Controlling Wind, “tunnel theorie”

- final report -

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Acknowledgement/Preface

The activities described in this report are part of the ECN project 7.8381 Controlling Wind, "tunnel theorie" carried out by the Unit Wind Energy during the period September 1, 2003 to September 30, 2011.
The project has been financially supported by the program BSE-2003 "Duurzame Energie" of the Dutch Ministry of Economic Affairs, carried out by Novem under project number 2020-03-11-10-006.

In the project a new approach for operation of wind turbines in a farm is investigated called "Controlling Wind". This approach is expected to lead to higher energy production in wind farms.

The colleagues Gerard Schepers, Jan-Willem Wagenaar and Edwin Bot are acknowledged for their comment and suggestions for the writing of this report.

Abstract

The project "Controlling Wind, tunnel-theorie" aimed at demonstration of the methods for Controlling Wind "diversion" and "rotation" and the development of an engineering model for optimization of farm control and farm lay-outs. Tunnel experiments in a boundary layer wind tunnel were thought to be suited for these purposes.

The development of an engineering model for both Controlling Wind "diversion" and "rotation" based on wind tunnel tests or CFD simulations appeared not to be feasible. Yet, a simple engineering model for CW-diversion alone could be derived and has been implemented in the FarmFlow code.
Further, experience gained with the tunnel tests and theoretical considerations about the scaling laws for the wake gave rise to drastic changes in the approach shifting the activities to scaled and full size experiments in open air at ECN's EWTW (ECN Wind Turbine Test Site Wieringermeer). Because of setbacks in the performance of these experiments only evidence for CW-diversion could be found. No experiments or CFD simulations have been carried out to investigate CW-rotation.

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Summary

ECN holds a patent for a method of farm control called “Controlling Wind” (CW) that aims at decreasing the losses of turbines in the wake of other turbines. Basically the method knows two different approaches.
CW-diversion is applied when the wind is blowing at small angles with a turbine row. In that case the windward turbine(s) are deliberately yawed at a certain angle with the wind direction. As a result the wake will be diverted, increasing the energy content for the downwind turbines.
In CW-rotation large scale circulation systems are generated by coordinated yaw or tilt control of a number of turbines. In this way energy form the undisturbed flow above or from the side of the farm is led into the farm replenishing the energy deficit in the interior.

The project “Controlling Wind, tunnel-theorie” intentionally would use scale experiments in the boundary layer wind tunnel of TNO in Apeldoorn for the development of an engineering model for CW-diversion and CW-rotation and for demonstration of both methods.
However, experience with the tunnel tests and analysis of the results gave rise to drastic changes in the approach shifting the activities for demonstration and validation to scaled and full size experiments in the open air at ECN’s Windturbine Test Site Wieringermeer (EWTW). Furthermore the attention was focussed to CW-diversion only.

Many setbacks have been encountered in making the scale wind farm fit for Controlling Wind experiments. Therefore only CW-diversion experiments could be performed in a row of three turbines at 3.8 rotor diameter spacing. It was not possible to perform experiments in rows with more turbines or different spacing.

The results from the scale wind farm are sensitive to data selection conditions. Yet the results show that at 4 m/s wind speed the performance of a row of 3 turbines is significantly increased at yaw angles of 4° and 6° of the first turbine. For other wind speeds possible CW-diversion effects are questionable.
The positive results at 4 m/s are considered as an encouragement to perform more measurements after which decisive conclusions could be drawn from the scale farm for other conditions.

Furthermore data from three turbines in the 5 x 2.5 MW test wind farm of ECN, stored during 6 years of operation, gave many data points where the turbines ‘accidentally’ were operating under yawed conditions. It led to evidence that the energy production in the test farm can be enhanced by enforcing a positive yaw angle of the first turbine in wind directions at small positive angles with the row and vice versa. The increase is larger at larger yaw angles.

1. Introduction

A wind turbine generates power by extracting energy from the flow. In doing so, it creates a wake downstream that may interfere with other turbines in the farm. Since the energy content in the wake is decreased compared to the undisturbed flow, the power output of turbines exposed to the wake is decreased too. Especially turbines in the inner part of the farm will suffer from this energy deficit. Of course, this effect will be harmful for the economy of a farm. Usually improvement is sought in enlarging the distance between individual turbines. This however is unfavorable for the power losses and the costs of the electrical infrastructure in the farm.

ECN holds a patent for a method of farm control [1], called “Controlling Wind” that aims at decreasing the aerodynamic losses in the wake. Basically the method knows two different approaches: CW-diversion and CW-rotation.

CW-diversion is applied when the wind is blowing at small angles with a turbine row. In that case the windward turbine(s) are deliberately yawed at a certain angle with the wind direction. As a result a lateral force will be exerted on the flow and the wake will be diverted. Consequently the leeward turbines will be exposed to a flow with a higher energy content compared to normal yaw control conditions of the windward turbines.
In CW-rotation large scale circulation systems are generated by coordinated yaw or tilt control of a number of turbines. In this way energy form the undisturbed flow above or from the side of the farm is led into the farm, replenishing the energy deficit in the interior. Many configurations are possible with or without dedicated wind turbine designs or other flow influencing devices.

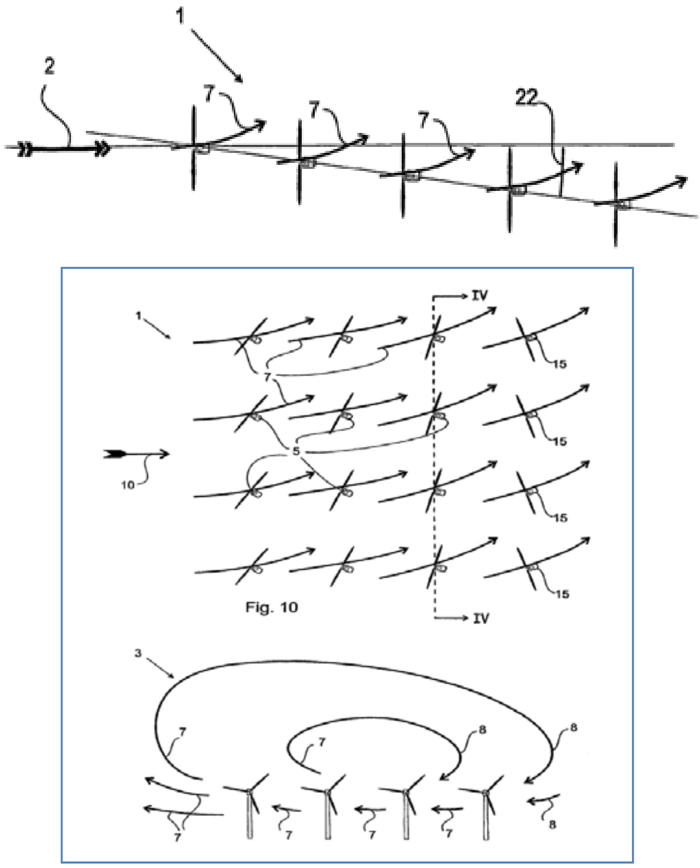

Figure 1 Examples of Controlling Wind: CW-diversion (top) and CW-rotation (bottom)

The project “Controlling Wind, tunnel-theorie” aimed at demonstration of the method, development of a preliminary model and knowledge transfer to the market.

Demonstration of the method (CW-diversion and CW-rotation) was planned in the boundary layer wind tunnel of TNO in Apeldoorn. The tunnel experiments also should give quantitative input for model development and qualitative information about the phenomena that should be implemented. The resulting model for Controlling Wind should predict the effects on energy production sufficiently accurate for optimization of farm control and farm lay-outs.
The project therefore involved wind tunnel tests and development of an engineering model for Controlling Wind and subsequent improvement, extension and validation of the model supported by further wind tunnel experiments.

However, experience with the tunnel tests and analysis of the results gave rise to drastic changes in the approach shifting the activities for demonstration and validation to scaled and full size experiments of CW-diversion in open air at ECN's Wind Turbine Test Site Wieringermeer (EWTW). Also the development of the model was not straight forward and needed an adapted approach supported by CFD modelling and simulations.
Further modifications in the execution of the plan mainly were caused by setbacks in the open air tests. In retrospective a drastically adapted program has been carried out compared to the original plan.

This report describes the originally contracted activities, the alterations and the respective motives and the respective shifts of the end dates in Chapter 2. The activities that have been performed eventually are described with some discussion in Chapter 3. Chapter 4 summarizes the main conclusions.

2. Contract matters

On January 29, 2003 the request for financial support for the ECN project proposal “Controlling Wind, tunnel theorie” [2,3] was granted by Novem under project number 2020-03-11-10-006 and order number 4800002754 [4]. The formal starting date of the project was September 1, 2003. The end date was set at April 30, 2006.

A major adaptation of the planned activities [5] has been approved by Novem [6] including a shift of the end date. Later, three further requests for shifting the end have been proposed and granted [7,8,9] with September 30, 2011 as the final end date.

The next paragraphs briefly describe the activities that were offered in the original contract, the modifications of the plan, the shifts of the end date and the respective motives.

2.1 Activities offered in the original contract

WP1 Analysis of earlier wind tunnel measurements
In May 2003 orientating experiments had been carried with scaled wind farms out in the atmospheric boundary layer wind tunnel of TNO Apeldoorn. The turbines at the windward side were oriented and loaded in such a way that large scale vortices were expected to occur. At first impression the tests revealed qualitatively promising results. In connection with modelling, further analysis of the results was offered in this work package in order to enable the definition of optimal specifications for a second series of wind tunnel experiments.

WP2 Development of a simple vortex farm model
Wind farm models would be needed capable to predict the diversion of the incoming flow and the generation of large scale vortices by slanted or tilted turbine rotors. For proper modelling of both options for flow control not only the drag but also the lift forces exerted on the flow should be described. It was expected that a relatively simple vortex model could do. In this model the rotors should be represented by a stationary wing shedding vortices from two sides of the surface. These vortices should be able to describe diversion of the wake and large scale circulation that guides energy rich flow from above down into the farm.
The work package envisaged the development of such a vortex farm model and calculations for various farm configurations to support the specification of experiments in the series of wind tunnel tests of WP3.

