Project funded by the European Commission under the 6th (EC) RTD Framework Programme (2002- 2006) within the framework of the specific research and technological development programme "Integrating and strengthening the European Research Area"

Project UpWind

Contract No.:
019945 (SES6)

"Integrated Wind Turbine Design"

Wp8: Flow
Deliverable D8.5
Wake reducing concepts

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Document Information

DOCUMENT TYPE	Deliverable D8.4
DOCUMENT NAME:	WP8Flow8.1D1.doc
REVISION:	
REV.DATE:	
CLASSIFICATION:	
STATUS:	

1. Abstract

Abstract: A number of approaches to reducing power losses to wakes were investigated. These include those developed at ECN 'Heat and Flux' and 'Controlling Wind' that focus on operational strategies. An alternative is to upscaling turbines or using different sizes of turbine. All of the approaches have potential but the conclusions are based on calculations with large uncertainties.

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Status				**Confidentiality**				**Accessibility**	
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S3	Draft for comments	**x**		**R3**	Restricted to WP members + PL	**x**			
S4	Under preparation			**R4**	Restricted to Task members +WPL+PL				

PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

3. Notations

a = axial induction factor
u = total velocity in the wake
U_∞ = free stream velocity
u_{def} = velocity deficit in the wake (U_∞- u)
u_m = (maximum) velocity deficit in wake centre
r = radial position in wake (wrt wake centre)
R_w = wake radius
A = rotor radius
D_{ax} = axial force on rotor
$C_{D.ax}$ = axial force coefficient
C_P = power coefficient
ϕ_y = yaw angle
χ_y = yaw angle
μ = radial position in wake relative to wake radius (r/R_w)
D = rotor diameter

4. Introduction

The majority of current wind turbines, both on-shore and off-shore, are located in wind farms, the size of which gets larger and larger. In these large wind farms, most turbines are located in the wake of one or more turbines by which the flow characteristics felt by these turbines differ considerably from the free stream flow conditions. The most important wake effect is generally considered to be the lower wind speed behind the turbine(s) since this decreases the energy production and as such the economical performance of a wind farm. The overall loss of a wind farm is very much dependant on the conditions and the lay-out of the farm but it can be in the order of 5-15%. Apart from the loss in energy production an additional wake effect is formed by increased velocity fluctuations (due to several causes) of a different character than free stream, which leads to higher fatigue loads. In the following we focus on power losses, changes in turbulence levels have not be considered.

With regard to minimisation of wake effects, two approaches can be distinguished

- A conventional approach in which the wind farm layout is optimized such that the wake effects are minimal. In this approach the turbine settings remain unaffected from their settings in free stream operation. All turbines in the farm are similar.
- An unconventional approach in which the wake effects are minimized using dedicated concepts.

In the first approach the turbine settings (e.g. pitch angle, rotor speed) are in principle optimized such that maximum energy output is balanced against minimal loads for an **individual** turbine. This generally implies that the turbines operate at maximum C_p although nowadays some turbines operate slightly below optimal C_P in order to reduce the thrust.

In this report the attention is mainly focused on the second approach. In the second approach the performance of the **entire wind farm** is optimised. It may then be beneficial to reduce wake effects by sacrificing some performance of the upstream turbines. Thereto the upstream turbine operates at sub-optimal conditions (sub-optimal in terms of individual wind turbine performance) where one can think of a non-optimal pitch angle/rotor speed, or a yaw misalignment. These sub-optimal settings will however lead to lower wake effects and hence an increased performance of the downstream turbines which can (over)compensate the loss in performance of the upstream turbines.

An intermediate approach lies in upscaling, since the rated power of a wind turbine increases with D^2 and the wake losses decrease linearly with D. Hence for given rated power and given area of a wind farm, upscaling of the turbines will allow a larger spacing between the turbines by which the wake losses will be lower.

Also non-conventional wind farms, e.g. wind farms which consist of turbines with unequal size may lead to an overall gain in energy production, since different sized wind turbines yield a different (and possibly a positive) wake impact. Furthermore the diameter can be used to design a 'wake specific' wind turbine (like it can be used to design a 'site specific' turbine, i.e. a turbine for a low wind speed climate will generally have a larger diameter).

The present report then summarizes research which has been carried out by the Upwind WP8 partners on the following wake reducing concepts:

- Heat and Flux. A wake reduction is achieved by setting the upstream turbines to a sub-optimal pitch angle.
- Controlling Wind: A wake reduction is achieved by yawing the upstream turbine.
- Upscaled turbines within a wind farm
- Turbines of unequal size within a wind farm.

Part of the research is carried out within Upwind but the research mainly builds on national projects. Results from these national projects are described in [1], [2], [4] and [9].

5. Heat and Flux

The work on the Heat and Flux (H+F) principle builds on previous work on a concept patented by ECN. In the Heat and Flux concept, the pitch angle of the upstream turbine(s) in a farm is set to a less optimal value. This obviously reduces the performance of the upstream turbine but it also reduces the axial force coefficient and the resulting momentum loss in the wake. The loss in performance on the upstream turbine may then be compensated by the reduced wake effects and as such the combined performance of both the upstream and downstream turbine can be increased. This is illustrated in figure 1. The figure shows the power coefficient and axial force coefficient as function of the axial induction factor, according to the well known relations:

$C_{D.ax} = 4a(1 - a)$ [2.1]

$C_P = 4a(1 - a)^2$ [2.2]

Since the axial induction factor decreases with pitch angle, the figure can also be interpreted as the C_P and the $C_{D.ax}$ as function of minus pitch angle. The figure shows that the maximum value of C_P in normal operation is accompanied by a high value of $C_{D.ax}$ and hence considerable wake losses. In the Heat and Flux operation the pitch angle is decreased. This obviously leads to a lower C_P but the flat behaviour of C_P makes the decrease in C_P very limited. However the decrease in $C_{D.ax}$ is very large which may decrease wake losses considerably.

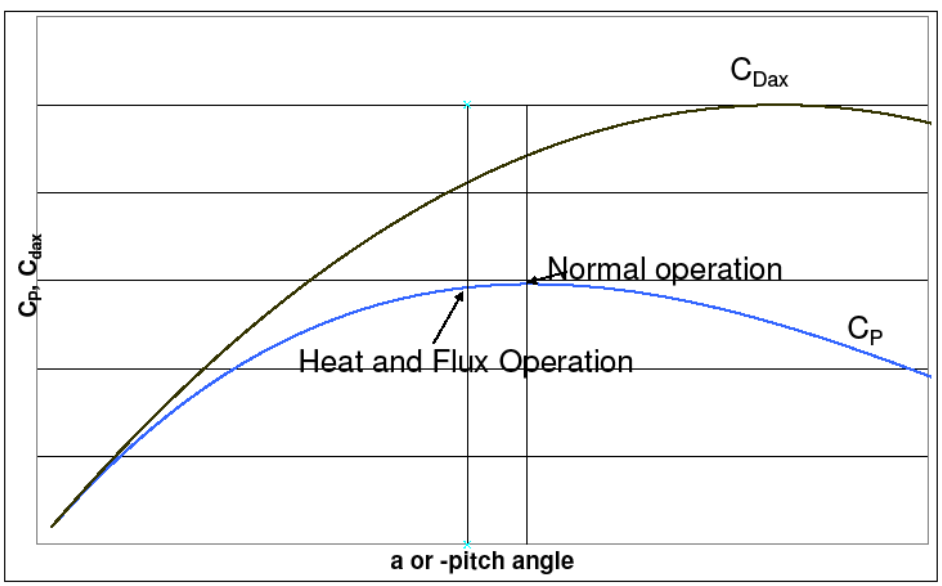


Figure 1: Power coefficient C_P and axial force coefficient C_{Dax} as function of axial induction factor from momentum theory

For the (very hypothetical) inviscid situation based on the conservation of momentum/energy, an increase of 4.1% of the combined power of 2 wind turbines in line is predicted where the axial induction of the 1st turbine should change to 1/5 instead of 1/3. Note that this assessment is purely based on the momentum theory under the assumption of full expansion. As such the outcome is not influenced by the distance between the turbines.

