Controlling Wind in ECN's Scaled Wind Farm

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This paper has been presented at the EWEA 2012,
Copenhagen, Denmark, 16-19 April 2012

ECN-M--12-007 APRIL 2012

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Abstract

ECN holds a patent called 'Controlling Wind' aiming at misaligning the upwind turbine in a row such that leeward turbines experience a higher wind and hence an increased power production. This concept was tested in ECN's scaled wind farm; to our knowledge for the first time on such a scale and in field conditions.

The farm consists of 10 turbines divided over the park in three lines of 2, 3 and 4 turbines and one single turbine. Furthermore, meteorological masts are scattered throughout the farm. The layout of the farm makes it possible to simultaneously measure free wind conditions, single and/or multiple wake conditions at various spacing.

Generally, it is concluded that, for the moment, no clear overall 'Controlling Wind' effect is seen. There is too much scatter in the data and the results are very sensitive to specific data selections. Nevertheless, the most promising 'Controlling Wind' effect is observed for low wind speed at a yaw misalignment of 4˚ and 8˚.

It was found that the wake skew angle is larger than the yaw misalignment, where the relation between the two is determined to be 1.37 for all wind speeds and 1.33 for wind speeds between 3-5 m/s and 5-7 m/s. These values seemingly are a bit higher than values in the literature.

A clear decrease in wind speed and increase in turbulence intensity is seen along the turbine row. No pattern can be seen in the wind speed and turbulence intensity as the result of the increase in yaw misalignment of the upwind turbine.

Keywords: Controlling Wind, ECN Scaled Wind Farm, Farm control, Increased power production, Yawed turbine, Yaw misalignment, Wake skew angle, Wake deflection

1 Introduction

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

ECN holds a patent for a method of farm control called "Controlling Wind" (CW) [1] that aims among others at decreasing the losses in the wake. "Controlling Wind" is applied when the wind is blowing from the appropriate direction, i.e. along a turbine row. In that case the windward turbine (or turbines) is deliberately yawed at a certain angle with the wind direction, i.e. it is misaligned, leading to a decrease in energy yield. Also, as a result a lateral force will be exerted on the flow and the wake will be diverted away. Therefore, the leeward turbines will be exposed to a flow with a higher energy content compared to normal yaw control conditions of the windward turbines. The idea is that the increased energy production of the leeward turbines overcompensate the energy loss of the first turbine leading to an overall increased energy production by means of the CW principle.

To a certain extent the CW principle has been tested before by means of models and in wind tunnels. With respect to the former CW was implemented in FarmFlow [2] based on the work of [3] simulating the ECN test field EWTW. This test field consists of 5 2.5MW turbines in a row with a turbine spacing of 3.8 rotor diameters (D)

[4]. It showed that an energy production gain of 1-1.5% is achieved [5,6].

We also mention the wind tunnel measurements of Dahlberg et al [7] and Adaramola et al [8], where the former consider a turbine with a rotor diameter of 250mm and the latter a rotor diameter of 900mm. Both indicate improved performance in power under certain (yawed) circumstances.

To our knowledge the present study assesses the CW principle for the first time in field conditions and with relatively large rotors.

2 Test conditions

The CW concept is investigated in ECN's scaled wind farm. It consists of relatively small wind turbines together with many measurement masts that measure the wind conditions in the wind farm and above. The scale of this wind farm is not too small to alleviate the dominant scaling effects and the scale is not too large to permit the building of sufficient meteorological masts. The scaled wind farm has been erected in March 2008 and is located on ECN's test field EWTW in between locations for prototype turbines. The test field and its surroundings are characterised as flat terrain near the lake "IJsselmeer".

The farm consists of 10 Aircon 10P turbines divided over the park in three lines of 2, 3 and 4 turbines and one single turbine. The 3-bladed turbines have a diameter of 7.6 m and a hub height of 7.5 m with variable speed and pitch control. Distances between turbines that are interesting for studying wake effects vary from 3.7 to 12 rotor diameters, where the distances between the turbines in a row is 3.7D. 15 Small and large meteorological masts are placed within and around the farm which measure the wind velocity field from 3.6m to 18.9m height. In total 146 wind signals including many 3-dim sonic anemometer signals are measuring up to one diameter above the rotor.

