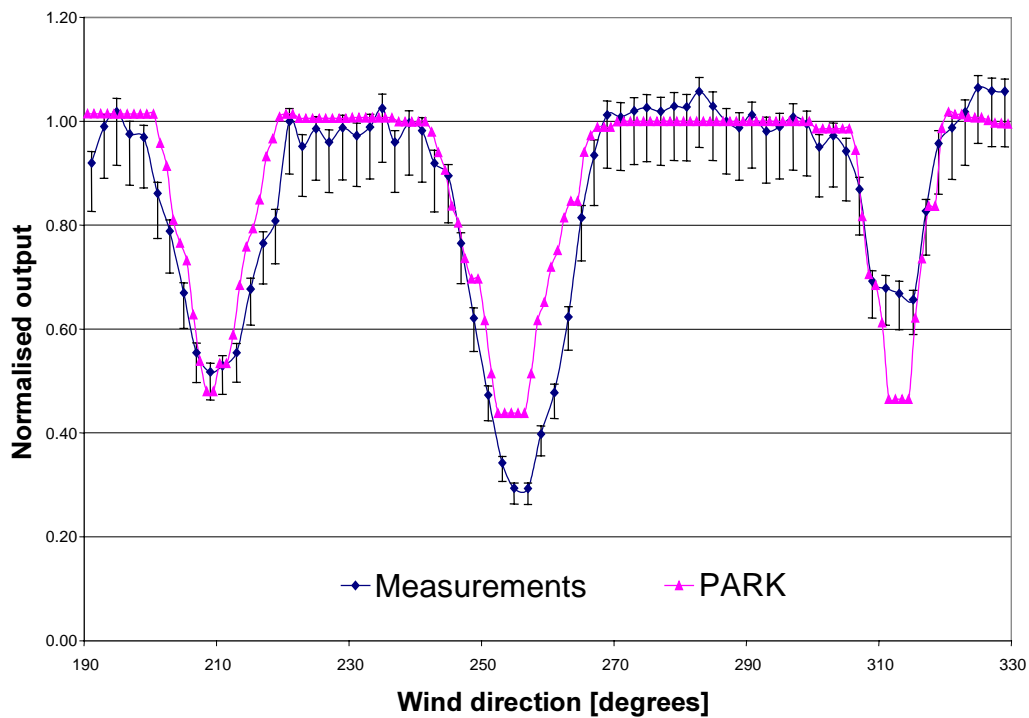

Figure 9.8: Measured data with errors compared to calculations by PARK

The PARK model seems to estimate the velocity deficit in the wake of the closest turbine (#2) better than the other models. It is possible, however, that the linearity of the model makes it difficult to make accurate predictions when the disturbing turbine is farther away. When looking at turbine number 1, PARK actually overestimates the deficit in the wake, the only model among the ones studied in this report to do so.

