Energy research Centre of the Netherlands

Evaluation of "Heat and Flux" Farm Control

- Final Report -

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Acknowledgement

This report is part of the project 'Heat en Flux fundamenteel'. In this project, a new approach for wind farm control is investigated that optimizes the axial induction of upwind turbines. This kind of control is expected to lead to a higher production of the farm and simultaneously to a reduction of the mechanical loads on the turbines in the farm.
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Abstract

ECN holds a patent for the "Heat and Flux" concept. This concept aims at maximizing the power output of a wind farm by adjusting the axial induction of the windward turbines below their individual optimum for power production. This will reduce the velocity deficit in the wake and increase the output of the downwind turbines. Other benefits are decreased average loading of the upwind turbines and decreased fatigue loading of the turbines in the wake.

The reported activities aimed at the quantification of the effects of "Heat and Flux" farm control. For this purpose models have been developed for calculating the power and energy production with "Heat and Flux" operation. The models have been developed in close interaction with wind tunnel experiments on model turbines and farms and have been tested in full scale experiments on a row of five 2.5*MW* turbines.

Qualitatively, the wind tunnel tests and the field experiments revealed positive effects of simple "Heat and Flux" control settings on several occasions.
Quantitatively, the accuracy and reliability of the wind tunnel measurements are questionable because of the large scatter and the conditions that deviate from full scale in various aspects.
The full scale experiments point at comparable optima for "Heat and Flux" control settings as model predictions. However, quantitative predictions of the energy production benefits cannot be compared with measurements yet because of a shortage of suited measurement data for analysis. Therefore, additional measurement effort is needed for reliable quantification of the "Heat and Flux" effect on power performance and energy production.

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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 wind speed in the wake is decreased and turbulence is increased, the power output of turbines exposed to the wake will decrease and fatigue loads will increase. These effects are harmful for the economy of the wind farm.

Due to the aerodynamic interference of turbines and wakes, an optimum yield of the wind farm will only be found by *global* optimization of the whole farm, instead of *local* optimization of each individual turbine.
The “Heat and Flux” concept proposed by Corten and Schaak [1] aims to maximize the wind farm power output by operating the windward turbines below their individual optimum for power production by adjusting the axial induction. This will reduce the wake effects and increase the output of downwind turbines. Other benefits are decreased average loading of the upwind turbines and decreased fatigue loads of the turbines in the wake.

The overall purpose of the project is to reduce wake losses and loads of turbines in (large) wind farms by quantification of the effects of a first generation “Heat and Flux” farm control. For this purpose models have been developed for calculating the power and energy production with “Heat and Flux” operation. The models have been developed using insights gained from model measurements in the boundary layer wind tunnel of TNO in Apeldoorn and tested in full scale experiments on the 2.5*MW* turbines of the EWTW[1] in the Wieringermeer polder [2].

The aim of the project is stated in Chapter 2. Chapter 3 lists the activities that were offered in the contract and describes their execution. Deviations in the execution compared to the contract are discussed in Chapter 4. Chapter 5 reports about the results of the modeling activities, wind tunnel tests and field tests. The main conclusions and recommendations are summarized in Chapter 6.

[1] EWTW: ECN Wind Turbine Test Site Wieringermeer

2. Aim of the project

The aim of the project is to reduce wake losses and loads, especially in large wind farms. When wind turbines are grouped together, upwind turbines hinder downwind turbines. Current practice is to operate a farm by maximizing the energy production of each turbine individually. ECN has discovered and patented a new control strategy called “Heat and Flux”, which involves a new mode of operation for wind turbines in a farm and which claims higher energy production of the farm as a whole. Simultaneously the average loading on the upwind turbines in the farm and the fatigue loading of the turbines in the wake will be reduced.

3. Activities

3.1 Introduction

The activities in the project extend from development of an analytical model for “Heat and Flux” to full scale verification of different “Heat and Flux” control settings in a field test.

The model development comprised development of an analytical model and integration of “Heat and Flux” routines in existing ECN computer programs for calculation of wake characteristics and energy production in wind farms. The development used insights that were gained from measurements of wake characteristics and power production in a boundary layer wind tunnel with simulated offshore conditions.
Eventually, various settings for “Heat and Flux” farm control have been investigated in wind tunnel tests and checked at full scale in field tests in the EWTW test farm of ECN consisting of five state of the art wind turbines of 2.5*MW*.

The activities of the project were organized in the following work packages:
1. Management
2. Theory
3. Preparation of tunnel experiments
4. Boundary layer tunnel
5. Field test
6. Patent
7. Transfer of knowledge

The paragraphs below shortly describe the purpose of the activities in each work package as mentioned in the contract and discuss the execution in more detail.

3.2 WP1 Management

Aim
This work package aimed at usual project management activities, with special attention to the organization of wind tunnel experiments and field tests and the in- and output relations between both kinds of tests.

Execution
In the original contract, field experiments were scheduled in the Kenetech wind farm of Essent near Eemshaven. However, during preparation it became clear that reliable experiments with “Heat and Flux” control were impossible in this farm. The reasons are described in Chapter 4.
A solution was found by relocating the field tests to the EWTW test farm of ECN. However, this involved additional management effort related to cancelling of existing agreements and settlement of new agreements with the sponsors, the owner of the EWTW and the turbine manufacturer.
Furthermore, because of the relocation, it was no longer possible to perform the field test between the two series of wind tunnel tests as envisaged in the contract. This caused a rescheduling of the project planning, too.

3.3 WP2 Theory

Aim
This work package addressed the development of models for predicting the power and energy production in farms with “Heat and Flux” control.

To this aim an analytical model should be developed and calculation of the power performance and energy production of “Heat and Flux” farms should be enabled by adapting existing ECN computer programs.
The model development should be carried out in close interaction with the wind tunnel experiments and field tests.

Execution
An analytical model for “Heat and Flux” has been formulated in [3] and [4], based on the axial momentum theory. The turbines in a row are modeled by uniformly loaded actuator disks and the wakes are assumed to be fully expanded before they reach the next disk. Viscosity effects and exchange of momentum with the outer flow are not considered. The power outputs of the successive turbines are expressed in dependence of their axial inductions and the total power output is maximized.
Because of the simplification, this approach gives an upper limit for the possible gain due to “Heat and Flux”.

WAKEFARM [5] and FluxFarm [6], two already existing ECN programs, have been adapted for calculations of the effects of “Heat and Flux” control on the power production of wind farms. These adaptations have been carried out in the FyndFarm II project (SenterNovem 2020-02-11-10-003).

WAKEFARM is a modified version of the UPMWAKE model of Crespo et al. [7]. The program computes the velocity and turbulence intensity profiles in the wake. The initial conditions for the wake are determined by the axial force on the rotor. The axial force has been calculated with a rotor aerodynamics code while considering the specially developed strategy for “Heat and Flux” turbine control that gives the relation between the axial force coefficient and the blade pitch angle, while maintaining conventional torque control [8].

FluxFarm 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.
The empirical wake maps were determined from measurements with scaled turbine models (1: 400) in simulated offshore conditions in a boundary-layer wind tunnel. In the numerical simulations, the wake maps have been calculated by WAKEFARM.
With the FluxFarm program optimal combinations of “Heat and Flux” blade pitch settings have been determined for different farm lay-outs with empirically as well as numerically determined wake maps. The results are described in [9].

At first, the empirical and the calculated wake maps in FluxFarm only described the velocity and turbulence profiles in single wakes. The cumulative effects on the velocity and turbulence profiles caused by additional turbines in the wake were not considered. However, from the measurement results of the field tests a need occurred for computational analysis of more realistic situations with multiple wake conditions.
To this aim the FluxFarm program was adapted in this project for using an improved version of the WAKEFARM model as a dynamic link library because of the programs capability to calculate velocity and turbulence profiles for multiple wakes. Finally, additional calculations have been performed for turbine rows of different length in oblique flow with and without simulated wind direction variability [10].

The main results of the modeling activities will be presented in section 5.1.

3.4 WP3 Preparation of wind tunnel experiments

Aim

In this Work package the wind tunnel experiments had to be prepared. The main activities consisted of the specification of measurement matrices, functional testing of turbine models, calibration of the signals for the operational parameters of the models, testing and calibration of the data acquisition system of the tunnel and measuring the velocity profile in the empty tunnel.

Execution

30 Turbine models were available for farm experiments in the wind tunnel. All models had rotor diameters of 25*cm* but different pitch angles varying from -2.5° to 7.5° in steps of 2.5°. The rotors with 0° pitch angle were designed to operate in the “classic way” meaning close to the Lancester-Bertz limit for the maximum power coefficient C_p at an axial induction $a = 1/3$.
The range for the rotor speed of the models could be adjusted by adjusting the electric load.

Generator voltages and generator currents were measured in all models and bending strains in the tower in part of the models. From these signals the operational parameters turbine power and axial force were derived.
The measured signals have been calibrated in the laboratory and the accuracies for the conversion to operational parameters have been determined. In addition the rotor characteristics (power coefficient C_p and thrust coefficient C_t) were measured in the wind tunnel.

In order to judge the results of the wind tunnel measurements, the flow conditions in the tunnel without turbines had to be clear. For this purpose the horizontal and vertical structure of the flow was scanned during the first wind tunnel entry. This was carried out at various flow velocities by means of hot-wire anemometry [11] in the ‘empty tunnel’, i.e. without obstacles other than the hot-wire frame, anemometer, manometer, and a barrier in the front zone to set up the desired boundary layer profile [12].