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

In order to find a more firm confirmation of the potential for Heat and Flux, optimizations have been carried out with the program Fluxfarm. The Fluxfarm program is based on the WAKEFARM program [9], and it contains an optimisation module to find the optimal settings for Heat and Flux. The optimisations were performed on ECN's research farn EWTW, which is described in [10] and in section 2.1. The EWTW consists of 5 research turbines in a line set-up with a diameter and hub height of 80 m. The rated power of the turbines is 2.5 MW and the mutual distance between the turbines is 3.8D.

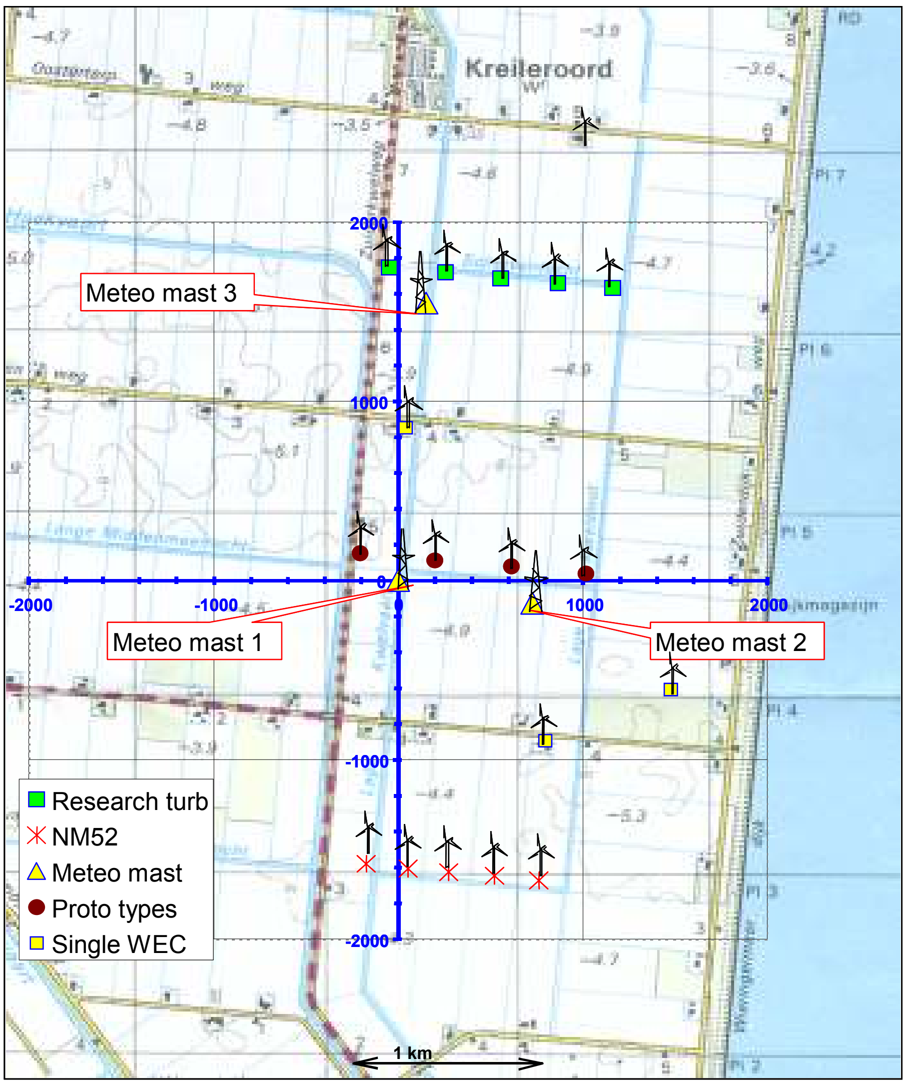


Figure 2: Lay-out of EWTW

Figure 3 presents the gain from Heat and Flux on the energy production of the EWTW. The results are given as function of wind speed and the misalignment between wind farm line and wind direction. Most important is that these results confirm a gain in energy production. Furthermore the figure shows a rapid decreasing gain with wind speed: The gain is in the order of 40% at the lower wind speeds and it reduces to zero at above rated conditions. Furthermore the gain decreases with the misalignment between wind direction and farm line but it is encouraging to see that even a 12 degrees misalignment in pitch angle still produces a gain. It must be noted that the large relative gain at low wind speeds is mainly a result of the fact that the H+F operation keeps the wake wind speeds just above the cut-in wind speed, where they fall below the cut-in wind speed at normal operation. The gain at low wind speeds however contributes little to the overall gain which is found from the summation over all wind speeds and wind directions.

Obviously the overall gain is very much dependant on the wind speed and wind direction distribution but it will generally be 0.5% or even less. At first sight, such gain may appear disappointing but most important is that the gain can be reached at very little additional cost. As a matter of fact, the only costs lie in the modification of the control algorithm, which should be made wind direction dependant and which should assure that the H+F settings only appear at wake conditions (in non-wake conditions, the H+F settings lead to a loss in production). In view of the uncertain and fluctuating wind direction this obviously requires some safety margin in the wind direction. As already mentioned above, a 12 degrees misalignment still produces a gain in energy production.

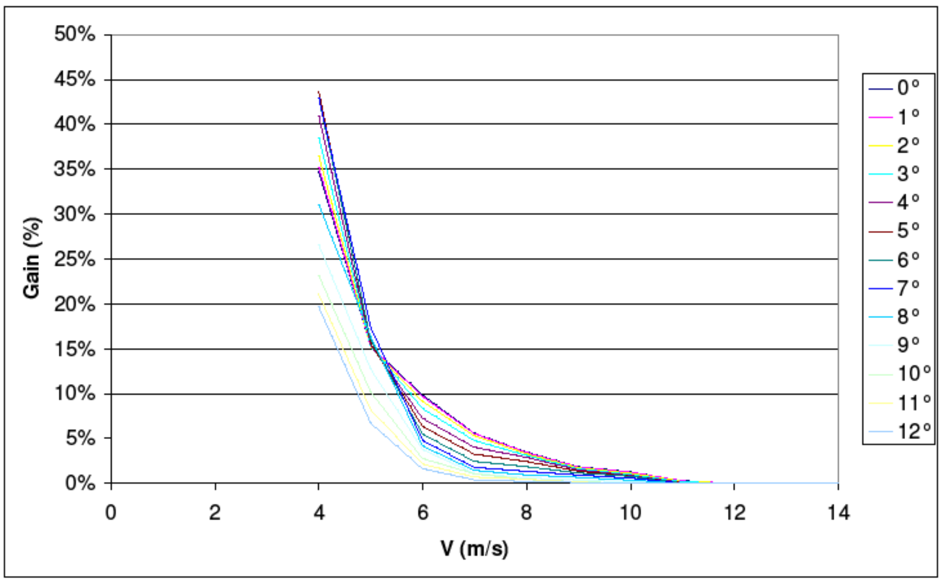


Figure 3: Gain in production of EWTW from Heat and Flux as function of wind speed and alignment

5.1 EWTW measurements on Heat and Flux

In order to validate the above mentioned Heat and Flux Concept several experiments have been performed on the ECN Wind Turbine Test Site (EWTW), the layout of which is given in Figure 2.