A layout of the farm is given in figure 1. All sonic anemometers indicated in the figure measure the wind at hub height. The sonic anemometers 10, 11 and 12 are placed behind turbines 6, 7 and 8 with a distance of 1.8D and the sonic anemometers 9 and 13 are at a distance of 4.1D from turbine 6. The instrumentation of the scaled wind farm is extensively described in [9].

The layout of the farm (turbines and meteorological masts) makes it possible to simultaneously measure free wind conditions, single and/or multiple wake conditions at various spacing as well as wind conditions above the park. We stress that this is a very unique situation. Because of the possibility for simultaneous comparison of a turbine row with CW control with standard (non-yawed) control the scaled farm is very suitable for investigations into the effects of wake diversion.

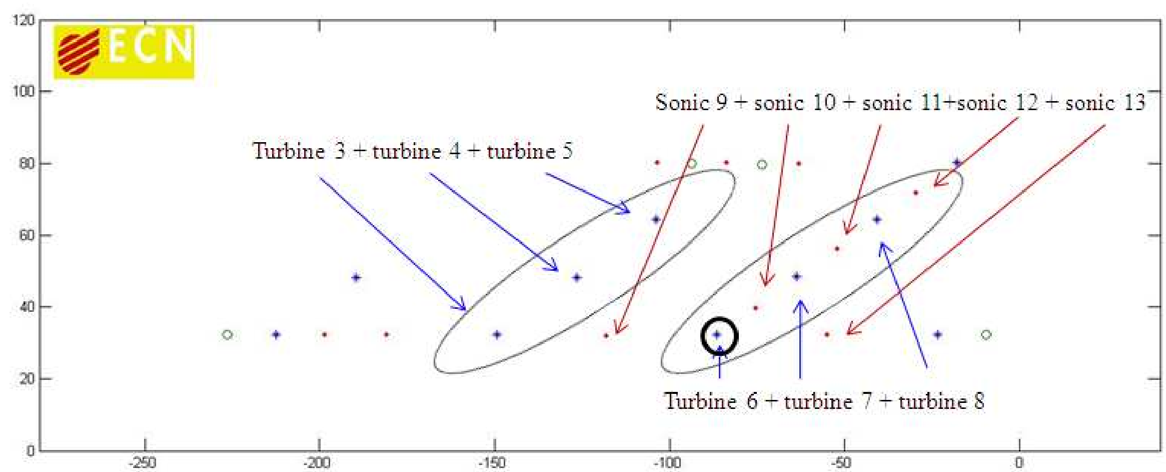

Figure 1: Layout of the scaled wind farm. Turbines 3, 4 and 5 form the reference row (Row 1) and turbines 6, 7 and 8 the CW row (Row 2). Turbine 6 is misaligned.

The CW concept was investigated in two rows of three turbines (turbines 3, 4, 5 and turbines 6, 7, 8). If the expected wind direction is in line with the turbine row the yaw orientation of all turbines is fixed at that orientation (235°) apart from turbine 6 which is set at 235°, 239°, 241°, 247° or 251° according to a predefined sequence. We note that the misalignment is in clockwise direction. In this way the performance of a row with an oblique first rotor can be compared with a row with all rotors facing the wind.

The measured data are stored in a database automatically. From the stored data 10 second statistical data are calculated for analysis. This averaging time is a compromise between a high number of data points required for small deviations in the results and sufficient correlation between the wind and performance variations. 10 seconds is somewhat longer than the travelling time of the wind from the first to the third turbine at 7.3D spacing: 7 seconds at 8 m/s wind speed.

Considering only the CW experiment data, i.e. specific turbine yaw settings and wind directions parallel to the wind turbine rows, a total of 18016 data points are gathered. However, additional selections as optimal turbine performance and valid wind data reduce this number to about 170 data points per yaw angle of turbine 6. For comparison, when 10 minute statistical data are considered this comes down to about 3 data points.

