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Active wake control: application to the Prinses Amalia wind farm

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August 2015
ECN-X--15-097
Abstract

Active Wake Control is an approach of operating wind farms in such a way as to maximize the overall wind farm power production. It consists of two concepts: pitch-based Active Wake Control (called Heat & Flux), and yaw-based Active Wake Control (called Controlling Wind). ECN holds patents for both approaches.

The Heat & Flux concept achieves increased power output by reducing the axial induction factor (i.e. increasing the “transparency”) of the wind turbines at the windward side of the farm. This is achieved by pitching the blades of the wind turbines or, equivalently, by derating them. While these derated upstream turbines will produce less electricity, the wind velocity in their wakes increase, enabling the downstream turbines to increase their power production. This results in a net increase of power output of the farm. In addition to that, the loads reduce and are more evenly distributed over the turbines.

The Controlling Wind approach to Active Wake Control consists of introducing yaw misalignment to the rotors of the upstream wind turbines with respect to the wind direction. As result of that, the wakes behind the yawed wind turbines are diverted away from the downwind wind turbines. The yaw misalignment itself reduces the effective rotor area, decreasing the power production. However, the wind speed at the downwind turbines increases due to the wakes being moved aside, which causes an increase of the total power production of the wind farm.

Two different optimization concepts are considered, namely maximization of the yearly power production of the farm, or maximization of the lifetime power production of the farm. The difference between these is that the latter includes the effect of Active Wake Control on the fatigue loads on the main turbine components, whereby loads reduction is translated into a lifetime extension factor for the farm. The report demonstrates that for the Prinses Amalia US wind farm:

- Heat & Flux increases the yearly power production by 0.33% (as well as small load reduction)
- Controlling Wind increases the yearly power production by 1.28% (with <1% increase on tower base moment fatigue)
- both Heat & Flux and Controlling Wind are capable of reducing the lifetime fatigue loads (for Controlling Wind at the expense of some yearly power benefit)
- besides lifetime extension, there seems to be an additional advantage with respect to reduction of costs for corrective maintenance

This report describes the results from the feasibility study of applying Active Wake Control to an upscaled version of the Prinses Amalia wind farm of Eneco. The goal of this study is to optimize and evaluate these two Active Wake Control strategies for this wind farm. The results are meant to assess the potential benefits of applying Active Wake Control in terms of power production increase and its effect on fatigue loads for a typical large offshore wind farm.

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Introduction

Active Wake Control aims at improving the overall wind farm performance in terms of power production at below rated wind conditions. Active Wake Control should be seen as a part of a wind farm control scheme that improves the performance when the farm is operated at maximum achievable power production mode. It consists of a pitch-based approach (also known as Heat & Flux), and a yaw-based approach (called Controlling Wind).

The idea behind the Heat & Flux concept, patented by ECN [3], is to operate the turbines at the windward side at a lower axial induction factor than the Lanchester-Betz optimum of 1/3. To achieve this, the pitch angle of the blades is increased. This reduces the power production of these upstream turbines, but the downstream turbines in their wakes get higher wind speed and make up for this power production loss, resulting in a net increase of the power output of the farm. Also the loads reduce and are more evenly distributed over the turbines.

The Controlling Wind concept, also patented by ECN [4], consists of yawing the upstream wind turbines away from the wind. Due to the resulting yaw misalignment, the wakes behind the yawed turbines are redirected aside from the downstream wind turbines, which therefore receive (a larger portion of) the undisturbed wind stream. Controlling Wind optimizes the yaw misalignment angles of each individual wind turbine in such a way, that the overall power production of the whole wind farm is maximized.

The goal of this study is to optimize and evaluate these Active Wake Control strategies for the wind farm Prinses Amalia US, an upscaled version of the Prinses Amalia wind farm of Eneco. The results, reported here, are meant to assess the potential benefits of applying Active Wake Control in terms of power production increase for a typical large offshore wind farm.

The report is structured as follows. In chapter 2, the approach used to optimize the performance of the wind farm is presented. Chapter 3 presents the obtained results of applying Active Wake Control to the Prinses Amalia US wind farm. Finally, chapter 4 concludes the report with some final comments. Appendix A shows a comparison of the V80 wind turbine and the generic wind turbine model used for the Active Wake Control.
study. Appendix B shows the scaling of the Prinses Amalia US wind farm. Appendix C compares FarmFlow calculations to measurements on that wind farm.
This chapter describes the method used to optimize the Active Wake Control settings. First, the Heat & Flux and Controlling Wind concepts are described in Sections 2.1-2.2, respectively. The developed optimization scheme relies on accurate computations of wake effects using FarmFlow, a software tool developed by ECN. The modelling included into FarmFlow is described in more detail in Section 2.3. Finally, in Section 2.4, the optimization approach is detailed.

2.1 Heat and Flux

Wind turbines are more and more placed in large farms, especially offshore. This raises the question: Does the optimal (selfish) operation of the individual wind turbines lead to maximum yield of the wind farm? Or can the wind farm production increase when the individual turbines operate in a more social concept.

2.1.1 The concept

The Heat & Flux concept has been developed at ECN beginning of this century [2]. It is a wind farm operating strategy for improving the power output and reducing the loads of the wind farm as a whole. The term heat reflects the energy dissipation (as heat) when two flows of air with different velocities mix, i.e. the stream tube around the rotor and the outer flow. Flux refers to the flow of air through the farm.

The general idea behind the concept is to reduce the heat losses and the flux deficit of an aligned row of wind turbines by lowering the induction of upstream turbines. Reducing the induction can be achieved by changing (either one or both) the turbines’ blade pitch angle $\theta_b$ and tip speed ratio $\lambda$. While the upstream turbine(s) will produce less, the downstream turbines make up for this, resulting in a net increase of power output. Also the loads reduce and are more evenly distributed over the turbines.

Heat&Flux has been patented by ECN [3].
2.1.2 Proof of principle and field tests

In the past, a number of studies have been performed to proof the Heat&Flux concept. [12] gives an overview of the evaluation of the Heat & Flux concept. The key findings are briefly mentioned below, completed with some recent results.

First of all a proof of principle test has been performed [2] in the boundary layer wind tunnel at TNO Apeldoorn. Despite the scaling issues (rotor diameter of 25cm), this test under controlled conditions clearly demonstrated the effect. The measured increase in power output between the Heat & Flux and reference row was about 4%, although this could be partly due to scaling effects. Also, the scatter in the data was large.

The next step was a full scale test on the ECN Wind turbine Test site Wieringermeer (EWTW, see [13]). The EWTW consists of a row of five 2.5MW Nordex N80 wind turbines spaced 3.8D apart. Although no optimal settings could be used, this test still showed power increase and load reduction for the aligned Heat & Flux case. Unfortunately, these measurements were taken with difference in turbulence intensities, which should be accounted for.

Simulation results on a farm of $10 \times 10$ spaced 4.8D apart showed an increase in energy yield of 0.7% when a uniform wind rose is assumed.

Recently, a study with FarmFlow [11] quantified the effect of spacing and turbulence intensity on the performance of Heat & Flux strategy. Increased spacing of the turbines reduces the power increase gained from Heat & Flux. The FarmFlow simulation results on the EWTW indicate a power increase of about 3.5% at best for the Heat & Flux scenarios compared to the base case. Increasing the spacing between the turbines to 8D, the benefit from Heat & Flux reduces to 0.2% increase of energy yield. The Heat & Flux benefit is highest for the EWTW when the turbulence intensity is about 9% (calculated at 8 m/s).

2.1.3 Implementation

In case of Froude’s actuator disc model, the relation between thrust coefficient $c_t$ and axial induction $a$ is:

$$c_t = 4a(1-a)$$

(2.1)

To change the transparency of the wind turbines at the windward side of the farm, the wind turbine control algorithms of the relevant turbines need to be slightly adapted. Conventional control for variable speed wind turbines uses the generator torque $T_g$ to obtain maximum power below rated, while keeping the blade pitch at a constant optimal angle. Reduced transparency can be achieved by changing the tip speed ratio $\lambda$ (through $T_g$), the blade pitch angle $\theta_b$ or both. However, previous studies [15] have shown that using only the blade pitch angle to achieve a desired transparency is an almost optimal solution, i.e. by controlling the generator torque, in addition, does not result in a noticeable improvement of the performance. As a result, the Heat & Flux implementation used in this report only requires that the wind turbine control algorithm is simply adapted to realize a blade pitch angle that is slightly higher than the fine pitch angle at below rated wind conditions. Fine pitch is the optimal blade pitch angle at below rated wind condition, achieving highest power production for a single wind turbine; the Heat & Flux pitch angle, on the other hand, is optimal with respect to a selected cost function (e.g. maximal power, minimal loads, or a combination of those) for the whole
It needs to be pointed out that the optimal Heat & Flux pitch angle depends on the wind direction, since this is the parameter that determines the spatial configuration of the wind farm. As a result, Heat & Flux has the highest effect when the wind direction is such that a large number of wind turbines are in the wake of another wind turbine at a distance of less than several rotor diameters. On the other hand, when the wind direction is such that this condition is not satisfied, Heat & Flux has little to no effect on the overall wind farm power production and loads.

If there would be no turbulence in the wakes (and therefore no mixing with the surrounding undisturbed air flow), the optimum induction (and thus blade pitch angle) could be estimated with the relation between thrust and induction as shown in [2]. Of course, this is not the case in reality, and therefore in this study an accurate wake modelling tool, FarmFlow, is used to determine the optimum pitch angle setting (see section 2.4).

For constant lambda operation, the farm effects (and therefore the optimal heat and flux pitch angle setting) are not wind speed dependant. Figure 1 shows the tip speed ratio as function of the wind speed for a 6MW wind turbine, which indicates this assumption is valid up to about 9m/s. The optimal heat and flux pitch angle can thus be determined at a single wind speed below rated (and used for all below rated wind speeds).

![Figure 1: Tip speed ratio as function of wind speed for three different below-rated operation modes: optimum pitch angle (blue line), pitch angle offset of 2 degrees (red) and 4 degrees (magenta)](image)

NOTE: The relation between tip speed ratio and wind speed has been determined using the given rotor characteristics and the power curve (PV curve), estimated losses and assuming equal generator torque control for Heat & Flux operation (i.e. equal torque-speed curve [QN-curve], as shown in Figure 2).
2.2 Controlling Wind

2.2.1 The concept

Controlling Wind is an alternative approach to control the wakes in a wind farm, which is based on yaw misalignment, i.e. yawing the rotors of the upstream wind turbines away from the wind. As a result of that, two things happen: the power production of the yawed wind turbines decreases because the effective rotor area affected by the incoming wind flow becomes smaller, and the wakes behind these turbines is redirected aside from the downstream wind turbines (see Figure 3). Due to the fact that the wake is being diverted, the downstream turbines can get (a larger portion of) the undisturbed wind field instead of the wake of the upstream wind turbine, which increases their power production substantially.