|	PARK Area	Measurements Area	Difference [%]
Turbine 1	4.38	3.30	32.65
Turbine 2	7.44	9.25	19.52
Turbine 3	5.08	6.18	17.81
Total	16.90	18.72	9.76
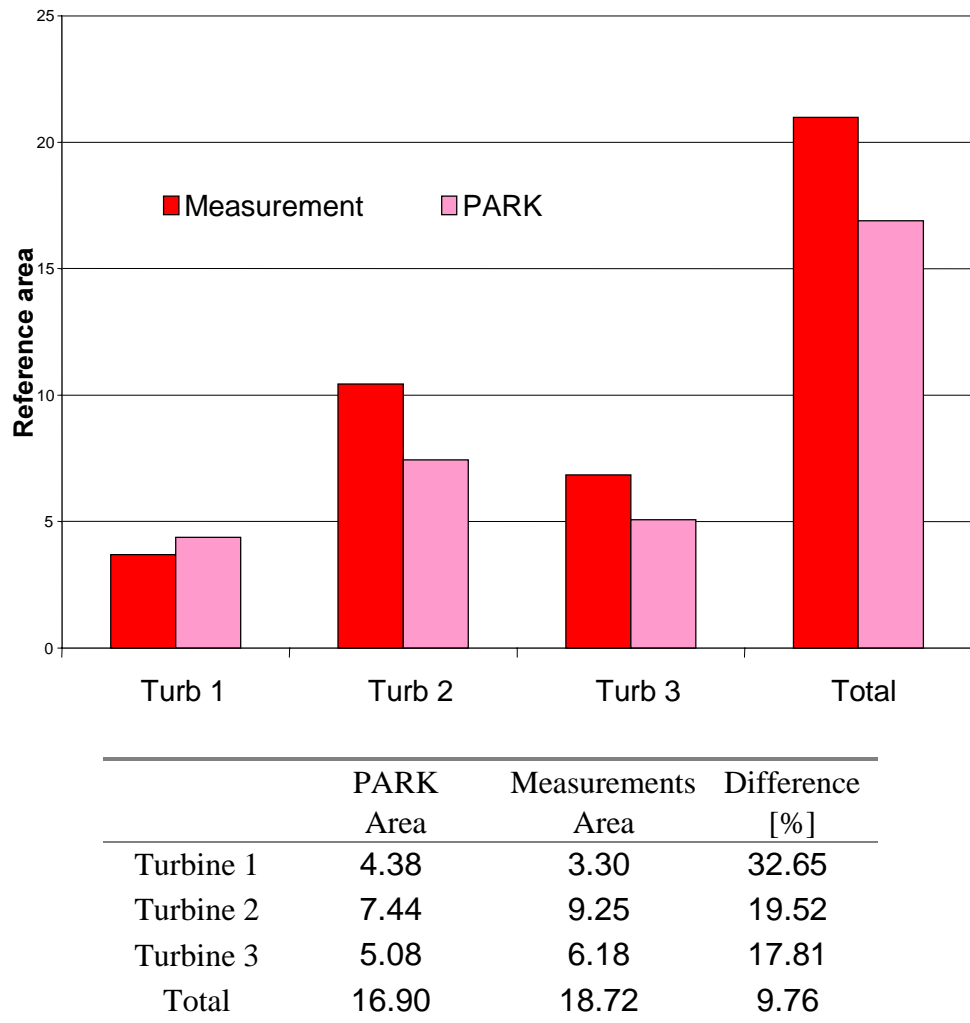
Figure 9.9 and Table 9.4: Comparing calculations by PARK to the measurements

As can be seen in the figure, PARK over estimates the deficit in the wake of turbine 1, while underestimating the deficits in the other two wakes. This has the peculiar effect of actually making a better prediction if the total area is studied. This is of course because the over- and underestimation of the deficits cancel each other out.

9.2   Predicting the total energy yield

The other thing that is interesting to look at when comparing the models to the measured data is the total energy production during the course of one year in GWh. How much energy will be produced by this farm every year? The amount of data collected from Alsvik is very large, but when the data is sorted and only the choice pieces are picked out, there is not that much data left. The total amount of measurements made in Alsvik is equivalent to about 175 twenty-four hour periods. However, if one introduces the conditions that all four turbines have to be operating and the yaw angle can not be more than 10 degrees in the positive direction, there remains the equivalent of about 30 twenty-four hour periods. This data was used to project the energy production over the course of a whole year.
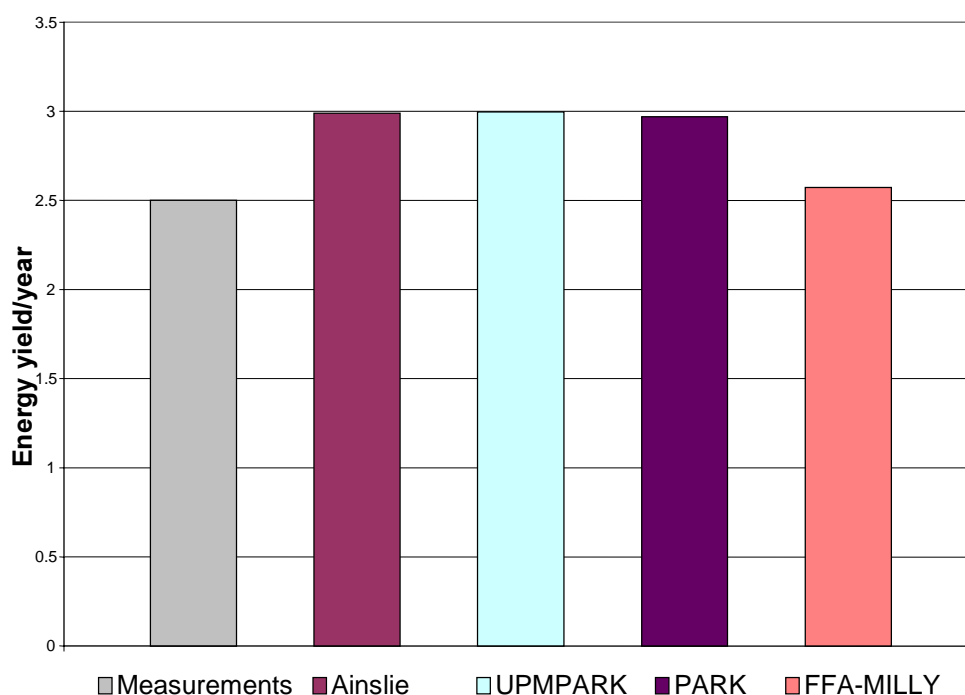
	Measurements	FFA-MILLY	Ainslie Step	UPMPARK	PARK
Energy yield [GWh]	2.500	2.572	1.736	2.997	2.970