WP3 Wind tunnel experiments
This work package envisaged the definition of the measurement matrix, the adaptation and functional testing of model turbines and turbine measurement system preceding the preparation and performance of new measurements in the boundary layer wind tunnel of TNO. Interesting farm configurations that could not be modelled (by that time) might be investigated too.

WP4 Validation of vortex farm model
The model predictions would be compared with the measurement results. The outcome and the results of experiments with interesting farm configurations were aiming at the identification of essential improvements of the model.

WP5 Optimisation of Controlling Wind with vortex farm model
This work package would deal with further development of the vortex farm model to enable optimisation of large farms with basic lay-outs and specific interesting configurations. Special turbine concepts, designed for optimal flow diversion, will be incorporated. Further, calculations would be carried out to quantify the additional energy that could be produced with optimal farm lay-out and control and by application of dedicated turbine concepts.

WP6 Wind tunnel experiment with optimal farm designs

A measurement matrix would be defined for experiments with optimal Controlling Wind farm lay-outs and farm designs that are of special interest for the industrial partners. Necessary adaptations of model turbines and turbine measurement system would be carried out and tested preceding the preparation and performance of wind tunnel experiment itself.

WP7 Validation of vortex farm model/Analysis of wind tunnel measurements
The predictions of WP5 and the measurement results of WP6 would be compared in order to check the improvements and accuracy of the adapted model. Model capabilities and accuracies will be specified and further improvements of the model identified.

WP8 Information transfer
Activities for information transfer towards the industrial partners involved in the research, the principal and the scientific community.

WP9 Project management
Project management tasks with emphasis on continuous monitoring and evaluation of the progress.

2.2 Contract modifications

2.2.1 Alteration of the plan

2.2.1.1 Rationale

As mentioned, the project aimed at development of an engineering model for Controlling Wind by which it would be possible to predict the effects on energy production sufficiently accurate for optimization of farm designs.
The project therefore started with analysis of already performed experiments with model farms with the windward turbines oriented at angles with the flow direction (WP1) followed by the development of an engineering model for Controlling Wind (WP2), additional wind tunnel experiments (WP3) and analysis (WP4) for improvement of the model (WP5) and another series of wind tunnel tests (WP6) for validation of the improved model (WP7).
Clearly, wind tunnel experiments played an important role in the original plan. By that time such experiments were preferred over tests in the open air for reasons of configuration flexibility, adjustability of test conditions, test rate, costs etcetera.

However, owing to theoretical considerations about the behavior of the wake and some results obtained with analysis of previous wind tunnel experiments serious skepticism occurred about the suitability of tunnel tests for the development of reliable models. Eventually it became clear that wind tunnel experiments suffered from unbridgeable objections with respect to scale effects in the wake, tunnel wall interference and lack of similarity with atmospheric conditions.

Scale effects in the wake
The wake behind small and full scale turbines is considered to consist of two parts: the near wake and the far wake. The near wake extends to about 2 or 2.5 rotor diameters behind the turbine in flow direction. Its velocity distribution mainly is governed by rotor aerodynamics and inviscid momentum theory. The remaining part of the wake is called far wake. In this part the velocity deficit in the wake gradually disappears because of turbulent mixing with the surrounding flow.
Assuming a zero pressure gradient in cross flow direction and in flow direction in the far wake it can be shown that the effect of scaling is small in the far wake (Appendix B of [5]). As a consequence the velocity profile in the wake behind a scale model is comparable to that behind a large turbine provided that the profile at the transition from near to far wake is comparable. This however is not the case because of the large differences in Reynolds numbers of the scale turbines compared to state of the art turbines. The scale turbines in the project are about 400 times smaller than state of the art turbines with Reynolds numbers of 2.10^4 to 4.10^4 compared to

6.10^6 to 7.10^6, respectively. As a consequence large differences will occur between the lift and drag coefficients of the aerodynamic profiles leading to strongly deviating velocity profiles in the near wake of both turbine sizes. So the wake behind scale models in the wind tunnel will not have the same properties as full scale wakes.

Tunnel wall interference
Wall interference does not play an important role in tests with model turbines in line with the flow and with properly aligned rotors. But the main interest for Controlling Wind should come from experiments with turbine rows that have a big part of the rotors oriented at largely deviating angles. Such arrangements however cause wake diversion and occurrence of Controlling Wind vortices leading to interference between wake and tunnel walls. Further, measurements with an empty tunnel showed non-uniformity of the cross flow caused by wall effects (Figure 2) causing a pressure gradient perpendicular to the flow, where the absence of pressure gradients is considered to be a pre-requisit for similarity in the far wake.

Similarity with atmospheric conditions
The measurements took place in an atmospheric boundary layer wind tunnel. However, measurements of the flow properties showed that the anisotropy of the turbulence in the tunnel was not representative for ambient conditions. This of course would give interactions between wakes and the surrounding flow that are not scalable to full size situations.

These objections forced the decision to stop the tunnel experiments and instead to perform measurements at full scale in EWTW test farm and in the scale wind farm of ECN. The matter has been explained in more detail in the requests for alteration of the plan [5].
After some communication SenterNovem approved the proposal for modification on December 8, 2006 [6].

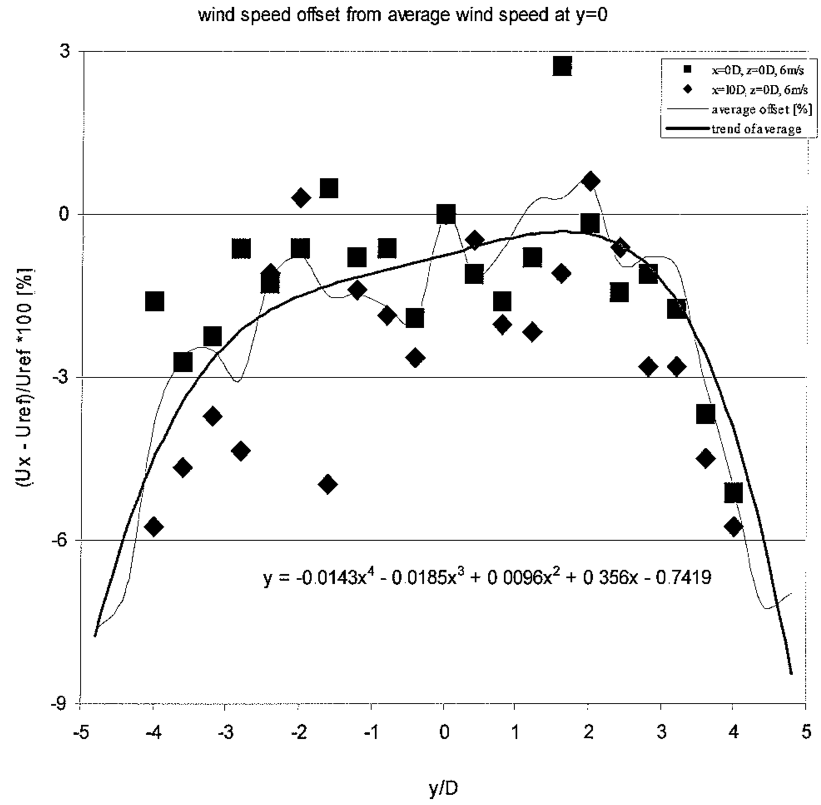

Figure 2 Horizontal wind speed profile measured in the empty wind tunnel.

2.2.1.2 Revised approach

The revised plan provided in a complete stop of tunnel tests because of the objections with respect to scale effects in the wake and tunnel wall interference. Instead the measurement data for model improvement and validation should come from full scale tests in the EWTW test farm and the planned scale wind farm of ECN. The experiments again would be used to identify the aerodynamic effects that should be incorporated in the models and the results would be used for model validation.

The intension was to develop one engineering model for both CW methods: wake diversion and large scale rotation.
However, soon it became clear that CW-diversion could be described in a simple model based on the available wind tunnel results, but CW-rotation could not. Therefore, only the CW-diversion model has been integrated in FarmFlow, the ECN model for farm design. Further, it became clear that the engineering model for CW-diversion better could be developed separately with the aid of advanced CFD codes instead of experiments.

In short, the goals of the project still could be reached but with the aid of full scale and scale measurements in the open instead of wind tunnel experiments.

2.2.1.3 Modified plan

2.2.1.3.1 Modified activities

By the time the project modifications were formulated part of the activities in the original work packages 1, 2, 3 and 4 already had been carried out including some explorative tunnel experiments in WP3. Therefore, the wind tunnel experiments that had been carried out already would be analyzed together with wind tunnel tests by other parties into the behavior of model turbines in oblique flow. Based on the results a model for CW-diversion would be developed and implemented in FarmFlow in the revised work package 2. With this functionality FarmFlow would be able to predict the CW-diversion effect for some configurations and control conditions Though the reliability of the model will be limited for certain yaw angles as the tunnel results on may be influenced by disturbances due to wall interference.

In the modified WP2 the engineering model for CW-rotation would be developed with the aid of an advanced CFD code. The adopted approach consisted of a step by step analysis of simplifications that are allowed for obtaining a functional and reliable description of the wind velocity distribution at the transition to the far wake starting from detailed geometric Navier-Stokes modeling of the turbines. From the simulations simplified descriptions for the rotor aerodynamics would be derived that could serve as starting points for the engineering model. The commercial CFD code CFX-10 of NRG (a daughter of ECN) was selected for these calculations.

The old work packages 5, 6, and 7 were canceled because of the ending of the wind tunnel experiments.
The work packages 8 an 9 for information transfer and project management respectively were maintained.

2.2.1.3.2 New activities

Three new work packages were defined for measurements in the field i/ at scale (SWFW) and ii/ at full scale (EWTW) and iii/ for evaluation.

WP10 Full scale measurements in the EWTW
Full scale measurements do not suffer from scale effects and therefore are of the utmost representativeness, except of course for specific local effects like the influence of the surroundings on the atmospheric turbulence.

