The influence of wind farms on the wind speed above the wind farms

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Abstract. This paper addresses the effect of clusters of wind farms on the flow above the wind farms and their power productions. In the first part past and present modelling approaches are reviewed. In the second part computational results are presented and discussed. These results comprise the wind speeds within, in between and above two offshore wind farms, plus the power of these wind farms, as calculated with the wind farm design tool FarmFlow. It is shown that the wind speed deficit due to a cluster of wind turbines may extend to large heights, and that increasing the space between wind farms may not always assist in the recovery of the external wind speed. It is concluded that the wakes of large offshore wind farms may cause production losses at other wind farms even when they are separated at huge distances.

1. Introduction

In clusters of wind farms, particularly in large clusters offshore, the wind turbines affect the flow in and outside the wind farms because of the collective aerodynamic wake effects of the wind turbines. This effect decreases the wind speed and increases the turbulence intensity of the wind turbines that are placed in downstream positions, but also influences the atmospheric boundary layer in which the wind farms are placed.

In fact, a cluster of wind farms has a complex system of internal velocity and turbulence wakes, similar in appearance as but at a larger scale than the internal wakes system of a single wind farm. Because of the strong impact of a wind farm cluster on the wind, such a cluster is expected to change the local wind climate. This will result in modifications in the sectorwise Weibull-distribution of the mean wind speed in a given location, but also in modifications in the distribution of the turbulence intensity.

Apart from influencing the wind, some argue that large concentrations of wind turbines may even affect the local weather, in particular temperature or precipitation. (See for example Rooijmans [1].) The rationale is that the added turbulence dissipates into extra heat which causes an increase in the temperature, a higher humidity, and eventually more precipitation. The magnitude of these changes however is expected to be small, as is the expected effect on the local climate.

To date, reliable public data from the still few clustered offshore wind farms are not available, but this is expected to change with the commissioning of the new wind farms in the North Sea. May the effect on the local weather be a matter of debate to date, the concentration of wind turbines in particular areas may provide evidence in the future.

In this paper the effect of a cluster of wind farms on the wind speed and the power production is addressed. The paper starts in section 2 with a review of previous studies on this matter and the definition of the research questions of the current study. Next, in section 3, the results from the current study are presented and discussed. Finally, section 4 summarizes and concludes the paper.

2. Modelling approaches

May information on observed wind farm wake effects be scarce, predicted effects are available from a number of models. Wind farm wake modeling requires simulation of mesoscale atmospheric flow together with energy extraction/redistribution due to wind turbines. This section presents the various approaches in these studies and a critical review of these approaches [2]. On basis of that review the research questions of the current study are presented.

Liu et al. were the pioneers in this field [3]. They developed a numerical model based on the primitive equations in order to study the behaviour of turbulent wakes behind large-scale wind turbines. This model is based on a numerical solution of the Navier-Stokes equations for the planetary boundary layer with the hydrostatic approximation, in combination with a Monin-Obukov description of the turbulent diffusivities. To demonstrate the utility of the model, it was applied to three different configurations of wind turbine arrays, among which one wind turbine immediately downwind of another. The results of the model simulations were found not only to retrieve major features of turbulent wakes observed behind wind turbines but also to compare favorably with corresponding measurements from wind tunnel experiments.

In order to analytically model the effect of a wind farm on the atmospheric boundary layer, Hegberg and Eecen first estimate the artificial roughness length of the wind farm [4]. Next they calculate the internal boundary layer which results from the roughness change due to the wind farm. With this information the new turbulent drag force and subsequently the new equilibrium between the forces (turbulent drag force, the Coriolis force and the pressure gradient force) are determined. From that equilibrium the new wind speed and direction are calculated, which are found to be quite different from the conditions outside the wind farm.

Frandsen et al. developed an analytical model for the flow in and near a wind farm [5]. The model distinguishes between two flow directions (parallel to the rows in a rectangular wind turbine configuration, and not parallel) and identifies three flow regimes (multiple wakes, merging wakes from neighbouring rows, and equilibrium between the wind farm and the boundary layer). The multiple wakes model and the merging wakes model were derived from the Lanchester-Betz theory, whereas the equilibrium model was derived from the geostrophic drag law. The effect of turbulence is included in the modeling of the equilibrium regime only by using the skin friction velocity and the surface roughness length. The model is reported to predict offshore wind recovery distances in the range between 2 and 14 km.

Hegberg et al. developed a numerical model in order to study the effect of a wind farm on the planetary boundary layer [6]. Similar to their preceding model [4], a wind farm is modeled as surface roughness but now a number of sub-models is proposed to do so. In addition they add an innovative element in the form of an atmospheric boundary layer model which apart from velocity also takes temperature into account. Turbulence is modeled in terms of Reynolds stresses of velocity and temperature so that the door is opened to treating small departures from the neutral situation.