Figure 9.10 and Table 9.5: Comparing measured and calculated energy yield

All the models seem to overestimate the energy production of the farm. This is not really a surprising result since, as has been noticed before, all of the models underestimate the velocity deficit in the wakes. The model that actually comes closest to predicting the actual energy yield is FFA-MILLY.

10 Conclusions

10.1 WindFarm

WindFarm is a relatively new and untried software product, which naturally contains bugs and faults. In addition, the program requires a number of parameters, calculation options and input data to be set and defined by the user, thus offering ample opportunity for mistakes and errors.

Whilst working with WindFarm a number of programming bugs were encountered. The effects of these bugs were not always apparent and sometimes difficult to detect, as with problems due to incorrect settings and erroneous input data. Encountered programming errors have been reported to the program manufacturer and have since been corrected. However, it is recommended that users exercise caution and always view results with criticism. It is also recommended that users examine the effects of probable deviations in input data and experiment with different calculation methods, to get an understanding of the validity and precision of the results.

There are some relatively large differences between the available modelling methods. Determining which model is to be preferred is difficult to do solely on the basis of investigations made in this report. To make an accurate and fair evaluation of wind farm modelling methods, accurate data from larger wind farms than Alsvik would be needed. However the results of this report should give a hint to which parameters dominate the calculation results, which in turn may help WindFarm users judge the validity of calculations and possibly how to improve them.

According to WindFarm calculations, the effectiveness of wind farms configured in single file converges towards a minimum value. It is reasonable to believe that the same is probably also true of a square configuration, only that it occurs when the number of turbines in the rows are the same as the above-mentioned single row. This implies that very large wind farms are more effective if configured in a single file than in a large evenly spaced group.

From the results in this report it is clear that the choice of modelling methods and the accuracy of certain input data becomes successively more decisive as turbine interference increases. Furthermore, the question concerning which modelling methods, of those available in WindFarm, produce the most accurate results is yet to be clearly defined. WindFarm should therefore not be relied upon for the production of absolute figures concerning energy production, optimisation etc, but used more as a guiding tool.

The difference in results, between FFA-MILLY and WindFarm with recommended settings, for the southern Kalmarsund case are small. However this could be due to the fact that the layout of the southern Kalmarsund wind farm is sparse, thus making the effects of wakes small.

Furthermore it is not possible to evaluate which of the two programs that is the more accurate in this case, since there are no field measurements to compare with.

10.2 Alsvik data

When evaluating the models and comparing them to the measured data, it appeared as if FFA-MILLY was the model that came closest to predicting the actual energy yield of the farm. FFA-MILLY is based on the MILLY model originally developed by Vermeulen. The FFA version has been modified based on experience gained from the measurements on the Alsvik wind farm. The fact that the alterations made in the MILLY model are based on measurements made in Alsvik could be the reason that FFA-MILLY makes such a good prediction of the energy yield in this particular case. It would therefore be interesting to see how FFA-MILLY performs when it is applied on another wind farm.

