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Wind farm design and active wake control

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Summary An overview is given of ECN's work on wind farm design and active wake control in the first round of activities in the EU/FP7 project ClusterDesign. Firstly, a validation is described of power predictions for the offshore wind farm Alpha Ventus as calculated with the wind farm wake model FarmFlow. In a benchmark of wake models FarmFlow is found to have the better ability to predict double, single and no-wake situations, in combination with a good balance between accuracy and run-time. Secondly, the potential benefits are described of wind farm management called Active Wake Control. In the offshore wind farm Nordsee Ost, which is designed for minimal wake losses in the governing wind climate, these benefits are found to be small and of the same order of magnitude as those of the other wind farm management option that is considered. Benefits of 4% extra energy and 3% less loads on the other hand are expected in a single line of turbines at main separation of 7.2D when a moderate to fresh breeze blows along the line. These power and load predictions are to be validated in real life in the second round of ClusterDesign activities.

1 Introduction

Wind farm design traditionally was just aimed at maximizing the output of a wind farm as a whole and took into account the internal wakes in a wind farm only. Gradually came the view that a wind farm is a system where the control loop is closed through the turbine wakes, and that the interaction between energy production and turbine wear must be taken into account as well. ECN has been working on this since the late nineties and has developed dedicated software and control solutions. Specifically ECN developed the wind farm wake model FarmFlow [1, 2], and the patented Active Wake Control concept [3, 4]. The FarmFlow model has been employed in commercial wind resource assessment for several years and has some good selling points. The concept of Active Wake Control was proven in wind tunnel test and was demonstrated numerically on a variety of wind farms.

In the EU/FP7 project ClusterDesign wind farm wake modeling and active wake control come together for the first time in a large offshore wind farm. Obviously, a proper understanding of wake propagation is essential when calculating the potential benefits of active wake control. To this end, in the first round of activities (2012-2013), ECN improved and advanced FarmFlow into an accurate wind farm wake model with a good balance between accuracy and run-time. Subsequently, ECN employed FarmFlow to feed the consortium partner Senvion's turbine mechanical load model with data, and together with Senvion validated the power and load predictions for a small offshore wind farm in the North Sea [5, 6, 7]. Also in that round of activities ECN used FarmFlow to calculate energy productions and fatigue loads for three modes of operation of a large offshore wind farm in the North Sea developed by the consortium partner RWE Innogy. These predictions are to be validated in the second round of activities (2014-2015) [8].

This paper gives an overview of the first round of activities of ECN in the project ClusterDesign, in particular the current status of FarmFlow and the potential benefits of Active Wake Control. The paper starts with descriptions of the FarmFlow model (in section 2.1) and the Active Wake Control concept (section 2.2). Next follow presentations of the performance of FarmFlow (section 3.1) and the potential benefits of Active Wake Control (section 3.2). The paper ends with a summary and conclusion.

2 Methodology

2.1 Wake modelling

The wind farm wake model FarmFlow uses a parabolized Navier-Stokes solver for the mean flow in combination with a kε sub-model for the turbulence, based on the UPMWAKE model [9, 10]. It employs a vortex-wake sub-model for the turbine near wakes [1, 2, 11], and profiles of the wind speed and the air temperature that are valid up to the heights where the multi-megawatt wind turbines operate [1, 2, 12, 13, 14, 15].

The computational domain of the ECNWake model in FarmFlow has the dimension of a rectangular box of 6.5 rotor diameters *D* in width and height, and a variable length. It contains a minimum of 96 equidistant grid cells in width and height directions both, and a minimum of 112 grid cells along the length. The grid in length-wise is stretched to resolve near wake effects. As a result, the rotor diameter has the dimension of 15 grid cells, and the rotor area is covered by approximately 175 grid cells. The step size in flow direction begins with 0.005*D* at the rotor area, and increases exponentially. After a distance of 20*D*, the maximum step size of 1*D* is reached.

The dimensions of the computational domain are a compromise between acceptable calculation effort and necessary grid size for accurate results. Test calculations with grid refinement have shown that at least 13 nodes on the rotor diameter are necessary for accurate results. Other test calculations have shown that dimensions of at least 6 rotor diameters are necessary for accurate results when arrays with more than 20 turbines are modelled.