Due to the yaw misalignment introduced, Controlling Wind can increase or decrease the loads on the wind turbines for some wind directions. For this reason, it is important to evaluate the damage equivalent fatigue loads and compare these to those in the reference case without Controlling Wind. To this end, an extensive loads database has been developed. The database is constructed using aeroelastic simulations under many different operating conditions such as a range of wind speeds, turbulence intensities, wake...
deficit profiles, wake locations, and yaw misalignment, and uses FarmFlow output regarding the operating conditions as input.

2.2.2 Development status

As of present, Controlling Wind has not yet been tested in the field. However, numerous simulation studies indicate its huge potential [9, 8]: even for a row of just 3 turbines, an energy yield increase of more than 10% can be realized by Controlling Wind when the wind direction is aligned with the row. For long rows containing many wind turbines, this gain in energy can even reach up to 30%!

2.2.3 Implementation

For implementing Controlling Wind in the field, it needs to be possible to control the yaw misalignment angle of each individual wind turbine from within the wind farm controller. The wind turbine controller should, therefore, accept external setpoint for the yaw misalignment, which is no standard feature of wind turbine controllers. Implementation of Controlling Wind will, therefore, require the collaboration and support of the wind turbine manufacturer, which should enable the wind turbine controller to accept yaw misalignment setpoints.

The yaw misalignment angle of each individual wind turbine will, in general, depend on the wind direction and wind speed. The Controlling Wind optimization produces a look-up table, containing the optimal yaw misalignment settings for each wind turbine, each wind direction and each wind speed. This look-up table will need to be implemented in the wind farm controller; however, to prevent the yaw misalignment setpoints to change too fast, appropriate filtering needs to be applied to the wind speed and direction before they "enter" the lookup table.

2.3 FarmFlow

The FarmFlow program is an advanced and validated tool for the calculation of wake effects of offshore wind farms. The tool computes both the average wind speed and the turbulence intensity in the wake of each wind turbine. The turbulence intensity in FarmFlow is defined as the standard deviation of the wind speed divided by the average wind speed, and is described by the $k-\varepsilon$ turbulence model (see below).

The inputs of FarmFlow consist of:

- wind direction distribution (wind rose),
- turbulence intensity distribution,
- wind speed distribution,
- wind turbine data: power curve, thrust curve, rated rotor speed, rotor diameter, hub height, air density.

The program performs computations for a number of selected free-stream wind speeds and wind directions. The user interface of FarmFlow is depicted on Figure 4.

The wake model in FarmFlow is based on the UPMWAKE code [5], originally developed by the Universidad Polytechnica de Madrid. UPMWAKE is a 3D parabolised Navier-Stokes
code, using a $k$-$\epsilon$ turbulence model that accounts for turbulent processes in the far wake. Herein $k$ defines the turbulent kinetic energy, and $\epsilon$ – the dissipation rate of the turbulent kinetic energy. The turbulence model describes the production, transport and dissipation of $k$ and $\epsilon$.

The ambient flow is modelled in accordance with the method of Panofsky and Dutton [14]. The free stream wind as a function of height is calculated for a prescribed ambient turbulence intensity and Monin-Obukhov length, which takes the atmospheric stability into account. Coriolis effects are not considered.

In the original model, the wake is divided in a near wake region with a length of 2.25 rotor diameters (D), and a far wake region. Due to the parabolization, axial pressure gradients are neglected. Since the flow deceleration and wake expansion in the near wake are forced by axial pressure gradients, the original modelling started at the far wake, using an initial wake velocity profile at 2.25D.

The wake model has been improved by prescribing the stream wise pressure gradient as a source term in the flow equations. The stream wise pressure gradients are calculated via an inviscid, axisymmetric, free vortex wake method. With this method, the pressure gradients are a function of the axial force coefficient only. To save computational effort, the pressure gradients are calculated a priori for a large number of axial induction factors, so that the wake model only needs to interpolate the pressure gradients between the two nearest induction factors in this database. This hybrid method of wake modelling in the near wake region, including an adapted near wake turbulence model, gives very accurate results in an acceptable amount of computational time.

The code FarmFlow has been validated in [1] using a large amount of accurate experimental data from ECN Wind Turbine test station Wieringermeer (EWTW). Additionally, experimental data from three large offshore wind farms have been compared with FarmFlow model results. The calculated wake velocity deficits and turbulence intensities agree very well with experimental data for all wind speeds and ambient turbulence intensities. Excellent agreement between calculated and measured turbine performance is found for the large offshore wind farms Horns Rev and Nysted.
In FarmFlow, axial and radial pressure gradients that arise when a flow passes an actuator disk, are prescribed as radial and axial forces in the flow equations. When a turbine is yawed from the wind direction (oblique inflow) these forces are still prescribed in radial and axial direction of the rotor disk, which causes the wake to deflect from the wind direction. The effect of this deflection is validated from measurements in a scaled wind farm and with wind tunnel measurements. The power of a wind turbine with a yaw misalignment angle $\gamma$ is reduced by applying a reduction factor for the wind speed. This wind speed reduction factor, $\cos(\gamma)^{0.7}$, is confirmed by results from measurements on full scale wind turbines.

2.4 Optimization procedure

2.4.1 Optimization criterion

The purpose of Active Wake Control is to operate the wind farm so as to increase the economical profit over the lifetime. The economical benefit, however, is influenced by many factors, such as the power curve of the farm, the wind resource, the O&M costs, turbine availability, power limitations imposed by the transmission system operator, etc. The Active Wake Control farm operation strategy has influence on the power production of the farm and on the fatigues loads of the wind turbines, but has no effect on the remaining factors. The fatigue loads, in turn, are related to the O&M costs, even though this relation is difficult to model mathematically. For this reason, the most straightforward goal will be to maximize the yearly power production of the wind farm which can be expressed as follows

$$J_{yr}(\theta^{AWC}, \phi^{AWC}) = \sum_V \sum_{\alpha} p(V, \alpha) P(V, \alpha, \theta^{AWC}, \phi^{AWC}),$$

(2.2)

wherein $p(V, \alpha)$ is the discrete (binned) probability density function for the variables wind speed $V$ and wind direction $\alpha$, and

$$P(V, \alpha, \theta^{AWC}, \phi^{AWC}) = \sum_{i=1}^{N} P_i(V, \alpha, \theta_i^{AWC}, \phi_i^{AWC})$$

with $P_i$ being the yearly power production of the $i$-th turbine for wind speed $V$, direction $\alpha$ and Active Wake Control settings for the pitch angle bias ($\theta_i^{AWC}$) and yaw misalignment bias ($\phi_i^{AWC}$).

Considering the effect of the loads on the profit is much more difficult to consider due to the lacking relationship between loads and O&M costs. Rather than trying to model this relationship, a different approach is proposed here based on the well established relationship between loading and material failure, such as the widely used in wind turbine design inverse power low model describing the relationship between lifetime $L$ and stress $S$ as $L(S) = \frac{1}{K S^M}$, $K$ and $M$ being parameters describing the material properties. This model allows us to directly relate load reduction to lifetime extension, assuming that it is possible to extend the lifetime of the wind farm. This approach requires, however, that the loads are considered on all design-critical locations throughout the wind turbine, and that the worst-case (i.e. smallest) loads reduction is used to determine the effect on the turbine lifetime. Hence, even if a certain Active Wake Control strategy happens to increase the load on even just one single location (e.g. blade root), it will be considered to reduce the lifetime of this turbine.

To describe the optimization criterion including loads explicitly, suppose that the loads at $L$ locations are considered, and that for the $i$-th turbine the damage equivalent loads

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in the nominal case (without Active Wake Control) at these locations are $S_{i,l,i} = \frac{1}{N}$, $l = 1,...,L$. If under some Active Wake Control strategy these loads become $S_{i,l}^{AWC} = S_{i,l}$, then from the inverse power model follows that the lifetime at each location changes by a factor of $\left(\frac{S_{i,l}}{S_{i,l}^{AWC}}\right)^M$. The wind farm lifetime extension factor is defined as

$$f_{life}(\theta^{AWC}, \phi^{AWC}) = \min_{l \in \{1, \ldots, L\}} \left( \frac{1}{N} \sum_{i=1}^{N} \left( \frac{S_{i,l}}{S_{i,l}^{AWC}} \right)^M \right).$$  \hspace{1cm} (2.3)$$

The optimization criterion including loads effects then becomes the farm power production over the (extended) lifetime:

$$J_{life}(\theta^{AWC}, \phi^{AWC}) = f_{life}(\theta^{AWC}, \phi^{AWC}) J_{1yr}(\theta^{AWC}, \phi^{AWC}).$$  \hspace{1cm} (2.4)$$

To evaluate the yearly production of the farm $J_{1yr}(\theta^{AWC}, \phi^{AWC})$ for given Active Wake Control settings the FarmFlow software is used (see Section 2.3) to calculate the power productions. For the lifetime power optimization in equation (2.4), the effect of the fatigue loading on a pre-defined set of wind turbine components on their lifetime is used to estimate the lifetime of the wind turbine in the farm (see equation (2.3)). These components are

- tower fore-aft moment (at bottom and top)
- tower bottom torsion moment
- torque acting on drive-train support
- tilting moment on the rotor shaft
- yawing moment on the rotor shaft
- axial force on shaft at the hub
- blade root out-of-plane bending moments

The FarmFlow software does not provide these loads estimates, but provides sufficient output to characterize the operating conditions of each turbine. During the optimization process the loads on these components are interpolated using a lookup table of pre-computed loads (loads database). The database is constructed using aeroelastic simulations under many different operating conditions such as a range of wind speeds, turbulence intensities, wake deficit profiles, wake locations, and yaw misalignment, and uses FarmFlow output regarding the operating conditions as input. However, the database does not include the effect of pitch angle variations on the load, and therefore cannot be used in combination with the Heat & Flux strategy. For that reason, Heat & Flux is only applied to maximize the yearly power production, therefore not considering the loads.

In the following sections it is explained how the two optimization problems (2.2)-(2.4) are addressed in a numerically efficient manner.

### 2.4.2 Selected approach and assumptions

This section describes the optimization procedure used for computing the optimal Active Wake Control settings for both the optimization criteria defined in the previous section.
**General considerations**

Under nominal operation, the wind turbines are operated at below rated wind speed with the blades being kept at a constant pitch angle and with the rotor orientation aligned with the wind direction so as to maximize the power production for each *single wind turbine*. The Active Wake Control strategy operates the wind turbines at different pitch angles and yaw misalignment angles, which are suboptimal for the individual wind turbines, but achieve an overall increase of the power production of the wind farm. Hence, for each wind direction and (below rated) wind speed, the optimal Active Wake Control settings will be determined for all turbines that have a turbine in their wake at a downwind distance of less than 20D (previous studies [11] indicate that the effect of Heat & Flux becomes very small when the distances between the turbines are larger than about 10D).