3 Results and Discussion

3.1 Yaw misalignment and Wake skew angle

Important aspect of the CW concept is that the wake skew angle X is larger than the yaw misalignment γ. Here, the wake skew angle is defined to be the angle between the centre of the wake and the normal of the rotor plane and the yaw misalignment is the angle between the wind direction and the yaw angle; see figure 2. A qualitative argument is already given in the introduction, namely a lateral force will be exerted on the flow diverting the wake away. Equivalently, one could argue that the rotor only extracts energy from the normal component of the incoming wind and that the parallel component causes the wake to divert. Consistent to this the skew angle is often expressed as (see [10])

$$\tan(X) = U \sin(\gamma) / (U \cos(\gamma) - u), \qquad (1)$$

where U is the upwind wind speed and u the axial induced velocity.

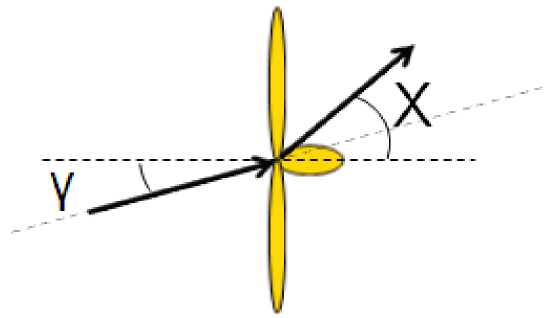

Figure 2: Yaw misalignment and wake skew angle. The arrows indicate the wind and wake directions.

A theoretical relation between the yaw misalignment and the wake skew angle is given by the Vortex cylinder model exposed in [11] based on [12]

$$X = (0.6a + 1)\,\gamma, \qquad (2)$$

[1] where a is the induction factor, and from free wake calculations and wind tunnel measurements the author of [13] finds a relation including the thrust coefficient

$$X = (0.3C_T + 1)\,\gamma. \qquad (3)$$

It must be noted that the MEXICO measurements as analysed in [13] clearly indicate a varying skew angle in the wake, but the angle from [13] can be considered as an average value. In light of the C_T inclusion we also mention the work of [14], where an LES model is compared to an analytical model. Furthermore, a relation has been obtained [5] from measurements from KTH [3]

$$X = 1.222\,\gamma. \qquad (4)$$

Now, the thrust coefficient can be related to the induction factor via momentum theory $C_T = 4a(1-a)$ and by using the optimum induction factor a = 1/3, the above equations correspond to the following

[1] Actually (2) is a linear approximation of a more general formula (see [11]), similar to (1).

$$(1) \Rightarrow \quad X = 1.2\,\gamma\,,$$
$$(2) \Rightarrow \quad X = 1.27\,\gamma\,, \qquad (5)$$
$$(3) \Rightarrow \quad X = 1.222\,\gamma\,.$$

In this work a relation between the wake skew angle and the yaw misalignment is obtained as well. To this end additional data have been gathered where the yaw angle of turbine 6 is, again, fixed at the earlier mentioned yaw angles, but the inflow wind direction is not fixed. The wind speed deficit in the wake of this fixed yaw turbine is measured as function of the inflow wind direction, where the inflow wind conditions (wind speed and direction) are characterized by the mean of the readings from sonic anemometers 9 and 13 (see figure 1). The wind speed in the wake of turbine 6 is measured with sonic anemometer 10. These wake profiles are fitted with a 4^{th} order polynomial in order to determine the minima, representing the centre of the wakes. The fits and the minima are exposed in the left plot of figure 3 for all wind speeds. From the wind directions at which the minima are found the yaw misalignment is determined and the wake skew angle is given by means of the turbine yaw angle and the orientation of the meteorological mast with respect to the turbine. The yaw misalignments and the wake skew angles are plotted and fitted, assuming a linear relation, in the right plot of figure 3. The same procedure as described above has also been applied for wind speeds of 4 ± 1 m/s and 8 ± 1 m/s.