2.2 Active wake control

Active Wake Control is a patented wind farm management solution aimed at a reduction of the cost of wind energy by acting on two cost components [3, 4]: the operational costs of wind turbines over time and the output of the wind farm as a whole. Specifically, Active Wake Control aims at reducing the O&M costs of the wind turbines by reducing the mechanical loads and increasing the overall energy production.

Active Wake Control aims at mitigating the negative effects of wind turbine wakes by leaving more energy in and/or diverting the wakes of upstream wind turbines. There are three modes: control by pitch operation, by yaw operation, and by a combination of both. In control by pitch, formerly known as Heat & Flux, the upstream wind turbine is operated at a sub-optimal axial induction so that the wind speed deficit in its wake is reduced [3]. This mode is typically realized by changing the blade pitch angle of the upstream wind turbine. In control by yaw, formerly known as Controlling Wind, the wake is diverted from the downwind turbine by yawing the upstream turbine [4].

For the offshore wind farm Nordsee Ost Active Wake Control by pitch operation is considered.

3 Results

3.1 Accurate prediction of wake losses

The wind farm wake model FarmFlow predicts wake losses in a wind farm in an accurate way. This is the outcome of an extensive benchmark of state-of-the art and commercially available wake models [6], in combination with a comparison with measured data on the basis of specially designed performance indicators and associated tests [5].

The test case is the wind farm Alpha Ventus, which is located at around 45 km to the north of the island Borkum. It consists of 12 turbines of the 5 MW class and a met mast, see figure 1. The six turbines in the north are REpower 5M with a hub height of 92 m and a rotor diameter of 126 m. The six turbines in the south are AREVA Multibrid M5000. In the west, the predominant wind direction, there is the highly equipped met mast FINO1.

In this paper the performance of FarmFlow is shown on the basis of one of the three performance indicators and associated tests:

$$-1 \le \frac{\Delta_{pow}}{E_{pow}} \le +1 \;;$$

the prediction error should not be greater than the experimental error. Here the prediction error Δ_{pow} is defined by

$$\Delta_{pow} \equiv m_{pow} - P_{pred} \; ,$$

where m_{pow} is the mean value of the power observations and P_{pred} is the power predicted by a wind farm wake model. The experimental error E_{pow} is given by

$$E_{pow} = f_{N_{pow}} \frac{s_{pow}}{\sqrt{N_{pow}}} \, ,$$

where f_{Npow} is Student's t-factor for the N_{pow} observations in the sector and, in this case, a probability of 97.5% [5]. (The Student t-factor is a parameter used to test the hypothesis that a random sample of normally distributed observations has a given mean.) The other quantities s_{pow} and N_{pow} are the standard deviation and the number of observations of the turbine power in a given wind speed bin or wind direction sector.

Figure 2 shows the ratio of the prediction error and the experimental error for turbine AV6 in double, single and no-wake situations. FarmFlow clearly is the better of the considered models because the prediction errors remain the closer to zero and exceed one the lesser. On the other hand there are some flaws: the double wake situation and the single wake situation with the upstream turbine at greater distance are harder to predict.

3.2 Reduction of wake losses

The potential of Active Wake Control by pitch operation is calculated for the wind farm Nordsee Ost (figure 3). This is an already designed but yet to be built large offshore wind farm in the North Sea located 35 km to the north west of the island of Heligoland. It consists of 48 REpower 6M wind turbines, 5 of which are equipped for mechanical load measurements. All turbines deliver standard data from their SCADA. In addition there is a met mast in the south west corner of the wind farm, which delivers the ambient conditions.

The Active Wake Control calculations are made for the following conditions and assumptions:

- The wind climate originates from 5 years of measurements at the nearby Amrumbank West met mast.
- Wind speeds between cut-in and rated are considered.
- Turbulence intensity depends on the wind speed.
- Only those turbines are considered which are within 10D distance from upwind turbines.
- The load optimization procedure minimizes the damage equivalent load of the thrust.
- A dedicated cost function is applied.

Three modes of operation are considered: normal operation, power maximizing, and load minimizing.

As referenced to the energy loss under normal operation, in the power maximizing mode 0.25% extra energy is achievable in the whole wind farm given the governing wind climate. For the line of 7 turbines with 7.2D main spacing (solid markers in figure 3), 4% extra energy can be achieved under ideal conditions: moderate to fresh breeze, blowing parallel to the row of turbines.

In the load minimizing mode up to 1% less fatigue loads can be achieved in the whole wind farm without compromising the yield. For the line of turbines the load reduction is 4% in combination with 3% extra energy under the ideal conditions.