Since small changes in the wind direction can have large effects on the Active Wake Control settings, a fine wind direction grid size of 1 degree is used in the Active Wake Control optimization, resulting in a total of 360 wind directions. Due to the large distance limit of 20D, in each wind direction a row of wind turbines exists that qualifies for application of Active Wake Control. In order to determine whether a given wind direction needs to be considered in the optimization, a simple wind farm model is used, known as the model of Jensen [10]. This simple Jensen model is only used for determining if the optimization procedure should be started for a given wind direction; the optimization procedure itself uses the accurate FarmFlow wake model, described in Section 2.3. Even though the Jensen model is conservative and over-estimates the number of wind directions for which turbines are in the near wake of other wind turbines, it is suitable for this purpose as it ensures that no beneficial wind direction is excluded from the optimization. The wake expansion factor of 0.05 has been used in the Jensen model.

The output of the Active Wake Control optimization is a 3D table giving the optimal settings (pitch angle offset or yaw misalignment) for each wind turbine in the park for the considered sets of wind speeds and wind directions. However, the effect of wind speed on the optimal Active Wake Control settings turns out to be small and rather inconsistent, which makes it from implementation point of view preferable to remove the dependency of the Active Wake Control settings on the wind speed and let them only depend on the wind direction.

Before summarizing the optimization algorithm, a final note is made on the accuracy of the results. The accuracy in mainly determined by two factors: 1) the modelling uncertainty and the calculation precision of FarmFlow, and 2) the variability of the actual wind resource. Many validation studies of FarmFlow (e.g. [1]) have indicated that the accuracy of the calculated wake losses in a wind farm is very high, when averaged over larger wind sectors. In the optimization, a faster version of FarmFlow is used which uses a courser grid. It delivers approximately 20 times faster calculation at the expense of less than 5% accuracy loss. As an indication, the fast version calculates the power production of a farm of around 100 turbines for 360 wind directions and 20 wind speed in a few hours on a computer cluster of 80 cores. Optimizing the Active Wake Control settings for such a farm then takes 1-2 days of calculations.

**Considerations when loads are not considered**

When loads are not considered (i.e. the optimization criterion being the yearly power production of the farm in equation (2.2)), the Active Wake Control settings can be op-
timized by considering one wind speed and direction at a time. Indeed, it can be observed from equation (2.2) that optimizing $J_{1yr}$ can be achieved by combining the results from individual optimizations of the farm power production for each wind speed-direction couple.

Furthermore, the Heat & Flux optimization could be restricted to just to the so-called leading wind turbines, i.e. wind turbines that are not in the wake of other turbines, but have turbines in their wakes. Indeed, the previous study [11] indicates that, in terms of yearly power production, little is to be gained by applying Heat & Flux also to the turbines in the wake of the leading ones. The reason for that is that the turbulence intensity, already behind the first wind turbine, is too high, leading to a substantial wake recovery. As a result of this, by applying Heat & Flux to the second turbine, the additional power increase behind the second wind turbine becomes relatively small compared to the power loss at that turbine. For this reason, when optimization criterion (2.2) is considered, the Heat & Flux optimization is only applied to the first row of leading wind turbines. However, when loads are included into the optimization criterion as in equation (2.4), application of Heat & Flux to turbines deeper in the row could be beneficial.

Another important point when considering the criterion in equation (2.2) is that, due to the fact that FarmFlow cannot simulate variations in the wind speed and direction, the Active Wake Control optimization can be performed separately for each wind speed $V$ and wind direction $\alpha$. Even though this significantly simplifies the optimization problem, the number of optimization variables is still too large because (depending on the farm layout and wind direction) there can be many (for large farms even more than 100) wind turbines that have other turbines in their wakes at a distance of less than 20D. This kind of complexity, combined with the calculation speed of FarmFlow, renders efficient numerical solution practically impossible. To significantly reduce the computational complexity, two simplifications will be applied:

- **row-by-row optimization**: for a given wind direction, the Jensen model is used to determine rows of wind turbines that are in each others wakes. For each such row, a separate Active Wake Control optimization is performed to determine the optimal settings that maximize the power production. However, in order to obtain an accurate solution, all turbines from the wind farm that are affected by the wakes of the considered row of turbines are also included in the simulation even though their setting remain nominal. To illustrate this, consider Figure 5, in which the wakes (according to the Jensen’s model) are depicted for the Prinses Amalia US wind farm for a wind direction of 272 degrees. The top row of wind turbines, enclosed within the green rectangle, is an example of one row for which the Active Wake Control optimization will be applied. This optimization will, however, also include all turbines that are in the wake of the turbines in this row, as depicted by the shaded polygon area in the figure.

- **at most two variables per row**: as already pointed out above, when loads are not considered the Heat & Flux strategy will only be applied to the leading wind turbines. Hence, in a row-by-row optimization it here will be just one variable (the first turbine in the row) at each optimization step. The Controlling Wind concept, however, will be applied to all turbines in the row but the second last one even when loads are not considered in the optimization. However, it has been shown in previous studies that Controlling Wind optimization for a row of wind turbines results in an almost linear distribution of the yaw misalignment angles over the row, with the
largest yaw angle at the leading wind turbine. For that reason, to reduce the number of optimization variables in this case, the yaw misalignment angles within a given row will be restricted to vary linearly over the wind turbines in the row. This results in two optimization variables per row: the yaw angles of the leading and the second last turbine in the row. This restriction has just a minor effect on the final benefit from Controlling Wind: for a row of wind turbines less than 1% of the yearly power gain is lost due to this restriction. In other words, for the example with the top row again, optimization variables will be the yaw angles of turbines 43 and 66 only, while the yaw angle of any turbine in between will be obtained by linear interpolation of these two yaw angles. Clearly, the last turbine (number 1) in the row will not be operated at yaw misalignment since there is no turbine in its wake for Western winds.

Considerations when loads are considered

Contrary to the case when loads are out of consideration, the optimization criterion including loads, defined in equation (2.4) involves the lifetime extension factor $f_{life}$, the computation of which requires to simulate all wind conditions. Strictly speaking, this optimization will then need to be solved in one shot, considering all wind speeds and directions and the corresponding settings of all wind turbines. However, the complexity of such optimization is prohibitive from computational point of view. To make the problem computationally tractable one may consider alternatively to perform the optimization for each individual wind direction by taking the power productions and loads equal to their nominal values for the remaining wind directions and speeds. This approach, however, is expected to result in a biased (suboptimal) solution because the optimization for a given wind direction will only consider the nominal (and not the optimized) powers and loads at other wind directions. Furthermore, in the case of Controlling Wind the loads might increase for some wind directions due to the wake being moved from full to partial wake. In such cases Controlling Wind will not be applied for this direction, while application might very well be possible should one consider the op-
timized loads for other directions. This is because for some direction Controlling Wind could change the wake condition for a turbine from full-wake to partial wake (leading to loads increase), but for a slightly different direction it could have a positive effect on the loads on the same turbine by moving the wake completely away from it relieving it from an nominally partial wake situation.

For this reason, the approach selected in this case is to perform sector-based optimization row-by-row, i.e. to optimize the Active Wake Control settings for a given row of turbines for a whole sector of wind directions at a time. More specifically, for a given wind direction $\bar{\alpha}$, the idea is to identify rows of turbines that are aligned with this wind direction. For each such row of turbines, a sector $[\bar{\alpha} - \Delta\alpha, \bar{\alpha} + \Delta\alpha]$ of wind directions is defined for which the optimization over the Active Wake Control settings (within this sector) is to be performed. This is visualized in Figure 6, where a farm layout consisting of three rows of turbines is considered. However, the orientation of each row is slightly different, so that sector-based optimization for the first row will be performed when the wind direction is $\bar{\alpha} = 297^\circ$, for the second row $\bar{\alpha} = 292^\circ$, and for the third one $\bar{\alpha} = 289^\circ$. The sector width is selected broad enough to cover all directions around $\alpha$ for some turbines from the row are in the wakes of other turbines of this row. Again, as mentioned above regarding row-by-row optimization, all other turbines that don’t pertain to the row but nevertheless are (partially) in the wake of turbines from the row for at least one direction from the sector $[\bar{\alpha} - \Delta\alpha, \bar{\alpha} + \Delta\alpha]$ will also be simulated during the sector-based optimization, since Active Wake Control will influences their loads and productions as well. It is considered that especially Controlling Wind will benefit from this sector-based optimization because the above-mentioned effects of partial wake situations on the loads will now be properly treated, being analyzed over a whole sector of directions rather than one single direction.

It should be pointed out that, even though the sector-based approach is developed for dealing with the loads-based (lifetime power production) optimization (2.4), it is perfectly suitable for addressing the yearly power production optimization problem (2.4) as well. Therefore, the sector-based approach will be developed for both Heat & Flux and Controlling Wind, even though Heat & Flux is only applicable to the yearly optimization problem as discussed above.

However, the sector-based approach also suffers from the “curse of dimensionality” problem: depending on the distances between the turbines the sector can be as broad as 40 degrees, and even if only 2 optimization variables per row are considered using the approach described in the previous subsection, the number of optimization variables is too large. Therefore, it has been decided to optimize the parameters of properly shapes rather than the actual Active Wake Control settings within the direction sector. As pointed out earlier, analysis of Active Wake Control optimization results have indicated that in the optimal settings no clear trends can be observed with respect to the wind speed variations, while there are clear trends visible with respect to the wind direction. The idea is thus to optimize the Active Wake Control settings by constraining them to have the form of suitably selected smooth curves that only depend on the wind direction, and not on the wind speed. The curve to be used for the Heat & Flux settings is selected to be a Gaussian curve defined as:

$$\theta(\alpha) = A e^{-\frac{(\alpha - \bar{\alpha})^2}{2d^2}},$$

wherein the parameter $A$ defines the maximum of the function attained at $\alpha = \bar{\alpha}$, and $d$ defines the width of the “bell”. This choice is motivated from the result in Figure 7 (left),

20
where the optimal (with respect to criterion (2.2)) Heat & Flux settings for a row of wind turbines for different wind speeds and directions (dashed curves) are well approximated by a Gaussian curve (solid line) that depends on the wind direction only. Further analysis has indicated that the seemingly large variations in the optimal pitch angle for different wind speeds are primarily due to convergence to local optima, and have interestingly rather small effect on the final power production gain.

For some layouts, however, the optimum width on the left side (for $\alpha < \bar{\alpha}$) can differ from that at the right side, so it makes sense to consider different width parameters for the left and right region as follows

$$d = \begin{cases} 
    d_1, & \text{if } \alpha < \bar{\alpha} \\
    d_2, & \text{otherwise}
\end{cases}$$

As a result, the total number of parameters for a sector-based Heat & Flux optimization becomes 3 ($A, d_1$ and $d_2$), defining the shape of the Gaussian curve for the leading wind turbine in the row.