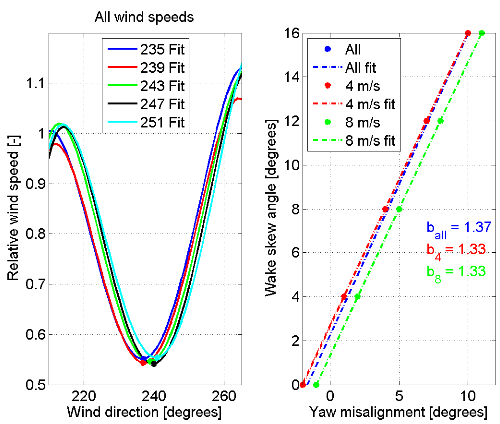

Figure 3: Wind speed deficit in the wake of the turbine as function of the inflow wind direction for different fixed yaw angles (left plot). Wake skew angle as function of yaw misalignment for all wind speeds, 4 m/s and 8 m/s (right plot).

From figure 3 it is concluded that, ignoring the offsets, the wake skew angle linearly depends on the yaw misalignment with a coefficient of b = 1.37 for all wind speeds and b = 1.33 for wind speeds of 3-5 m/s and 7-9 m/s. These results confirm that the wake skew angle is indeed larger than the yaw misalignment but are a bit higher than the values given in (5). The difference may be explained by the uncertainties in the applied analysis of finding the minima and on the other hand by the assumptions made in models (Vortex cylinder model and momentum theory). Furthermore, the (skew angle of the) wake of a turbine may depend on the number of blades, the blade geometry and the tip speed ratio [15]. In this light we note that the turbines in the ECN's scaled wind farm as well as the MEXICO rotor of [13] have 3 blades and that the turbine of [3] has 2 blades. In order to improve the comparison the induction factor should be known in the experiments. Unfortunately, this is at present not the case.

3.2 Turbine performance

The performance of the individual turbines has been examined in order to determine to what extend the turbines behave the same. This is to confirm that differences between the turbine rows should be attributed to CW operation and not to differences in turbine behaviour. To this end we note that the rotational speed (with respect to the free wind speed) compares for all turbines quite well. The rotational speed of turbine 7 is a bit higher and the rotational speed of turbine 8 is a bit lower than the rest, but the differences are considered to be acceptably small.

For the power of the turbines (again, with respect to the free wind speed) something similar is seen: all turbines compare quite well, only the power of turbine 7 is somewhat larger. This is corrected for by subtracting throughout the analysis 300W from the power of turbine 7.

It is promising to see that only with this small correction the turbines look sufficiently similar to enable the search for qualitative CW effects, as only relative changes in the performance of both rows need to be identified. This is also reflected in the comparison of the two rows as depicted in figure 4. Here, the CW data have been used and especially the data where all turbines have the same yaw angle, namely 235 degrees. The mean power and standard deviation of the mean is indicated for each turbine in the row. This is also done for the relative mean power.

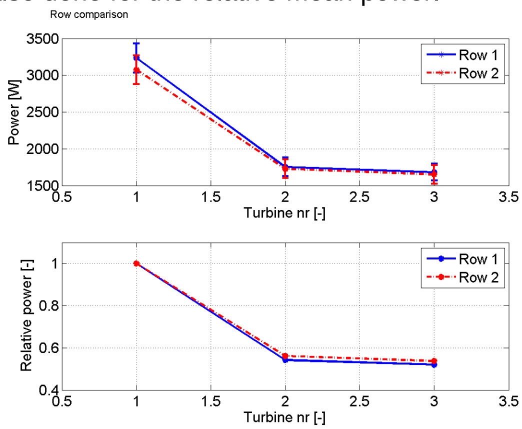

Figure 4: Absolute power (upper plot) and relative power (lower plot) row comparison. The turbine position indicates the position in the row: position 1 is for turbine 3 (Row 1, reference) and turbine 6 (Row 2, CW), etc.

Nevertheless, it is noticed that all results are very sensitive to specific data selections. This also applies for following discussions of analyses.

3.3 Controlling Wind

The CW concept was studied for all wind speeds exerted on the two rows and for specific wind speed selections. Generally, it is concluded that, for the moment, no clear overall CW effect is seen. There is too much scatter in the data and, therefore, more data are required [6].