In the experiments with the model farms special attention was paid to minimize the harmful effects on measurement accuracy caused by blockage effects and systematic errors in the sensors and generators of the models. Partly, the solution was found in differential measurements between two rows of model turbines next to each other and parallel to the flow. One row was equipped with rotors for the Lancaster-Betz optimum for axial induction (0° pitch angle) and the other with “Heat and Flux” blade pitch angle settings. After measurement of the performance differences the rotors of both rows were exchanged and the difference was measured again. The results of both measurements than were averaged.

3.5 WP4 Boundary layer tunnel

Aim

In this work package extensive wind tunnel experiments were planned to investigate the performance of downscaled wind turbines in different farm arrangements and “Heat and Flux” settings in a scaled boundary layer representative for offshore conditions.
Two measurement campaigns were scheduled in the contract: the first series mainly for model development and preparation of the field tests and a second series for elaboration of the field test.

Execution

As will be explained in Chapter 4 the intended field test in the Kenetech wind farm in Eemsmond was moved to the EWTW in the Wieringermeer polder. Because of the consequences for the time planning of the project it was decided to base the second measurement campaign in the wind tunnel solely on the results of the first campaign and on model calculations and not to wait for the outcome of the field test.

The measurement campaigns have been carried out in November 2003 and September/October 2004 in the boundary layer wind tunnel of TNO in Apeldoorn. Rotating wind turbine models have been used with various blade pitch angles. The dimensions represent a 1:400 scale of commercial wind turbines of 100*m* in diameter and 100*m* hub height. The tunnel ambience represented an offshore boundary layer on the same scale with roughness length $z_0 = 0.001m$.

Campaign of November 2003
In this tunnel entry the horizontal and vertical structure of the flow in the 'empty tunnel' were measured as well as the power (C_p) and thrust characteristics (C_t) of the different rotor types.
Other experiments addressed the flow distribution behind model rotors with different pitch angles and the difference in power production between 2 rows of 7 turbines; one "Heat and Flux" row and one reference row.

The experiments are described in [13] [14]. The main results are discussed in section 5.2.

Campaign of September/October 2004
Measurements have been performed with a model farm consisting of two parallel rows of 14 wind turbines in the flow direction (Fig. 3.1). According to the same procedure as described earlier, a row of turbines with 0° pitch angles for maximum performance in free flow conditions was compared with a row with "Heat and Flux" blade pitch angles.

The description of the experiments can be found in [15] and a (brief) analysis in [16]. The main results are discussed in section 5.2.

Fig. 3.1 *Installation of two rows of 14 turbines in the boundary layer wind tunnel of TNO: one row of models with "Heat and Flux" control and one row of models with conventional blade angles of 0°. The picture is taken in the direction of the flow.*

3.6 WP5 Field test

Aim
In this work package a field test in the Kenetech wind farm of Essent near Eemshaven was scheduled aiming at the full scale verification of the performance effect of a first generation "Heat and Flux" control.

Execution
Deviating from the contract, the field tests have been carried out at the EWTW in the Wieringermeer instead of the Kenetech wind farm. The reasons for the change will be explained in Chapter 4.

While the Eemshaven farm is one of the older wind farms in the Netherlands, the EWTW test farm consists of modern turbines of state-of-the-art technology and dimensions. It is located in flat open farmland and consists of a row of 5 turbines of 2.5*MW* [2]. The variable speed, pitch controlled turbines have rotor diameters and hub heights of 80*m*. The spacing between the turbines is about 3.8 rotor diameters (305*m*). The row is oriented in the direction of 275°, with 0° being North and a clockwise counting. Turbines in the farm are numbered from 5 to 9 from West to East.
The test farm is provided with a meteorological measurement mast and extended means for automatic acquisition of meteorological data and operational parameters of all turbines.
A description of the farm and the data acquisition system can be found in [17]

Additional effort was needed in this task because of the shift to the EWTW farm. Negotiations had to be opened with ECN Wind Energy Facilities BV, the owner of the farm, about the use of the turbines for the research and with the turbine manufacturer about the possibilities of modifying the turbines' control. Important items in these negotiations were the production losses at non-optimal settings of the control, turbine safety aspects (consequences for operation control and effect on loads), the technical implementation of the control modification and the guarantees in the contract.

Initially a test matrix was specified for automatic turbine operation at a series of alternating blade pitch angles in order to enable the measurement of the expected (small) production increase with sufficient significance. The different pitch settings should follow each other rather quickly in order to minimize the lack of coherence in time caused by changing ambient conditions. These differential measurements were expected to demonstrate the performance effects of "Heat and Flux" with sufficient reliability within a period of 1 year.

However, when this plan was presented, the turbine manufacturer did not agree with modifications that enabled automatic winding up of a series of blade pitch angle settings and the plan had to be abandoned. The main argument was that modification of the turbine control involved a new design release. As a consequence the one-off modification had to comply with the extensive (and costly) internal Quality Assurance procedures of the manufacturer. Further, because of the long lead time the modification did not fit in the project schedule as well.

Instead it was agreed that the manufacturer would manually change the pitch settings of the individual turbines by means of their remote supervision system on request when suited wind conditions were expected. For this procedure a tool was developed to monitor the wind predictions and to specify the expected start and duration of turbine operation with adapted pitch settings for "Heat and Flux" measurements.

Eventually 3 field test campaigns have been carried out in which normal operation (*NO*) of the turbines has been compared to 3 different modes of "Heat and Flux" operation:

1. noise-reduced operation (*NRO*).
   NRO is a build in mode of operation that reduces the noise production. The turbine is operated at increased minimum blade pitch angle (4°) and the tip speed is reduced above approximately 7*m/s* wind speed. As a result the power production is reduced making the rotor more permeable to the flow. Operation of the most upwind turbine in *NRO* mode was expected to be suited for validation purposes. This is especially the case for operation below 7*m/s* where the rotor speed is not adapted and the turbine operates in a kind of exaggerated "Heat and Flux" mode.

Because *NRO* is build in as a standard it was immediately available for test purposes and could be easily remotely activated by the manufacturer. During the measurement campaign the mode of operation of turbine 5 and of turbine 9 automatically switched from normal operation to *NRO* and vice versa each 12 hours. This was done independent of the wind direction and therefore led to unnecessary energy production losses for the owner of the farm.

2. operation in "*22220*" mode.
   This mode of operation comprises minimum pitch angles of 2° for the first 4 wind turbines upwind in the row and no change for the last turbine. This setting should be about optimal in offshore conditions according to preliminary FluxFarm calculations [6]. For this reason and because of the unnecessary yield losses with *NRO* this setting was applied in the second campaign. In order to avoid unnecessary energy losses the desired mode of operation was set by the manufacturer by means of the remote supervision system on request of ECN when suited wind speeds and directions were predicted.
3. operation in "*20xxx*" mode.
   A third campaign with "*20xxx*" control setting was performed in succession of the campaign with *22220* control. The *20xxx* setting was based on the observation that the dominant changes in performance occurred in the first 2 turbines, only.
   The *20xxx* mode comprises a minimum pitch angle setting of 2° for the first turbine. For the analysis the measurement records were filtered for minimum pitch angles 0° of the second turbine. No adjustment of pitch angles or filtering was applied for the other turbines.
   Again the desired mode of operation was set manually by the manufacturer by remote control upon request.

The operational parameters of the 5 turbines, the loads on turbine 6 and the meteorological data of the measurement mast were continuously measured during the field tests and stored in the measurement database automatically.

The measurements for the analysis of the *NRO* operation have been carried out from August 1st to September 14th, 2006. During this period 173 10-minute measurement records with normal operation and 133 records with *NRO* operation of turbine 5 have been gathered from westerly wind directions that were suited for the analysis [18]. These numbers of records correspond to about 1.2 and 0.9 days of observation time.

Table 3.1 gives the relevant settings for the *22220* and *20xxx* modes of operation. Data have been gathered with westerly winds coming from directions within a range of ± 10° with the farm's center line [19]. The resulting data set was further filtered for yaw angles of turbine 5 where the strongest performance response of turbine 6 occurred for the wake of turbine 5. The amounts of data that eventually have been used for the analysis are given in the table.

The main results of the field tests are reported in section 5.3

Table 3.1 *Minimum blade pitch angle (β) settings for the analysis scenarios 22220 and 20xxx with some details about the measured data sets. The limits for pitch angles allow for a measurement uncertainty of 0.5°.*

Operation mode		Normal operation		"Heat and Flux"	
Scenario		00000	00xxx	22220	20xxx
Turbine nr.	5	$-0.5^\circ<\beta<0.5^\circ$	$-0.5^\circ<\beta<0.5^\circ$	$1.5^\circ<\beta<2.5^\circ$	$1.5^\circ<\beta<2.5^\circ$
	6		$-0.5^\circ<\beta<0.5^\circ$	$1.5^\circ<\beta<2.5^\circ$	$-0.5^\circ<\beta<0.5^\circ$
	7		any	$1.5^\circ<\beta<2.5^\circ$	any
	8		any	$1.5^\circ<\beta<2.5^\circ$	any
	9		any	$-0.5^\circ<\beta<0.5^\circ$	any
Measurement period		Feb. 2006 – Sept. 2007		Feb. 2007 – Sept. 2007	
Nr. of data points		1,090,547	1,314,414	252,122	201,139
Equiv. time [days]		≈ 3.16	≈ 3.8	≈ 0.73	≈ 0.58

3.7 WP6 Patent

Aim

The purpose of this work package is the managing of the national and international patent application procedures and the extension of the legal protection to new "Heat and Flux" ideas, if applicable.