For Controlling Wind, a good approximation of the optimal settings are obtained using two quadratic Bézier curves, one for $\alpha < \bar{\alpha}$ and one for $\alpha > \bar{\alpha}$ (see right-hand side plot in Figure 7). Generally speaking, a quadratic Bézier curve is defined by the two end points of the curve, $P_0$ and $P_2$, and an intermediate control point $P_1$ generally not lying on the curve

$$B(t) = (1 - t)^2 P_0 + 2t(1 - t) P_1 + t^2 P_2, \quad 0 \leq t \leq 1,$$  \hspace{1cm} (2.5)$$

wherein $B(t), P_0, P_1, P_2 \in \mathbb{R}^2$ are all points in the 2-dimensional plane. For our purposes, the plane is defined by the pairs $(\alpha, \phi)$, i.e. the wind direction and the yaw misalignment angle. Denoting $B(t) = [\alpha, \phi]^T$ and $P_i = [\alpha_i, \phi_i]^T, i = 0, 1, 2$, in order
to obtain the yaw misalignment angle $ϕ$ for a given wind direction $α$ we then first need to solve the first equation in (2.5) for $0 \leq t \leq 1$, i.e.

$$α = (1 - t)^2 α_0 + 2t(1 - t)α_1 + t^2 α_2.$$ 

This is a standard quadratic equation with solution

$$t(α) = \begin{cases} 
0.5 \frac{α - α_0}{α_1 - α_0}, & \text{if } α_1 = 0.5(α_0 + α_2), \\
α_0 - α_1 + \sqrt{(α_1 - α_0)^2 + (α_0 - 2α_1 + α_2)(α - α_0)} \over α_0 - 2α_1 + α_2, & \text{otherwise}
\end{cases}$$

Substitution of this solution into the second equation in (2.5) gives

$$ϕ(α) = (1 - t(α))^2 ϕ_0 + 2t(α)(1 - t(α)) ϕ_1 + t^2(α)ϕ_2.$$ 

Therefore, each of the above-mentioned two quadratic Bézier curves (for $α < \bar{α}$ and for $α > \bar{α}$) will be defined by three 2-dimensional points, giving a total number of six variables for each curve. However, since the end points of the curves will be constrained as shown in Figure 8, the control points become

left curve in Figure 8: $P_{left,0} = \begin{bmatrix} \bar{α} \\ 0 \end{bmatrix}$, $P_{left,1} = \begin{bmatrix} α_{left,1} \\ φ_{left,1} \end{bmatrix}$, $P_{left,2} = \begin{bmatrix} α_{left,2} \\ 0 \end{bmatrix}$,

right curve in Figure 8: $P_{right,0} = \begin{bmatrix} \bar{α} \\ 0 \end{bmatrix}$, $P_{right,1} = \begin{bmatrix} α_{right,1} \\ φ_{right,1} \end{bmatrix}$, $P_{right,2} = \begin{bmatrix} α_{right,2} \\ 0 \end{bmatrix}$.

Therefore, $\bar{α}$ being given, just three parameters per curve will need to be optimized per curve ($α_1$, $α_2$ and $ϕ_1$). This approximation with two Bézier curves is, of course, valid for one single wind turbine. As Controlling Wind will need to optimize the yaw misalignment settings for the leading and the second last wind turbine, there will be two such pairs of Bézier curves required for one sector-based Controlling Wind optimization. That leads to a total of 12 parameters.

### 2.4.3 Optimization algorithm

The optimization approach is summarized as follows: for each wind direction (0 to 359 degrees) perform the following steps:

---

1. The optimization could also be performed for each pair of wind direction and below rated wind speed. However, as pointed out previously, the effect of the wind speed on the optimal settings turns out to be very inconsistent, making it difficult to implement in practice. For this reason it is recommended to let the Active Wake Control settings only depend on the wind direction.
Step 0  Reference calculation (Active Wake Control not applied): the FarmFlow software is used to calculate the power productions of the individual wind turbines in the whole park for the current wind direction and all below rated wind speeds.

Step 1  Determine, using Jensen’s wind farm model, rows of (at least two) wind turbines that are in each others wakes. No turbine is allowed to belong to two different rows (for a given wind direction).

Step 2  For each row, determine if Active Wake Control optimization is to be applied to it. The condition for this is that there are wind turbines in the row separated by at most 20D (distance measured in downwind direction).

For sector-based optimization, the direction of the row of turbines (direction defined in least-squares sense when turbine do not lie exactly on a line) is required to be aligned with the wind direction (±0.5 degrees) to ensure that the optimization will be performed just once for a given sector of wind directions.

For Heat & Flux there is an additional condition, namely that the leading turbine is not in the wake of other turbines.

If these conditions are not satisfied, Active Wake Control optimization is not performed to this row in this wind direction. The procedure moves to the next row (Step 2 again), or to Step 4 if all rows have been considered.

Step 3  Numerical optimization takes place to calculate the optimal Active Wake Control settings that minimize the selected optimization criterion (the yearly power production in equation (2.2) when loads are not considered, or the lifetime power production in equation (2.4) when loads are included). To this end, a derivative-assisted nD-section method (n-dimensional extension of the well-known bisection algorithm) is utilized. This algorithm converges fast and reliable within just a few iterations.

**Single direction based optimization**  (loads are not considered)

- For Heat & Flux, there is just one variable to be optimized: the pitch angle offset of the leading wind turbine for the considered row.
- For Controlling Wind, there are two optimization variables: the yaw misalignment of the first wind turbine and that of the second last one in the row. The yaw misalignment angles of the wind turbines in between are then calculated using linear interpolation between these two angles.
**Sector-based optimization** (loads are considered)

- For Heat & Flux, the three Gaussian curve parameters \(A, d_1, \text{ and } d_2\) are optimized, describing the the pitch angle offset of the leading wind turbine for the considered row for the complete sector of wind directions.
- For Controlling Wind, the settings of two wind turbines are optimized, i.e. the leading one and the second last one. Again, the yaw misalignment angles of the wind turbines in between are then calculated using linear interpolation between these two angles. For each of these two turbines, two Bézier curves relate the yaw misalignment angle to the wind direction, each curve being defined by 3 parameters \(\alpha_1, \alpha_2\) and \(\phi_1\). This leads to a total of 12 parameters for the sector-based Controlling Wind optimization.

**Step 4** The optimal Active Wake Control settings, optimized per row, are combined and a final FarmFlow calculation is performed with the complete wind farm to evaluate the final power production gain for the current wind direction and all below rated wind speeds.

The following needs to be pointed out here with respect to analysis of the overall benefit from Active Wake Control. When *single direction based* optimization has been performed, one simply needs to collect the Active Wake Control settings for each individual wind direction (and, eventually, wind speed). This will result in a 2D table that gives, for a given wind direction \(\alpha\) and wind speed \(V\), the Active Wake Control setting (pitch angle \(\theta\) or yaw misalignment \(\phi\)) of each wind turbine in the farm. Similarly, the final benefit can be calculated based on the benefits at each individual wind direction (and speed) using the results from the farm simulations performed in Step 4, which just need to be processed using the wind distributions.

In case of *sector-based* Active Wake Control optimization, much more post-processing is required. Firstly, for a given turbine there can be intersecting sectors, i.e. the turbine can pertain to two (or more) rows of turbines the orientations of which are close enough for their corresponding sectors to intersect (see the three rows in Figure 6). When collecting the Active Wake Control settings into a 3D table, for wind directions belonging to the intersection of sectors the settings for some wind turbines will not be uniquely defined. In these cases it is suggested to choose the largest Active Wake Control settings. And secondly, the farm simulations performed at Step 4 of the optimization algorithm above are in general not sufficient to properly analyze the overall benefit of Active Wake Control. The reason for that can be easily explained using Figure 6 again. When wind direction \(292^\circ\) is considered, the sector-based optimization will be applied to row 2 only as this is the only row aligned with the wind direction \((\pm 0.5^\circ)\), while the optimal settings of the wind turbines in rows 1 and 3 will not be considered. Therefore, the simulation in Step 4 will in this case only include the optimized Active Wake Control settings for row 2, and will disregard those of rows 1 and 3, and the Active Wake Control benefit would hence not be properly evaluated. Therefore, when the farm layout is such that sectors intersect, after the complete Active Wake Control optimization has been performed the farm must to be simulated again for all (relevant) wind conditions using the final settings as collected in the mentioned table.

**2.4.4 Implementation issues**

As explained above, the optimization procedure results in Active Wake Control settings (pitch angle biases for Heat & Flux, and yaw misalignment angles for Controlling Wind).
that depend on the wind direction and (to a lesser extend) on the wind speed. These
settings are optimized for fixed wind speeds and directions, while in practice both con-
tantly vary. Obviously, the AWC settings, and especially the yaw misalignment angles,
cannot be modified as fast as the wind changes. This is due to the very slow dynamics of
the yaw control algorithm in the wind turbine controller. The wind turbine controller re-
receives (rather inaccurate) measurements from the wind vane about the wind direction,
which are then filtered by a very low pass filter (typically similar to 10 minute averag-
ing) and compared to the rotor orientation. If the resulting yaw error (misalignment)
becomes larger than a predefined value for some time, the yaw control algorithm yaws
the rotor slowly so as to align it with the wind direction. Active Wake Control does not
require that either the yaw or the blade pitch control algorithms are modified; only their
setpoints will need to be altered.

For Controlling Wind, for instance, the original yaw misalignment setpoint of zero de-
grees will be substituted by the optimized yaw misalignment for each wind direction
and each wind turbine. These yaw misalignment setpoints shall also be adapted based
on a very low-pass filtered wind direction signal, resulting in slow variations in the set-
points. Moreover, a relay logic will need to be implemented to avoid that the yaw mis-
alignment setpoint often changes sign when the wind direction fluctuates around the
direction of a row of wind turbines. Of course, such filtering and relay logics will lead
to the yaw misalignment angles not following the wind direction fast enough, resulting
in periods of suboptimal settings. Notice, however, that this also holds for the nomi-
nal situation without Active Wake Control applied: the wind direction changes will re-
sult in less power production than predicted for a given wind direction. Therefore, this
“smoothing” effect is expected to deviate by less than 20% from the calculated theo-
retical power gain. Finally, it needs to be pointed out that for implementing Controlling
Wind, the wind turbine controller will need to be able to accept external setpoints for
the yaw (misalignment) angle (which is easy to implement, if necessary).

Similar discussion holds for Heat & Flux. The dynamics of the blade pitch control loop
are faster than the yaw dynamics, allowing for faster adaptations of the pitch angle so
as to better track the wind direction changes. Still, also here low-pass filtered wind di-
rections, combined with relay logic, will be used to ensure smooth operation in practice.
This will again have a mitigating effect on the total power production gain due to Heat &
Flux. Finally, it should be pointed out that the wind turbine controller may not be able
to directly accept external pitch angle setpoints. If that is the case, Heat & Flux can be
implemented indirectly by applying an external active power setpoint instead of pitch
angle setpoint: this must be possible for turbines located in farms that comply with the
(European) grid codes. The optimized Heat & Flux pitch settings per wind direction will
then need to be converted into power curves (power as function of wind speed) to be
used to generate power setpoints for the wind turbine controller.
3 Results of AWC for Prinses Amalia US

In this section, results obtained with the Active Wake Control optimization on the Prinses Amalia US wind farm are presented for the following conditions/assumptions:

- wind speed dependent turbulence intensity (averaged over all wind directions)
- include turbines for Active Wake Control within 20D distance in the wake of upwind turbines
- optimization of the Active Wake Control settings for each wind speed below rated

The operational characteristics (such as power, thrust force as function of wind speed for different pitch angles) have been derived from the $C_p$ and $C_t$ tables.