Although the overall CW effect could not clearly be demonstrated some interesting effects are seen. In figure 5 the power coefficient of each turbine is considered. Here, it is defined as

$$C_p = P / (1/2 * \rho * \pi * (D/2)^2 * U^3), \qquad (6)$$

where P is the power of the turbine, ρ the air density (here taken as 1.225 kg/m^3), D the rotor diameter (7.6m) and U the upwind wind speed at hub height as measured with sonic anemometer 9 (see figure 1). The power coefficient is in figure 5 chosen over the power of each turbine for better comparison of the different yaw conditions and to have a less wind speed dependence.

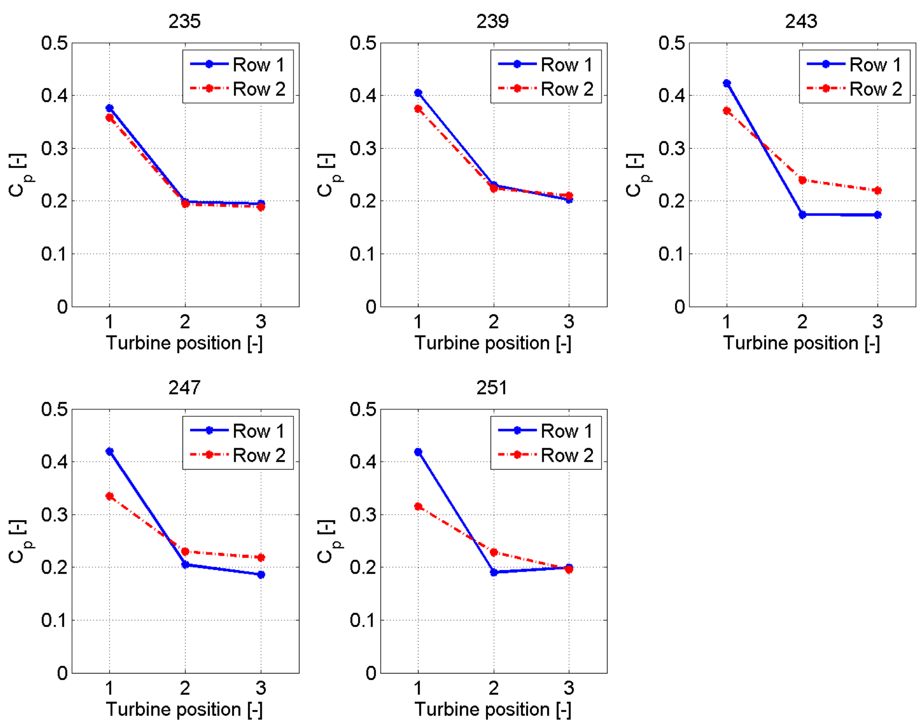

Figure 5: Cp factor for each turbine. The turbine position indicates the position in the row, where Row 1 is the reference row and Row 2 is the CW row. The yaw angle of turbine 6 is indicated in the title of the graphs.

From figure 5 it is seen that with respect to the reference row (Row 1) the C_p factor of the first turbine in the CW row (Row 2) decreases with increasing yaw angle of this turbine (turbine 6). Also, the C_p factors of the downwind turbines increase with increasing yaw angle with respect to the reference row.

The relative sum of power ($\Sigma_i P_i/(3 * P_3)$; i=3,4,5 and i=6,7,8) for both rows is presented in figure 6 for all wind speeds, for 4 m/s and for 8 m/s. Again, the wind speed is measured with the sonic anemometer 9 (see figure 1). It is noticed that the most promising CW effect is seen at low wind speeds. This relative sum of power is increased for the CW row (Row 2) with respect to the reference row (Row 1) for yaw angles of turbine 6 of 239˚ and 243˚ (corresponding to 4˚ and 8˚ misalignment). At higher wind speed this (seeming) effect is less pronounced or not even seen.

The fact that the most promising CW effect is observed for low wind speed may be due to the thrust coefficient C_T (also referred to as $C_{D,ax}$), which increases for increasing tip speed ratios and hence decreasing wind speed. An increasing C_T would according to (1) result in an increased wake skew angle through the increased axial induced velocity. However, a higher wake skew angle for low wind speed is not seen in our analysis as presented in figure 3.