Baidya Roy et al. applied the Regional Atmospheric Modeling System model to explore the possible impacts of a large (100x100 km^2) onshore wind farm in the Great Plains [7]. This model solves the full three-dimensional compressible non-hydrostatic dynamic equations, a thermodynamic equation and a set of microphysics equations. The system of equations is closed with a Mellor-Yamada scheme that explicitly solves for turbulent kinetic energy while other second-order moments are parameterized. A wind turbine was approximated as a sink of energy (operating at a fixed power coefficient of 0.4) and source of turbulence (adding a fixed amount of turbulent kinetic energy), and the wind farm was created by assuming an array of such turbines. Results show that the wind farm significantly slows down the wind at the turbine hub-height level.

Rooijmans simulated the meteorological effects of a large-scale (150x60 km^2) offshore wind farm in the North Sea by using the MM5 mesoscale model [1]. The wind farm was simulated by introducing a higher roughness length (0.5 m) in the area of the wind farm. The meteorological effects were examined by comparing model runs with and without wind farm. Turbulent kinetic energy, cloud formation, precipitation and wind speed reduction were studied. As to wind reduction the MM5 model was found to yield comparable results (in and near the wind farm wind speed reduction up to 50% in a high wind speed case) as obtained from a conceptual model which calculates the reduction of horizontal wind speed from a balance between loss of horizontal momentum and replenishment from above by turbulent fluxes.

These studies can be subdivided into two categories: self-similar approaches and mesoscale approaches [2]. In a self-similar approach the convective force and the spanwise turbulent flux gradients are assumed to dominate the flow, allowing for standard wake-like solutions [5, 6]. In a mesoscale approach, on the other hand, the flow is assumed to be dominated by the Coriolis force and the vertical turbulent flux gradients, opening the door to either extra surface drag approaches [4] or more generic mesoscale approaches [1, 3, 7].

Neither the self-similar wake approach nor the extra surface drag approach however is sufficient because over the separation distance between wind farms the convective and the Coriolis forces are of equal order of magnitude [2]. This implies that a wind farm wake may be deflected. Although this was already implicitly recognized in the more generic approaches, these studies lack realistic formulations for the turbulence and the wind turbines.

Subsequent approaches are aimed at either employing the potential of the mesoscale models developed in the meteorological sector or expanding the scope of existing wind farm models rather than developing dedicated flow models.

ForWind explores the first route by employing the Weather Research and Forecasting (WRF) model [8]. WRF is a mesoscale atmospheric model that has been designed to serve both operational weather forecasting as well as atmospheric research needs [9]. It provides information on atmospheric conditions (e.g. wind speed, wind direction) on a kilometer scale. WRF is driven by long-term global reanalysis data and high resolution sea surface temperature data in order to obtain long-term time series describing the wind and stability conditions in the North Sea Region on a grid with a horizontal resolution of about 2 km. The effects of wind farms was implemented in the form of a parameterization.

ECN follows the second route by extending the wind farm design model FarmFlow to a scope larger than the single wind farm. FarmFlow is a CFD based wind farm design method that calculates the energy production of the individual wind turbines and the wind conditions in a cluster of wind turbines [10, 11]. Required input data are wind turbine data (coordinates, rotor diameter, hub height, power and thrust curve and if possible also the number of blades and the rotational speed), and wind data (time-series of wind speed, wind direction and standard deviation, or just Weibull distributions and turbulence intensities, always including air density). Surface information is implicitly accounted for via the input turbulence.

The qualitative picture emerging from these approaches is that the wind speed is significantly reduced behind and above a wind farm, and recovers only after several (tens of) kilometers. The resulting research question is to quantify the effect of a cluster of wind farms on the wind speed near these wind farms and on their productions.

3. Results and discussion

In the current study the mutual wake losses of two offshore wind farms are investigated. This configuration is the same as one wind farm with a slot between two turbine rows. The wind speeds and the power productions are determined by using the CFD based wind farm design tool FarmFlow [10, 11]. The computational domain includes the atmospheric boundary layer up to a height of 1 km. Both wind farms consist of 10 columns with 10 rows of NREL 5 MW wind turbines with a hub height H of 90 m and a rotor diameter D of 126 m. The distance between the turbines is 7 rotor diameters. The rows of the second (downwind) wind farm are aligned with those of the first (upwind) wind farm. Seven distances between the wind farms are considered:

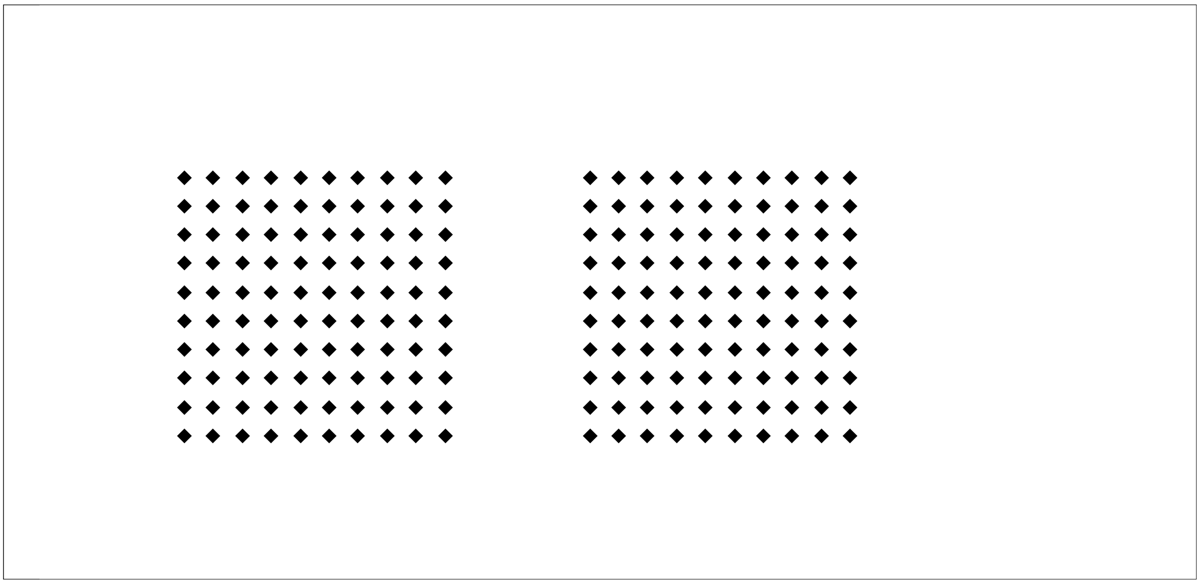

Figure 1. The disposition of the wind turbines in two wind farms separated over, or one wind farm with a slot of, 35 rotor diameters. The turbine separation distance is 7 rotor diameters.

- 7D (which gives a total farm layout equal to one large farm of 20x10 turbines),
- 21D (i.e. an extra separation of two columns between the farm),
- 35D (4 extra columns; see figure 1),
- 49D (6 extra columns),
- 70D (9 extra columns, which is equal to the size of one farm),
- 100D, and
- 140D.

All calculations are performed at an ambient turbulence intensity of 5% and a free stream wind speed of 9 m/s at hub height. The wind direction is parallel to the rows.

Table 1 presents the ratio of the power production P_2 of the second (downwind) wind farm and P_1 of the first (upwind) wind farm, as a function of the distance between both farms. And figure 2 shows the productions of the individual wind turbines as a function of that distance. It appears that the second wind farm benefits fairly from a farm spacing of 21 rotor diameters. A further increase of the farm spacing however does not increase the power significantly. (However note that this outcome is only valid for the wind direction parallel to the orientation of the two wind farms. For other wind directions, the wake losses are much less severe while an increasing part of the wakes of the first wind farm will not disturb the turbines of the second wind farm when the distance between the farms increases.)

This very limited and almost linear increase of the power production ratio P_2/P_1 after an initial farm spacing of 21 rotor diameters is explained by the turbulence in the wake of the first (upwind) wind farm. The turbulence generated by the first wind farm accelerates the mixing process of the wakes from the turbines in the first column of the second (downwind) wind farm. In this way, the turbines in the second column of the second wind farm actually benefit from the presence of the first wind farm. However, simultaneous with the recovery process of the velocity profile, the added turbulent kinetic energy dissipates slowly. This means that when the distance between both wind farms increases, the turbines in the first column of the second wind farm benefit from further recover of the velocity profile, while the turbines in the second column of the second wind farm take less advantage of the turbulence generated by the first wind farm.