The EWTW consists of two rows of wind turbines, i.e. a Southern row with 'Prototype turbines' and a Northern row with 'Research Turbines'). The row with prototype turbines is reserved for commercial testing of wind turbines. These turbines are numbered from 1 to 4. For the present study, the 5 research turbines at the northern part are of relevance. The research turbines are numbered from 5 to 9 with turbine 5 the most Westerly wind turbine. The turbines are variable speed, pitch controlled, and they have a diameter and a hub height of 80 m. The rated power is 2.5MW. Near the research farm, there is a 108 m high meteorological mast (which is denoted as M(et)M(ast) 3).

The wind farm line is directed 95-275 degrees with respect to the North and the distance between the turbines is 3.8D. The operational parameters of the 5 turbines, the loads on turbine 6 and the meteorological data of the measurement mast were continuously measured during the field tests and stored in the measurement database.

In order to experimentally validate the Heat and Flux gain in the EWTW several problems were encountered:

- As mentioned above, the overall gain in the EWTW is expected to be in the order of 0.5%. Such low number is obviously very difficult to verify under atmospheric conditions. It should be realised however, that this overall gain is a summation over all wind directions, where the verification only needs to consider the ’wake wind directions’. Under these conditions the higher gain from Figure 3 at a misalignment around 0 degrees is expected.
- The selection of relevant data was not straightforward. The data have been selected on basis of 10 minute averaged values. As mentioned above the wind farm is directed from Φ_w = 95 to 275 degrees. Data have only been selected at the westerly wind direction (i.e. at ~ 275 degrees), since this wind direction happens much more frequently than the easterly wind direction. Obviously some margin around this wind direction is needed in order to have sufficient data points, where on the other hand the margin may not be too large since the data should represent ‘pure’ wake conditions. Eventually wake conditions were selected to be at Φ_w = 275 +/- 10 degree where in addition a selection was made on the yaw angle of the upstream turbine (turbine 5): $\Phi_{yaw,turbine5}$ = 263.65 +/- 4 degrees. (Note that this angle differs from the wind farm line due to an off-set in the measured yaw angle).
- Initially a test matrix was specified for automatic turbine operation at a series of alternating blade pitch angles in order to measure the relatively small production increase with sufficient significance but such procedure required a control software modification which was only allowed by the manufacturer after very lengthy and costly quality control procedures. Therefore initial measurements were performed with the upstream turbine alternately under the Normal Operation (NO) for 12 hours, followed by 12 hours under the Noise Reduced Operation (NRO). The Noise Reduced Operation is a standard operational mode of the turbines and did not require any control changes. At the NRO, the turbine operates at an increased pitch angle and (above 7 m/s) a reduced rotor speed, which altogether leads to a significant decrease in axial induction factor and hence an ‘exaggerated’ Heat and Flux setting. After the measurements at the NRO were completed the manufacturer approved a procedure in which the pitch settings of the individual turbines were changed by means of its remote supervision system on request when ECN expected appropriate wind conditions. With this procedure measurements were conducted in the so-called “*22220*” mode. In this mode the pitch angles of the turbines 5 to 8 (ie the 4 upstream turbines) was set to 2 degrees where the pitch angle of turbine 9 is 0 degrees. This setting was calculated to be about optimal according to preliminary FluxFarm calculations [1]. Nevertheless they turned out to be unsuccessful in the sense that this setting led to a reduction in energy production (see section 2.1.2). Therefore a next campaign with “*20xxx*” control setting was performed. This implies a pitch angle of 2° for the first turbine (number 5) where the second turbine (number 6) operates at a pitch angle of 0°. The pitch angles of the remaining turbines remained unaffected. These pitch angles were beforehand calculated to be optimal for the combined power production of the turbines 5 and 6.
- The number of data points was limited. This is in particular true for the 20xxx campaign for which only 0.58 day of data points were collected (distributed over the entire wind speed range).

5.2 Noise Reduced Operation (NRO)

The results from the Noise Reduced Operation measurements are presented in Figures 4 and 5. They show the power binned versus wind speed. In Figure 4 the results for the upstream turbine (number 5) are given, whereas Figure 5 shows the summed power of the first two turbines (turbines 5 and 6) in the row. Figure 5 also indicates the standard deviation and it shows a comparison with calculations from ECN's WAKEFARM program. Figure 4 shows that the Noise Reduced Operation leads to a clear reduction in power of the upstream turbine. Nevertheless the summed power is almost similar (Figure 5).This then indicates that the losses from the NRO on the upstream turbine are fully compensated by the reduced wake effects which asserts the Heat-and-Flux hypothesis.

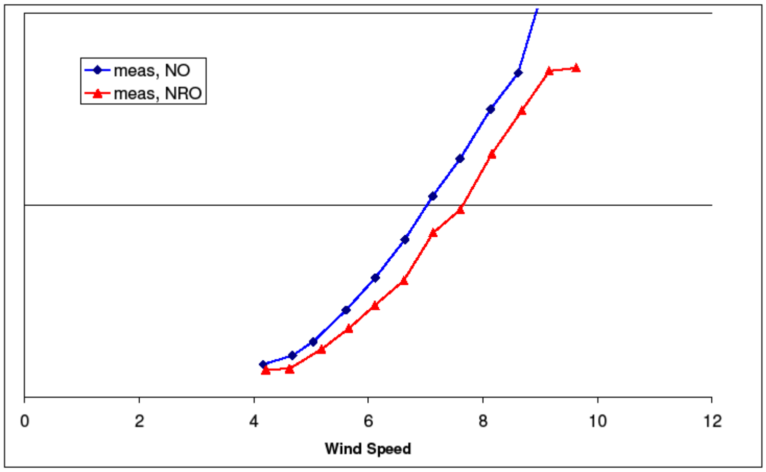


Figure 4: Power curve of upstream turbine (nr 5) at normal operation and Noise Reduced Operation