Because of the large scatter in data it was decided to keep this analysis qualitative and not to quantify any observed possible improvement.

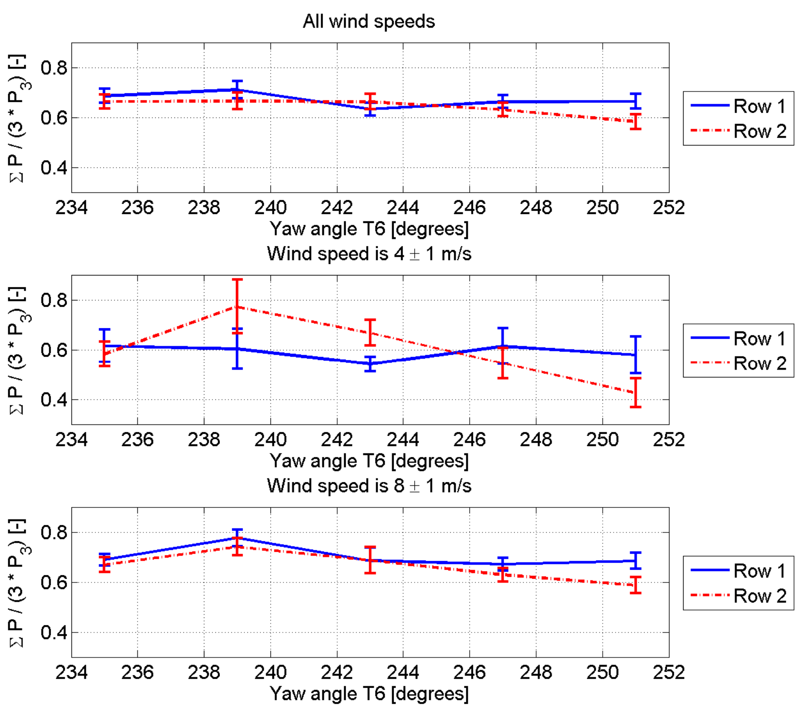

Figure 6: Relative sum of power including statistical uncertainty of both rows as function of the yaw angle of turbine 6 for all wind speeds (upper plot), for 4 m/s (middle plot) and for 8 m/s. Row 1 indicates the reference row and Row 2 is the CW row.

Besides the power of the turbines the extensive instrumentation of the scaled farm made it possible to investigate the wind speed and the turbulence intensity (TI) too, where the former is related to the yield of a turbine and the latter to the loads on a turbine. This could be done for the CW row, because only in this row meteorological mast between the turbines are present (see figure 1). The upwind wind speed and turbulence intensity is determined by averaging the measurements from sonic anemometer 9 and 13 (see figure 1); unfortunately, there are hardly measurements from sonic anemometer 11. In figure 7 the relative wind speed and the relative TI is given for various locations in the CW row.

A clear decrease in wind speed and increase in TI is seen along the row. The behaviour of the downwind wind speed and TI at different yaw angles of the upwind turbine is not explained and is in our view due to the large scatter in the data. To put it differently, no clear pattern can be distinguished in the wind speed and TI as the result of the increase in yaw angle of the upwind turbine.

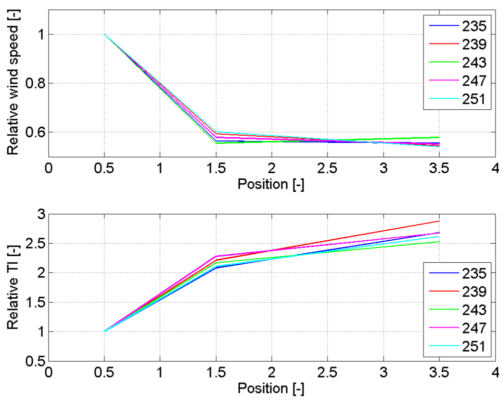

Figure 7: Relative wind speed (upper plot) and relative TI (lower) plot for the different positions in the row (position 0.5 indicates sonic 9-13, position 1.5 and 3.5 indicate sonic 10 and 12, respectively). The different yaw angles of turbine 6 are also indicated.