The EWTW farm [10] consists of a row of five 2500 kW turbines with variable speed-pitch regulated control. These turbines have a diameter and a hub height of 80 m and are placed at mutual distances of 3.8 rotor diameters.
The EWTW farm is very suited for CW experiments because of its state of the art turbines, the possibility to adapt the yaw control for the experiments, the comprehensive and reliable measurement infrastructure for turbine and meteorological data and the availability of reference data [11,12].

The disadvantage of the EWTW is the shape of the farm i.e. one single row. The effect of CW large scale rotation will be weaker when caused by a single row of turbines compared to multiple rows. Another drawback of the single row is that only in 2 directions of the wind the turbines stand in each other's wake. So only a small percentage of time will be suited for measurements.

The farm is oriented from west to east (95° - 275°, Figure 3). In winds from these directions the turbines stand in each other's wake. According to the modified plan the windward turbine would be yawed alternately at various angles to the wind direction in these conditions. The differences in power production would be compared with the production during normal yaw operation of the windward turbine.
Further the wind characteristics in the wake behind a misaligned rotor would be measured with the meteorological tower at 2.5D, 3.5D and 5.D distance.

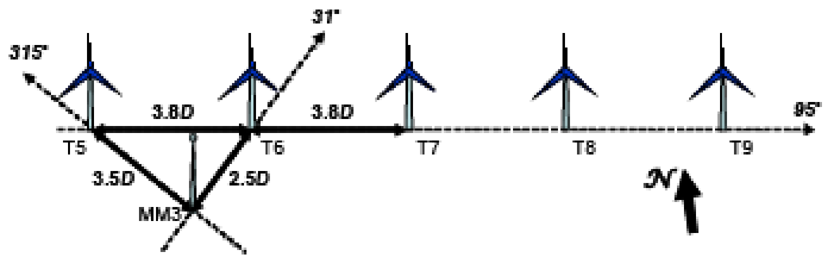

Figure 3 Main dimensions and directions in the EWTW farm. T5 to T9 are the turbine positions, MM3 indicates the measurement mast.

For execution of the plans cooperation with the turbine manufacturer and their approval were needed for implementation of an adapted yaw control that would enforce a series of predefined yaw angles of the windward turbine under specified conditions.

WP11 Measurements in the scale wind farm SWFW
The scale wind farm has been erected in March 2008 on the EWTW in between locations for prototype turbines. The farm [13] consists of 10 Aircon 10P turbines with 7.6 m diameter and 7.5 m hub height with variable speed and pitch control.
Because of the relatively small size the difference in properties with full size turbines will be much smaller compared to the difference between full size turbines and wind tunnel models.

Figure 4 Scale wind farm on the EWTW, in between 2 prototype turbines and a tall measurement mast.

At 7.5m rotor diameter the profile Reynolds number will be about $7\ 10^5$. The profile drag coefficient is expected to be about 1.5 times higher than the drag coefficient on a corresponding full scale commercial turbines, the lift will only differ a few percent. Also the location of the boundary layer transition point will not differ too much. So the rotor aerodynamics of the scale turbines - and consequently the wake profile at the transition to the far wake - will be much more representative compared to tunnel models with drag and lift coefficients that are 8 and 2 times the coefficients in commercial turbines respectively.

The farm lay-out comprises three lines of 2, 3 and 4 turbines and one single turbine. Distances between turbines that are interesting for studying wake effects vary from 3.8 to 12 rotor diameters. The farm lay-out therefore makes it possible to investigate the behaviour of turbines in single and multiple wake conditions at various spacing.
Further, the scale farm is provided with many masts that measure the wind conditions within the farm and above. 15 Meteo masts are placed within and around the farm which measure the wind velocity field from 3.6m to 19m height. In total 146 wind signals including many 3D sonic anemometer signals are measured up to one diameter above the rotor. Together with the measurements from three other 108m high masts on the site data is gathered about the wind from all directions and above the wake but also in single and multiple wake conditions.

Because of the instrumentation and the possibility for simultaneous comparison of a turbine row with CW-diversion control with standard yaw control the scaled farm should be very suited for investigations into the effects of wake diversion.
The farm also should be suited for generation of large scale vortices and investigation into effects thereof because turbines are placed in parallel lines.

For this reason and because the intended experiments in the EWTW have been eliminated emphasis in the project was shifted to measurements in the scaled farm.

WP12 Evaluation
In this work package all experience and knowledge gained in the experiments should be compared and used for model validation. From these activities possible improvements and extensions of the models should be formulated.

2.2.2 Shifts of the end date

On 31st July 2006 a shift of the end date to 30th March 2009 has been requested, simultaneously with a proposal for major changes in the project plan [5]. The request has been granted by Novem on December 8, 2006 [6]. The changes in the plan originated from the insight that wind tunnel experiments could not produce reliable data for model validation and that data from scale and full size farms should be used instead. The delay was caused by the time that was needed for development of new plans, unfortunately at the same time that major changes occurred in the project staff causing additional delay by transfer of information and knowledge.

In 3rd March 2008 [14] a second request for shifting the end date has been sent to SenterNovem (former Novem). The alteration was necessary because of the delay that occurred in the planning of the scale wind farm. Originally the commission of the farm was scheduled for June 2007. However the turbines became operational only by March 2008. After sending some additional information about the background of the delay the request was granted [7]. The new end date was fixed on December 31 2009.

On 29th October 2009 ECN again asked for an alteration of the end date motivated by the technical problems that were encountered in the realization of the scale farm. Because of design errors in found during commissioning the turbines had to be sent to the manufacturer for modification. Other problems occurred with the control software resulting in over-speed excursions for some of the turbines followed by necessary modification of the control software and the safety system. Further delay was caused by technical problems with the pitch and yaw mechanism of some turbines. Also being dependent of the service of a small manufacturer abroad negatively influenced the time span needed for modification and repair. Based on the expectation that the measurements in the scale wind farm would start in the beginning of 2010. 31th December 2010 was proposed as the new end date [15]. The request was accepted on December 18, 2009 [8].

A last shift of the end date was asked for on 24th November 2010 [16]. The alteration was caused by continuing technical defects and failures of the Aircon turbines. Measurements also showed that the performance characteristics of the turbines were different from each other while similar characteristics were a condition sine qua non for the scale experiments. Presumably, the differences were caused by different operational pitch angles so calibration and adaptations of the control software were unavoidable. With consent of Agentschap NL (former SenterNovem) on 1st December 2010 the end date of the project was shifted to 31th December 2011 [9].

3. Activities and discussion

3.1 WP1 Analysis of wind tunnel measurements

Before the start of the project experiments have been carried out in the atmospheric boundary layer wind tunnel of TNO Apeldoorn with model wind turbines. The tunnel floor had a roughness length of $4.3*10^{-7}$m representing a full scale offshore boundary layer at scale 1:400. The model turbines had devices for adjustment of the electric load, and measuring rotational speed, electric power and axial force.
Various tests have been carried out with the empty tunnel, model wind turbines and model farms in various lay-outs.

In the work package these wind tunnel experiments have been analysed [17] together with wind tunnel results of other parties. The activities have resulted in the insights that led to a drastic change in the approach: abandoning the tunnel experiments and shift the measurements to the scale and full size wind farms of the EWTW (see 2.2.1.2)
The results contributed to the empirically determined wake maps in FarmFlow (next paragraph)

3.2 WP2 Vortex farm model

Originally it was envisaged that a relatively simple vortex model could describe the power and rotor loads generated by CW-diversion and CW-rotation.

However, soon it became clear that the development of such a model would bring along many complications. Therefore the revised work package 2 provided in the development of a separate engineering model for CW-diversion and one for CW-rotation.

3.2.1 Engineering model CW-diversion

AWC (Active Wake Control), a model for wake diversion has been developed and implemented in FarmFlow [18].

FarmFlow calculates the energy production of turbines in a farm for a specified wind climate. The program uses a data base with wake maps that contain profiles for the wind speed and turbulence intensity in the wake at hub height. The user can choose between empirically determined wake maps and wake maps determined by numerical simulation.

AWC, the model for wake diversion [19] is based on PIV (particle image velocimetry) measurements performed at KTH [20] at 1 to 4.5 rotor diameters behind a 2 bladed wind turbine model of 0.25m diameter at yaw angles of 0, 10, 20 and 30 degrees (see Figure 5). The results show that the wake approximately is diverted at a constant angle with the undisturbed wind direction that is proportional to the yaw angle.
In AWC the wake skew angle φ is supposed to depend on yaw angle γ and induction a by:

$$\varphi = -\frac{2}{3}a\gamma$$

At the scale of the EWTW test farm with five 2.5 MW turbines, FarmFlow calculations with the AWC model predict a 1.3% energy production increase from a sector of $^{+}/_{-}$ 15° with the turbine line at a wind speed of 8 m/s and specified enforced yaw angles [19].

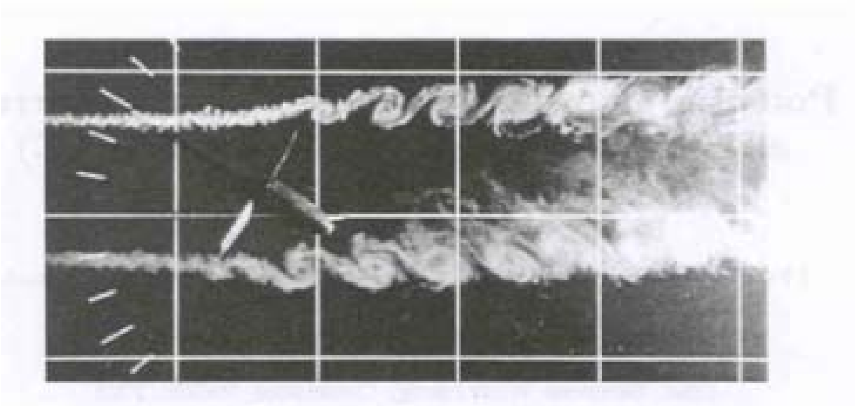

Figure 5 Flow visualisation of wake deflection from a turbine yawed at 30°. Experiments conducted at the Royal Institute of Technology (KTH) [20]

3.2.2 CW-rotation model

As mentioned earlier, the development of the engineering model for CW-rotation had to be carried out with the aid of an advanced CFD code. The approach should involve a step by step analysis of simplifications that are allowed to arrive at description of the velocity distribution at the transition from near wake to far wake. From the results simplified relations for the rotor aerodynamics should be derived for the engineering model. Verification of the simulations would be carried out by comparison with the measurements from the Mexico project [21].