In the power maximizing mode the benefit in the prevailing wind climate is of the same order as what can be obtained by minimizing electrical losses, the other wind farm management option considered in ClusterDesign. Obviously, there is little to win in a wind farm which is designed for minimal wake losses in the governing wind climate.

The figure 4 shows how power, thrust and damage equivalent load of thrust are redistributed in the line with 7 turbines at main separation of 7.2D, when the thrust is maximum and the wind blows along the row, resulting in maximum power and minimal loads. The figures show that the upwind turbine in the line produces less power and is subject to less thrust, while the other turbines all have increased power and loads. This adds up to the net extra production and load and fatigue reduction.

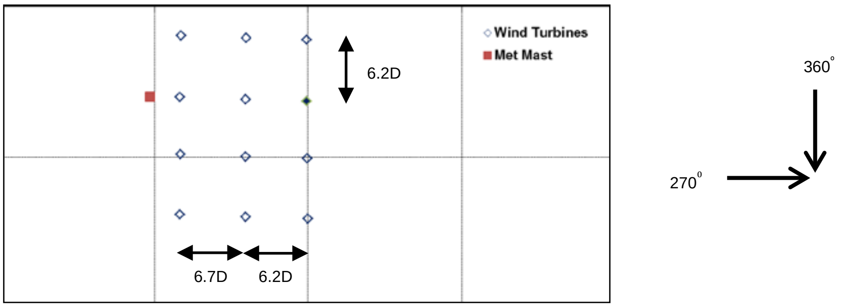

Figure 1. Positions of the wind turbines and the met mast in Alpha Ventus. A solid marker indicates the wind turbine AV6 which is discussed in the text. Distances are expressed in rotor diameters; a square measures 2x2 km^2

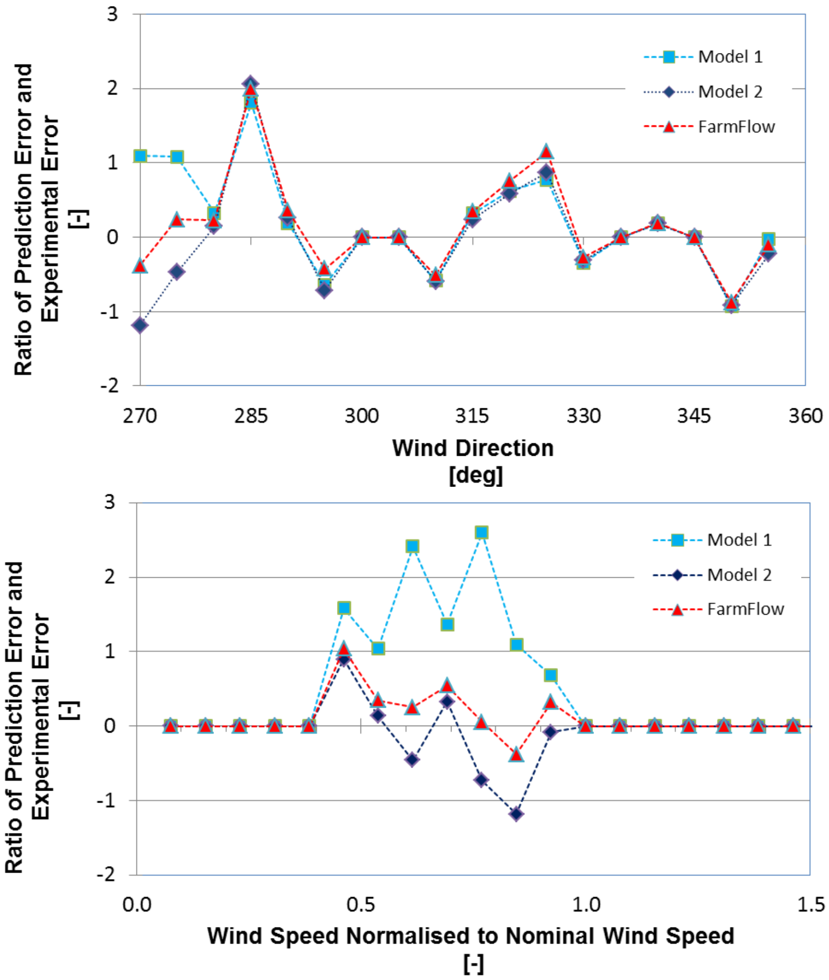

Figure 2. The ratio of the prediction error and the experimental error as a function of the wind direction if the wind speed is 85% of the nominal wind speed (top) and the wind speed if the wind direction is 270 deg (double wake, bottom); wind turbine AV6. The closer to zero the better the prediction