Although CW in the strict sense is tested in ECN's scaled wind farm, CW configurations might happen unintendently in full scale farms as well. For a period of over 6 years data have been gathered from 5 full scale research turbines (2.5MW) in a line and a meteorological mast at ECN's test field EWTW [4]. The raw data have been sampled to 2 minute statistics, which averaging time was expected to be a fair compromise between a high number of data points required for small deviations in the results and sufficient correlation between wind and performance variations. This time interval is somewhat longer than the travelling time of the wind (1.3 min) between three turbines at 3.8D spacing and 8 m/s wind velocity. Only three turbines were comprised in the analysis. This number was considered to be suited for the identification of CW effects. Unintended CW configurations are found and from the data it is concluded that the energy production in the test farm can be enhanced by enforcing a positive yaw angle of the first turbine in wind directions at small positive angles with the row and vice versa. The increase is larger at larger yaw angles [6].

4 Conclusions

Important aspect of the Controlling Wind principle is that the wake skew angle is larger than the yaw misalignment. It was found that this is indeed the case, where the relation between wake skew angle and the yaw misalignment is determined to be 1.37 for all wind speeds and 1.33 for wind speeds between 3-5 m/s and 5-7 m/s. These values seemingly are a bit higher than values found elsewhere, where the differences may be explained by the uncertainty in the analysis, the assumptions in the models and the differences in the rotor specifications. Therefore, in order to improve the comparison the induction factor should be known in the experiment.

It is promising to see that only with a small correction in the power of turbine 7, the turbines look sufficiently similar to enable the search for qualitative CW effects as only relative changes in the performance of both rows need to be identified.

Generally, it is concluded that, for the moment, no clear overall CW effect is seen. There is too much scatter in the data and the results are very sensitive to specific data selections. Therefore, more data are required.

Nevertheless, the most promising CW effect is observed for low wind speed at a yaw misalignment of 4° and 8°. This may be due to an increasing thrust coefficient, which should result in a higher wake skew angle, although this is not confirmed in our analysis.

A clear decrease in wind speed and increase in TI is seen along the turbine row. No pattern can be seen in the wind speed and TI as the result of the increase in yaw angle of the upwind turbine, i.e. an increase in yaw misalignment.

Acknowledgements

The project was carried out with funding from AgentschapNL (formerly known as SenterNovem).

E.T.G. Bot and K. Boorsma of our institute are acknowledged for reviewing this paper and for stimulating discussions.

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Controlling Wind in ECN's Scaled Wind Farm

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ECN

Content

- Introduction
- ECN "Controlling Wind" principle
- Scaled Wind Farm
- Analysis of results
  - Wake deflection
  - Assessing "Controlling Wind"
- Conclusions and way forward

ECN

Introduction

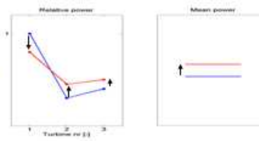
Wind turbines operated in a wind farm.
Turbines suffer from wake losses.
➤ Less power production.

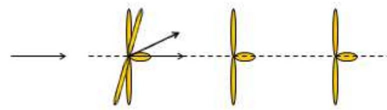
ECN: Controlling Wind.
➤ Reducing wake losses
➤ Increase power production

ECN

Controlling Wind – The basic principle

- Wind farm control strategy
- Increased power production
- Yawing first turbine





ECN

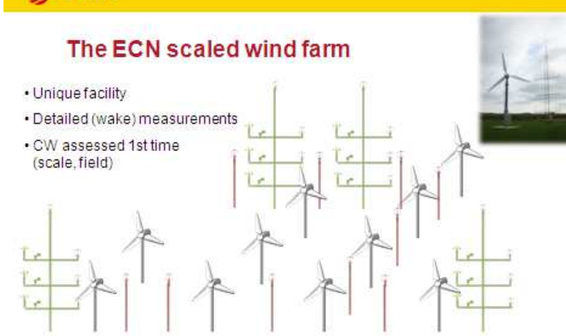
The ECN scaled wind farm

- 10 Turbines (H=7.5m, D=7.6m)
- 10 Small meteo masts (hub height)
- 4 Large meteo masts (18.9m)