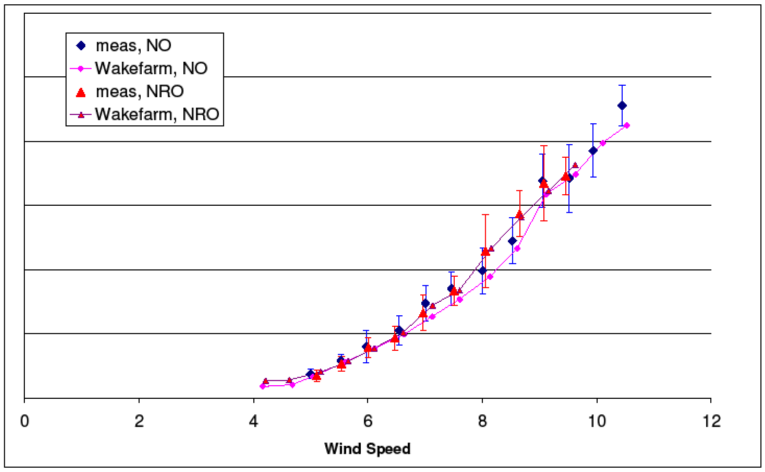


Figure 5: Power curve of downstream turbine (nr 6) where upstream turbine nr 5 is in normal operation or the noise reduced operation. A comparison is shown with WAKEFARM calculations

5.3 "22220" Operation

Figure 6 shows the power performance of the 5 turbines at the 22220 scenario, compared with the power performance at normal conditions (00000 scenario). A clear deterioration in power performance is visible when the turbines are in Heat and Flux operation. This holds for each individual turbine and ergo for the wind farm as a whole. Hence, although preliminary FluxFarm calculations indicated this configuration to be optimal, the measurements clearly show this to be wrong! Several explanations have been offered. One explanation lies in the poor multiple wake model which was applied in the preliminary FluxFarm calculations (later calculations with a more reliable multiple wake model indicated a loss for this configuration indeed). It must however also be realized that wake operation of all 5 turbines is based on the measurements taken at MM3 and the yaw angle of turbine 5, which are both far remote from the most downstream turbines (figure 2). As such the Heat and Flux settings may have been applied with the downstream turbines in non-wake operation, which then leads to a loss in power of these turbines.

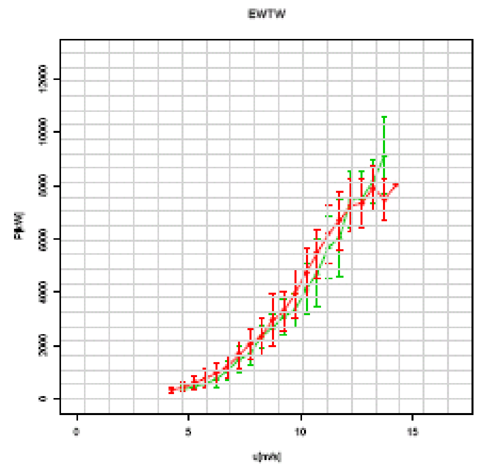


Figure 6: Total power performance of the EWTW farm for scenario 22220 (green triangles) compared with scenaro 00000 (red bullets)

5.4 20xxx" Operation

In the 20xxx operation, the attention has been focused on an assessment of the Heat & Flux operation of the first 2 turbines (turbine 5 and 6) in the farm: turbine 5 operates at a pitch angle of 2 degrees (Heat and Flux) and turbine 6 operates at the normal pitch angle of 0 degrees. As such it is only a single wake situation which needs to be considered without the complicating effect of multiple wakes. Additionally the wind direction measured at MM3 and the yaw angle of turbine 5 are believed to be good indicators for the operation of the first turbines.

Figure 7 shows a slight deterioration in power performance of turbine 5. This slight deterioration is expected since, as mentioned before, the power decreases only very slightly with pitch angle. As a matter of fact the deterioration is within the statistical uncertainty. At the same time an improvement of the performance of turbine 6 can be observed by which the combined power performance of turbine 5 and turbine 6 shows a systematic increase.

Note that scenario 20xxx also increases the overall wind farm production, i.e. the production of the turbines 5 to 9. More information on the results can be found in [1].

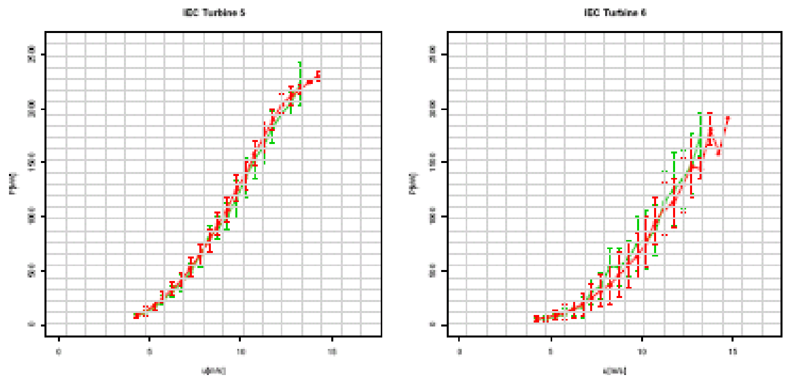


Figure 7: Power performance of turbine 5(left) and 6(right) for scenario 20000 (green triangles) and scenario 00000(red bullets)

5.5 Conclusions on Heat and Flux

An important conclusion from the Heat and Flux experiments is that an increased pitch angle of 2 degrees on the upstream turbine (number 5) hardly decreases the power of this upstream turbine where it does decrease the wake losses and increase the power of turbine 6 and so the summed power of the turbines 5 and 6. Nevertheless some remarks should be made:

- The amount of measurement data is limited.
- The distance between the turbines in the EWTW farm is only 3.8D where it is known that for larger distances between the turbines, the gain will be less.
- The determination of the optimal control settings beforehand is not straightforward since it should be realized that the dependency of **BOTH** power and wake losses to the pitch angle should be known very accurately since the loss in rotor power due to a sub-optimal pitch angle should be balanced with the increase in power of the downstream turbines due to reduced wake effects. Hence the optimal pitch angle can only be determined beforehand if very good **wake** and **rotor** models are available. Alternatively the optimal pitch angle could be determined by measurements.
- The current procedure where the wake effects are determined from the MM3 and turbine 5 measurements is not appropriate for multiple wake conditions. The variability of wind directions under these circumstances asks for mutually dependant control of the turbines, ie. the control of turbine x should depend on the wind direction and yaw angle of turbine (x-1) in order to avoid Heat and Flux Operation in non-wake conditions. The requirement of accurate wake models is even more difficult to fulfil for multiple wake situations.

6. Controlling Wind

The Controlling Wind concept is based on a deliberate yaw angle of the upstream turbine. This obviously produces a lower power and higher loads, but on the other hand, the yaw will deflect the wake behind the upstream turbine which may make it possible to control the wake such that the downstream turbine is not located in the wake of the upstream turbine anymore.

The successful implementation of a Controlling Wind strategy obviously requires a very good insight of the wake structure behind a yawed turbine. It should then be realized that yaw modeling on wind turbines is one of the most difficult areas in wind turbine aerodynamics, see eg [3] where it is explained that the flow around a yawed turbine is determined by the so-called advancing and retreating blade effect which interferes with a variation of the induced velocity over the rotor plane. Moreover the azimuthal variation of the angle of attack will often lead to dynamic stall effects which add to the complexity of the flow problem.