The first section shows the layout of the wind farm and the wind characteristics (§3.1). Then, the results of the reference calculation are shown (§3.2), i.e. the calculation without Active Wake Control. Section 3.3 describes the application of Heat & Flux for maximizing the yearly power of the wind farm. Then Controlling Wind is applied for maximizing both the yearly power production and lifetime power production performance criteria, and the results are described in section §3.4.

3.1 The Prinses Amalia US wind farm

The wind farm that served as a basis for this study is the Prinses Amalia offshore wind farm, located 23km NorthWest of Velsen, The Netherlands. The wind farm consists of 60 wind turbines of 2.0 MW and has a total output of 120 MW. For this study the wind farm is scaled (denoted as Prinses Amalia US), to contain 60 5.0 MW wind turbines. The scaling is based on rotor diameter, see B for details. The wind farm layout is given in Figure 9.

The wind speed distribution, the wind direction rose and turbulence intensity distribution for this site are calculated from measurement data of the nearby OWEZ meteorolo-
Figure 9: Layout of the Prinses Amalia US wind farm. The axes scales are given in number of rotor diameters (D). Encircled are turbines on which will be zoomed in.

logical mast, taken in the period Jul2005-Jun2006 ([7],[6]). During this period there was no influence on the measurements from the OWEZ wind farm yet. The resulting distributions can be found in figures 10, 11 and 12. Figure 10 provides the Weibull distribution fit. The corresponding Weibull distribution parameters are $\lambda = 7.63$ and $k = 2.53$. The most dominant wind direction is SouthWest.

The wind turbine used for this study is the 5MW Aerodynamic Reference wind Turbine (ART5). This wind turbine design shows close resemblance to the original Vestas 2MW V80 machine used in the Prinses Amalia wind farm. Details on the comparison can be found in A. The ART5 has the following characteristics:

- rated power: 5.0 MW
- rated rotor speed: 12.1 rpm
- rotor diameter: 128.4 m
- hub height: 90 m

3.2 Reference case

This section shows the results of the reference FarmFlow calculation of the Prinses Amalia US wind farm. The first part shows the setup and assumptions, followed by an overview of the results in the second part.
Figure 10: Wind speed intensity distribution

Figure 11: Wind direction rose
3.2.1 Layout and setup

The farm layout and external conditions are as described in Section 3.1.

The wind speed range for which the turbines are active is 4-25 m/s. Even though Active Wake Control is only applied below rated, the wind speed array that is investigated is set to 4-25 m/s with 1 m/s increment to get a complete picture of the farm lifetime operation.

3.2.2 Results

This section shows the results of the reference case. Focus is on the azimuthal dependency, as this is a key factor for the performance of the Active Wake Control strategy.

The first set of polar plots are given for below rated condition ($V_w = 8 m/s$):

1. wind speed (Figure 13)
2. power (Figure 14)
3. turbulence intensity (Figure 15)

and for around rated condition ($V_w = 12 m/s$):

1. wind speed (Figure 16)
2. power (Figure 17)
3. turbulence intensity (Figure 18)

The four lines in the figures are for four selected turbines in the farm (blue:T1, red:T34, magenta:T56, cyan:T57); see figure 9 for the location of these turbines. The first and last
two are located on respectively the NorthEastern and Southern and Western outer side of the farm and the second on the inside (see layout in section 3.1). The plots are in line with the expectations. Figure 15 shows the large farm influence on turbulence intensity; for the turbines in the more closely spaced rows, a turbulence intensity of above 20% is observed for wind direction aligned with the row.

Figure 19 shows the normalized (per unit) power curve of the complete farm, averaged over the wind direction distribution. Also shown is an upper bound: the theoretical power output when no farm effects would be present. Figure 20 shows the normalized (per unit) power curve of the complete farm, averaged over the wind speed distribution. Using the Weibull distribution from figure 10, the total energy production of the farm for a 20 year lifetime as calculated with FarmFlow is $24.4 \times 10^9$ kWh. The wake losses amount to 11.13%.

Figures 21 and 22 show the farm effect below rated for a single row (the main diagonal from NorthWest to SouthEast, consisting of turbines T23-T31).

![Figure 13: Azimuthal dependency of wind speed for selected turbines in the farm ($V_w = 8 m/s$)](image)
Figure 14: Azimuthal dependency of power output for selected turbines in the farm ($V_w = 8 m/s$)

Figure 15: Azimuthal dependency of turbulence intensity for selected turbines in the farm ($V_w = 8 m/s$)
azimuthal dependency of windspeed (at $V_w = 12\text{ m/s}$)
for selected turbines in the farm (b:1, r:T34, m:T56, c:T57)

**Figure 16: Azimuthal dependency of wind speed for selected turbines in the farm ($V_w = 12\text{ m/s}$)**

azimuthal dependency of power (at $V_w = 12\text{ m/s}$)
for selected turbines in the farm (b:1, r:T34, m:T56, c:T57)

**Figure 17: Azimuthal dependency of power output for selected turbines in the farm ($V_w = 12\text{ m/s}$)**
Figure 18: Azimuthal dependency of turbulence intensity for selected turbines in the farm ($V_w = 12 \text{ m/s}$)

Figure 19: Normalized (per unit) power curve for the complete wind farm, including theoretical upper bound
Figure 20: Normalized (per unit) power distribution for the complete wind farm, including theoretical upper bound

Figure 21: Farm effect on wind speed and turbulence intensity in horizontal row for aligned wind direction ($V_w = 8 \text{m/s}, \alpha_w = 300^\circ$)
Figure 22: Farm effect on power and thrust in horizontal row for aligned wind direction ($V_w = 8\text{ m/s}$, $\alpha_\omega = 300^\circ$)
3.3 Heat & Flux optimization of the power production

As explained in Section 2.4, two performance criteria are considered for optimizing the Active Wake Control settings for the wind turbines, i.e. maximization of either the yearly power production (see equation (2.2)) or the lifetime power production (see equation (2.4)). However, as explained in the beginning of Section 2.4, the Heat & Flux strategy can at present not be applied to the lifetime optimization problem because the loads database does not include pitch angle variations. For this reason, only yearly power production maximization is considered for Heat & Flux.

The yearly power optimization can be addressed by both the single-direction and sector-based approaches. For Heat & Flux, only single direction optimization has been performed. For Controlling Wind both will be considered, and their results compared.

First, consider the wind direction 179° that is most beneficial for Heat & Flux (see simplified wakes visualization in Figure 23).

For this wind direction, the Heat & Flux optimization scheme determined that the best Heat & Flux pitch bias is around 2.5° for turbine T56. Let’s first inspect the result of this Heat & Flux setting on the row of turbines T56-T3. Figure 24 gives the power productions, the turbulence intensity and pitch angle setting per wind turbine in this situation, both in the reference case (blue bars) and with Heat & Flux (red bars). The plots represent the results for single-direction optimization. It is clear from the figure that, as expected, Heat & Flux results in the leading turbine producing less power due to the increased pitch angle, while the remaining wind turbines all achieve increase in power production. As a result, the single-direction Heat & Flux increases the total power production for row T56-T3 with 2.2% for the considered wind direction (179°) and wind speed (8 m/s). Looking at the whole park, the effect of single-direction Heat & Flux reduces to 2.0% increase in power production (still for one single wind direction and wind speed). Considering that Heat & Flux has effect only at below rated wind speeds, and
since the Heat & Flux is independent on the wind speed, using the wind speed distribution we get that the *yearly increase* of the power production for the whole wind farm for this particular wind direction drops to 0.88% in the case of single-direction optimization. Table 1 gives an overview of the results for yearly power optimization.

**Table 1:** Power gain for single-direction Heat & Flux for yearly power optimization

<table>
<thead>
<tr>
<th>case</th>
<th>result</th>
<th>Power gain single-dir. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>row T56-T3 (spd=8m/s, dir=179deg)</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>farm (spd=8m/s, dir=179deg)</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>farm (all spd, dir=179deg)</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>farm (all spd, all dir)</td>
<td>0.33</td>
<td></td>
</tr>
</tbody>
</table>

Considering all directions and the wind speed distribution on site, Heat & Flux results for yearly power optimization is summarized in Figure 25. As can be seen from Figure 25, Heat & Flux has its largest effect in a few wind direction intervals. The intervals wherein Heat & Flux has larger effect are small (around 6°), which is due to the relatively large distances between the wind turbines in the farm and its regular layout. Weighing the relative power increase per wind direction with the wind direction probabilities, the total yearly power increase for the whole farm due to single-direction Heat & Flux becomes around 0.33%. This boils down to a total of around $79.5 \times 10^6$ kWh extra energy due to Heat & Flux in 20 years. Looking at the gain of Heat & Flux with respect to the wake losses of the farm (2.97%); this result is better than the results obtained in recent Heat & Flux studies for different wind farms. The main reason for this is the regular layout of the farm, with nicely aligned rows of turbines.

Figure 26 shows the Heat & Flux pitch bias for wind turbines T1 and T48 (plots on top of the figure) and T23 and T29 (plots on bottom of the figure) as function of the wind direction for the single-based optimization. Notice that depending on the wind direction, different wind turbines are leading. Turbines T1 and T48 are both lying at the two edges of one of the central rows of the farm, and as result of that their Heat & Flux settings look are very similar when one of them is shifted by 180 degrees (see Figure 26). Clearly, in a real-life implementation the calculated single-direction Heat & Flux pitch angles will be smoothed out by removing the sharp changes in it. This will only have a small effect on the Heat & Flux performance. Such smoothing might also be necessary in the sector-based case (to a lesser extend) even though the Heat & Flux settings would then be optimized for each sector as smooth functions. The reason for that are closely-spaced or even partially overlapping sectors of wind directions.
Figure 24: Power production (upper), turbulence intensity (middle) and pitch angle settings for the row of wind turbines T56-T3 for wind direction 179° and wind speed 8 m/s. The blue (left) bars represent the reference case, while the red (right) bars represent Heat & Flux results.
Figure 25: Relative power production increase for Heat & Flux as a function of the wind direction.

Figure 26: Optimal Heat & Flux pitch bias as a function of the wind direction for turbines T1 and T48 (top plots), and T23 and T29 (bottom plots).
As mentioned already, the Heat & Flux strategy cannot be applied to the lifetime optimization problem because the loads database does not include pitch angle variations. For this reason, only yearly power production maximization is considered for Heat & Flux. However, since under Heat & Flux the pitch angle of the leading wind turbines is increased (i.e. these are derated), it is not expected that this would have any significant negative effect on the lifetime loading on the main components. Therefore, it remains interesting to inspect the loads by neglecting the Heat & Flux pitch basis.