ECN

The ECN scaled wind farm

- Unique facility
- Detailed (wake) measurements
- CW assessed 1st time (scale, field)

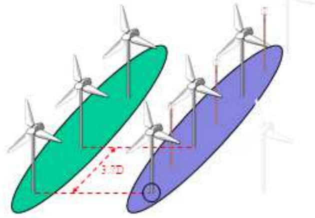


ECN

Scaled Test Case for CW

2 Rows (2 x 3 turbines)

- Row 1: Reference row
- Row 2: CW row



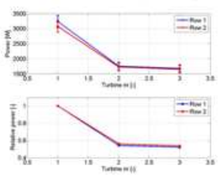
1st turbine CW row yawed:

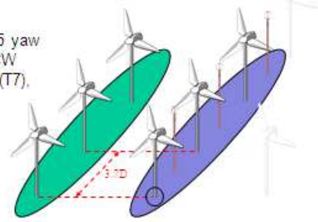
235 – 4 – 251°

ECN

Scaled Test Case for CW

- Comparison: all turbines 235 yaw
- Confirm differences due to CW
- With small power correction (T7), turbines sufficiently similar



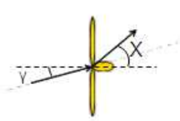


1st turbine CW row yawed:

235 – 4 – 251°

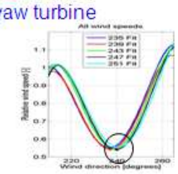
ECN

Wake deflection



γ = yaw misalignment
X = wake skew angle

- Mean: inflow ws and wd
- Wake ws
- Fixed yaw turbine



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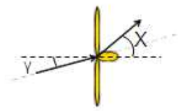
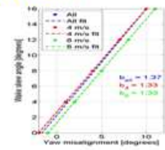
Wake deflection



γ = yaw misalignment
X = wake skew angle

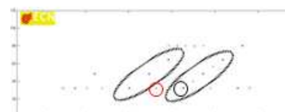
- Mean: inflow ws and wd
- Wake ws
- Fixed yaw turbine

- Wake skew (X) > Yaw mis (γ)
- Coefficient seems larger than literature (rotor characteristics?)



ECN

Assessing Controlling Wind



- Promising results
- Large scatter in the data.

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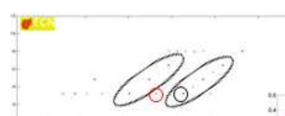
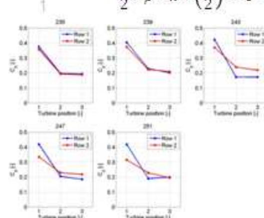


$$C_p = \frac{P}{\frac{1}{2}*\rho*\pi*\left(\frac{D}{2}\right)^2*U^3}$$

- Decreasing C_p upwind turbine with increasing yaw
- Increasing C_p downwind turbines with increasing yaw

What you see is what you expect.



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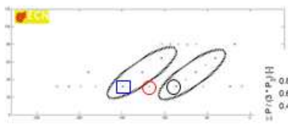
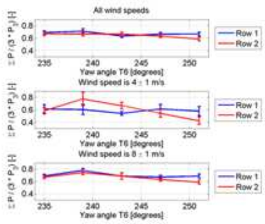


$$\text{relative sum} = \frac{\sum_i P_i}{3 * P_3}$$



- Biggest effect at low ws and at 4° and 8 ° misalignment
- Lower ws means:
  - Higher C_T ($C_{D,ax}$)
  - Hence higher χ

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Conclusions

- CW assessed for 1st time on such a scale and in field conditions
- With correction, turbines sufficiently similar
- Wake skew angle larger than yaw misalignment.
- Promising results. Also, large scatter in the data.
  - Change in C_p with increasing yaw
  - Most promising effect at low wind speed at 4° and 8 ° misalignment

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Way forward

We believe in the ‘Controlling Wind’ concept, i.e. overall increased power production.

Validation of concept:
- Scaled wind farm (additional)
- Full scale wind farm

We believe that the concept overcomes loads issues. If any.