Execution

At the start of the project a national patent application had already been submitted (OA 1021078). Parallel to the national application an international novelty research has been carried out. Based on the knowledge gained by the research an adapted national application (OA 1023666) and later on an international application (PCT/NL/2004/00421) were submitted.
The national application was granted on 20 December 2004. The international application procedures have not been completed by the end of 2007.

3.8 WP7 Transfer of knowledge

Aim

Transfer of knowledge and results gained from the project to various interest groups and by various means of communication.

Execution

The non-confidential knowledge that has been gained in the project has been transferred in various ways and forms. The table in section 5.4.1 gives an overview compared to the deliverables specified in the contract.

The co-sponsors have been informed in more detail about the technical progress and time schedule on 2 occasions: one project meeting in April 2006 and during the Dutch Wind R&D Work Shops in October 2006. In between the co-sponsors have been kept informed mainly by communication by telephone or e-mail.

4. Contract and contract modification

In the original contract field experiments were scheduled in the Kenetech wind farm of Essent near Eemshaven. In order to reach this goal and to enable “Heat and Flux” operation it was required to implement a first “Heat and Flux” control algorithm at least in part of the turbines. Furthermore a control for farm operation had to be implemented that enabled automatic switching between normal and “Heat and Flux” operation for selected turbines and ambient conditions.

From the start of the preparation of the field test it became clear that insufficient expert knowledge of the turbines was available with Essent to support the design and implementation of the “Heat and Flux” control in the turbines. This knowledge could not be obtained from the turbine manufacturer as well because the manufacturer Kenetec ended their activities years before because of bankruptcy. Even attempts to hire an ex-employee of Kenetec who was involved in the design of the turbine control did not lead to a satisfying arrangement.
Furthermore the farm control system was not suited for automatic changes of the operation mode of selected turbines.

A solution of the problem was found by relocating the field test to the test farm of EWTW. This farm was considered to be much more representative for the current technology with its five state-of-the-art wind turbines of 80*m* rotor diameter and 2.5*MW* nominal power. Furthermore, the cooperation with the manufacturer and the owner of the farm should enable the adaptation of the turbine control and the farm control. In addition a reliable and accurate data acquisition and storage system already was installed for the measurement of turbine performances, loads and operational conditions as well as for the measurement of the meteorological data.

The mentioned problems and the proposal to carry out the field test in the EWTW have been presented to SenterNovem and the co-sponsors in a meeting on April 13, 2006. As a result a request for adaptation of the contents of the contract and extension of the contract period has been send to SenterNovem in a letter of July 31, 2006. The request was granted on October 6, 2007 and the project duration was extended from August 31, 2006 to October 31, 2007.

Fig. 4.1 *The EWTW test farm seen from the IJsselmeer. The turbines have a rotor diameter and a hub height of 80m and a capacity of 2.5MW each. The turbines are numbered from 5 to 9 from left to right.*

5. Results

5.1 Modeling results

The effect on the power performance and energy production has been estimated with the analytical model and with the computer programs FluxFarm and WAKEFARM. The results are discussed in the following paragraphs.

5.1.1 Analytical model

The analytical model has been used to predict the maximum possible power performance increase of 2 wind turbines in line with the flow. The model [4] predicts an increase of 4.1% for the combined power by lowering the axial induction of the first turbine to 1/5 instead of 1/3, the induction for maximum power production of a free turbine. See Fig. 5.1.
This increase is achieved when the second turbine is completely covered by the wake. In the model the efficiency (power coefficient C_p) only depends of the axial induction. The wind speed, pitch angle and distance between the turbines are not a parameter in the model.
As stated earlier, the results of this approach are regarded to give an upper limit for the potential gains of the "Heat and Flux" concept.

For the general case of a row of *n* turbines in line with the flow, it was derived that the optimum setting of the axial induction for the most upwind turbine equals 1/(2*n*+1) and for the following turbines 1/(2*n*-1), 1/(2*n*-3),…., 1/7, 1/5, 1/3.

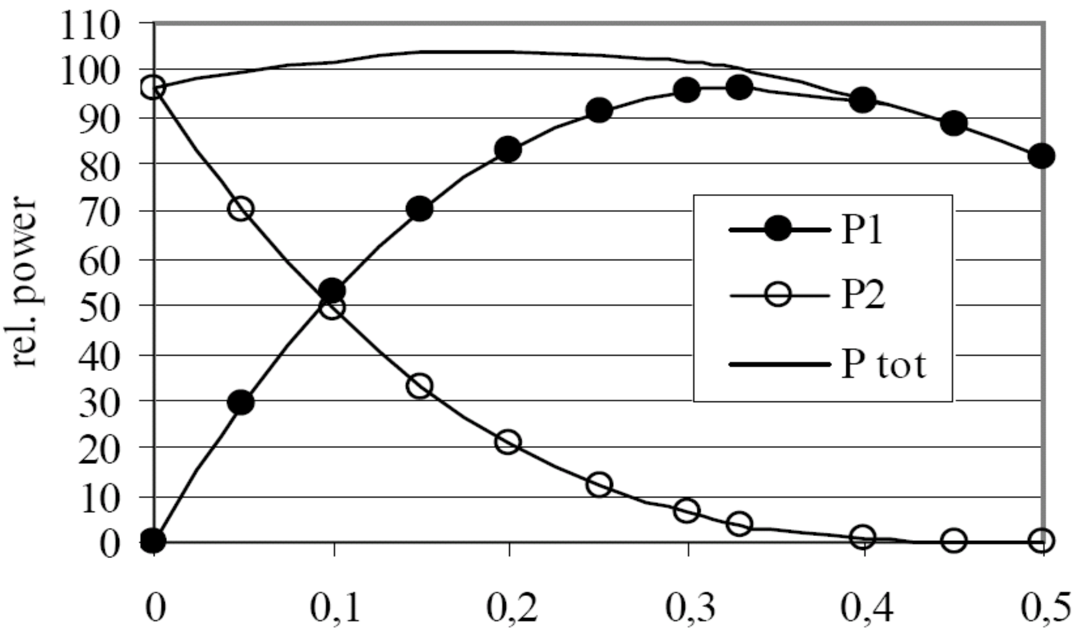

Fig. 5.1 *The relative power production of two actuator disks in line with the wind. The downwind disc is fully in the wake of the upwind disc. The combination reaches maximum output (104.1%) at axial inductions of 1/5 for the upwind disk and 1/3 (Betz limit) for the downwind disc respectively.*

5.1.2 Computer model

Power performances have been calculated with FluxFarm for rows of turbines with "Heat and Flux" control with various lengths in line with the wind direction [6]. The calculations were based on single wake maps calculated by UPMWAKE as well as empirical maps that were

derived from wind tunnel measurements. The most profitable "Heat and Flux" settings for the blade pitch angles of the EWTW turbines have been established for various spacing.
For the EWTW spacing (3.8*D*) and offshore conditions (z_0 = 0.001*m*), the maximum gain in power production at 9*m/s* ambient wind speed is ≈ 4.8% based on the empirical wake maps and ≈ 3.2% for the maps calculated with UPMWAKE. See Fig. 5.2.

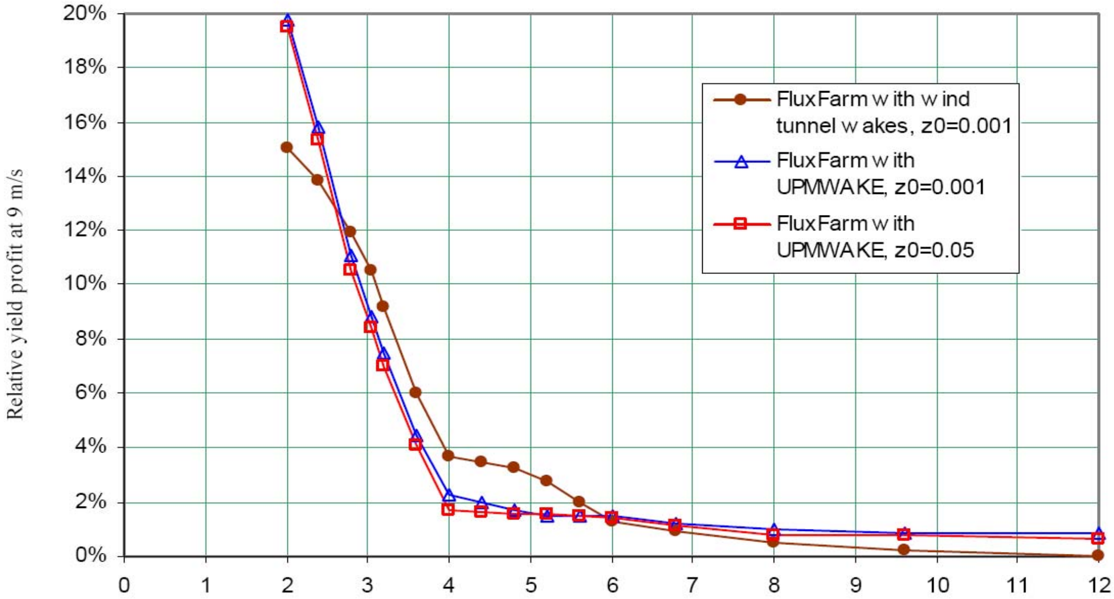

Fig. 5.2 *Maximum relative power gain for "Heat and Flux" operation in a row of five EWTW type turbines in line with the wind direction as function of the turbine spacing in rotor diameters for a wind speed of 9 m/s. The results are calculated [6] with FluxFarm and single wake maps derived from calculations ("UPMWAKE") and wind tunnel measurements ("tunnel wakes").*