A start was made by simulations with the commercial CFD code ANSYS CFX-10 of NRG. For sake of validation the blade of the Mexico test turbine was used to build the 3D simulation model.
At first the 2-dimensional pressure field around the aerodynamic profile (NACA 64-418) was simulated and compared with wind tunnel measurements and with predictions from the airfoil design code RFOIL [22]. Good predictions of the aerodynamic coefficients could be observed at low angles of attack but large deviations occurred at higher angles (Figure 6). The deviations apparently were caused by deficiencies in the transition and the turbulence models. These models should be modified in such a way that transition from laminar to turbulent flow and the onset of separation should occur earlier with increasing angle of attack [23].

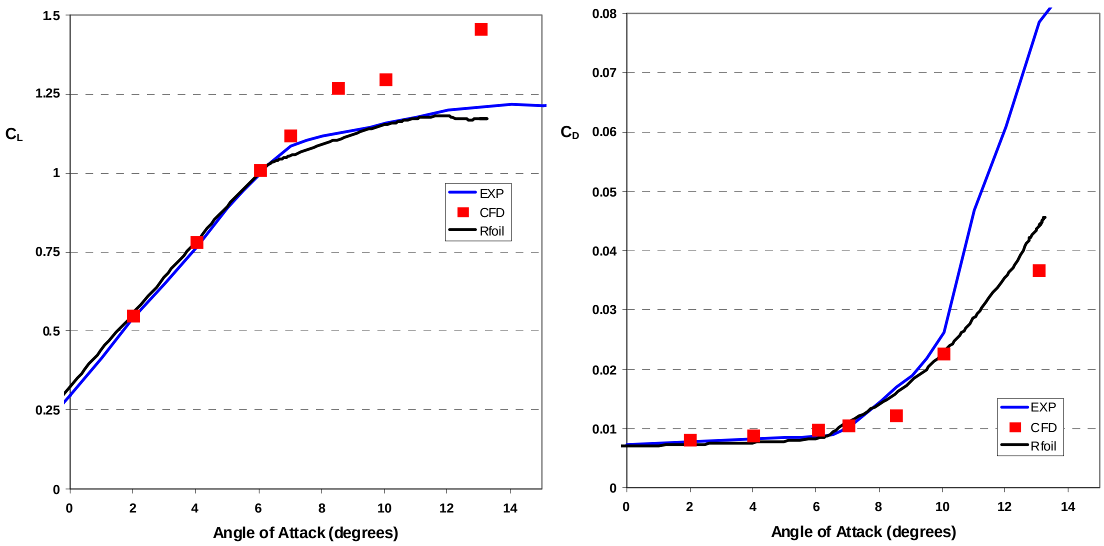

Figure 6 Lift coefficient C_L (left) and drag coefficient C_D (right) calculated with the CFX-10 code for the NACA 64-418 profile as a function of the angle of attack. Plotted are the experimental values, CFD simulation and RFOIL results.

By that time, it also became clear that modeling of the blade geometry 3-D simulation in a system rotating at 100 Hz (the Mexico rotor) required a very fine mesh and was not a practical way to go. As a result and because of the experience with the CFX model a switch was made to Fluent, another commercial CFD code.
With Fluent a number of axi-symmetric flow cases were simulated and compared with Mexico measurements. In general terms a very good agreement was found. It can be mentioned that, as a spin-off, these results played an important role in the start-up of the international project IEA Task 29 “Mexnext” since these results were the first available on the Mexico rotor. In a later stage all major players in wind turbine aerodynamics supplied CFD calculations. The accuracy of these results however were not significantly better than those from ECN/NRG [24].

In a next step CFD calculations were performed for yawed conditions. The attention was focused on the flow deflection. To avoid the time consuming detailed modeling of the blade geometry in axi-symmetric cases the blades were described by momentum sources in an actuator disk. The momentum sources are generated by Blade Element Theory in a user defined VMB (Virtual Blade Model) and coupled to the surrounding flow by momentum equations [25]. This approach eliminated the time consuming and costly meshing of the blade geometry.

The feasibility of the VMB-Fluent model for reliable and accurate predictions of flow characteristics in the wake was checked by:

- reference simulations without tunnel geometry for testing of the VBM and for validation of the required mesh,
- simulations with symmetric and anti-symmetric tunnel geometry to investigate the comparability of the influence of a virtual wind tunnel in numerical simulations compared to the real tunnel environment,
- simulations of the model rotor with yaw angle 0^o in 10, 15 and 24 m/s wind speed and 30^o at 15 m/s and comparison with the Mexico wind tunnel measurements.

VMB simulations qualitatively agree with the expectations in all considered cases. They also show that the influence of the wind tunnel on the flow characteristics can be neglected. Figure 7 shows as an example the calculated flow speed and vorticity distributions in the wind tunnel.

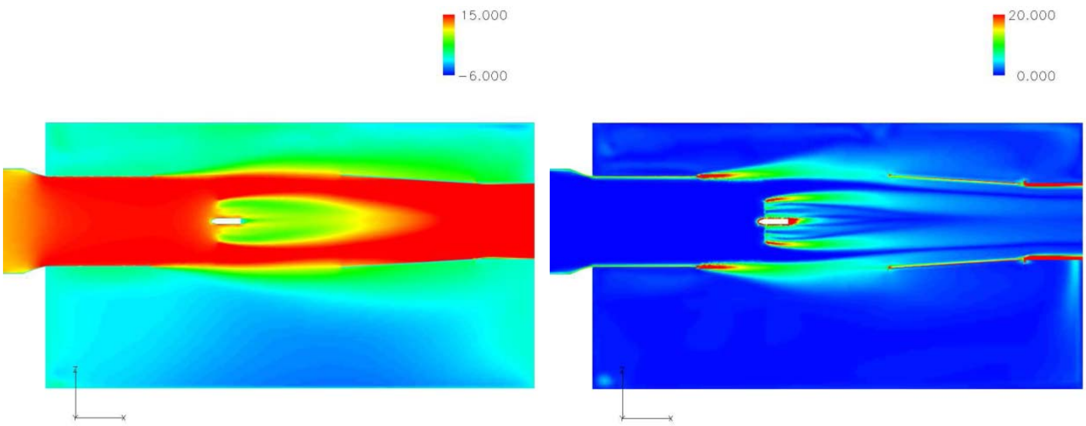

Figure 7 Axial flow speed (left) and vorticity (right) distributions in the wind tunnel sections as calculated with VBM-Fluent for a tunnel speed of 15 m/s.

Figure 8 compares axial velocity profiles for wind speeds measured at 0.82R behind the Mexico rotor at 10, 15 and 24 m/s as with VBM-Fluent simulations.
For 15 m/s wind speed the calculation results agree well with the Mexico measurements. Quantitatively this is not the case for the other wind speeds. At low wind speed (10 m/s) the blockage effect gives negative velocities and the velocity profile is significantly under predicted while for 24 m/s the velocities in the wake are over predicted. This however does not disqualify the calcu-

lation results. This is because the Mexico experimental results are not well suited for validation of the VBM. The reason is that the experimental velocity data are always taken at specified locations in the wake when the blade is in upright position. So the averaged velocity measurements may be influenced by specific rotor azimuth dependent flow characteristics and not be suited for comparison with circumferentially averaged predictions from the model.

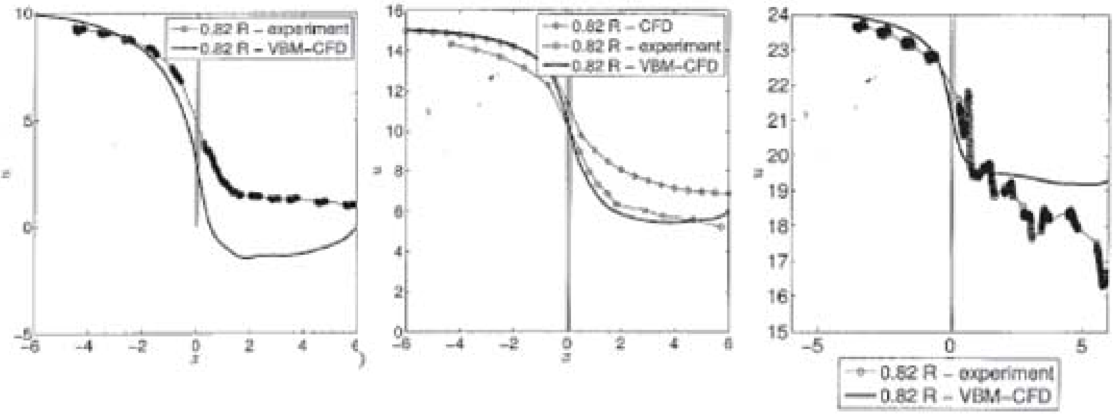

Figure 8 Axial velocity profiles for wind speed 10 (left), 15 (middle) and 24 m/s (right). Comparison of Mexico experiments with VBM-Fluent code and CFD calculations in the Mexico project.

The VMB-Fluent model also has been used for prediction of the wake characteristics at a yaw angle of 30^{o} in 15 m/s wind speed. At this large angle it was not possible to use the same position of the momentum sources in the model so the rotor geometry had to be constructed and meshed once more. The most important conclusion is that qualitatively good results were obtained but that the quantitative deviations with the measurements were too large.

Summarizing, it can be concluded that validation of the VMB model was not possible mainly because the measured velocity in the wake in the Mexico project may be influenced by specific rotor azimuth dependent flow characteristics and are therefore not suited for comparison with circumferentially averaged predictions from an actuator disk based model like VMB.