Most important for the Controlling Wind strategy is the determination of the so-called wake skew angle (χ), ie the angle between the wake flow and the nacelle direction. This wake skew angle is generally assumed to be constant and an often applied estimate for this angle assumes the in-plane velocity component unchanged from the in-plane free stream component ($V_w \sin \phi_y$) where the axial velocity changes from V_w to $V_w(1-a)$. This yields

$$\chi = \arctan (V_w \sin \phi_y / V_w \cos \phi_y (1-a)) \sim \phi_y (1 + a) \qquad [3.1]$$

(for small yaw angle and axial induction factor)

On basis of (a limited amount of) measurements from KTH [5], ECN derived a different formula of the following form

$$\chi = \Phi_w (1 + 2/3\ a) \qquad [3.2]$$

This formula has been implemented in Fluxfarm. which showed that Controlling Wind can yield a gain in the EWTW energy production of 1-1.5% (for the wind direction the wind farm line).
A slightly modified relation for the wake skew angle has been derived by TUDelft, [6]:

$$\chi = \Phi_w (1 + 0.3\ C_{Dax}) = \Phi_w (1 + 1.2a(1-a)) \qquad [3.3]$$

This formula has been derived on basis of free wake calculations, TUDelft wind tunnel measurements and Mexico [7] wind tunnel measurements.

It is noted that the formula from TUDelft and ECN compare rather well for design conditions (a=1/3), see Figure 8, which shows the wake deflection from both formula for different yaw angles in comparison with the relation from 3.1. The situation where the wake angle remains unaffected, i.e. where the wake angle remains equal to the yaw angle, is also shown (no skew).

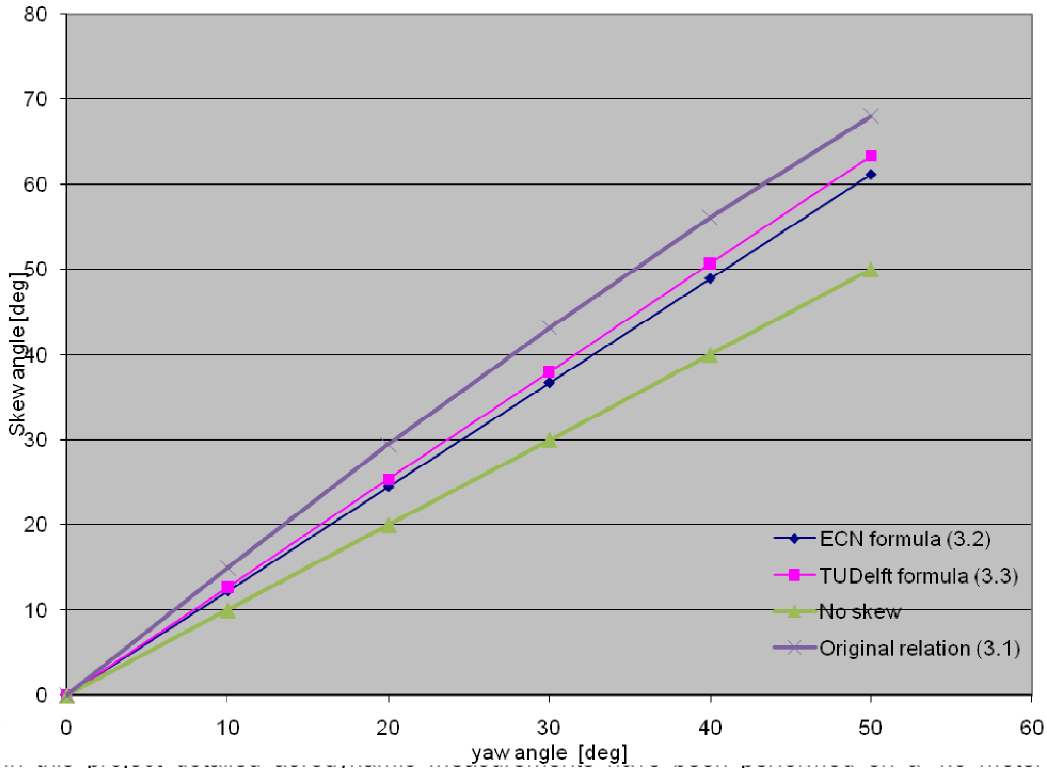


Figure 8: Wake skew angle as function of yaw angle according to the eqn's 3.1 to 3.3. The situation without skew (wake angle = yaw angle) is also shown

vortices have been tracked, see [7] for more details.

Figure 9 shows the resulting wake deflection from the tip vortex tracking experiments (red spots). The dashed line gives the tip vortex positions as derived from the axial traverses. The PIV measurements are done at an azimuth angle of 270 degrees but it is assumed that the measurements at negative yaw and an azimuth angle of 270 degrees correspond to positive yaw and an azimuth angle of 90 degrees. Furthermore the wake deflection from a so called cylindrical wake model with a constant wake skew angle according to relation 3.1 is shown.

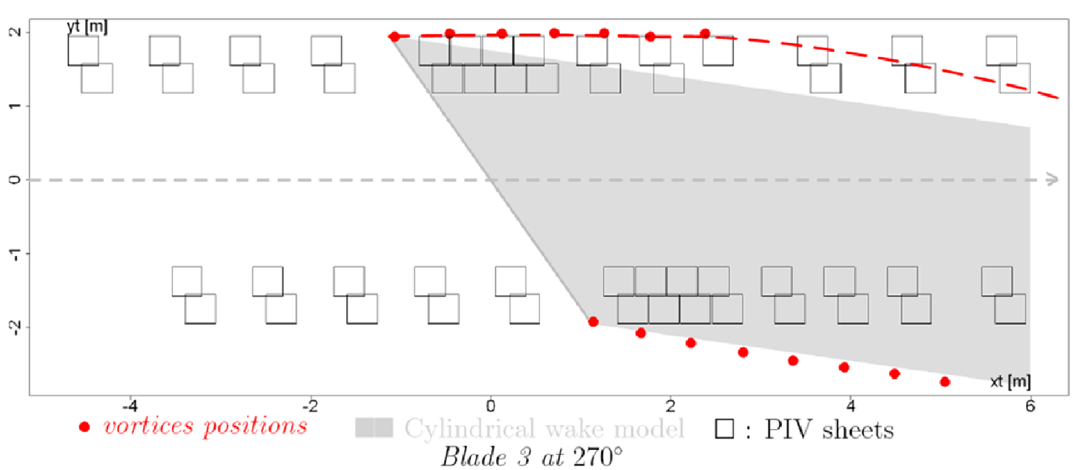


Figure 9: Mexico experiment: Tip vortex positions from vortex tracking experiments (red spots) and axial traverses (dashed line). The wake from a cylindrical vortex sheet method based on the skew angle from formula 3.1 is also shown

It can be seen that the skew angle does not only vary over the axial coordinate but also over the azimuth angle. The analysis from [4] shows this variation to be a result of the flow obstruction from the nacelle and of the variation in induction over the rotor plane. As a matter of fact the aim from [4] was to investigate the capabilities of CFD to reproduce the wake deflection as measured in the Mexico experiment. The main conclusion was that the results are predicted well in a qualitative sense but there is a large quantitative disagreement. Some improvements might be anticipated by refining the CFD model (The assessment from [4] was based on an actuator disc approach) but it is unlikely that CFD can provide the details of the wake deflection sufficiently accurate to form a basis for a successful control strategy. As such a good controlling wind strategy will most likely require tuning on basis of measurements.