Furthermore, total gains have been calculated for farms in specified wind climates with uniform wind direction distributions.
For instance, the energy production of an offshore "Heat and Flux" farm with 10 rows of 10 turbines at 4.8*D* spacing is about 0.7% higher than of a conventional farm. This is the result of calculations with empirical single wake maps for a wind climate with Weibull factors A = 10*m/s* and k = 2. When using calculated wake maps the increase is about 0.45%.
The gain in energy production is less for a smaller farm. In the same wind climate and at the same spacing the energy gain decreases to about 0.1% for a wind farm consisting of 5 rows of 5 turbines when calculated with both kinds of wake maps.

However, in these calculations only single wakes are considered without the effects of other turbines in the wake. Multiple wakes will have substantially different profiles because the extra power extracted from the wake changes the velocity and turbulence distribution. The performance and load response of a turbine in a multiple wake therefore will differ, too.

For this reason the FluxFarm program was linked to WAKEFARM to enable automatic computation of velocity and turbulence profiles in single and multiple wakes. After the modification a series of energy production calculations have been performed for the EWTW and for a row of nine turbines at the same spacing. The effect on power performance has been computed assuming an undisturbed wind speed of 8*m/s* at hub height. However, this condition is far from realistic. Therefore, the effects of oblique flow and variability in the wind direction have also been simulated by assuming a wind direction frequency distribution around the average that is typical for neutral atmospheric conditions: $\sigma_\theta = 0.79\ I$ (with standard deviation of wind direction σ_θ and turbulence intensity I). The results are summarized in Table 5.1

Table 5.1 *Power performance improvement by "Heat and Flux" as calculated with FluxFarm for rows of five and nine turbines at 3.8D spacing in oblique flow [10]. A wind speed of 8m/s is assumed in offshore conditions (z_0 = 0.001 m) at constant (steady) or quasi-dynamic wind directions.*

Inflow angle	Row of 5 turbines (EWTW farm)		Row of 9 turbines	
	steady	variable	steady	variable
0°	0.91%	0.70%	5.27%	3.90%
3°	0.84%	0.60%	4.54%	3.36%
6°	0.40%	0.22%	2.15%	1.68%

The gain in production is lowered by the variability of the wind direction. The results also show that the positive effect of "Heat and Flux" gradually is lost at increasing angles between the flow and the line of turbines.
For both row lengths the best results were obtained at normal blade pitch angles of 0° for the 2 or 3 most down wind turbines and 2° for the other turbines.

5.2 Results of wind tunnel experiments

5.2.1 Model characterization

The rotor models have been characterized by measuring the power coefficient C_p and thrust coefficient C_t in the wind tunnel. It was concluded that the thrust coefficient C_t could be sufficiently adjusted while maintaining a good maximum performance by selection of rotors with different pitch angles [13]. However, determination of the measurement accuracies showed that the error in both coefficients was rather high (±10%). This was due to the inaccuracies of the torque and rotor speed measurements and because of the uncertainty about the vertical position of the resulting aerodynamic force that acts on the rotor.

5.2.2 Tunnel effects

The velocity profiles in the empty tunnel (no model turbines installed in the measurement section) have been measured using the hot-wire traverse system of the tunnel. The measurements have been reported and analyzed in [12].

The measurements showed that vertical velocity profile and the turbulence in the tunnel could be considered to be a good representation of neutrally stable atmospheric offshore conditions scaled by a factor 400. Yet, the conditions differ with ambient because of blockage effects and the unrealistic negative pressure gradient that was created by the fan of the tunnel to drive the flow. Consequently the effects of "Heat and Flux" in the wind tunnel will differ from ambient.

Further, an angle of a few degrees was measured in the vertical plane between the flow and the horizontal, even very close to the floor. Probably, this was at least partly due to erroneous probe orientation. Therefore a correction has been derived and applied to all horizontal and vertical wind speed data.

In addition a theoretical analysis has been carried out into the similarity of the scaled wake conditions in the tunnel compared to full scale [20]. From this analysis it was concluded that the wake behind a scaled rotor is representative only if the velocity profiles within about 2*D* distance behind the rotors are similar, too. This however is not the case. Due to large differences in Reynolds numbers the lift and drag coefficients differ much leading to large differences in rotor flow.

5.2.3 First series of farm experiments

The first series of farm experiments in this project (November 2003) compared the power production of two rows of seven turbines next to each other. One row had "Heat and Flux" blade pitch angle settings and the other row had conventional pitch settings. The spacing between the model turbines was 4.5*D* and the distance between the rows was 5*D*.
Five different combinations of pitch angles were examined: the first turbine was set at -2.5° or 0° or 2.5° with the remaining turbines all set at 0° or the first 2 turbines were set at 2.5° or at 5° and the others at 0°. These five combinations were denoted as "Heat and Flux" units from -1 to 4. Each combination was measured two times: once with the "Heat and Flux" farm along one side of the measurement section and the reference farm at the other side and vice versa. The difference in power output between the farms in both arrangements was averaged.

The measurements are reported in [14] and discussed in [13].

Results of the power performance measurements are given in Fig. 5.3. When the blade pitch angle of the first turbine is set at 2.5° the average gain of the "Heat and Flux" farm is 2% over the power production of the classic farm. The measurements also showed that at the same time the axial force on the upwind turbine was reduced by 20%.

However, these results can not be considered to be reliable because of the large and not systematic differences between different wind speeds and "Heat and Flux units" and because the average should be zero at zero units.

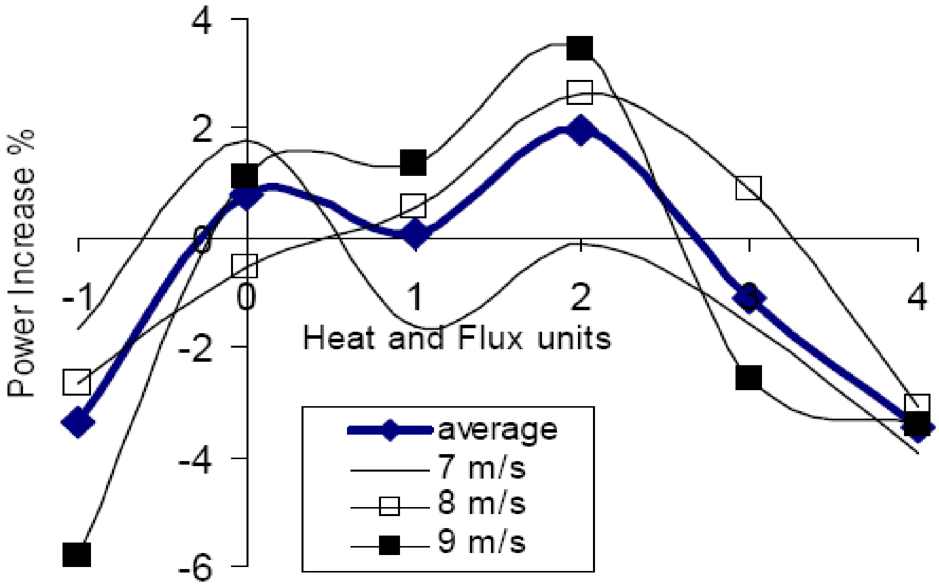

Fig. 5.3 *Results of the differential experiments between a farm in classic operation and a farm in "Heat and Flux" operation [13]. On the horizontal axis the Heat and Flux "units" are given: -1 means the 1st turbine at pitch angle -2.5°, 0 means all pitch angles equal to 0°,1 means the 1st turbine at pitch angle 2.5°, 2 means the 1st 2 turbines at pitch angle 2.5°, and so on. With the first two turbines set at 2.5° (2 Heat and Flux "units") and the remaining five turbines all set at 0° 2.0% more power is produced compared to the classic farm.*

5.2.4 Second series of farm measurements

The second series of farm experiments in the wind tunnel (September/October 2004) measured the power production of a “Heat and Flux” row of 14 turbines. In this series the spacing between the turbines was 3*D* (33% smaller than in the entry of November 2003). Also much more different “Heat and Flux” settings were investigated, 22 in total with blade pitch angles varying from -2.5° to 7.5°. The measurements and a short analysis are reported in [15] and [16].

The measurements were carried out in the same way i.e. measuring the power difference between turbines in the row with “Heat and Flux” control and the turbines in the reference row and repeated measurement after exchanging the rows. From these data the average power gain was calculated for rows of various lengths. Table 5.2 gives an overview of the results for a tunnel speed of 7*m/s*.