3.3 WP10 Full scale measurements in the EWTW

3.3.1 EWTW

3.3.1.1 CW experiments

According to the plan measurements under intentionally yawed conditions should be carried out with the 2.5 MW turbines of the EWTW.
However, because deviating yaw angles will introduce additional dynamic loading of the turbine legal and warrantee regulations required the approval by the manufacturer for the execution of the plan. Although the manufacturer promised to perform a study into the possibility of these kind of measurements, they abandoned this position later on. Eventually the manufacturer even stopped the communication with regard to this subject altogether [26]. Most probably the work and costs associated with certification of the adapted yaw control for only two turbines hampered a positive decision.

Eventually the plan to carry out CW experiments in the EWTW farm was abandoned too [14].

3.3.1.2 Analysis of stored EWTW data

3.3.1.2.1 Background

Due to the disappointing lack of cooperation from the side of the manufacturer dedicated CW diversion experiments could not be performed.

But bearing in mind that most commercial turbines are only yawing after a certain delay and that the wind direction varies all the time, most likely every rotor will be more or less misaligned on many occasions. And as ECN is gathering data from the 2.5 MW turbines since 21st June 2005 it could be worthwhile to look in the database for misalignment conditions for the first turbine and the related performance of other turbines. A first examination of the 10 min statistical data from the database was not very successful probably because the time delay in yaw actions is much shorter. Fortunately, the raw measurement data still are available for processing so analysis at shorter averaging time was possible.

3.3.1.2.2 Data processing

Raw data from the first three turbines (numbers 5, 6 and 7) of the EWTW measured during about six years have been processed into 2 minute statistical data. This averaging time was expected to be a fair compromise between a high number of data points required for small deviations in the results and sufficient correlation between wind and performance variations. This time interval is somewhat longer than the travelling time of the wind (1.3 min) between three turbines at 3.8D spacing and 8 m/s wind velocity.
Only three turbines were comprised in the analysis. This number was considered to be suited for the identification of CW effects.

Only data were selected from the undisturbed sector for measurement mast MM3 i.e. the sector from 100° to 300° [27]. The wind measurements were taken from the anemometer and vane on the boom at hub height pointing in direction 240°.

For proper analysis only data should be considered from turbines that are producing net power below rated wind speed, so during variable speed operation without pitch movement. Also the yaw movement of the first turbine has to be minimal. Therefore further filters have been applied for:

- operational mode of all turbines: only variable speed mode without pitch action,
- power production: power of turbine 5 >1% Pnom,
- yaw action: standard deviation of the yaw angle of the first turbine less than 1%.

Preliminary analysis further showed that the gains of the wind direction signal and the yaw signal of turbine 5 slightly differ in the considered sector (Figure 9). Therefore the yaw signal of turbine 5 was corrected for this difference.

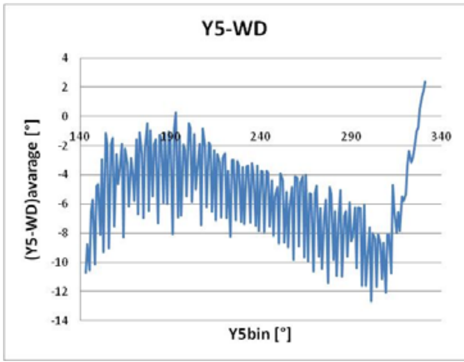

Figure 9 Average difference between the yaw angle of turbine 5 (Y5) and the wind direction (WD).

3.3.1.2.3 Results

The presented represent data filtered from wind directions between 250° and 300°. In total 78322 records were used for the analysis corresponding to 2610 hours of measuring time.
The data have been analysed by means of binning techniques. Unless otherwise indicated the least number of records per bin is 6.

Figure 10 shows the average power of the first three turbines (turbines 5, 6 and 7) at relative yaw angles of $^{+}/_{-}$ 6° and $^{+}/_{-}$10° for turbine 5 with wind from westerly directions. The data are compared with the average values for all relative yaw angles. It can be seen that the shapes of the curves are similar with almost equal minima but that the curves are shifted over small angles. This means that the energy yield can be increased in wind directions from about 250° to 275° if turbine 5 is yawed in counter clockwise direction and in clockwise direction in the sector from about 275° to about 300°. The highest difference occurs with winds north of the turbine line at small positive angles and at positive values for the misalignment of T5.

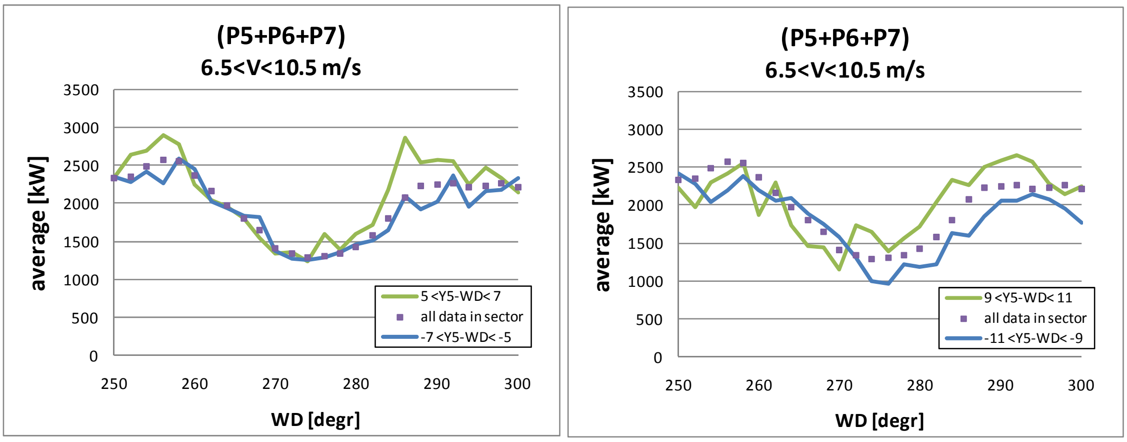

Figure 10 Average power (P5+P6+P7) as function of the wind direction for relative yaw angles ($^{+}/_{-}$ 6°, $^{+}/_{-}$10°) of turbine 5 compared with the average values for relative yaw angles between -12° and 12°. Bin width 2^{o}.

The effect also is visible in Figure 11 where an increasing trend of the total power of the first three turbines is visible with increasing misalignment angle of turbine 5 for wind direction 282°. Conversely the trend decreases with increasing misalignment angle at wind direction 266°.

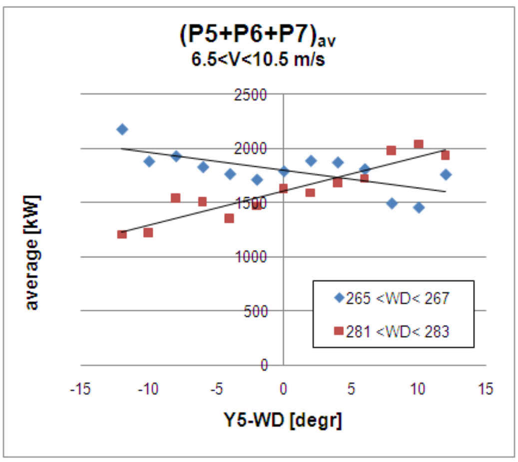

Figure 11 Average power (P5+P6+P7)/(3P5) as function of the relative yaw angle of turbine 5 for different wind directions. Bin width for wind direction 2^{o}.

It will be clear that the maximum power in the wake should be obtained with a yaw control that enforces a positive misalignment angle x= Y5-WD when the wind is coming at small angles north of the farm line and negative misalignment angle at small angles south of the line. Figure 12 gives the obtainable average power over a 36° wide sector in the wake for different enforced misalignment angles.

Figure 12 clearly shows that enforced yawing in principle should be able to increase the power production of a line of turbines in wake conditions.

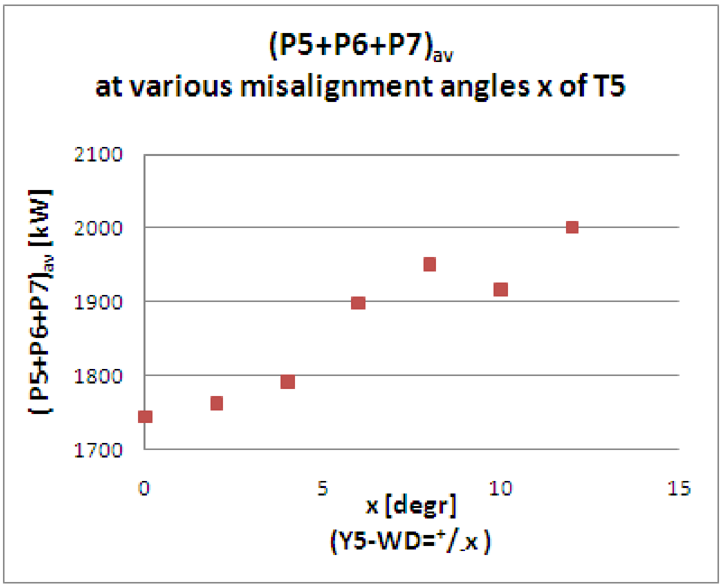

Figure 12 Average power of the first three turbines achievable by yawing of turbine 5 at an angle $^{+}/_{-}$ x to the wind. The average is calculated from wind direction sectors 255°<WD<273° and 273°<WD<291°. Bin width for the wind direction: 2°. Wind speed: 6.5<V_{av}<10.5 m/s.

In reality the attainable gain of course will depend on many parameters like the size of the turbines compared to the time and scale parameters of the turbulence, the distance between turbines, yaw control properties like yawing speed and delay and the energy consumed by yawing.

This result of course raises the question if the performance of the three turbines can be approved further by forced yawing of turbine 6.
Figure 13 shows the effect of yawing turbine 6 relative to turbine 5. The data show much scatter but the conclusion looks justified that with the first turbine having a beneficial orientation the second should not differ much from that orientation as well. At least large positive yaw angles relative to turbine 5 should be avoided at wind directions having small angles north of the farm line.