For this purpose experiments are foreseen in the scaled farm of ECN. These experiments serve a twofold goal. They should demonstrate a potential for Controlling Wind but they should also provide the experience and guidelines for a successful implementation of a Controlling Wind strategy on other wind farms.

Another aspect which needs to be considered when applying a Controlling Wind strategy lies in the load increase which is expected from yawing the upstream turbines. Thereto it should be realized that the yawed load cases might for some turbines and components even be design driving[11]. However, these design driving load cases generally appear at relatively high wind speeds (rated or above rated wind speed) where Controlling Wind will mainly be applied at low wind speeds (wake losses donot play a role at above rated conditions).

6.1 Conclusion on Controlling Wind

Controlling Wind seems a promising technique to reduce the wake losses in a wind farm. It is however a far from simple technique. In order to determine the optimal Controlling Wind strategy beforehand, very accurate yaw aerodynamic models are required but unfortunately the modelling of a wind turbine under yawed conditions is extremely difficult. As such an optimal Controlling Wind strategy can only be derived from measurements. A reliable yaw model is also needed to assess the increased loads on the upstream turbine since yawed load cases can be design driving. Possibly Controlling Wind should be applied at low wind speeds only.

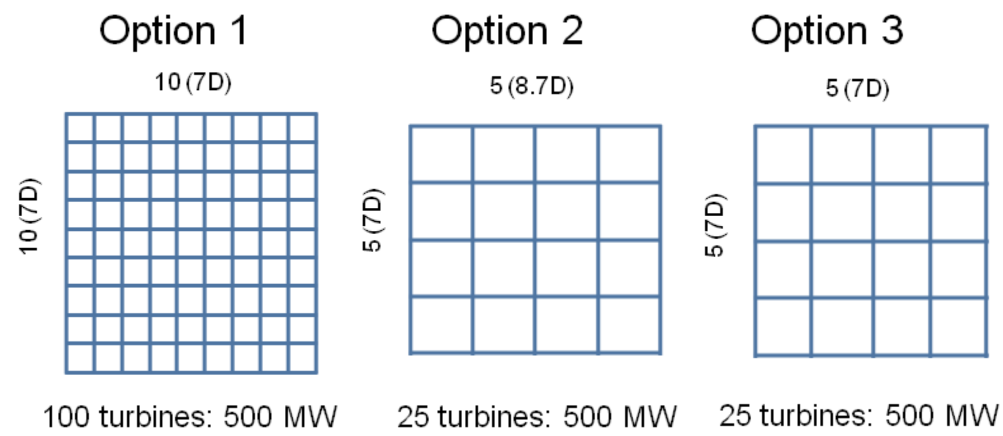
7. Upscaling

7.1 Results obtained with WASp

Indiana University/Risoe DTU performed a study to investigate how the size of wind turbines and the scale of wind farms impacts the amount of energy that can be extracted from a given land area [12]. A number of options were considered for a 500 MW farm and simulations were conducted with WAsP for different turbine size and spacing as shown in Figure 10. The results are summarized in Table 1. This research indicates that increasing turbine size from 5 MW to 20 MW could increase energy capture from about 28.3 to at least 34.7 GWh km^{-2} where the wake losses can be decreased from 14.5% to 6.5%. A major assumption in this type of calculation is to understand whether wind turbine wake losses can be scaled linearly as they have been for small to medium wind farms disregarding any large wind farm impacts. If power output from large wind farms is also controlled by meteorological variables on a larger scale (e.g. [13],[14]) then this assumption will no longer be valid. Therefore, there is major uncertainty in this type of linear upscaling.

Table 1. Prediction of power output using WAsP

	Option 1	**Option 2 "Equal area"**	**Option 3 "Equal spacing"**
Turbine	5 MW	20 MW	20 MW
Hub height/rotor diameter (m)	90/126	153/252	153/252
Installed capacity (MW)	500	500	500
Area of installation (km^2)	8.8 × 8.8 = 77.4	8.8 × 8.8 = 77.4	8.8 × 7.1 = 62.1
Area capacity (W m^{-2})	6.5	6.5	8.1
Turbine wake losses (%) (WAsP k=0.04, U=8.6 ms^{-1})	14.5	6.5	9.0
Annual production (GWh a^{-1}) (WAsP k=0.04, U=8.6 ms^{-1})	2197	2211	2152
Production density (GWh km^{-2})	28.3	28.6	34.7



Option 1 **Option 2** **Option 3**

Figure 10: Layouts considered: Left 100 turbines with a rated power of 5MW, middle and right 25 turbines with a rated power of 20 MW

7.2 Results obtained with CRES–Farm

CRES also carried out a study to investigate how the size of wind turbines and the scale of wind farms affect the wake losses and the capacity factor. A number of options were considered for a 500 MW and a 1000 MW wind farm. Simulations were conducted with CRES–Farm tool for different turbine sizes (from 5 MW to 20 MW) using 7D x 7D spacing. CRES–Farm is an in-house tool that is used for the estimation of the annual energy production from wind farms that is based on the prediction of the effective wind roses at the machines' hub heights for a given wind farm layout. CRES–Farm employs the amended GCL wake model. The major assumption behind this simulation is that wind is not affected by meteorological variables on a larger scale. The wind turbine characteristics are included in Table 2. It is noted that in this preliminary estimation it is assumed that the difference in size does not affect the aerodynamic performance of the wind turbine (i.e. all wind turbine featured the same power coefficient and thrust coefficient distributions). The calculations have been performed for an annual wind speed of 10 m/s at a height of 90 m and a wind shear coefficient of 0.14

WT Rated power [MW]	5	10	15	20
WT Diameter [m]	126	178	218	252
Tip Speed [m/s]	80	80	80	80
Hub Height [m a. s. l.]	90	116	136	153

Table 2: Wind turbine characteristics as used by CRES

The details of the different configurations are summarized in Table 3. It is noted that small differences in the overall capacity of the wind farm appear in the various configurations (since the overall power capacity would not precisely be realized with some wind turbines) that are reflected in small variations of the area used.

Wind turbine size [MW]	5	10	15	20
		500 MW wind farm		
Machines	10x10	7x7	6x6	5x5
Capacity [MW]	500	490	540	500
Area [km^2]	77.80	76.07	83.83	77.80

	1000 MW wind farm			
Machines	14x14	10x10	8x8	7x7
Capacity [MW]	980	1000	960	980
Area [km^2]	152.47	155.25	149.04	152.47

Table 3: Wind farm case details as used by CRES

The results are presented in Figure 1 and 2 in the form of the capacity factor and the wake losses as a function of the wind turbine rated power for the two wind farm sizes. This research indicates that increasing turbine size from 5 MW to 20 MW contributes to a direct decrease in the wake losses and therefore the capacity factor is increased. A contribution to the increase of the capacity factor should also be attributed to the increase in hub height that accompanies the increase in the rated power since a normal wind shear profile was assumed.