Table 5.2 *“Heat and Flux” power performance profit at 7m/s tunnel speed depending on row length and blade pitch setting combinations reported in [16]. “H&F Setting” lists the blade pitch settings, for example: '2x50, 6x25' refers to a “Heat and Flux” row with 2 turbines with pitch 5.0°, 6 turbines with pitch 2.5° and 6 turbines similar to the conventional farm (0°). The table shows the profit in case the farm would have had as much rows as mentioned in the header.*

H&F Setting	**Heat and Flux profit [%] for row length:**													
	1	2	3	4	5	6	7	8	9	**10**	11	12	13	14
1x25	-1.2	3.8	1.4	1.7	1.7	1.6	1.5	1.6	1.6	**1.5**				
2x25	-0.8	2.4	1.0	1.1	1.2	1.2	1.2	1.3	1.2	**1.2**				
1x50, 3x25	-15.5	1.7	-2.9	-1.8	0.7	1.2	1.3	1.6	1.7	**1.6**	1.6	1.5	1.5	1.3
1x50	-16.4	1.1	-3.4	-1.7	-1.1	-0.7	-0.5	-0.4	-0.3	**-0.3**	-0.2	-0.3	-0.4	-0.5
2x50	-16.3	-3.0	-3.2	-2.6	-1.5	-1.1	-0.7	-0.6	-0.5	**-0.5**	-0.4	-0.5	-0.6	-0.6
10x25	-2.0	1.6	-1.1	-0.8	-1.2	-1.9	-2.6	-3.0	-2.3	**-2.7**	-2.4	-2.4	-2.1	-2.0
12x25	-0.1	3.3	0.5	1.0	0.6	-0.1	-0.7	-1.3	-0.6	**-0.9**	-2.0	-2.0	-1.3	-1.2
1x50, 11x25														
2x50, 6x25	-14.9	-1.8	-3.4	-2.9	-2.8	-3.1	-3.5	-3.9	-3.1	**-2.9**	-2.6	-2.4	-2.3	-2.3
2x50, 10x25	-17.3	-3.7	-4.4	-3.5	-3.2	-3.4	-3.4	-3.5	-2.6	**-2.7**	-3.4	-3.4	-2.6	-2.3
4x50	-15.7	-2.4	-7.4	-8.0	-5.0	-4.7	-3.7	-3.0	-2.5	**-2.3**	-2.1	-1.9	-1.7	-1.6
1x75, 3x50, 8x25	-31.4	-8.2	-12.2	-12.0	-9.0	-8.7	-8.0	-7.3	-6.0	**-5.8**	-6.3	-6.2	-5.4	-5.2
4x75, 4x50, 4x25	-30.8	-15.6	-17.6	-17.8	-15.7	-14.7	-15.0	-14.5	-11.8	**-11.3**	-11.3	-10.7	-9.4	-8.7
1xmin25	-12.7	-9.9	-6.1	-5.2	-4.6	-4.3	-4.1	-3.9	-3.7	**-3.4**	-3.3	-3.2	-3.2	-3.1

Fig. 5.4 shows the difference between the “Heat and Flux” farm and the classic farm at row length of 10 turbines for 7 and 8*m/s* tunnel speeds.

Again, it looks like a gain in energy production is achievable by “Heat and Flux”. And again, the scatter in the data is considerable for different wind speeds and settings. For instance the differences that were observed when changing position of the farms are in the same order of magnitude as the effects that were looked for. Also the differences between de measurement results for 7 and 8*m/s* tunnel speed suggest considerable scatter.

From the results of both measurement series it was concluded that more accuracy was needed for future wind tunnel tests. Furthermore it was recommended to restrict the variation in pitch angles to the first 4 turbines and to apply smaller pitch angle intervals in order to enable gradual changes of the axial induction in the row.

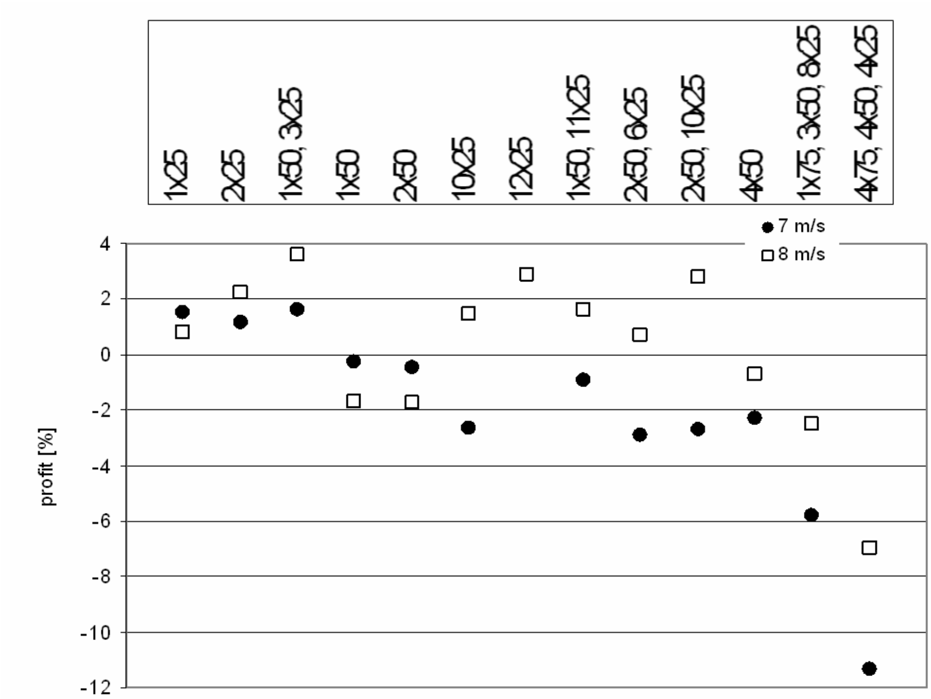

Fig. 5.4 *Difference in total power produced by a row of 10 "Heat and Flux" model turbines compared with a row of 10 "conventional" turbines reported in [16]. The relative difference* $(P_{H\&F}-P_{conv})/P_{conv}$ *x 100% is given for 7 and 8m/s tunnel speed and different combinations of pitch settings.*

5.3 Results of the field tests

The field test have been carried out in the EWTW and consisted of 3 measurement campaigns wit different "Heat and Flux" blade pitch settings in the wind turbines.

5.3.1 Noise Reduced Operation (*NRO*)

The power production during *NRO* has been compared with the production in normal operation (*NO*) in ref [18]. The measured P-V curves, constructed from 10-minute averaged values of power and wind speed show that the power output of turbine 5 is reduced and the power output of turbine 6 is increased. The summed power production of both turbines indicates that the power reduction of the windward turbine is compensated by the decreased wake effects on the second turbine. So a neutral power production seemed to be possible for this far from optimal "Heat and Flux" setting. However, this promising result was considered to be premature because of the relative large spread in the measurement results. In addition, the atmospheric stability was left out in the analysis while the two modes were active during two distinct periods of the twenty-four hours each day.

5.3.2 "*22220*" Operation

The datasets for this mode have been analyzed and compared with datasets for normal operation (*NO*). To increase the significance three independent methods have been used for the analysis [19]: an IEC 61400-12-1 alike power performance analysis based on 10 minute averages and a maximum likelihood method and quantile-quantile analysis based on the raw data with sampling rate of 4*Hz*. All three methods show the same systematic deterioration in power performance while turbines are in "Heat and Flux" operation. This holds for each individual turbine and ergo for the wind farm as a whole. Therefore there is no doubt that this specific configuration failed.
Most probably this is caused by the wind direction changes in time and space but also by the characteristics of the yaw control of the turbines. Because of these effects the wind direction is seldom inline with the complete line of turbines which is needed to harvest the full benefits of "Heat and Flux".

It also should be mentioned that the most recent calculations with FluxFarm for multiple wakes (se paragraph 5.1.2) did not point at the *22220* setting as the best configuration for "Heat and Flux". The calculations predicted the highest power gain at normal blade pitch angles of 0° for the 2 or 3 most down wind turbines and 2° for the other turbines.