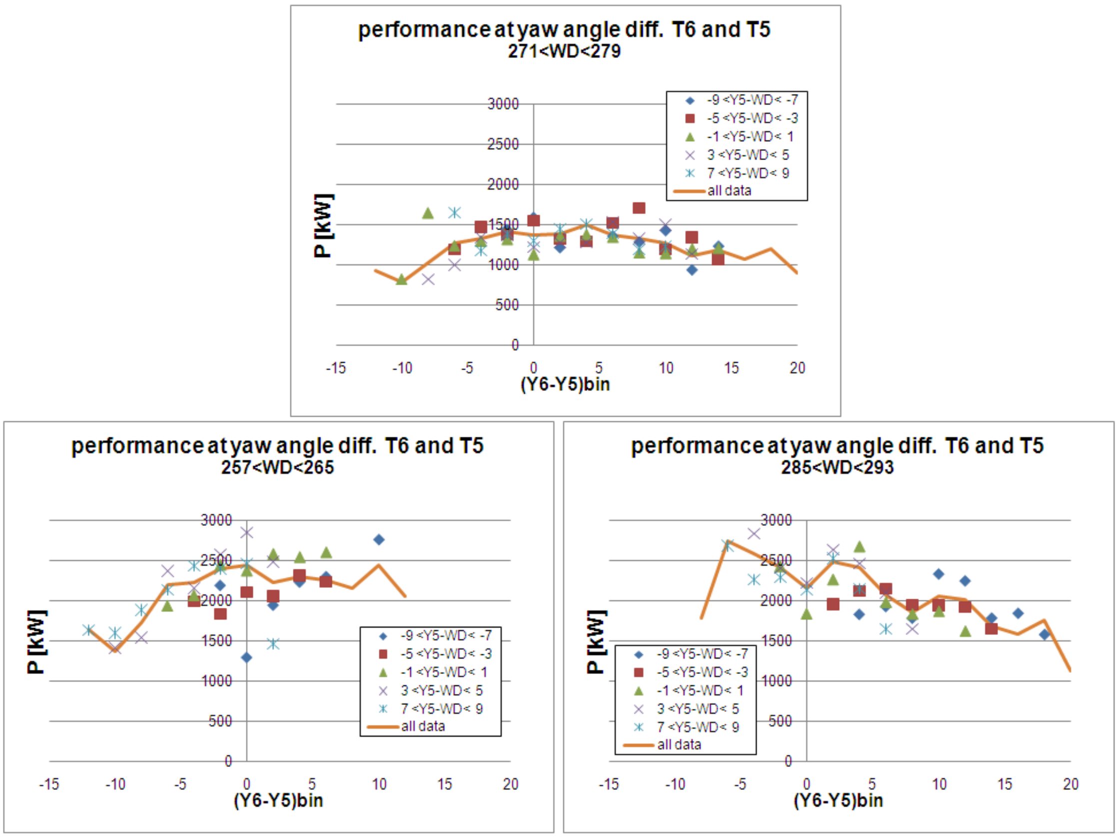

Figure 13 Effect of yawing of turbine 6 relative to turbine 5 on the power production at wind directions along (top), south (left) and north (right) of the farm line. Bin width 2^{o}. Wind speed: 6.5<V<10.5 m/s.

Another interesting parameter is the wake skew angle depending on the yaw angle. Figure 14 gives the location in terms of wind direction for the power minimum of turbine 6 in the wake of turbine 5. It may be assumed that this point coincides with the largest velocity deficit in the wake.
However, it is doubtful whether this graph might be used for validation of the AWC model of paragraph 3.2.1 because it is not clear yet how the directions of local minima should be determined in a proper way. The reason is that the yaw mechanism has preferred positions ( )resulting in a strong dependency of the results for the applied averaging method.

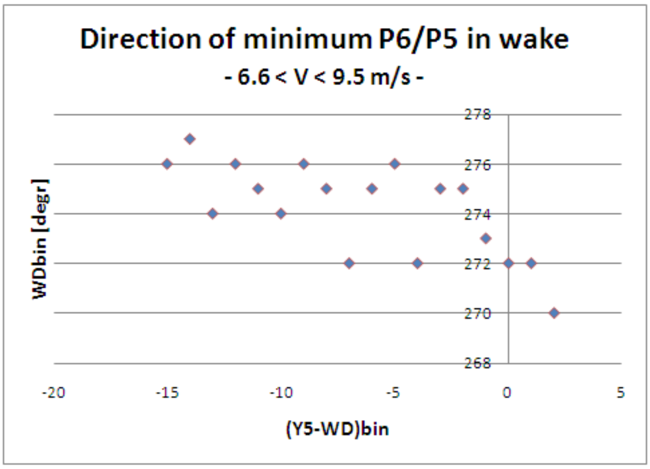

Figure 14 Direction of the minimum relative power of turbine 6 (P6/P5) in the wake of turbine 5 at wind speeds from 6.5 to 9.5 m/s.

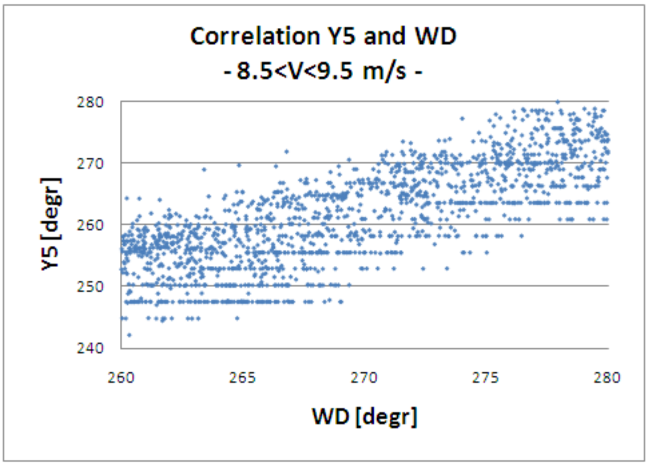

Figure 15 Comparison of 2 minute average values of the yaw angle of turbine 5 with the wind direction.

3.4 WP11 Measurements in the scale wind farm SWFW

3.4.1 Measurements and data processing

The realisation of the scale farm suffered from many setbacks, see 2.2.2. Due to these delays CW-diversion measurements only could start in January 2011. By that time six wind turbines were considered to be suited for CW experiments with respect to similarity and availability. Therefore and because of the approaching end date it was neither possible to perform experiments in rows with different number of turbines and/or different spacing nor experiments into CW-rotation.

During 3.5 months CW-diversion was investigated in two rows of three turbines (turbines 3, 4, 5 and turbines 6, 7, 8). See Figure 16 Plan of the scale wind farm. The red stars indicate the turbines used for the experiment. Turbines 3, 4 and 5 are in the left row (row 1) and turbines 6,7 and 8 in the right row (2). If the expected wind direction was in line with the turbine row the yaw orientation of all turbines was fixed at that orientation (235° $^{+}/_{-}$ 0.5°) apart from turbine 6 which was set at 235°, 239°, 241°, 247° or 251° ($^{+}/_{-}$ 0.5°) according to a predefined sequence. In this way the performance of a row with an oblique first rotor could be compared with a row with all rotors facing the wind (reference row).

The measured data were stored in a database automatically. From the stored data 10-second statistical data were calculated for analysis. This averaging time is a compromise between a high number of data points required for small deviations in the results and sufficient correlation between the wind and performance variations. 10 Seconds is somewhat longer than the travelling time of the wind from the first to the third turbine at 3.8 diameter spacing: 7 seconds at 8 m/s wind speed.

Further selection took place for wind direction (between 234.5° and 235.5°), rotor speed (Ω>0) and pitch angle (position for normal operation).
Only records with valid sonic data from the meteo-mast between the windward turbines (numbers 3 and 6) of both rows were considered .

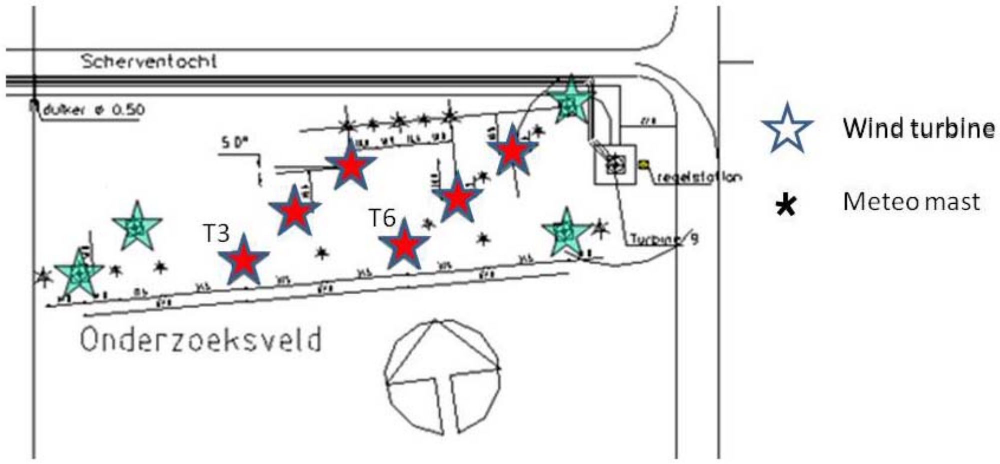

Figure 16 Plan of the scale wind farm. The red stars indicate the turbines used for the experiment. Turbines 3, 4 and 5 are in the left row (row 1) and turbines 6,7 and 8 in the right row (2).

3.4.2 Results

At first the power curves of the involved turbines have been compared [28]. This showed that turbine 7 had to be corrected by a constant offset of -300W. After correction the performances of the turbines looked sufficiently similar to enable the search for qualitative Controlling Wind effects as only differences in performance with the reference row had to be identified.