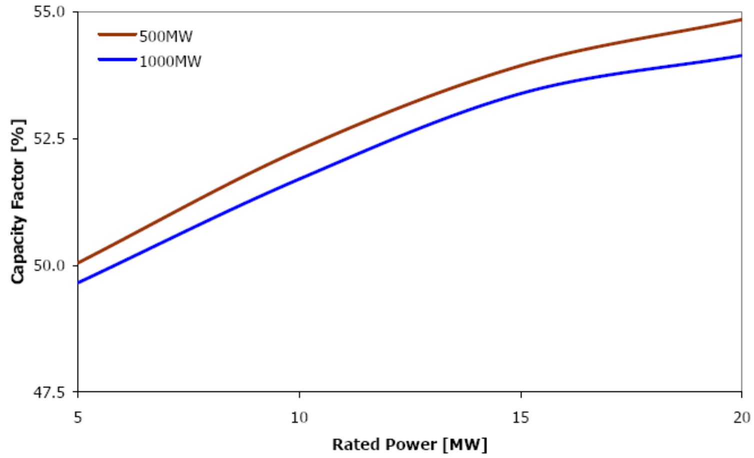


Figure 11: Wind farm capacity factor as a function of the wind turbine rated power for the wind farm cases as presented in table 3

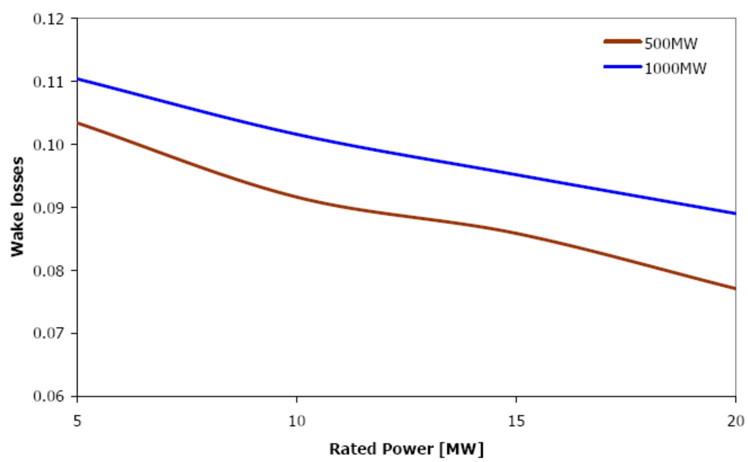


Figure 12: Wind farm energy loss due to wakes as a function of the wind turbine rated power for the wind farm cases as presented in table 3

7.3 Upscaling results obtained with Farmflow

In [2] a study is presented where the wake losses has been determined with the ECN code Farmflow. All scenarios which are investigated are based on the lay-out of the ECN Wind Turbine Test Site Wieringermeer, EWTW, see section 2.1.

The scenarios presented in this report all assume the basic lay-out unchanged from the original set-up i.e. a line set-up with 5 equi-spaced turbines. However some, or all, turbines have been upscaled to a diameter of either 90m or 100 meter compared to the original diameter of 80 meter. The length of the wind farm line was also made variable and ranged between 1220 m (the original length) to 2880 m.

It should be noted that it is not only the diameter which changed but also the power curve and the C_{Dax}-V curve. Until rated wind speed, the C_{Dax}-V curve is independant of turbine size but the rated power is also kept unchanged by which the wind speed reduces for an upscaled turbine. Since wake effects only play a role at above rated conditions, an upscaled turbine suffers less from wake effects. Hence, to some extent, an upscaled turbine can be seen as a wind turbine design suited for wake operation.

The results are presented in Figure 11. It can be seen that for given farm length, the wake losses for 5 equally sized turbines often decrease with increasing diameter despite the fact that the relative distance between the turbines is smaller for a larger diameter. This is most likely a result of the lower rated wind speed for the larger turbine as discussed above. The results also indicate that increasing the diameter of the downstream turbines in the farm (i.e. the turbines which are heavily exposed to wake effects) generally reduce the overall wake losses.

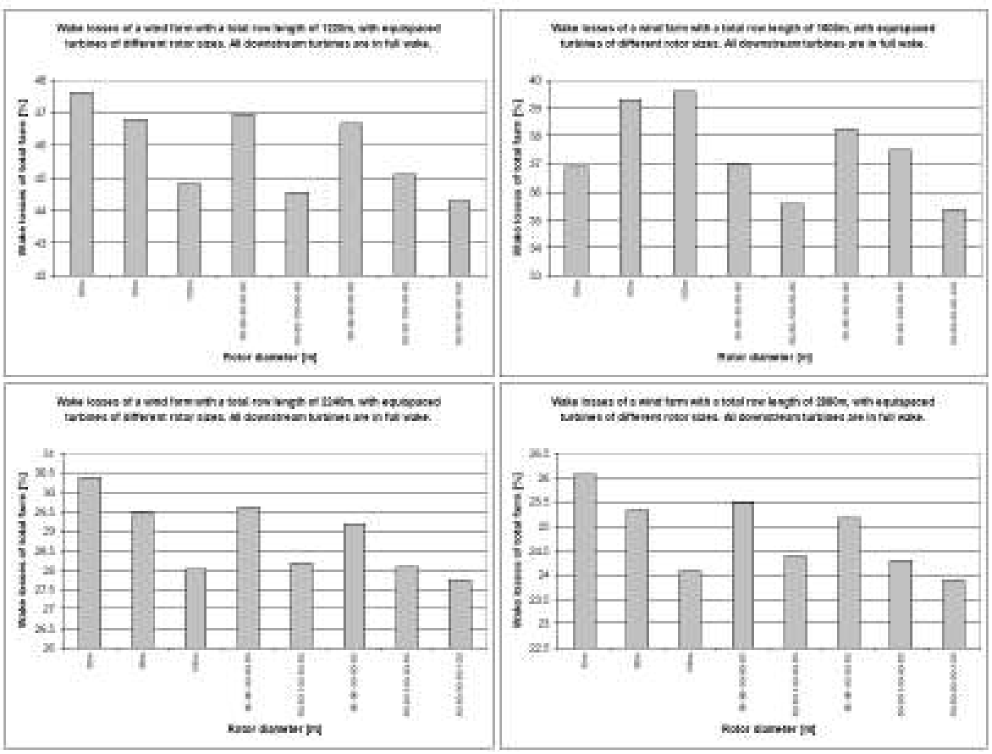


Figure 13: Wake losses for different EWTW lay-outs where all downstream turbines are in a full wake situation. Each graph represents a farm length (original farm length is 1220 m) . The diameters of the different turbines are presented along the horizontal axis (original diameter is 80 m). The three left bars assume all 5 turbine diameter to be the same (80m, 90m or 100m).

7.4 Conclusion on upscaling

On basis of calculations, it may be concluded that upscaling is a very promising option to reduce the relative wake losses. The wake losses in a farm with the same rated power but larger wind turbines are much less than the wake losses on a farm with small turbines. Also the use of 'wake specific designed turbines' i.e. differently scaled turbines within a wind farm has shown to have potential.

8. Aerodynamic scaling effects

The results as presented in the previous sections assume the aerodynamic wake effects to be scale independent. In this section the question will be addressed how valid this assumption is. First it is noted that several scaling dependencies could play a role but this study only considers scaling of ‘single far wake’ effects. Scaling effects are also expected to appear on the aerodynamic phenomena in the near wake but these scaling effects may be considered as secondary importance for the far wake (section 4.6). Moreover the mutual interaction of the wakes and the interference of the wake with the ground and upper atmosphere might be scale dependant phenomena. These phenomena are not considered in the present analysis.