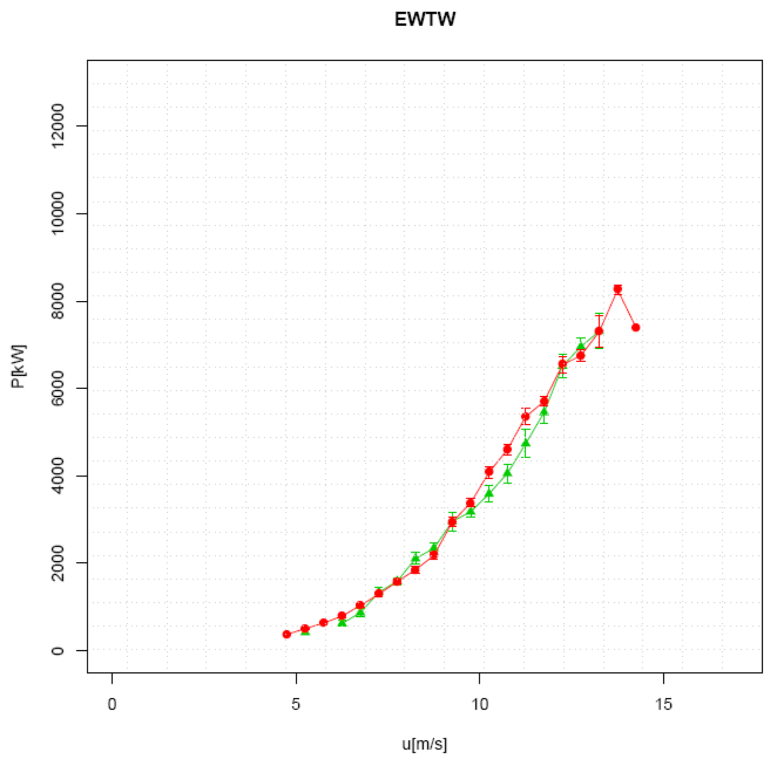

Fig. 5.5 *Power performance characteristics of the EWTW according to the IEC 61400-12-1 alike power performance analysis for scenario 22220 (green triangles) and scenario 00000 (red bullets). Error bars denote the standard deviation. In [19] the method of analysis is described.*

5.3.3 "*20xxx*" Operation

In the *22220* mode operation it was observed that the largest effects on average power occurred in the 2 turbines at the front of the row. The other turbines show only little difference with their next upstream turbine. Based on this observation the *20xxx* mode focuses on the effect of "Heat and Flux" operation of the first 2 turbines.
In the *20xxx* mode the first turbine is set at minimum blade pitch angle of 2°. The data set for analysis is filtered for 0° pitch angle of the second turbine.

Again the three independent statistical methods of analysis mentioned in the previous section were applied [19]. All three methods show a slight deterioration in power performance of turbine 5, which is within the statistical uncertainty, while at the same time an increase of the power of turbine 6 can be observed. The combined power performance of both turbines shows a systematic increase (Fig. 5.6).

The influence of the scenario 20xxx on the wind farm as a whole has been investigated, too. It has been shown that the overall performance has not been negatively influenced by this mode of "Heat and Flux" operation.

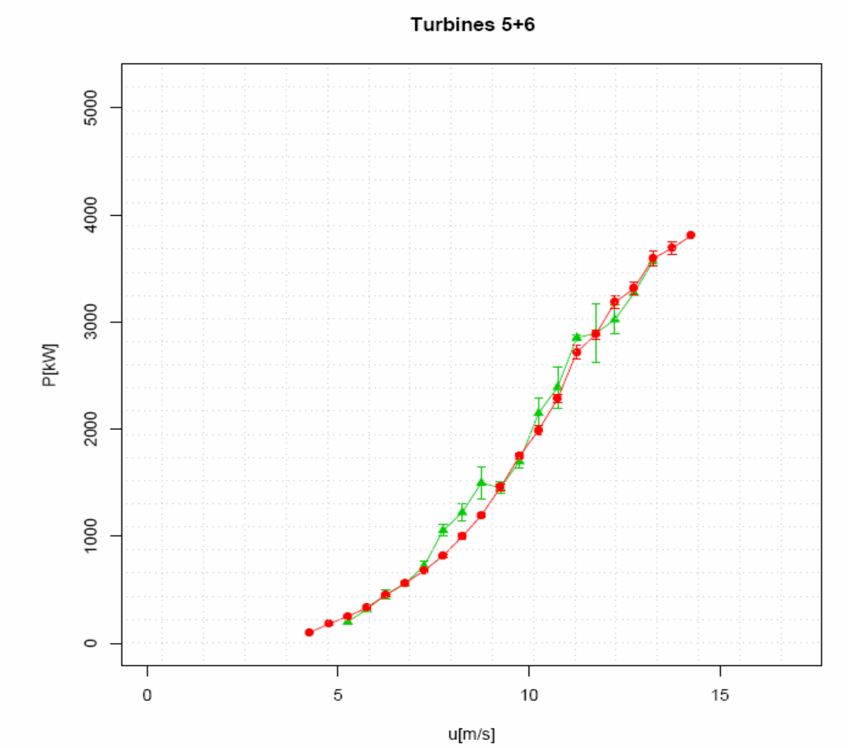

Fig. 5.6 *Power performance characteristics of turbine 5 (left) and 6 (right) according to the IEC 61400-12-1 alike power performance analysis for scenario 20xxx (green triangles) and scenario 00xxx (red bullets). Error bars denote the standard deviation. In [19] the method of analysis is described.*

5.3.4 "*40xxx*" Operation

In *NRO* the rotational speed of the turbine is reduced above about 7*m/s* wind speed. Below this limit the relation between the rotational speed and the generated power does not differ from normal operation. Therefore, in such conditions *NRO* behaves exactly like an "exaggerated Heat and Flux" operation of the first turbine with minimum blade pitch angle of 4° and normal pitch angles for the other turbines.

To investigate the behavior of this kind op operation, denoted by *40xxx,* the dataset for *NRO* has been analyzed once again at the end of the contract period [19]. Additional filtering is applied for wind speeds below 7*m/s*. This reduced the observation time from about 0.9 days for *NRO* to about 0.33 days.

Again the data have been analyzed with 3 different and independent methods. Although the number of available data points is very limited, three important conclusions could be drawn:

- the exaggerated "Heat and Flux" operation *40xxx* showed that previous observations of the *20xxx* scenario are real effects of the "Heat and Flux" pitch control,
- a pitch angle of 2° for "Heat and Flux" seems to be a good first choice, since 4° is already too much,
- variation of the rotational speed characteristic is an important part in finding the optimal farm control setup.

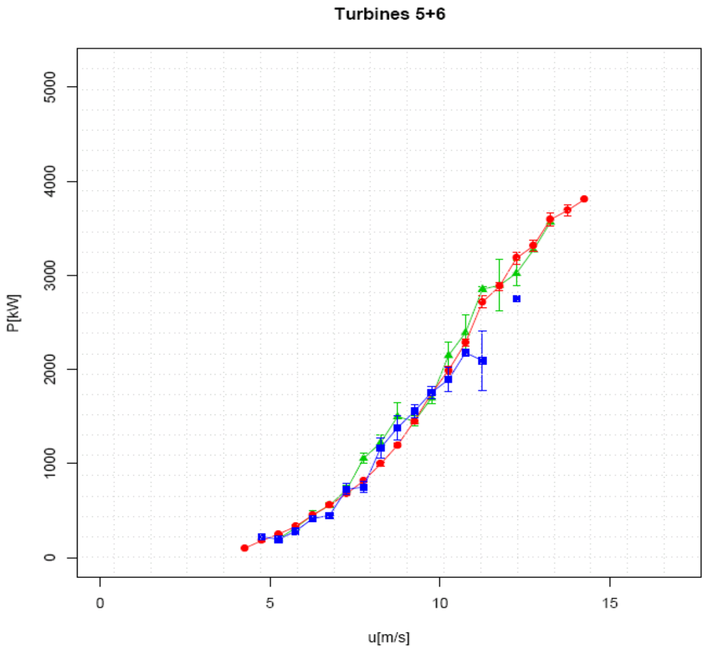

Fig. 5.7 *Combined power performance characteristics of turbine 5 and 6 according to the IEC 61400-12-1 alike power performance analysis for scenario 40xxx (blue squares) 20xxx (green triangles) and scenario 00xxx (red bullets). Error bars denote the standard deviation. In [19] the method of analysis is described.*

5.3.5 Mechanical loads

Apart from the improved performance, another advantage of the "Heat and Flux" control is the reduction of the loading of the turbines.

In order to investigate whether the mechanical loads are really reduced considerably, turbine 6, which is equipped with strain gauges, has been set to a minimum blade pitch angle of 2° in free wind directions from the South. The measured data were compared with data from normal operation of turbine 6 from the same wind direction sector [19]. The numbers of data points were 1,064,731 and 9,096,241 respectively corresponding to observation times of about 3 and 26 days.

A direct comparison between the situation with "Heat and Flux" settings and normal settings for the most upstream turbine can be found in Fig. 5.8. As it has been expected the "Heat and Flux" setup leads to a considerable diminishment of mechanical loads. This is evident in the blade root flapwise moments as well as in the tower foot moment.

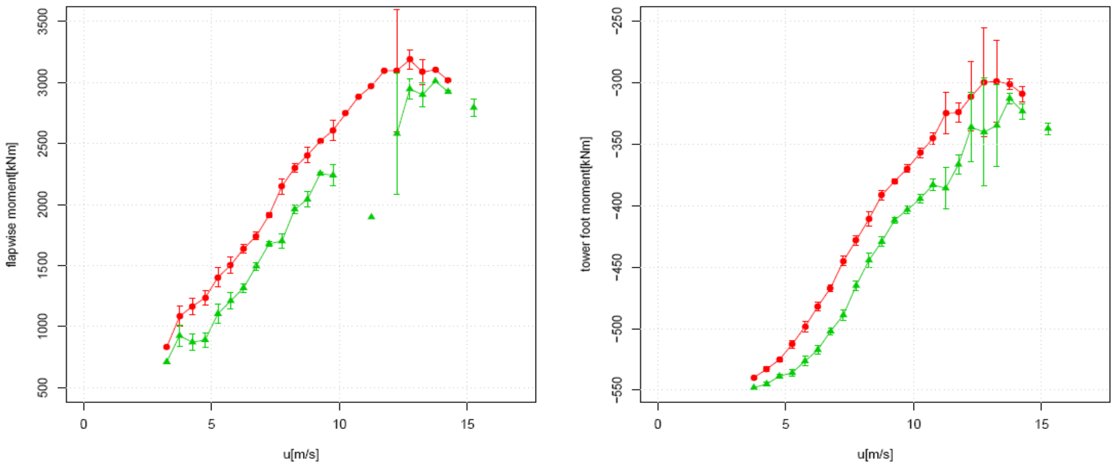

Fig. 5.8 *Mean blade root flapwise moment of turbine 6 (left graph) and tower foot moment of turbine 6 (right graph) for "Heat and Flux" pitch (green triangles) and standard pitch (red bullets). Error bars denote the standard error. In [19] the method of analysis is described.*

A comparison of mechanical loads measurements of turbine 6 in the wake of turbine 5 during *20xxx* and *00xxx* operation is shown in Fig. 5.9. Especially the tower foot moment shows the increase in thrust on turbine 6 if turbine 5 is set to "Heat and Flux" operation.