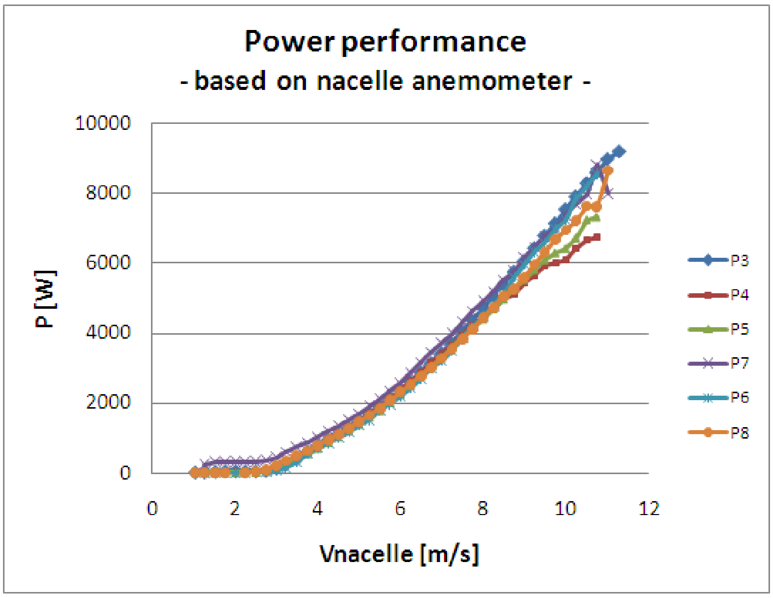

Figure 17 Power performance of turbines 3 to 8 based on nacelle anemometer readings. All turbine rotors are yawed in direction 235°; no CW control applied. From this graph it was concluded that the power of turbine 7 should be corrected by ΔP= -300W.

When comparing the performance of both rows the measurement results clearly appeared to be sensitive to data selection. An example is shown in Figure 18 where the relative power of both rows, without yawing of turbine 6, is compared for different selections of the wind direction sector (234.5° <WD<235.5 ° and 234 ° <WD<236°) from the same data set. The values of the relative power of the second and the third turbine clearly differ from each other.
Another indication of sensitivity for data selection is shown in Figure 19. The relative power production $P_{rel} = \sum P/(3P_{1th})$ is shown for the reference row (turbine 3, 4 and 5) and the CW row at different yaw angles of turbine 6. Results are given from the same data set but for two different choices of bin width, 0.5 and 1 m/s.

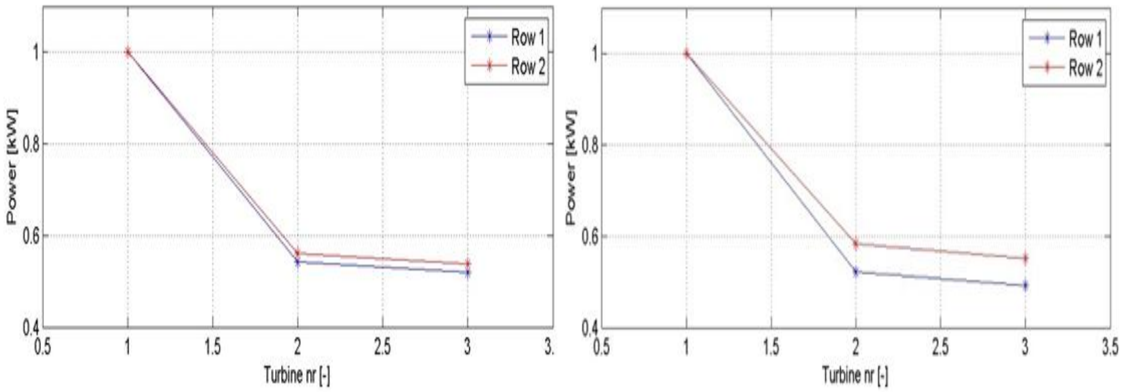

Figure 18 Relative power production $P_{rel} = \sum P/(3P_{1th})$ of both rows for different selections of the wind direction sector: 235° $^{+}/_{-}$ 0.5° (left) and 235° $^{+}/_{-}$ 1° (right). Each average value contains at least 85 data points. All turbine rotors are yawed in direction 235°; no CW control.

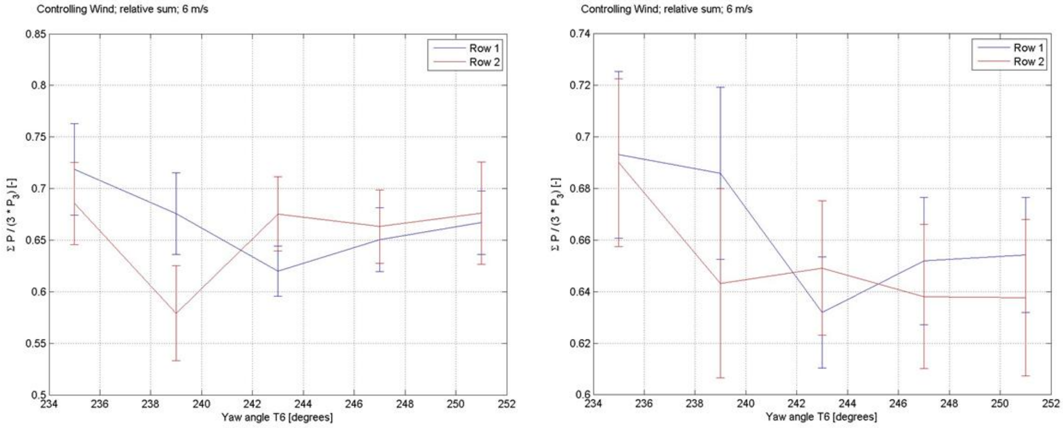

Figure 19 Relative power production $P_{rel} = \sum P/(3P_{1th})$ of the two rows at V=6 m/s depending on the yaw angle of turbine 6. The same data set is presented at two values of the bin width: 1 (left) and 2 m/s (right). The averages contain at least 20 and 39 data points respectively.

Figure 20 compares the absolute performances of the turbines in both rows for different wind speeds with all rotors heading in the same direction as the wind direction ($235^\circ\ ^{+}/_{-}\ 0.5^\circ$) so without oblique rotor of turbine 6. The average performances and the standard deviations of corresponding turbines are quite comparable. The performance deficits of turbines in the centre of the wake show the expected course with about equal values for the 2nd and the 3rd turbine albeit at higher values (≈50%) as measured in the full scale farm with 2.5 MW turbines at 3.8D (30 to 35%) [12].

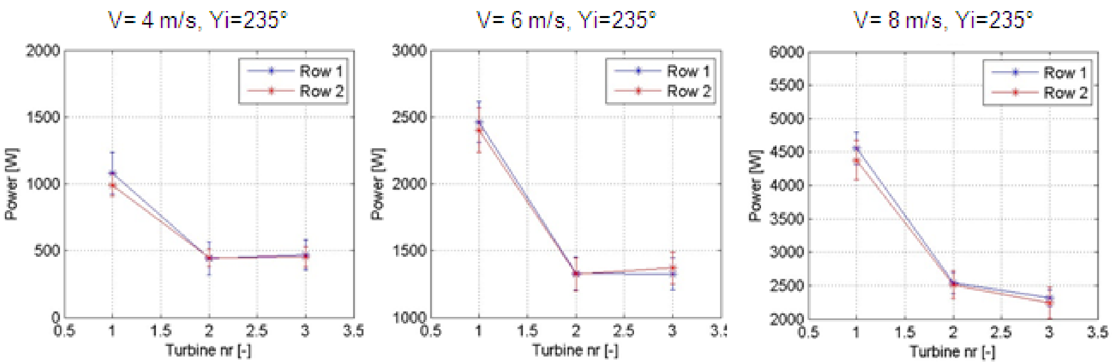

Figure 20 Comparison of the performance of the turbines in the reference row (1) and the CW row (2) for wind speeds of 4, 6 and 8 $^{m}/_{s}\ ^{+}/_{-}$ 1m/s. All turbine rotors are yawed in direction 235^{o}; no CW control. Wind direction: $235^\circ\ ^{+}/_{-}\ 0.5^\circ$.

Figure 21 compares the relative power $P_{rel} = \sum P/(3P_{1th})$ of the CW controlled row 2 with the reference row for different values of the yaw angle of turbine 6. At 4 m/s wind speed the performance of the reference row is almost constant, as expected. The performance of the CW row is significantly increased compared to the reference at yaw angles of 239° and 241°, probably caused by wake diversion. A decrease is shown at large yaw angles. At these yaw angles the large decrease in power of turbine 6 turns out to be larger than the positive effect of diversion on the performance of turbines of turbines 7 and 8.

For 6 and 8 m/s possible CW-diversion effects are questionable. E.g. this can be concluded when looking at the absolute power of the individual turbines at 6 m/s wind speed and different yaw angles (Figure 22). The performance of the first turbine clearly decreases with increasing yaw angle, as expected. The performances of the 2nd and 3rd turbines in the CW row are higher than the performance in the corresponding turbines of the reference row. This might be an indication for improved performance caused by wake diversion. However it is questionable whether these differences can be attributed completely to the yawing of turbine 6 because the performance of the last two turbines in the reference row are at relatively low levels from itself.

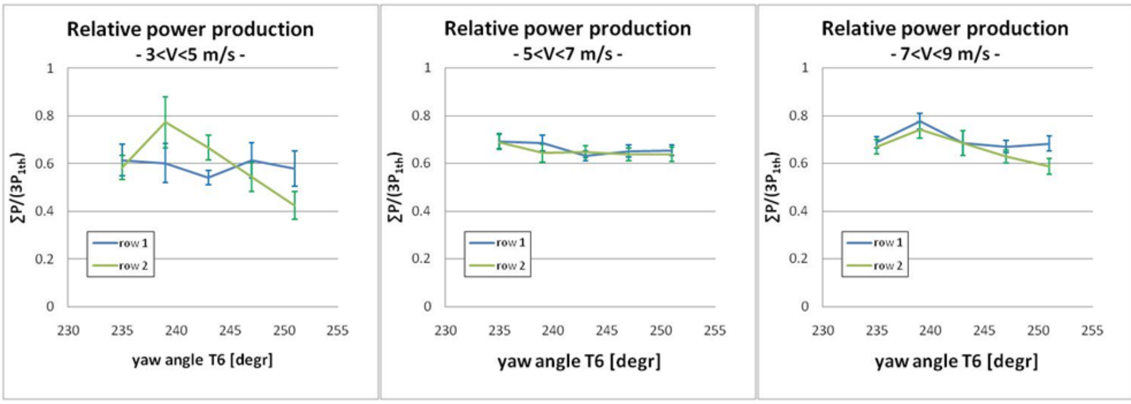

Figure 21 Relative power production $P_{rel} = \sum P/(3P_{1th})$ of the reference row (1) and CW row (2) for different yaw angles of turbine 6 at wind speeds of 4, 6 and 8 $^{m}/_{s}$ $^{+}/_{-}$ 1m/s. The number of data points for yaw angles (235, 239, 243, 247, 251) are respectively: (12, 9, 23, 13, 10), (39, 39, 53, 43,39) and (29, 14, 12, 21, 17). Wind direction: 235° $^{+}/_{-}$ 0.5°.