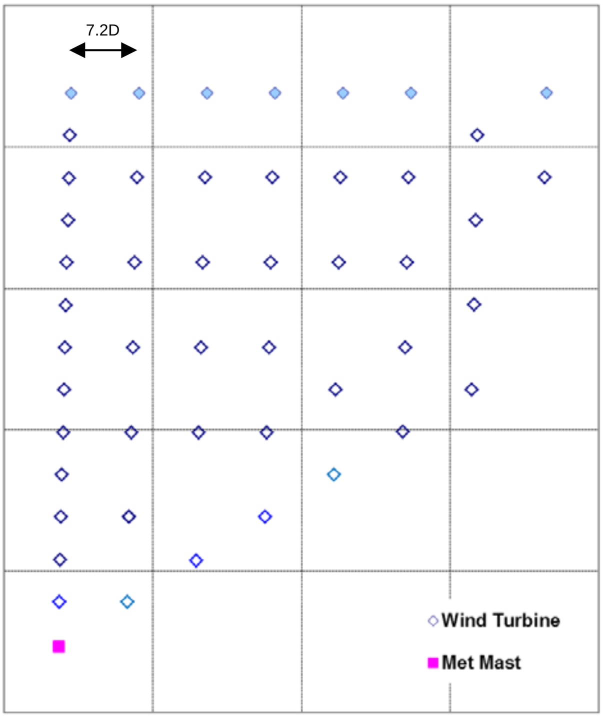

Figure 3. Positions of the wind turbines and the met mast in Nordsee Ost. Solid markers indicate the wind turbines in the line discussed in the text. Distances are expressed in rotor diameters; a square measures 2x2 km^2

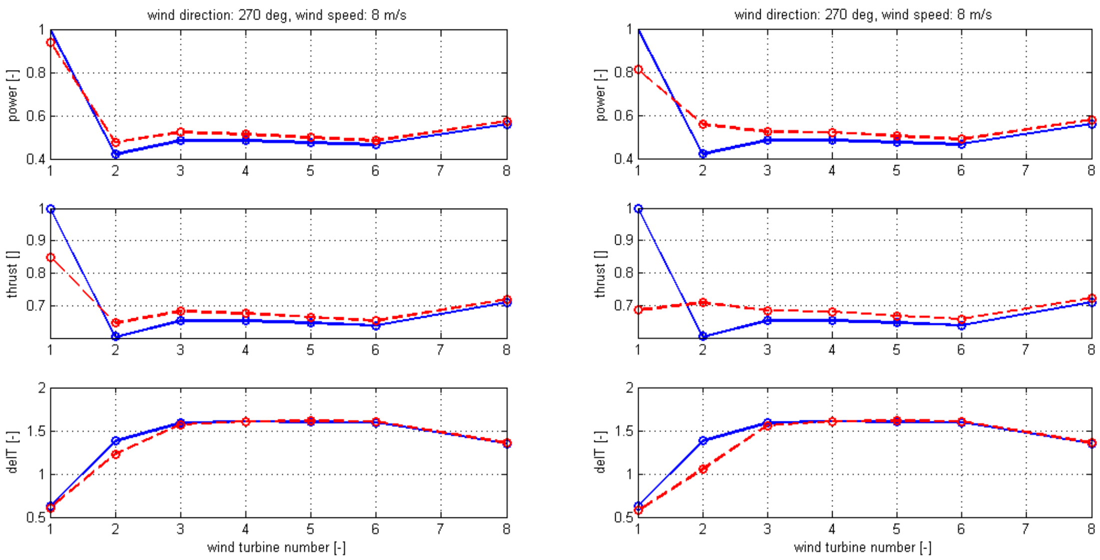

Figure 4. Redistribution of power (top), thrust (centre) and damage equivalent load of thrust (bottom) in a row with 7 turbines at main separation of 7.2D, when the thrust is maximum and the wind blows along the row, resulting in maximum power and minimal loads. Blue solid line: Normal operation; Red dashed line: Optimized operation

4 Summary and conclusion

In this paper an overview is given of ECN's work on wind farm design and active wake control in the first round of activities in the EU/FP7 project ClusterDesign.