Another result gained from the comparison of the models to the calculations is that all the models seem to underestimate the wake deficits when the disturbing turbine is close upstream. One reason for this could be the short distances involved in Alsvik. All of the models then seem to get better at predicting the wake losses as the distance to the upstream turbine increases. The description of the wakes and the definition of the models are such that the calculations start at about 4-5 diameters downstream of the turbine. This is the shortest distance, between turbine 2 and 4, which is involved in the Alsvik wind farm. It might be the case that the models simply work best when the distance is around 7 diameters and higher.

The fact that the models under estimate the wake losses leads to the result that they over estimate the total energy yield of the wind farm. One aspect of this that should be taken into consideration though is that the measured data available represents 30 twenty-four hour periods. This data has then been scaled up to be valid for an entire year. This might mean that the measured energy yield should be regarded with certain scepticism. There just were not enough measurements available to be able to get readings for an entire year.

When discussing the measured data obtained from Alsvik, it should be mentioned that they seem to be good, as long as it is taken into consideration that they contain certain inherent errors. In measurements on future wind farms extra care should be taken when performing the wind direction and wind velocity measurements, as they are heavily dependent upon these parameters.

In this study it has been possible to determine the uncertainties within the data to the limits set in chapter 8. However, when looking at the uncertainties from the yawed flow, the limits set in the graph is the maximum error. These errors could probably be decreased if one looked at how often the nacelle is misaligned with respect to the wind direction, and

the data weighed accordingly. Also, it would be very interesting to take a closer and look at the effects of yawed flow. This is an area in which a more detailed study should be made, which incorporates both measured and calculated data.

Acknowledgments

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Appendix A: Map of the Alsvik wind farm
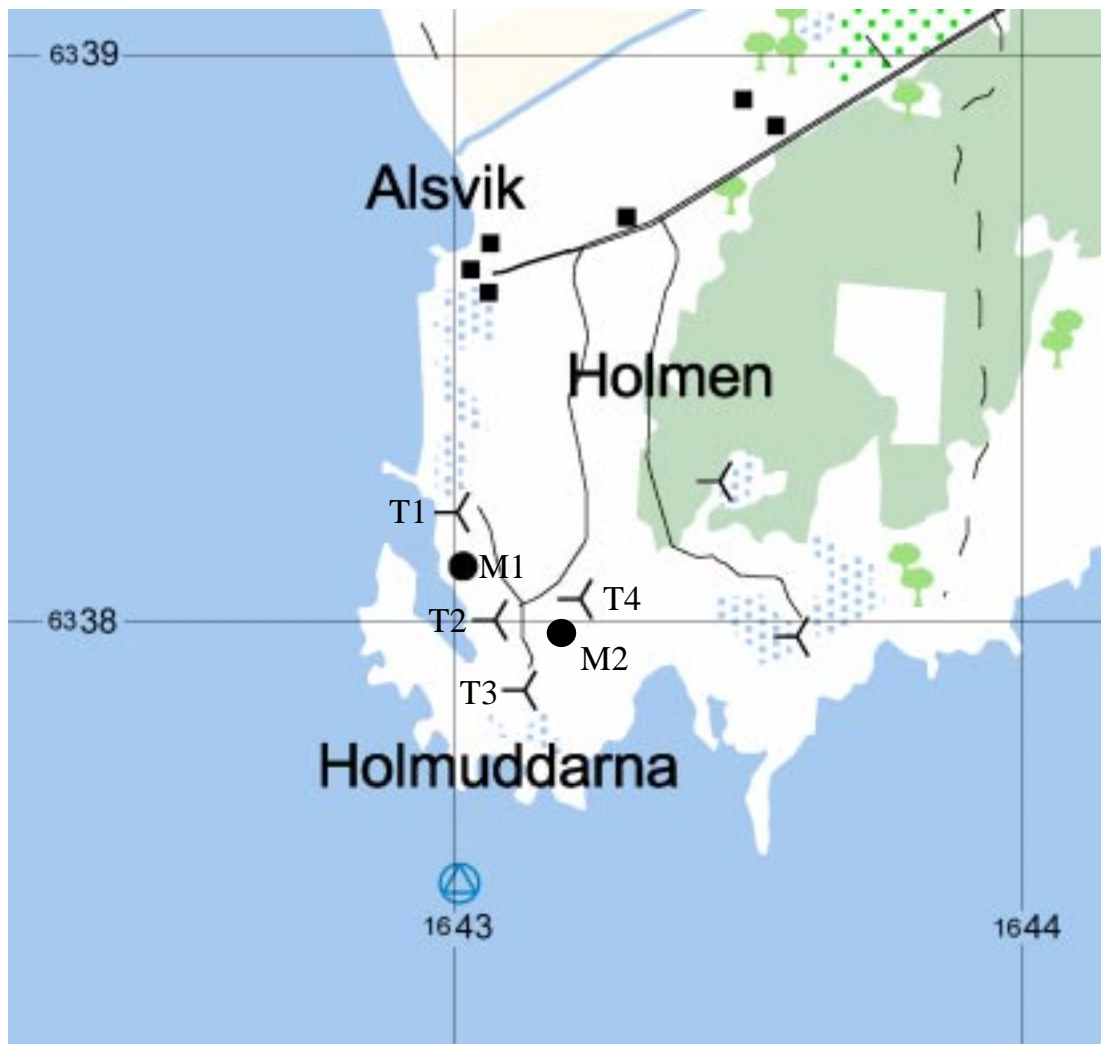
Appendix B: Description of WindFarm modules