For this purpose, Table 2 is provided. The table shows, for each of the considered components (see Section 2.4), the reduction of the yearly fatigue loading averaged over the turbines (denoted as LOAD Avg in the table) and the corresponding lifetime extension factor (LIFETIME Avg), as well as the worst-case (the smallest one over the turbines) load reduction (LOAD WC) and corresponding lifetime extension factor (LIFETIME WC). It can be observed that, even though the loads reductions seem small in terms of percentages, the lifetime extension factors are interesting. Indeed, even if we assume that the loads on the considered components are equally important, it appears from the table that the turbines in the farm can be operated on the average 0.32% longer than 20 years before the tower reaches its fatigue lifetime. The lifetime energy gain would then be 0.65%.

Looking at the worst-case loading among all turbines, a small increase is observed for the tower base moment (last two columns in the table).

Notice also that the lifetime extension factors for the tower bottom are the lowest, much lower than those for the other considered components. This suggests that there might also be important advantage with respect to corrective maintenance costs, since the significant loads reductions there imply lower failure rates. This benefit is, unfortunately, difficult to evaluate numerically, and hence not considered here.

<table>
<thead>
<tr>
<th>Component</th>
<th>location</th>
<th>Load Avg [%]</th>
<th>Lifetime Avg [%]</th>
<th>Load WC [%]</th>
<th>Lifetime WC [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>tower fore-aft moment</td>
<td></td>
<td>0.079</td>
<td>0.319</td>
<td>-0.035</td>
<td>-0.140</td>
</tr>
<tr>
<td>tower torsion moment</td>
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<td>2.284</td>
<td>0.468</td>
<td>1.895</td>
</tr>
<tr>
<td>tower fore-aft moment</td>
<td>top</td>
<td>0.513</td>
<td>2.070</td>
<td>0.436</td>
<td>1.762</td>
</tr>
<tr>
<td>torque on drive train support</td>
<td></td>
<td>0.176</td>
<td>2.673</td>
<td>0.493</td>
<td>3.524</td>
</tr>
<tr>
<td>rotor-shaft tilt moment</td>
<td></td>
<td>0.241</td>
<td>1.703</td>
<td>0.259</td>
<td>1.832</td>
</tr>
<tr>
<td>rotor-shaft yaw moment</td>
<td></td>
<td>0.256</td>
<td>1.806</td>
<td>0.254</td>
<td>1.795</td>
</tr>
<tr>
<td>axial shaft force at hub</td>
<td></td>
<td>0.285</td>
<td>2.013</td>
<td>0.284</td>
<td>2.011</td>
</tr>
<tr>
<td>blade 1 root flap moment</td>
<td></td>
<td>0.168</td>
<td>1.864</td>
<td>0.152</td>
<td>1.690</td>
</tr>
<tr>
<td>blade 2 root flap moment</td>
<td></td>
<td>0.149</td>
<td>1.659</td>
<td>0.110</td>
<td>1.220</td>
</tr>
<tr>
<td>blade 3 root flap moment</td>
<td></td>
<td>0.131</td>
<td>1.454</td>
<td>0.110</td>
<td>1.221</td>
</tr>
</tbody>
</table>

In order to get a better insight into the loads reduction figures, let’s look more closely at the dependency of the load at the rotor centre and the tower base in fore-aft direction on the wind direction, including the wind speed distribution therein. This is visualized in Figures 27 and 28 for the worst loaded turbine (T27). It can be seen from the figure that this turbine does not receive a significant load reduction at any wind direction. This is as expected since T27 is located at the centre of the wind farm (see Figure 23), and thus operating at high turbulence intensity levels that are not much affected by Heat & Flux. In general, the second turbine in the row gets the most significant reduction of turbulence intensity by Heat & Flux (see, as an example of this effect, the turbulence plots for a row of turbines in Figure 24).
3.4 Controlling Wind optimization

In this section, the results are presented from the Controlling Wind optimization for the Prinses Amalia US wind farm. As explained in Section 2.4, two performance criteria are considered for optimizing the Controlling Wind settings for the wind turbines, i.e. maximization of either the yearly power production (see equation (2.2)) or the lifetime power production (see equation (2.4)). These optimization problems are discussed in Subsections 3.4.1 and 3.4.2, respectively.

3.4.1 Controlling Wind optimization of the yearly power production

This section addresses the results obtained with Controlling Wind for yearly power optimization (see equation (2.2)). This optimization problem can be addressed by both the single-direction and sector-based approaches; both will be considered, and their results compared, in this section.

To understand the operation of Controlling Wind and the obtained results, let us first consider one wind direction and one single row of wind turbines. For Controlling Wind, wind direction 6° is the most beneficial one, achieving the highest power gain. For this wind direction, row of turbines T1-T48 has the highest contribution to the power gain.
For this row, Figure 29 gives the power productions, the turbulence intensity and yaw misalignment angles per wind turbine in this situation, both in the reference case (blue bars) and with Controlling Wind (red bars). The left-hand side plots represent the results for single-direction optimization, and right-hand side plots for sector-based optimization. It is clear from the figure that Controlling Wind results in the leading turbine producing less power due to the introduced yaw misalignment, while the remaining wind turbines all achieve increase in power production due to the higher wind velocity. The Controlling Wind optimization for wind speed of 8 m/s and wind direction of 6° results in the yaw misalignment distribution depicted in the bottom plots in Figure 29. It can be seen that, as explained in Section 2.4, a linear distribution of the yaw misalignment angles is obtained, with the leading wind turbine receiving the largest misalignment. The last turbine in the row is, of course, not misaligned; misalignment there would only result in energy loss that can no longer be regained behind it.

As a result, the single-direction Controlling Wind increases the total power production for row T1-T48 with 13.3% for the considered wind direction (6°) and wind speed (8 m/s). Looking at the whole park, the effect of single-direction Controlling Wind reduces to 11.4% increase in power production (still for one single wind direction and wind speed). Considering that Controlling Wind has effect only at below rated wind speeds, and since the Controlling Wind is independent on the wind speed, using the wind speed distribution we get that the yearly increase of the power production for the whole wind farm for this particular wind direction drops to 6.9% in the case of single-direction optimization. These results are also visible in Table 3 that gives an overview of the results for yearly power optimization.

As seen from Table 3, with sector-based Controlling Wind the power gains are comparable to those with single-direction for the inspected wind direction 6°. When the yearly production is considered, however, sector-based Controlling Wind turns out to achieve only two-third of the gain obtained with single-direction optimization. The reason for this seems to be that for some wind directions there are overlapping sectors for the same wind turbine which makes the Bezier curve approximation approach too restrictive.

Compare the power production results in Table 3 to the corresponding results with Heat & Flux in Table 1. For the Prinses Amalia US wind farm Controlling Wind is more beneficial than Heat & Flux, which is in line with the recently performed studies with Active Wake Control.

Considering the wind speed distribution on site, the power gain is expressed versus the wind direction in Figure 30 for the Controlling Wind yearly power optimization. Again, the left-hand side plot corresponds to the single-direction optimization, and the right-hand side one – to sector-based optimization. Again, similar to the case with Heat & Flux, Controlling Wind has its largest effect in a few wind direction intervals. Weighing the relative power increase per wind direction with the wind direction probabilities, the total yearly power increase for the whole farm due to single-direction Controlling Wind becomes around 1.28% (or 0.82% for the sector-based alternative). This boils down to a total of around $14.8 \times 10^9$ kWh extra energy per year due to Controlling Wind with yearly power optimization. Looking at the gain of Controlling Wind with respect to the wake losses of the farm (11.5%); this result is somewhat higher than the results obtained in recent Controlling Wind studies for different wind farms. The main reason for this is the regular layout of the farm, with nicely aligned rows of wind turbines.
Figure 29: Power production (upper), turbulence intensity (middle) and pitch angle settings for the row of wind turbines T1-T48 for wind direction 6 ° and wind speed 8 m/s. The blue (left) bars represent the reference case, while the red (right) bars represent Controlling Wind results. Left-hand side plots are for single-direction optimization, and right-hand side ones – for sector-based.

Table 3: Power gain for single-direction and sector-based Controlling Wind for yearly power optimization

<table>
<thead>
<tr>
<th>case</th>
<th>result</th>
<th>Power gain single-dir. [%]</th>
<th>Power gain sector-based [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>row T1-T48 (spd=8m/s, dir=6 deg)</td>
<td>13.3</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>farm (spd=8m/s, dir=6 deg)</td>
<td>11.4</td>
<td>11.3</td>
<td></td>
</tr>
<tr>
<td>farm (all spd, dir=6 deg)</td>
<td>6.89</td>
<td>6.74</td>
<td></td>
</tr>
<tr>
<td>farm (all spd, all dir)</td>
<td>1.28</td>
<td>0.82</td>
<td></td>
</tr>
</tbody>
</table>
Figure 30: Relative power production increase for Controlling Wind as a function of the wind direction. Left-hand side plot is for single-direction optimization, and right-hand side one – for sector-based optimization.

Figure 31: Optimal Controlling Wind setting as function of the wind direction for turbines T1 and T48 (top plots), and T23 and T29 (bottom plots). Left-hand side plot is for single-direction optimization, and right-hand side one – for sector-based optimization.

Figure 31 shows the Controlling Wind yaw angles for wind turbines T1 and T48 (plots on top of the figure) and T23 and T29 (plots on bottom of the figure) as function of the wind direction, both for the single-based (left-hand side plots) and sector-based (right-hand side plots) optimization. Yaw misalignment of up to 40° are observed. Similarly to the Heat & Flux settings, in a real-life implementation the calculated yaw misalignment curves may need to be smoothed out by removing the sharp changes in them.

Even though the loads are not directly included into the yearly power optimization, con-
considered in this subsection, it is important to study the effect of Controlling Wind on the loads carefully, since introducing yaw misalignment is often mentioned as a serious point of concern with respect to the loads. To this end, Table 4 is provided. The table shows, for each of the considered components (see Section 2.4), the reduction of the yearly fatigue loading averaged over the turbines (denoted as LOAD Avg in the table) and the corresponding lifetime extension factor (LIFETIME Avg), as well as the worst-case (the smallest one over the turbines) load reduction (LOAD WC) and corresponding lifetime extension factor (LIFETIME WC). It is important to see that the average loading over the turbines reduces for all components considered. Even though the loads reductions seem small in terms of percentages, the corresponding lifetime extension factors are more significant. On average, the tower bottom moment fatigue slightly increases with applying Controlling Wind, leading to a small reduction of the lifetime. However, the worst case loading occurs in a turbine that sees small load reduction with Controlling Wind, as shown in table 4. When the worst-case loading among all turbines is considered, a lifetime extension is achieved of 0.6%. With it, the total lifetime energy gain will become 1.9%.

Similar to the case with Heat & Flux optimization, but even more pronounced here, the lifetime extension factors for the tower bottom are the lowest, much lower than those for the other considered components. This suggests that there might also be important advantage with respect to corrective maintenance costs, since the significant loads reductions there imply lower failure rates. This benefit is, unfortunately, difficult to evaluate numerically, and hence not considered here.