Firstly, the paper describes a validation of power predictions for the offshore wind farm Alpha Ventus as calculated with the wind farm wake model FarmFlow. In a bench mark of wake models FarmFlow is found to have the better ability to predict double, single and no-wake situations, in combination with a good balance between accuracy and run-time.

Secondly, the paper describes the potential benefit of Active Wake Control by pitch operation on the power production of and the mechanical loads in the offshore wind farm Nordsee Ost. The benefits of this form of wind farm management are found to be small, and are of the same order of magnitude as those of the other wind farm management option that is considered. This is because there is little to win in a wind farm that was designed for minimal wake losses given the governing wind climate. Benefits of 4% extra energy and 3% less loads on the other hand are expected in a single line of turbines at main separation of 7.2D when a moderate to fresh breeze blows along the line. These power and load predictions are to be validated in real life in the second round of ClusterDesign activities.

Acknowledgements

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Industry Needs

Reduction of the Cost of Wind Energy

User Story

To give accurate projections of the energy production and the fatigue-life consumption, the designer of a wind farm must take into account wake losses.

User Story

To take the maximum out of a wind farm, the operator needs to find a balance between energy production and fatigue-life consumption of a wind farm.

Options to increase yield by wind farm control can be interesting.

Our Solutions

Accurate Wake Modelling

Active Wake Control

Wake and Load Models interface with Control Strategy

Selling Points

High accuracy with acceptable run-time.

Proven track record.