The **Energy yield** module calculates the energy yield. Topographic and wake effects are included and there are a number of wake calculation methods available.

The **Optimisation** module optimises the turbine layout for maximum energy yield or minimum cost of energy whilst subject to natural, planning and environmental constraints. The turbines can be constrained to have a minimum separation from each other, a separation from houses, to stay within or without given boundaries, not to be placed on steep terrain and to minimise noise levels in given areas.

The **Wind Flow** module that is based on the MS-Micro/3 program of the Atmospheric Environment Service of Environment Canada and Zephyr North. It calculates the wind flow over the terrain.

The **Noise Calculation** module calculates the noise levels over the site map region.

The **Turbine Studio** module provides for the input and editing of turbine data and geometry. It also has the capability to analyse individual wind turbines using different wind distributions (including frequency distributions) and air density.

The **Wind Analysis** module performs a measure-correlate-predict analysis of measured site wind data to obtain a prediction of long-term wind characteristics.

The **Data Conversion** module provides the facility to convert a number of data formats (e.g. height, roughness, turbine and wind distribution data) to the formats used within the WindFarm program. In addition it can process a set of raw measured wind data to create a wind frequency table.

The **Map Transform** module is used to eliminate distortion in a scanned bitmap image and to locate the bitmap in the map grid system of the wind farm being analysed.

The **Grid Viewer** and **Contour Viewer** modules are used to display grid and contour data sets respectively. This may be height or roughness data, or output from the wind flow calculation. They can also be used to digitise from a scanned map.

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Utgivare		Beteckning		
Flygtekniska Försöksanstalten		FFA 2000-30		
Box 11021		Datum	Sekretess	Ex nr
161 11 BROMMA		Augusti 2000	Öppen	
		Dnr	Antal sidor	
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Rapportens titel
Evaluation of the software program WindFarm and comparisons with measured data from Alsvik.

Författare
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Sammanfattning

FFA acquired the wind farm analysis program WindFarm for trial purposes. The first part of this report deals with the evaluation and testing of WindFarm. Among the questions asked were; How sensitive is WindFarm to variations in the input parameters? How well does it predict the energy output of a wind farm? The idea was to get a clearer understanding of the program functions, calculation methods, efficiency and the calculation accuracy.

The second part of the report examines measured data from Vattenfalls experimental wind farm in Alsvik on the island of Gotland in the Baltic Sea. The focus of this part of the report was to try to determine the accuracy of these measurements. The data was treated with a focus on trying to eliminate, or compensate for, as many consistent errors as possible and to make estimates of the remaining uncertainties.

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