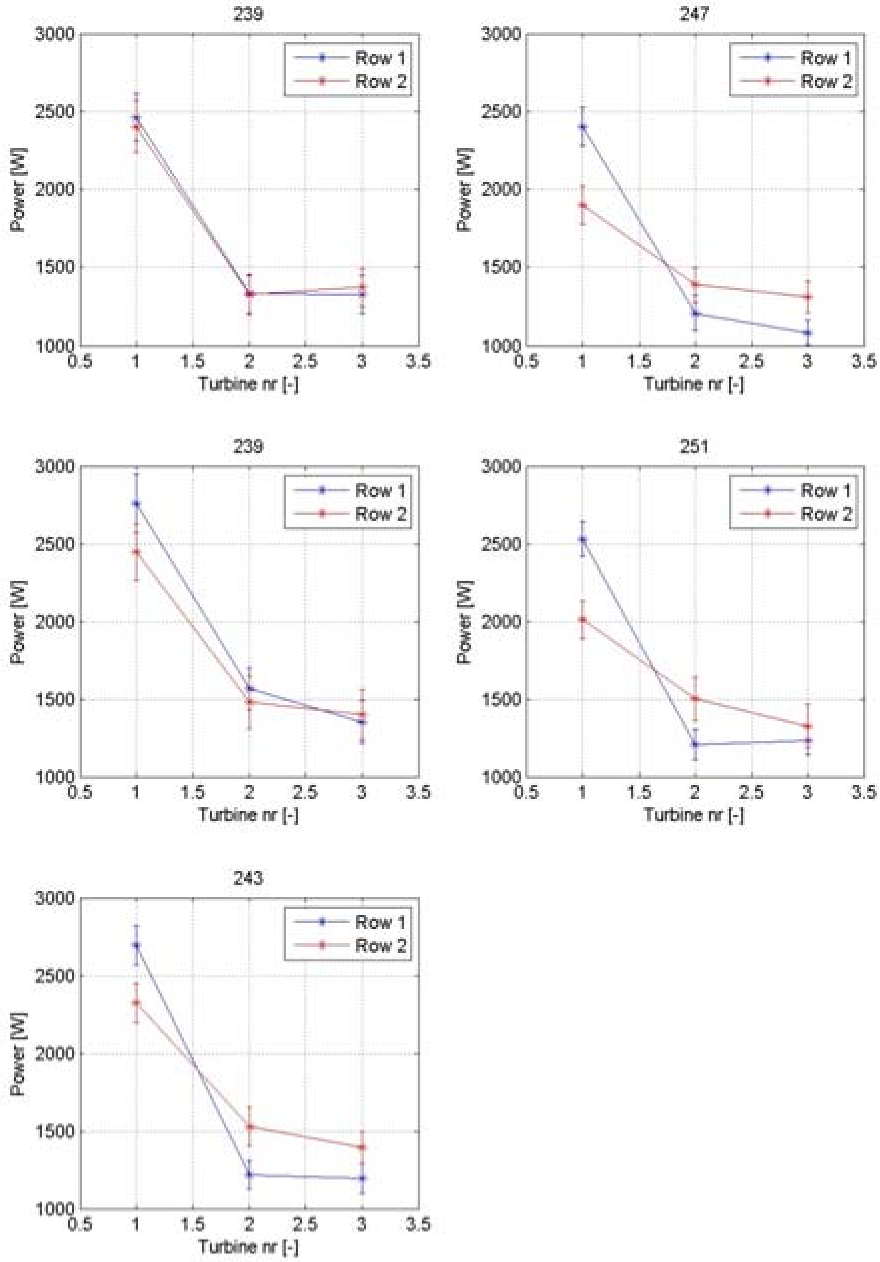

Figure 22 Power production of the turbines in the reference (row 1) and CW row (row 2) for different values of the yaw angle of turbine 6. Wind speed: $6\ ^{+}/_{-}\ 0{,}5\ ^{m}/_{s}$. Wind direction: $235° \ ^{+}/_{-}\ 0.5°$.

Clearly the measurement results are not unambiguous with respect to the occurrence of CW-diversion effects. Possible causes are scatter in the population of data, the sensitivity for filter conditions, the choice of the averaging time, the non-uniformity of the wind field, differences in turbine properties etcetera. It certainly looks like more measurement data is needed before one could draw decisive conclusions from experiments in the scale wind farm.

4. Conclusions

The project “Controlling Wind, tunnel-theorie” aimed at demonstration of the methods for Controlling Wind “diversion” and “rotation” and the development of an engineering model for optimization of farm control and farm lay-outs. Tunnel experiments in the boundary layer wind tunnel of TNO were thought to be suited for these purposes.
The development of an engineering model for both Controlling Wind “diversion” and “rotation” based on wind tunnel tests or CFD simulations appeared not to be feasible. Yet, a simple engineering model for CW-diversion alone could be derived and has been implemented in the FarmFlow code.
Further, experience gained with the tunnel tests and theoretical considerations about the scaling laws for the wake gave rise to drastic changes in the approach shifting the activities to scaled and full size experiments in open air at ECN’s EWTW (ECN Wind Turbine Test Site Wieringermeer). Because of setbacks in the performance of these experiments only evidence for CW-diversion could be found. No experiments or CFD simulations have been directed to investigate CW-rotation.

Experiments with model farms in the boundary layer wind tunnel appeared to be less suitable for the development of a reliable engineering model for Controlling Wind “diversion” and “rotation” because of scaling effects in the wake, tunnel wall interference and lack of similarity with atmospheric conditions:

- the difference in seize between the scaled turbines and full scale causes large differences in Reynolds numbers. The resulting differences in lift and drag properties of the aerodynamic blade profiles lead to strongly deviating flow distributions in the near wake. As this distribution forms the boundary condition for the far wake the model wake will not be representative,
- farm operation with oblique model rotors should form the main subject for the investigations. However by wake diversion a transverse flow component is introduced causing undesired wall interferences, disturbing the interaction between the wake en the surrounding flow,
- empty tunnel measurements showed that the anisotropy of the turbulence in the tunnel was not representative for ambient conditions. This leads to interactions between the wake and the surrounding flow that are not scalable to full size conditions.

The development of an integrated engineering model for predicting the power and rotor loads due to both flow control options, wake diversion and generation of large scale circulations, appeared not to be feasible starting from a relatively simple vortex model describing the drag and lift forces exerted on the flow by the rotor.

A separate model for wake diversion (AWC: Active Wake Control) has been derived from own and other parties’ wind tunnel experiments. AWC has been implemented in the FarmFlow code which calculates the energy production of turbines in a farm for a specified wind climate.

The development of an engineering model for CW-diversion with the aid CFD codes has been explored. A first step was made by simulation of the 2-dimensional pressure distribution around the aerodynamic profile of the test turbine of the Mexico project with the CFD code ANSYS CFX-10.
Good predictions of the aerodynamic coefficients could be observed at low angles of attack but better predictions at higher angles are needed. Therefore the transition model in CFX-10 has te be modified to predict transition from laminar to turbulent flow earlier with increasing angle of attack. In addition the turbulence model should predict the onset of separation earlier.

Further CFD simulations were carried out with another CFD code (FLUENT) on the Mexico rotor at non-yawed conditions. All three blades were modeled separately. Generally speaking a good agreement was obtained with measurements. Thereafter yawed conditions have been mod-

eled with Fluent code where the Mexico blades are represented by momentum sources as an actuator disk. The momentum sources are generated by Blade Element Theory in the VBM (Virtual Blade Model) and coupled to the surrounding flow by momentum equations. This approach eliminated time consuming and costly meshing of the blade geometry.
VBM simulations qualitatively agree with the expectations in all considered cases but the quantitative deviations with measurements were large except for the reference case (15 m/s flow velocity at 0^o yaw angle). This is explained by the specific rotor azimuth dependent flow characteristics which are not properly modelled with an actuator disk model like VBM.

After all, it was concluded that quantitative CW validation is not possible with an actuator disk model like VBM. CFD calculations where the separated blades are modelled as lifting lines might form an alternative.

Experiments at full scale with Controlling Wind control strategies were not possible in the 5 x 2.5 MW test wind farm of ECN because permission of the turbine manufacturer for such experiments could not be obtained.
Yet analyses of measurement data from three turbines, stored during 6 years of operation, showed many data points where the turbines were 'accidentally' operating under yawed conditions. These measurements showed

- that the energy production in the test farm can be increased by CW-diversion control by enforcing a positive yaw angle of the first turbine in wind directions at small positive angles with the row and vice versa. The increase is larger at larger yaw angles.
- the energy production at wind directions along the farm line is hardly influenced by yawing of the second turbine. At wind directions at small positive angles with the farm line it seems beneficial to avoid positive yaw angles relative to the first turbine.

Many setbacks have been encountered in making the scale wind farm fit for Controlling Wind experiments. Therefore only CW-diversion experiments could be performed in a row of three turbines at 3.8 rotor diameter spacing. It was not possible to perform experiments in rows with more turbines or different spacing.

The results from the measurements in the scale wind farm are sensitive to data selection conditions. This may be caused by the small data population, the chosen averaging time, the non-uniformity of the wind field, differences in turbine properties, etcetera.
Yet the results show that at 4 m/s wind speed the performance of a row of 3 turbines is significantly increased at yaw angles of 4° and 6° of the first turbine. At large angles (14° and 18°) the performance is decreased.
For other wind speeds (6 and 8 m/s) possible CW-diversion effects are questionable. The positive results at 4 m/s are seen as an encouragement to perform more measurement data in order to draw decisive conclusions for other conditions.

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