The study investigates the scaling dependency on the velocity deficit in a single wake which is written in terms of:

$U_{def}(y,z) = U_{\infty}(z) - U_{wake}(y,z)$

In this expression it is assumed that the free stream velocity (U_{∞}) is subject to a vertical wind shear only, ie. it is a function of the vertical coordinate **z** but the velocity in the wake and so the wake deficit has also become a function of *y,* the horizontal coordinate. As explained below it will be assumed that the velocity defect iis axi-symmetric around the wake center ie. it can be written as function of r, the radial coordinate with respect to the wake center.
The modeling of the velocity deficit is then largely in line with the model from Schlichting [8] where the following assumptions are made:

- The wake deficit u_{def} is assumed to be axi-symmetric around the rotor (wake) centre, i.e. the wake deficit is written in terms of a radial coordinate r
- The stream wise pressure gradient *dp/dx* is neglected (this assumption is valid for say $x > 2D$)
- The boundary layer assumption is made (i.e. the length scale in streamwise (*x*) direction is assumed to be long compared to length scale in radial (*r*) direction)
- The rotor is modelled as an actuator disc with axial force coefficient $C_{D.ax}$
- The wake flow is fully turbulent, ie. turbulent friction is much larger than laminar friction
- The velocity deficit u_{def} is small compared to the free stream velocity.

With the above given assumptions and a simple mixing length eddy viscosity model, a self similar velocity profile is found in the form of:

$$u_{def}(r) = u_m\, f(r/R_w) = u_m\, f(\eta) \qquad [4.1]$$

with η the ratio between the radial position and the wake radius R_w,

$$\eta = r/R_w$$

Hence equation [4.1] gives an axi-symmetric velocity deficit as function of η where the velocity deficit is maximum (u_m) in the wake centre ($\eta = 0$).

The self-similar solution $f(\eta)$ is given in [8] and takes the following form:

$$f(\eta) = [1 - \eta^{1.5}]^2 \qquad [4.2]$$

Note that equation [4.2] can be shown to approach closely an exponential behaviour

$$f(\eta) \sim exp(-\eta^2 / 0.27).$$

In order to express the velocity deficit u_m and the wake radius the momentum deficit over the wake is found by:

$D_{ax} = \int \rho u\, (U_\infty - u)\, 2\pi r dr$

Which gives, with the above mentioned assumption of small u_{def} and $\eta = r/R_w$ and equation 4.1:

$D_{ax} = \int R_w^2 \rho U_\infty u_m f(\eta) 2\pi \eta d\eta$

which gives:

$u_m/U_\infty = \lambda C_{D.ax} A/R_w^2$ [4.3]

in which λ is a constant $\lambda = \int 4\pi f(\eta)\ \eta d\eta)^{-1} \sim 0.6189$

Equation 4.3 shows the velocity deficit to scale with R_w^{-2}
The wake radius R_w is still unknown. It is modelled along the following lines:

- The rate of increase of R_w is proportional to transverse velocity v'
- v' follows from a simple eddy viscosity mixing length model:

  $v' \sim l\ du/dr$ [4.4]

  in which the mixing length scales with the wake radius

  $l = \alpha R_w$ [4.5]

  Where α is assumed to be constant and the average shear over the wake radius can be approximated as the maximum velocity deficit divided by the wake radius:

  $du/dr \sim u_m/R_w$ [4.6]

- Hence $dR_w/dt \sim U_\infty\ dR_w/dx \sim \alpha\ u_m$ by which

  $dR_w/dx \sim \alpha u_m/U_\infty$

  Which gives with eqn 4.3:

  $R_w \sim (\alpha\ \lambda\ C_{D.ax} Ax)^{1/3} + R_{w,0}$

  Or

  $R_w \sim (\alpha\ \lambda\ C_{D.ax} A)^{1/3} (x - x_0)^{1/3}$ [4.7]

  From which the 'relative' wake radius R_w/R is found as:

  $R_w/R = k(C_{D.ax})^{1/3} [(x - x_0)/R]^{1/3}$ [4.8]

  (with k a constant in which α is 'hidden')

With equation 4.8 the maximum velocity deficit can be found from equation 4.3:
$u_m/U_\infty = \lambda_2\ C_{D.ax}^{1/3} [R/(x-x_0)]^{2/3}$ [4.9]
(With $\lambda_2 = \lambda\ \pi\ k^{-2}$)

Note that, in principle, the unknowns λ_2 and x_0 can (for given $C_{D.ax}$) be found from equation 4.9 with two velocity measurements at hub height at different x positions.

8.1 Scaling dependencies

Wake effects are often considered in terms of

- u_{def}/u_m as $f(r/R)$
- R_w/R as $f(x/R)$
- u_m/U_∞ as $f(x/R)$

In this form the equations 4.1, 4.8 and 4.9 show that all scale dependencies (i.e. all dependencies on rotor radius (or rotor diameter)) are eliminated (note that r/R_w in equation 4.1 can be written as $r/R \cdot R/R_w$).

This is however only true when x_0/R and λ_2 (i.e. α) are independent of the rotor radius which is not a-priori known.

It is noted that a similar conclusion can be drawn when assessing scaling effects from a turbulent Reynolds number written in the following form:

$$Re_{turb} = U_\infty x/\nu_{turb} = U_\infty x / (l^2\, du/dr) = 1/[\alpha^2\ k\ \lambda_2\ C_{Dax}^{2/3}]\ x/R\ \ [(x-x_0)/R]^{1/3}$$

This again shows the turbulent Reynolds number at given x/R to be independent of rotor scale, apart from a possible scale dependency on x_0/R and α (or λ_2)

As such scaling (in)dependency can be determined if the values of x_0/R and λ_2 are calibrated for a number of experiments at different scales. As mentioned above this requires, theoretically speaking, only 2 measurement points per experiment (for given C_{Dax}). In practice however the scatter in the measurements, as well as the fact that the real velocity behaviour will not perfectly obey the above given modelling assumptions asks for a need of much more measurement data.

Finally it can be noted that the value of x_0 represents a boundary condition from the near wake. The near wake is obviously largely determined by the aerodynamic behaviour of the rotor in front of the wake which is known to be Reynolds number dependant. Nevertheless this dependency may be relatively weak at the high Reynolds numbers of nowadays turbines (> 5M) since scaling effects become weaker with increasing Reynolds number.

Furthermore, although some Reynolds number dependency on x_0 may be expected, the far wake will be rather insensitive on the precise value of x_0 (x_0 is often found to be in the order of 1.5-2D which is relatively small compared to the values of x in the far wake (5-10D)). As such the determination of the precise value of x_0 is expected to be of secondary importance.

8.2 Conclusion on scaling dependency of the 'far single wake'

The question of scaling (in)dependency of wake effects has been reduced to the determination of two parameters: λ_2 (basically α) and x_0 where most likely the overall influence of x_0 is limited in particular when rotor Reynolds numbers exceed values of say 3M. As such it is only the λ_2 (α) which remains to be calibrated from wake experiments at different scales.

The calibration of α in boundary layer experiments [8], showed little scale influence which leads to the expectation that scaling dependency in wake aerodynamics might also be limited.

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