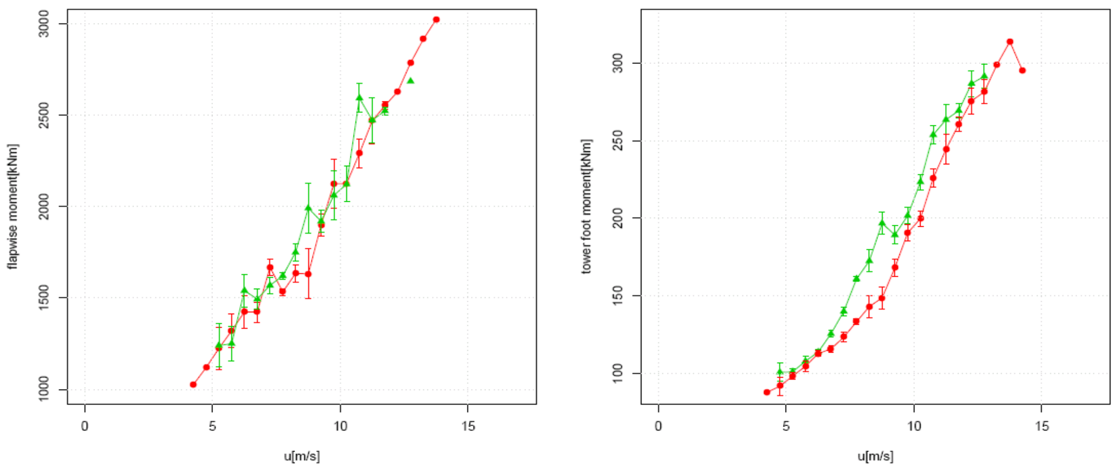

Fig. 5.9 *Mean blade root flapwise moment of turbine 6 (left graph) and tower foot moment of turbine 6 (right graph) for scenario 20xxx (green triangles) and scenario 00xxx (red bullets). Error bars denote the standard error. In [19] the method of analysis is described.*

5.4 Deliverables

5.4.1 Knowledge transfer deliverables

Deliverable as stated in the contract	**result**
Public report, digitally available	This report, also available on the ECN web-site www.ecn.nl
Article in newsletter or magazine	Not applicable
Information available on internet	Final report, 4 conference papers and some other references available on the ECN web-site.
Participation in or presentation on relevant congress/meeting/symposium	Participation, presentation and paper in conferences: Science of Making Torque, 28-31 August 2007 [18], EWEC 2004, 22-25 November 2004 [11] EWEC 2003, 16-19 June 2003, [3]
Development and publication of a manual/action plan/decision model	Development of a general method for the design of a transparent "Heat and Flux" control algorithm [9]
Development of software and make available	FluxFarm model is available for calculations in commission.
Providing expert support to other companies	Performed upon request for lectures [4] and for the set-up of experiments in a wind farm of one of the co-sponsors. Progress reports to the sponsor and co-sponsors.
Cooperation to programs in the media	Not applicable
Leaflet	No specific leaflet is made. Reference to "Heat and Flux" development is made in the ECN - Wind Energy Leaflet "Wind Farm Aerodynamics"

5.4.2 Scientific deliverables

Deliverable as stated in the contract	**result**
Physical models: models that elucidate the physical understanding of optimizing farm performances by axial force reduction.	Analytical model for "Heat and Flux" [3]
Momentum models: computational and analytical models for quantitative analyses of the new technology.	WAKEFARM adaptation for calculation of the wind speed and turbulence profiles with the "Heat and Flux" control. FluxFarm program adapted for the calculation of energy yield in "Heat and Flux" farms from empirical wake maps or maps calculated by WAKEFARM. FluxFarm with dynamic link to WAKEFARM for calculation of the energy production of ("Heat and Flux") farms considering multiple wakes.
Experimental data: measurement data especially collected for studying the effect of unconventional turbine control in wind farms.	Measurement results of wind tunnel tests [12,13,14] and field tests [16,17]
General approach to apply beneficial axial force reduction in wind farms: recommendations for the control of current and future wind farms.	Algorithm for "Heat and Flux" control of the turbine's axial induction by tuning blade pitch angles without changing the torque control of the wind turbine concept [9]
Commercial preparation: conceptual design of a wind farm controller for a wind farm to be chosen by the partners.	Not achieved due to the deficiency in the data measured in the field test and the resulting uncertainty about the quantitative effects of "Heat and Flux".
Quantification of the benefits: delivering estimates for production raise and load reduction for 2 farms to be selected by the partners.	Not achieved due to the deficiency in the data measured in the field test and the resulting uncertainty about the quantitative effects of "Heat and Flux".

6. Discussion and conclusions

The “Heat and Flux” concept aims at maximizing the power output of a wind farm by operating the windward turbines at a lower axial induction. This will reduce the velocity deficit in the wake and increase the power output of the downwind turbines. Simultaneously the average loading of the upwind turbines and the fatigue loads of the turbines in the wake are decreased. These benefits can be attained at negligible costs since only control software has to be adapted.

An analytical model for predicting the power performance of a row of turbines has been developed based on the axial momentum theory. The turbines are modeled by uniformly loaded actuator disks. The wakes are assumed to be fully expanded without momentum exchange with the outer flow.
The model predicts an increase of 4.1% of the total power of two turbines in line with the wind when lowering the axial induction of the first turbine to 1/5 instead of 1/3, the induction for the Lancaster-Betz limit. This result is considered to be the upper limit for the gain in power performance of two “Heat and Flux” turbines in line with the wind.

Computational models have been modified and extended for predicting effects of “Heat and Flux” control on the power performance and energy production of farms.
The FluxFarm program, that calculates the energy production of wind farms in specified wind climates, was modified for using wake velocity and turbulence maps of different origin. One version comprised the integration of a database of maps of single wakes that were measured with scaled models in a simulated offshore boundary layer. Another version comprised linking with WAKEFARM for calculation of the wind and turbulence profiles in single and multiple wakes. For this purpose also a general algorithm was developed and implemented for “Heat and Flux” turbine control that gives the relation between the axial induction of the turbine and the blade pitch angle, while maintaining conventional torque control.

The optimal “Heat and Flux” settings of the blade pitch angles for the upwind turbines that are calculated do not differ very much for different wake maps (empirical or calculated, single or multiple), the ambient conditions, the turbine spacing’s and the rotor coefficients Cp and C_T. In most cases the calculated optima are reached at minimum blade pitch angles of about 2°.

The FluxFarm calculations with empirical single wake maps for offshore conditions (roughness length z_0 = 0.001*m*) predict a power increase of about 4.8% for the EWTW (a row of five 2.5*MW* turbines with 80*m* rotors at 3.8 rotor diameters spacing) with optimal “Heat and Flux” blade pitch settings in a wind speed of 9*m/s* in line with the row. With calculated single wake maps an improvement of about 3.2% is predicted.
The increase in energy yield for an offshore farm of 10 x 10 turbines with 4.8*D* spacing in a wind climate with uniform wind direction distribution, Weibull factor *A*= 10*m/s* and *k*=2 amounts about 0.7% when calculated with empirical single wake maps and 0,45% with calculated single wake maps.

Calculations with the FluxFarm/WAKEFARM combination taking into account multiple wake effects and variability of in wind direction show that the predicted gain is somewhat lowered by the variability of the wind direction. Yet gains of 0.7% and 3.9% are predicted for rows of five and nine turbines respectively at a wind speed of 9*m/s* in line with the row.

Extensive wind tunnel experiments have been performed in the boundary layer wind tunnel of TNO in Apeldoorn to investigate the performance of downscaled wind turbines in different farm arrangements and “Heat and Flux” settings.

Rotating wind turbine models have been used with rotor diameters of 25*cm* and different pitch angles varying from -2.5° to 7.5° in steps of 2.5°. The rotors with 0° pitch angle were designed to operate in the "classic way" meaning close to the Lancester-Bertz limit for the maximum power coefficient C_p at an axial induction a = 1/3.
The dimensions of the models represent a 1:400 scale of commercial wind turbines of 100 meters diameter and 100 m hub height. The tunnel ambience represented an offshore boundary layer on the same scale.