Table 4: Loads reduction and lifetime extension per component for the case of single-direction Controlling Wind for yearly power optimization

<table>
<thead>
<tr>
<th>Component</th>
<th>Location</th>
<th>Load Avg [%]</th>
<th>Lifetime Avg [%]</th>
<th>Load WC [%]</th>
<th>Lifetime WC [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>tower fore-aft moment</td>
<td></td>
<td>-0.611</td>
<td>-2.396</td>
<td>0.150</td>
<td>0.603</td>
</tr>
<tr>
<td>tower torsion moment</td>
<td></td>
<td>6.156</td>
<td>27.294</td>
<td>9.569</td>
<td>49.530</td>
</tr>
<tr>
<td>tower fore-aft moment top</td>
<td></td>
<td>6.171</td>
<td>27.389</td>
<td>9.762</td>
<td>50.811</td>
</tr>
<tr>
<td>torque on drive train support</td>
<td></td>
<td>6.497</td>
<td>56.545</td>
<td>7.920</td>
<td>78.170</td>
</tr>
<tr>
<td>rotor-shaft tilt moment</td>
<td></td>
<td>6.836</td>
<td>60.242</td>
<td>9.107</td>
<td>95.109</td>
</tr>
<tr>
<td>rotor-shaft yaw moment</td>
<td></td>
<td>6.904</td>
<td>60.995</td>
<td>9.087</td>
<td>94.819</td>
</tr>
<tr>
<td>axial shaft force at hub</td>
<td></td>
<td>5.347</td>
<td>44.668</td>
<td>7.453</td>
<td>71.978</td>
</tr>
<tr>
<td>blade 1 root flap moment</td>
<td></td>
<td>5.674</td>
<td>85.053</td>
<td>7.055</td>
<td>123.622</td>
</tr>
<tr>
<td>blade 2 root flap moment</td>
<td></td>
<td>5.867</td>
<td>89.245</td>
<td>7.004</td>
<td>122.264</td>
</tr>
<tr>
<td>blade 3 root flap moment</td>
<td></td>
<td>5.361</td>
<td>79.210</td>
<td>6.541</td>
<td>110.463</td>
</tr>
</tbody>
</table>

In order to get a better insight into the loads reduction figures reported in Table 4, let’s look more closely at the dependency of the load at the rotor centre and the tower bottom in fore-aft direction on the wind direction, including the wind speed distribution therein. This is visualized in Figures 32 and 33 for the worst loaded turbine (T27). It can be seen from the figure that this turbine receives increased loading at several wind directions. This is due to the fact that T27 is located inside of the wind farm (see Figure 23), and therefore operates under significant yaw misalignment for some directions. The turbulence intensity in this situation, however, is reduced, so that the contribution of the loading at these specific wind directions to the overall lifetime loading remains small. The tower fore-aft loading, however, is very high for the wind directions aligned with a row, and therefore these directions are the main contributor to the lifetime fatigue loading on the tower fore-aft moment for this turbine. At these directions the load is reduced due to Controlling Wind. In total, this results in a small increase of the lifetime loading on the tower (see Table 4).
3.4.2 Controlling Wind optimization of the lifetime power production

The previous section addressed the results with Controlling Wind for yearly power optimization. In this section, Controlling Wind for lifetime power optimization is considered (see equation (2.4)), wherein the effects of the fatigue loading onto the lifetime of the wind turbines is included. The lifetime power optimization can only be addressed by sector-based approach. It is therefore reasonable to compare the results reported here to those for yearly power optimization using the sector-based Controlling Wind, reported in the previous section.

In terms of yearly power production, the lifetime optimization results summarized in Table 5 are somewhat lower compared to those from the sector-based yearly power optimization (compare to the last column in Table 3. When the loads are considered, these are reducing as expected. The tower bottom remains the critical component, but now a reduction of 0.068% on average and 0.34% worst case is observed. As a result, the lifetime power production is higher than for the yearly power optimization, 0.88% for average loading and 2.0% with worst case loads.
Figure 34: Relative power production increase for sector-based Controlling Wind for lifetime power optimization as a function of the wind direction.

The yearly power production of the farm as function of the wind direction (wind speed distribution included) is depicted in Figure 34. Comparison to the right plot in Figure 30 (sector-based Controlling Wind for yearly power optimization) confirms the conclusion drawn above.

Table 5: Power gain for sector-based Controlling Wind for lifetime power optimization

<table>
<thead>
<tr>
<th>case</th>
<th>result</th>
<th>power gain [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>row T3-T14 (spd=8m/s, dir=287 deg)</td>
<td></td>
<td>8.86</td>
</tr>
<tr>
<td>farm (spd=8m/s, dir=287 deg)</td>
<td></td>
<td>7.52</td>
</tr>
<tr>
<td>farm (all spd, dir=287 deg)</td>
<td></td>
<td>5.15</td>
</tr>
<tr>
<td>farm (all spd, all dir)</td>
<td></td>
<td>0.61</td>
</tr>
</tbody>
</table>

Table 6: Loads reduction and lifetime extension per component for the case of sector-based Controlling Wind for lifetime power optimization

<table>
<thead>
<tr>
<th>Component</th>
<th>location</th>
<th>Load Avg [%]</th>
<th>Lifetime Avg [%]</th>
<th>Load WC [%]</th>
<th>Lifetime WC [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>tower fore-aft moment</td>
<td></td>
<td>0.068</td>
<td>0.276</td>
<td>0.342</td>
<td>1.380</td>
</tr>
<tr>
<td>tower torsion moment</td>
<td></td>
<td>2.074</td>
<td>8.614</td>
<td>3.500</td>
<td>15.318</td>
</tr>
<tr>
<td>tower fore-aft moment</td>
<td>top</td>
<td>2.053</td>
<td>8.527</td>
<td>3.523</td>
<td>15.425</td>
</tr>
<tr>
<td>torque on drive train support</td>
<td></td>
<td>2.057</td>
<td>15.555</td>
<td>3.087</td>
<td>24.540</td>
</tr>
<tr>
<td>rotor-shaft tilt moment</td>
<td></td>
<td>2.423</td>
<td>18.590</td>
<td>3.605</td>
<td>29.310</td>
</tr>
<tr>
<td>rotor-shaft yaw moment</td>
<td></td>
<td>2.430</td>
<td>18.635</td>
<td>3.605</td>
<td>29.303</td>
</tr>
<tr>
<td>axial shaft force at hub</td>
<td></td>
<td>1.862</td>
<td>13.960</td>
<td>2.762</td>
<td>21.657</td>
</tr>
<tr>
<td>blade 1 root flap moment</td>
<td></td>
<td>1.855</td>
<td>22.819</td>
<td>2.098</td>
<td>26.271</td>
</tr>
<tr>
<td>blade 2 root flap moment</td>
<td></td>
<td>2.048</td>
<td>25.610</td>
<td>2.368</td>
<td>30.164</td>
</tr>
<tr>
<td>blade 3 root flap moment</td>
<td></td>
<td>1.848</td>
<td>22.782</td>
<td>2.169</td>
<td>27.273</td>
</tr>
</tbody>
</table>
In this report, the potential benefits of the Active Wake Control concept are assessed for the Prinses Amalia US wind farm with the main goal of increasing the power production of the farm. Active Wake Control consists of two different concepts, a pitch based (Heat & Flux) and yaw based (Controlling Wind), which have been assessed separately. An optimization scheme is used to automatically optimize the blade pitch angle and nacelle yaw angle settings of the leading wind turbines, i.e. the wind turbines that have other turbines in their wake at a downwind distance of less than 20 rotor diameters. For calculating the wakes of the wind turbines, their power production and thrust forces, ECN’s software tool FarmFlow is used.

Two different optimization objectives have been considered. The first one directly aims to maximize the yearly power production of the wind farm, called yearly power optimization. The second one includes, besides the yearly power production, also the effect of Active Wake Control on the fatigue loads on the main turbine components. The loads are included into the optimization through a lifetime extension factor that depends on the lifetime loads reductions achieved by Active Wake Control for a number of predefined wind turbine components. The relationships between fatigue loading and O&M costs is difficult to model and therefore not considered.

During the optimization process the loads on the considered components are interpolated using a lookup table of precomputed loads (loads database). The database is constructed using aeroelastic simulations under many different operating conditions such as a range of wind speeds, turbulence intensities, wake deficit profiles, wake locations, and yaw misalignment, and uses FarmFlow output regarding the operating conditions as input. However, the database does not include the effect of pitch angle variations on the load, and therefore cannot be used in combination with the Heat & Flux strategy. For that reason, Heat & Flux is only applied to maximize the yearly power production, therefore not considering the loads.

4.1 Heat & Flux

By increasing the pitch angle of the leading wind turbines, Heat & Flux increases the wind speeds in the wakes so that the overall farm power production can increase and/or
the loads can be reduced. The optimization of the Heat & Flux pitch angle is applied to all wind directions for which there are leading wind turbines and to all below rated wind speeds. Based on insights from earlier studies, the Heat & Flux optimization is constrained to only apply Heat & Flux to the leading wind turbines for a given wind direction (i.e. the pitch angle settings of the wind turbines in the wake of the leading turbines are left unchanged).

The Prinse Amalia US wind farm gets the highest benefit from Heat & Flux when the wind comes from a direction of 179°: for this direction and wind speed of 8 m/s the power production of the farm increases by 2.0%. Considering all wind directions and wind speeds and their probabilities, the yearly power production increase by Heat & Flux is 0.33%. This boils down to around 79.5GWh more electricity over the lifetime of 20 years.

As mentioned, the Heat & Flux strategy can not be applied to the lifetime optimization problem because the loads database does not include pitch angle variations. However, since under Heat & Flux the pitch angle of the leading wind turbines is increased (i.e. these are derated), it is not expected that this would have any significant negative effect on the lifetime loading on the main components. Therefore, it remains interesting to inspect the loads by neglecting the Heat & Flux pitch bias. It is shown that the lifetime loads decrease for all considered components and that the tower bottom is the critical component. The achieved loads reduction are shown to correspond to an average lifetime extension by 0.32%. The overall lifetime energy gain by Heat & Flux, including the loads' effect, becomes as much as 0.65%.

4.2 Controlling Wind

The Controlling Wind concept to Active Wake Control operates the wind turbines at yaw misalignment in order to redirect their wakes away from the downstream wind turbines, increasing the overall power production of the farm. The yaw misalignment angle of each individual wind turbine is optimized for each wind direction and below-rated wind speed. As mentioned, two performance criteria are considered for optimizing the Controlling Wind settings, i.e. maximization of either the yearly power production or the lifetime power production by including loads effects.

As in the case of Heat & Flux, Controlling Wind delivers most benefit in terms of power production increase when the wind direction is such that there are row(s) with wind turbines aligned with the wind direction. For the Prinse Amalia US wind farm, the highest power gain from Controlling Wind occurs at a wind direction of 6°. For this wind direction and wind speed of 8 m/s, Controlling Wind increases the power production of the farm by 11.4%. Considering all wind speeds and wind directions the total yearly power production gain is about 1.28%. This boils down to around 276GWh more electricity over 20 years. The loads in the rotor and nacelle do not increase when applying Controlling Wind, as one might expect with intentional yaw misalignment. Most loads even decrease compared to the reference calculation (up to 10% for worst case). However, the tower bottom is again the critical component and sees a small increase in loads of 0.61%.