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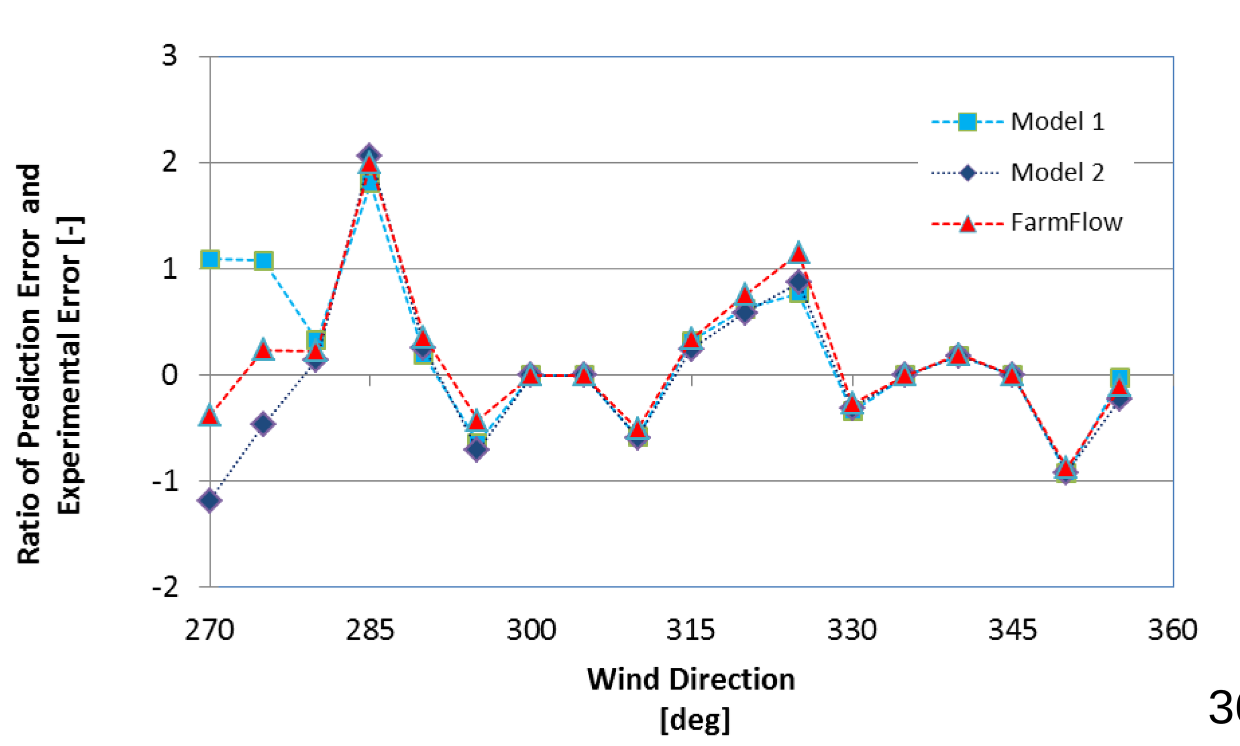
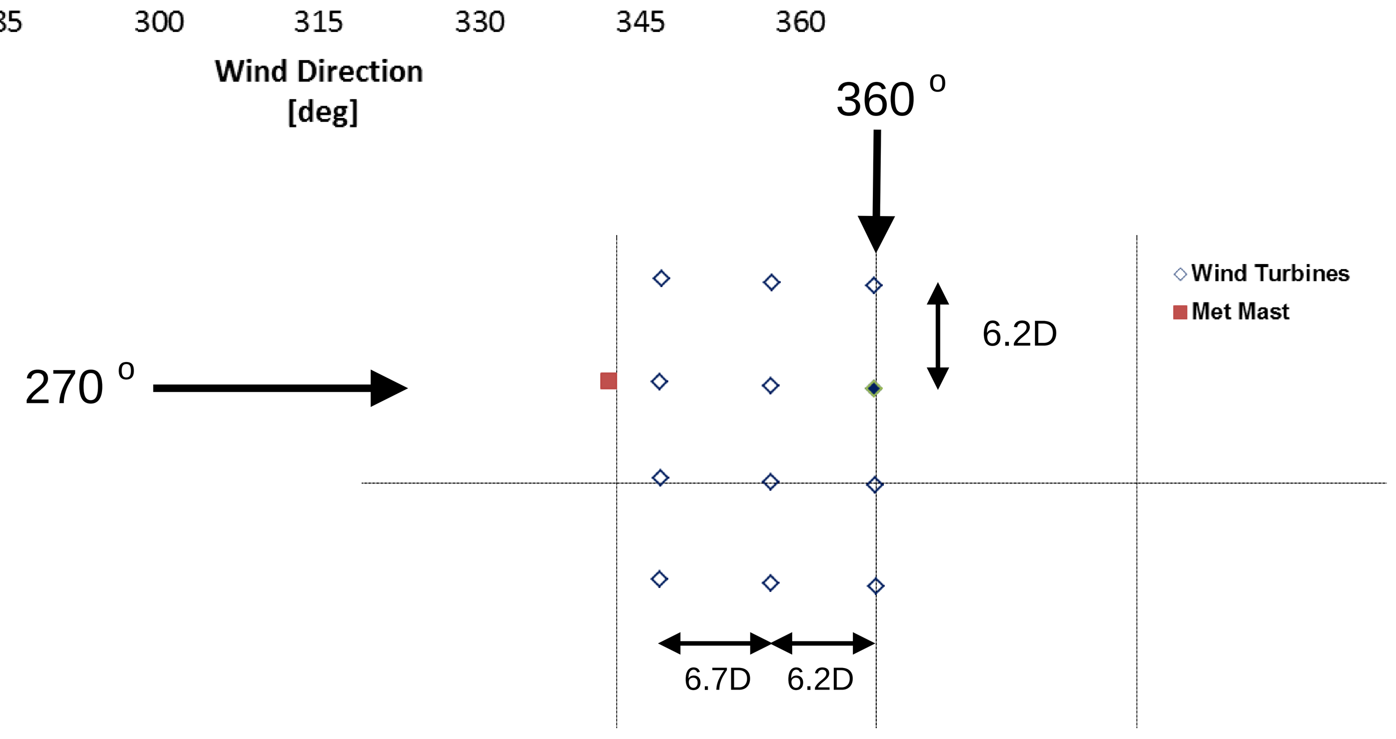
Selling Point

Extra energy.