The experiments investigated the difference in power production between 2 rows of turbines: one "Heat and Flux" row with different combinations of blade pitch settings and another row with 0° pitch for maximum performance of the wind turbines in free flow conditions. The difference was determined twice (mirrored configurations) and averaged. Two farm configurations have been investigated: one with 7 turbines at 4.5*D* spacing and another one of 14 turbines at 3*D* spacing.

While the vertical velocity profile and the turbulence in the tunnel were a good representation for offshore conditions, the results of the tunnel experiments showed large and not systematic differences for different wind speeds and "Heat and Flux" blade pitch angle settings. Consequently the results should be regarded qualitatively instead of quantitatively. The main reasons are that the tunnel conditions were far from representative for full scale. First, the wakes are not similar at both scales because the initial conditions for the wake strongly differ due to the difference in the rotor characteristics that are caused by the different Reynolds numbers. Secondly, in reality no negative pressure gradient and blockage effects occur like in the tunnel. And thirdly because of the rather low measurement accuracies in power and drag coefficients of the rotor.

Full scale field tests have been carried out in the EWTW test farm with five variable speed, pitch controlled turbines of 2.5*MW* of 80*m* rotor diameter in a row at a spacing of 3.8*D*. In the campaigns three different "Heat and Flux" blade pitch settings have been applied and four different scenarios for "Heat and Flux" blade pitch angle settings have been analyzed:
- noise reduced operation (*NRO*) with minimum blade pitch angle 4° and decreased rotor speed above 7*m/s* ambient wind speed for the first turbine in the row,
- "*22220*" mode of operation with a minimum pitch angle of 2° for all but the most downstream turbine in the row,
- "*20xxx*" mode of operation with minimum pitch angle 2° for the first turbine and 0° for the second,
- "*40xxx*", exaggerated "Heat and Flux" operation with minimum pitch angle 4° for the first turbine and 0° for the second turbine.

The data of the field measurements have been filtered for yaw angles of turbine 5 where the strongest performance response of turbine 6 occurred for the wake of turbine 5 and analyzed with 3 different and independent statistical methods. Although the number of available data points is very limited, the following important conclusions could be drawn:
- in the *22220* mode the power performance of every turbine is decreased and ergo the performance of the farm. At least partly, the decrease is attributed to the wind direction variability in combinations with the yaw control properties of the turbines.
- the combined power of the first 2 turbines is systematically increased in the *20xxx* scenario while the performance of the whole farm has not been influenced negatively,
- the average loading of the upwind turbine in *20xxx* scenario is reduced considerably by "Heat and Flux" control,
- the results of the exaggerated scenario (*40xxx*) suggest that a blade pitch angle of 2° is a good first choice and that the observed effects from the 20xxx scenario are really caused by the "Heat and Flux" phenomenon.

The preliminary results of all measurements are positive about a performance increase in “Heat and Flux” mode for a pair of turbines in the front of a farm. The final FluxFarm/WAKEFARM calculations with multiple wakes point at optimum blade pitch angle settings of 2° for the upwind turbines which seems consistent with the field measurements. But too little data have been gathered to make a distinctive conclusion about absolute figures and the possible yield enhancement in a farm. It will take additional measurement time to reduce the statistical uncertainty sufficiently. It is expected that another year of measurement time in the EWTW will be sufficient.

Unlike in calculations the turbines are not always aligned properly in reality. Since every turbine has its independent controller, situations where rotors are not parallel to each other can’t be considered to be exceptions. In addition the real flow can be very unsteady, so that local misalignments to the wind direction can be rather big.
It is advisable to conduct experiments with “Heat and Flux” control in the scaled farm. There the wind speed and direction are measured at multiple locations. Thus the unsteady wind direction can be measured in the wake and can be taken into account in the analyses.
These dynamic effects probably call for mutually dependent control of the yaw angles of “Heat and Flux” turbines in a row in order to maximize the possible benefits.

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References 4, 13, 19 and 20 have been completely generated in this project, references 5, 12, 14, 15, 16 and 18 partly.

Annex A Commercial execution of the project

The project aims at commercial exploitation of the "Heat and Flux" phenomenon. From the start two interested industrial parties have been involved and were acting as co-sponsor of the developments. During the execution another industrial party became interested. It is the manufacturer of the wind turbines in a commercial farm of one of the co-sponsors. That manufacturer and that farm owner cooperate in the full scale validation of "Heat and Flux" in that particular farm. The farm consists of 17 state-of-the-art wind turbines of 1.5*MW* capacity and is very suited for the purpose. Fist of all the location of the turbines with respect to each other is such that "Heat and Flux" measurements can be performed on pairs of turbines in the prevailing wind direction, so data are gathered at faster speed compared to the EWTW farm. Secondly, the power performance of another turbine can be measured in the undisturbed flow simultaneously for reference.

The measurement results of the commercial farm are being exchanged with the results of the EWTW research farm.
As stated in Chapter 6 the preliminary results of all measurements are positive about a performance increase in "Heat and Flux" mode for a pair of turbines in the front of a farm. But too little data have been gathered to make a distinctive conclusion about the absolute figures of the increase and the possible yield enhancement in a farm. It will take additional measurement time to get decisive answers. It is expected that another half year will be sufficient in the commercial farm. In the EWTW probably a year will be needed.
When the measurements show a positive and decisive outcome for the energy production increase with "Heat and Flux" the turbine manufacturer will buy a license for the commercial use of the patent.
Shortly after that moment the commercial application in the first farms can start. This nearly can happen without further delay because the "Heat and Flux" control reported in [9] can be implemented in every farm that is provided with a supervisory control without changes in the control of the individual turbines. In conclusion, the commercial use probably can start in the second half of 2008 by implementation in existing as well as in new farms.

The project clearly has reinforced the commercial strength of ECN by:
- intense cooperation and exchange of knowledge and ideas with the co-sponsors and the involved turbine manufacturer. The contacts with these industrial partners have strengthened the network ECN,
- the serious interest of the involved turbine manufacturer for the purchase of a license for "Heat and Flux" at a positive outcome of the field verifications,
- the interest of third parties for the "Heat and Flux" phenomenon and our research into the subject that was shown at conferences, exhibitions and working group activities,
- the increase in knowledge and expertise regarding the possibilities of production improvement and load reduction in farms, profiles in the wake, scaled experiments in a boundary layer wind tunnel, etcetera,
- improving the IP position of ECN because the knowledge gained has been used for strengthening the patent descriptions during the application process,
- the tools that have been developed or modified for "Heat and Flux": calculation of the energy output of farms (Flux Farm), calculation of wake profiles (WAKEFARM) and the method for farm control [9].

Annex B The benefits for primary energy mitigation

Innovation and price-performance
The innovation of the “Heat and Flux” project will consist of knowledge about the “Heat and Flux” phenomenon and the tools for the design and optimization of “Heat and Flux” farms with special emphasis on algorithms for the design of farm control, the influence of yaw angle variations on the energy production.

Controlling a wind farm on the basis of “Heat and Flux” will improve the price-performance ratio of renewable energy, since the farm production will increase and turbine loading will decrease (less wind pressure in front, less turbulence under the lee). Those advantages may be realized almost without inherent drawbacks. Besides, the improved price-performance ratio will encourage the erection of more farms and cause accelerated implementation.

In the contract proposal the amount of primary energy is estimated that will be mitigated by the innovations and the improved price-performance ratio resulting from the proposed research.
The estimated benefits are building up from the following components:
1. increased energy production of turbines operating under partial load,
2. increased number of turbines in operation near cut-in wind speed,
3. new production merits on the basis of the new insights
4. less failed turbines due to load reduction: the number of stand-stills and maintenance costs decrease,
5. speed up of the implementation because of the improved price/performance ratio.

The items 1 to 4 were expected to improve the energy production of “Heat and Flux” farms with 5.3% all together. The resulting increase of price-performance ratio will be the same, as the implementation of “Heat and Flux” only involves negligible costs for changing the software of the farm controller.
Due to the increased price-performance ratio the implementation was expected to be accelerated in such a way that the targets for 2020 will be reached 1 year earlier (item 5).

Adjustment of the prediction for mitigated primary energy
The benefits in increased energy production, improved price-performance ratio and accelerated implementation have not been realized yet. As stated in Chapter 6 no decisive and reliable figures can be presented about the production increase of a “Heat and Flux” farm. Though, the preliminary results confirm the predicted phenomena, no quantitative conclusions can be drawn in this stage, nor a judgment can be made about the possibility that the predictions are overestimating or underestimating the real effect. Adjustment of the predicted benefits therefore is premature at this very moment.

While there is no reason to adjust the potential benefits right now it is clear that they will be obtained at a later stage than predicted because of the delay in the project execution.
In the contract a first generation control for commercial introduction was predicted for 2005 and it was expected that from 2010 on “Heat and Flux” control would be implemented in all new Dutch wind farms. This would lead to such acceleration in the implementation that the projected target for 2020 is reached 1 year earlier, so not after 10 but already after 9 years.
With the project delay of 3 years the speed up in implementation will start 3 years later. Assuming the same benefits for the items 1 to 4, as stated before, the acceleration itself will remain the same but will start 3 years later. So the planned target for 2020 will not be reached 12 months but 8 months earlier.

The contract predicted a total of 10.67*PJ* of which 5.31*PJ* is caused by the speed up of the implementation. Due to the delay in the application of the project results 17% less primary energy will be saved in 2020 than predicted (8.9 instead of 10.67*PJ*).