In terms of yearly power production, the lifetime optimization results are somewhat lower compared to those from the sector-based yearly power optimization. However, the loads are reducing as expected. The tower bottom remains the critical component,
but now a reduction of 0.068% on average and 0.34% worst case is observed. As a result, the lifetime power production increase is 0.88% for average loading and 2.0% based on worst case loads.

4.3 Implementation

It needs to be pointed out that even though the used wake modelling software FarmFlow is considered as very accurate in predicting the power productions of individual wind turbines in a wind farm, the presented results remain theoretical and the practical benefit might turn out to be lower than predicted. Factors that influence the uncertainty in the presented results are:

- Time varying effects, such as meandering, are not modelled. Still, many validation studies have been performed with FarmFlow showing excellent capabilities for predicting the measured 10 minute average power productions in a wind farm.

- The Active Wake Control settings, optimized in this project, depend on the wind direction and (to a lesser extend) to the wind speed, both of which continuously change in practice. The AWC settings, especially the yaw angle control, cannot be modified as fast as the wind changes: the wind speed and direction will be low-pass filtered, and relay logic will need to be applied to the wind before determining the pitch and yaw setpoints. This will have a “smoothing” effect on the final power production gain, which is expected to deviate by less than 20% from the calculated here theoretical power gain.

Finally, it should be noted that Heat & Flux and Controlling Wind can be combined wind direction wise, i.e. by applying for each wind direction the strategy that gives the highest gain. This combination becomes interesting mostly for farms with layouts containing well defined rows of wind turbines. In that case, when the wind direction is in line with (several) rows of wind turbines, Heat & Flux usually produces higher benefit in terms of power production than Controlling Wind, but this benefit is high in a very narrow sector of wind speed around the one aligned with the rows (typically ±2 degrees). Outside of this sector, Controlling Wind achieves a higher power production benefit, and is also beneficial in a much broader sector of wind directions. For wind farms with symmetrical (grid-like) layouts, combining Heat & Flux and Controlling Wind achieves almost the sum of the power production benefits of the two strategies. However, for wind farms with very scattered layouts with no well-defined rows of turbines, combining Heat & Flux and Controlling Wind boils down to taking the higher production gain for each wind direction (i.e. only one of the concepts is operational for each wind direction, but not both).
A

Comparison of the V80 and ART5 wind turbine models

Due to the lack of turbine details (rotor characteristics) for the V80, it was decided to a generic reference wind turbine model for the Active Wake Control study, in combination with upscaling of the wind farm. In this appendix, the characteristics of the Aerodynamic Reference wind Turbine (ART5) selected for the study are shown and compared to the V80 turbine as used in Prinses Amalia.

Table 7 shows the main properties of the two designs, and a down scaled ART based on rotor diameter.

Table 7: Comparison of turbine properties

<table>
<thead>
<tr>
<th>prop</th>
<th>turb</th>
<th>V80</th>
<th>ART5</th>
<th>ART DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>rotor diameter [m]</td>
<td>80</td>
<td>128.4</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>rated power [MW]</td>
<td>2.0</td>
<td>5.0</td>
<td>1.94</td>
<td></td>
</tr>
<tr>
<td>rated speed [rpm]</td>
<td>18.1</td>
<td>12.1</td>
<td>19.4</td>
<td></td>
</tr>
</tbody>
</table>

Figure 35 shows the power curve of both machines, when the ART is scaled down (for power with rotor area \( \frac{2}{3} D^2 \)). Note that for the V80, a ‘dynamic’ power curve is shown (as occurs during operation in turbulent wind), while for the ART a ‘theoretical’ power curve is shown. This explains the difference around the rated wind speed.
Figure 35: Comparison of wind turbine power curves.
Scaling of the Prinses Amalia US wind farm

In this appendix the scaling of the Prinses Amalia US wind farm is shown. The basis for the scaling is the rotor diameter, which shows to be representative for the turbine (see A). The wind turbine labeled T1 (in the NorthEastern corner of the wind farm) is selected as origin. Figure 36 show to resulting farm layout.

Figure 36: Scaling of the Prinses Amalia US wind farm.
C

Comparison of calculations and measurements

In this section, results obtained with FarmFlow for the Prinses Amalia wind farm are compared to measurements taken in the farm during six months of operation. The first section shows the layout of the wind farm and the wind characteristics (§C.1). Then, the results of the reference calculation are shown (§C.2). Section §C.3 concludes with comparison to the measurements.

C.1 The Prinses Amalia wind farm

The wind farm that served as a basis for this study is the Prinses Amalia offshore wind farm, located 23km NorthWest of Velsen, The Netherlands. The wind farm consists of 60 wind turbines of 2.0 MW and has a total output of 120 MW. The wind farm layout is given in Figure 37.

The wind speed distribution, the wind direction rose and turbulence intensity distribution for this site are calculated from measurement data of the nearby OWEZ meteorological mast, taken in the period Jul2005-Jun2006 ([7],[6]). During this period there was no influence on the measurements from the OWEZ wind farm yet. The resulting distributions can be found in figures 38, 39 and 40. Figure 38 provides the Weibull distribution fit. The corresponding Weibull distribution parameters are $A = 7.63$ and $k = 2.53$. The most dominant wind direction is SouthWest.

The wind turbine used in this wind farm is the Vestas 2MW V80 machine with the following characteristics:

- rated power: 2.0 MW
- rated rotor speed: 18.1 rpm
- rotor diameter: 80 m
- hub height: 59 m
Figure 37: Layout of the Prinses Amalia wind farm. The axes scales are given in number of rotor diameters (D). Encircled are turbines on which will be zoomed in.

The power curve of this machine has been provided by Eneco, and is shown in figure 35. Relation of thrust coefficient and wind speed, required for FarmFlow, was not available and had thus been derived from the generic (ART) design.

C.2 Reference case

This section shows the results of the reference FarmFlow calculation of the Prinses Amalia wind farm. The first part shows the setup and assumptions, followed by an overview of the results in the second part.

C.2.1 Layout and setup

The farm layout and external conditions are as described in Section C.1.

The wind speed range for which the turbines are active is 4-25m/s. The wind speed array that is investigated is set to 4-25m/s with 1 m/s increment to get a complete picture of the farm lifetime operation. The wind direction increment is set to 1 deg, to be able to zoom in on the farm effect with wind direction for small sectors.

C.2.2 Results

This section shows the results of the reference case.

The first set of polar plots are given for below rated condition \( V_w = 8 \text{ m/s} \):

1. wind speed (Figure 41)
Figure 38: Wind speed intensity distribution

Figure 39: Wind direction rose
Figure 40: Wind speed dependent turbulence intensity of the undisturbed wind flow

2. power (Figure 42)
3. turbulence intensity (Figure 43)

and for around rated condition ($V_{w} = 12 \text{ m/s}$):

1. wind speed (Figure 44)
2. power (Figure 45)
3. turbulence intensity (Figure 46)

The four lines in the figures are for four selected turbines in the farm (blue:T1, red:T34, magenta:T56, cyan:T57); see figure 37 for the location of these turbines. The first and last two are located on respectively the NorthEastern and Southern and Western outer side of the farm and the second on the inside (see layout in section C.1). The plots are in line with the expectations. Figure 43 shows the large farm influence on turbulence intensity; for the turbines in the more closely spaced rows, a turbulence intensity of above 20% is observed for wind direction aligned with the row!

Figure 47 shows the normalized (per unit) power curve of the complete farm, averaged over the wind direction distribution. Also shown is an upper bound: the theoretical power output when no farm effects would be present. Figure 48 shows the normalized (per unit) power curve of the complete farm, averaged over the wind speed distribution. Using the Weibull distribution from figure 38, the total energy production of the farm for a 20 year lifetime as calculated with FarmFlow is $8.83 \times 10^9 \text{ kWh}$. The wake losses amount to 12.7%.

Figures 49 and 50 show the farm effect below rated for a single row (the main diagonal from NorthWest to SouthEast, consisting of turbines T23-T31).
Figure 41: Azimuthal dependency of wind speed for selected turbines in the farm ($V_w = 8\text{m/s}$)

Figure 42: Azimuthal dependency of power output for selected turbines in the farm ($V_w = 8\text{m/s}$)
Figure 43: Azimuthal dependency of turbulence intensity for selected turbines in the farm ($V_w = 8\text{ m/s}$)

Figure 44: Azimuthal dependency of wind speed for selected turbines in the farm ($V_w = 12\text{ m/s}$)
Figure 45: Azimuthal dependency of power output for selected turbines in the farm ($V_w = 12\text{ m/s}$)

Figure 46: Azimuthal dependency of turbulence intensity for selected turbines in the farm ($V_w = 12\text{ m/s}$)
Figure 47: Normalized (per unit) power curve for the complete wind farm, including theoretical upper bound

Figure 48: Normalized (per unit) power distribution for the complete wind farm, including theoretical upper bound
Figure 49: Farm effect on wind speed and turbulence intensity in horizontal row for aligned wind direction ($V_w = 8 \text{m/s}, \alpha_w = 300^\circ$)

Figure 50: Farm effect on power and thrust in horizontal row for aligned wind direction ($V_w = 8 \text{m/s}, \alpha_w = 300^\circ$)
C.3 Comparison to measurements

This section compares the results obtained with FarmFlow calculations as described in §C.2 to measurements on this wind farm provided by Eneco.

The available measurements consist of six month of 10min SCADA for all wind turbines in the farm, including:

- nacelle wind speed
- nacelle wind direction
- nacelle direction
- generator power
- rotor speed
- pitch angle
- turbine state of operation

The data is collected during the winter period (Okt2013-Mar2014). Total number of data points (timestamp and turbines) is 1572480, of which 27844 are NaN (1.8%). These will be left out of the analysis.

The availability has been determined using the turbine state ([0, 1, 3] indicate availability). When different states occur during the time series, the state is rounded to determine the turbine state for that timestamp. This leads to availability of the wind farm of 96.5%.

The power produced during this period is 296GWh. This amounts to $12.3 \times 10^9$ kWh when extrapolated to 20 years lifetime and 100% availability. Obviously, this is slightly higher than estimated by FarmFlow, as the winter period usually has stronger winds than yearly average.

It is therefore more interesting to look at relative comparison, starting with the wake losses of the complete wind farm. The wake losses as calculated from the measurements are 11.1%. Note that due to lack of meteo data, a leading (front row) wind turbine has been used as input for the standalone operation. These wake losses calculated from measurements are somewhat lower than calculated by FarmFlow, which is most likely due to the assumed thrust coefficient (being slightly higher). The lower wake loss also contributes to the higher measured power production.

Now let’s zoom in on a single row of turbines. Again, only relative comparison will be performed, due to lacking inflow measurements. Figure 51 shows the normalized power production of a single row, for a wind direction sector of 227-247 degrees and wind speeds below rated between 7-9 m/s.
Figure S1: Farm effect on power production in row (T57-T11) for aligned wind direction \((V_w = 8\, \text{m/s},\ \alpha_w = 237^\circ)\)