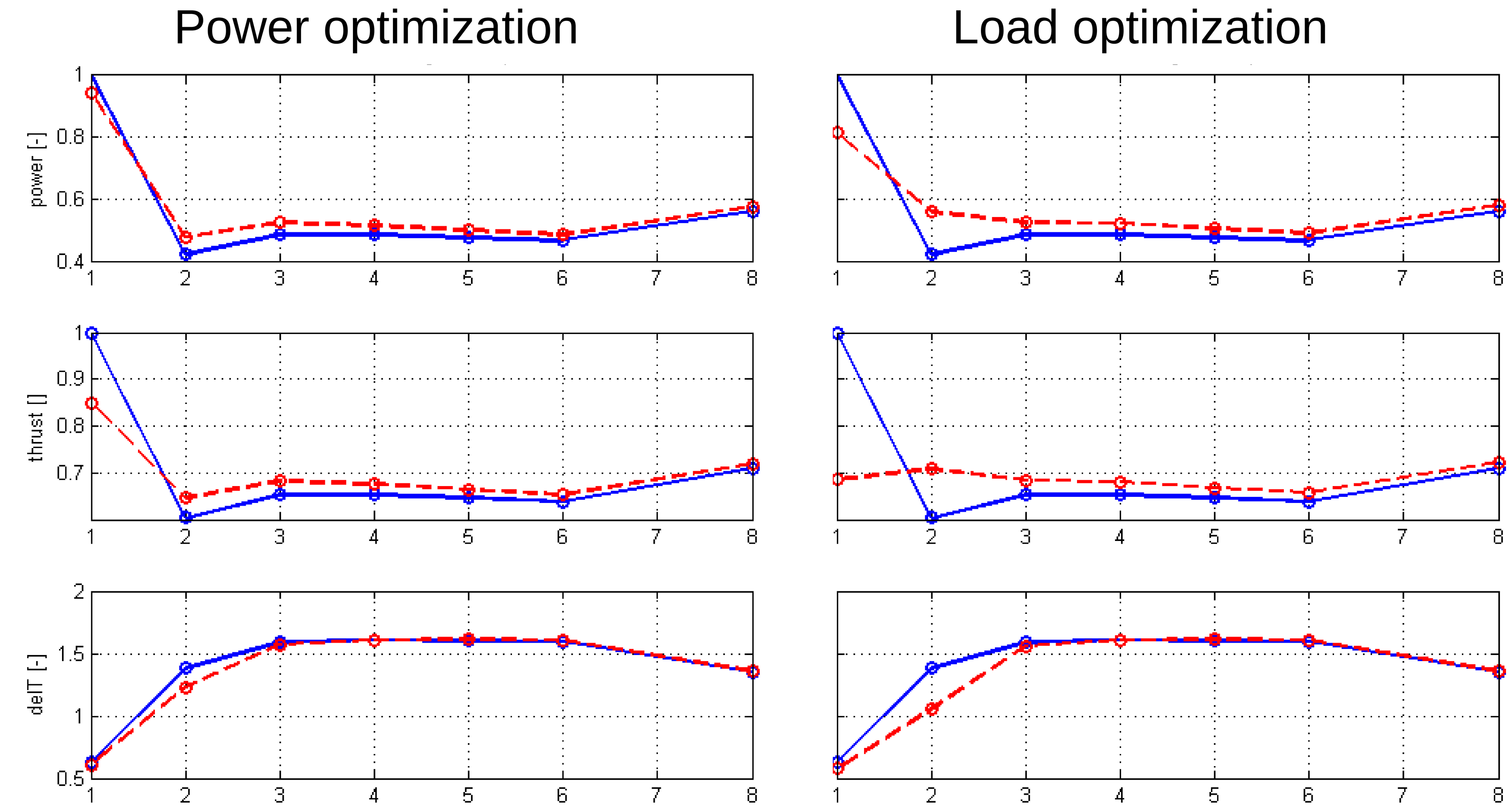
As referenced to the energy loss under normal operation, 4% in a single row 7.2D main spacing and 0.25% in the whole farm is achievable in a yet to be build offshore wind farm.

ECN Wake Modeling
can accurately predict power in double, single and no wake situations.
The ECN software was assessed to perform best in the ClusterDesign benchmark performed by Senvion.
In the example the closer to zero means the better the prediction.





Wind shadowing can be mitigated by employing
ECN Active Wake Control.
The examples show how power, thrust and damage equivalent load of thrust are redistributed in a row with 7 turbines at main separation of 7.2D, when the thrust is maximum and the wind blows along the row, resulting in maximum power and minimal loads.
Blue solid line: Normal operation
Red dashed line: Optimized operation



Acknowledgements

ClusterDesign

SEVENTH FRAMEWORK PROGRAMME

FP7-ENERGY-2011 283145 / ClusterDesign

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www.cluster-design.eu
Deliverable 1.4: Coupled wind farm wake and wind turbine wake models
Deliverable 1.5: Results of benchmarking test
Deliverable 3.4: Analytical validation report – loads and performance
Deliverable 6.1: Validation report