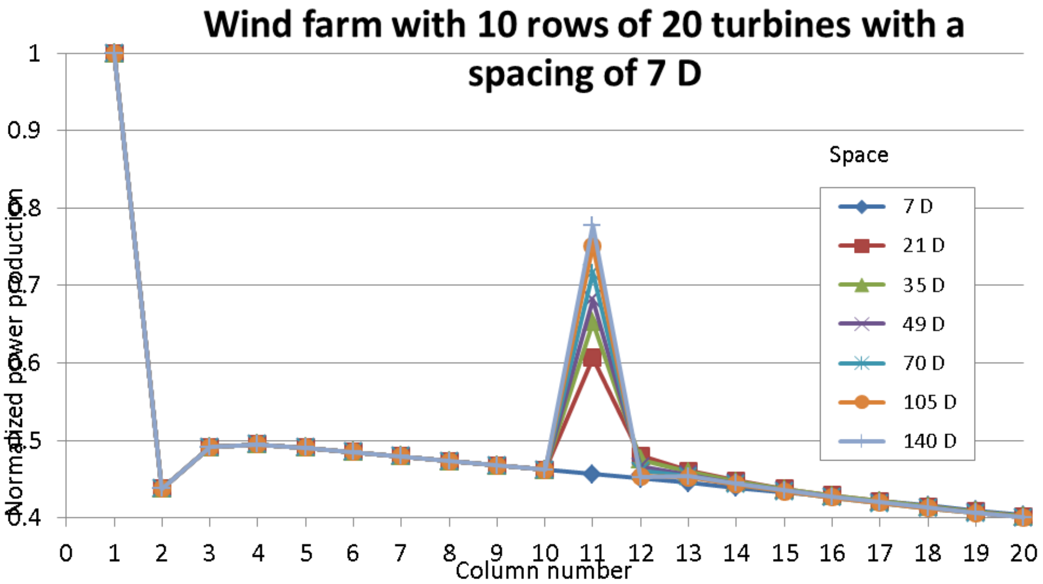

Figure 2. The power P_i of the i-th turbine normalized to the power P_1 of the first turbine in a row of 20 wind turbines separated 7 rotor diameters with a slot between the 10th and the 11th turbine.

The ever decreasing wind speed can be explained with the help of figure 3, showing the development of the wind speed over and through a row of 35 turbines with distances of 7 rotor diameters between the turbines. From this figure it is concluded that the wake loss increases with every next turbine in the row. In addition to that it is concluded that the shear in the velocity profile decreases more after every next turbine in the row, which decreases the production of turbulence. Finally, it is concluded that an internal boundary layer develops over the wind turbines, which effectively prevents the feed-in of high-speed wind from above.

Table 1. The power P_2 of the second (downwind) wind farm normalised to the power P_1 of the first (upwind) wind farm as a function of the distance S between the wind farms as normalised with the rotor diameter D. The wind direction is parallel to the turbine rows.

S (D)	P_2/P_1 (-)
7	0.9074
21	0.9268
35	0.9303
49	0.9309
70	0.9329
100	0.9353
140	0.9385

4. Summary and conclusion

Summarizing, it is found that increasing the slot between two large offshore wind farms does not benefit the production of the downwind wind farm significantly. The benefit of a separation larger than 21 rotor diameters is very limited. The explanation of the slow recovery of the production of the downwind wind farm is that the wake loss increases with every next turbine in the row because the added turbulence is decreased at every next turbine, which in turn decreases the shear in the wind speed profile.

Acknowledgments

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References

[1] Rooijmans P 2004 Impact of a large-scale offshore wind farm on meteorology - Numerical simulations with a mesoscale circulation model. Universiteit Utrecht. Masters thesis

[2] Brand A J 2009 Wind Power Plant North Sea - Wind farm interaction. Energy Research Centre of the Netherlands. Report ECN-E--09-041. 53p

[3] Liu M-K. et al. 1983 Mathematical model for the analysis of wind-turbine wakes. *J. Energy*, Vol. 7, No. 1, pp. 73-78

[4] Hegberg T and Eecen P J 2002 The effect of large wind farms on the atmospheric boundary layer. Global Wind Power Conference 2002, Paris, France

[5] Frandsen S et al. 2004 The necessary distance between large wind farms offshore - Study. Risø National Laboratory. Report Risø-R-1518(EN)

[6] Hegberg T, Corten G P and Eecen P J 2004 Turbine interaction in large offshore wind farms - Atmospheric boundary layer above a wind farm. Energy Research Centre of the Netherlands. Report ECN-C--04-033

[7] Baidya Roy S et al. 2004 Can large wind farms affect local meteorology? *J. Geoph. Research*, Vol. 109, D19101

[8] Skamarock W C et al. 2008 A description of the advanced research WRF Version 3. National Center for Atmospheric Research. NCAR Technical Note

[9] Steinfeld G 2012 Private communication

[10] Schepers J G and Van der Pijl S P 2007 Improved modelling of wake aerodynamics and assessment of new farm control strategies. The Science of Making Torque from Wind II

[11] Bot E T G 2012 FarmFlow - Validation against four full scale wind farms. Energy Research Centre of the Netherlands. Report ECN-E--12-005

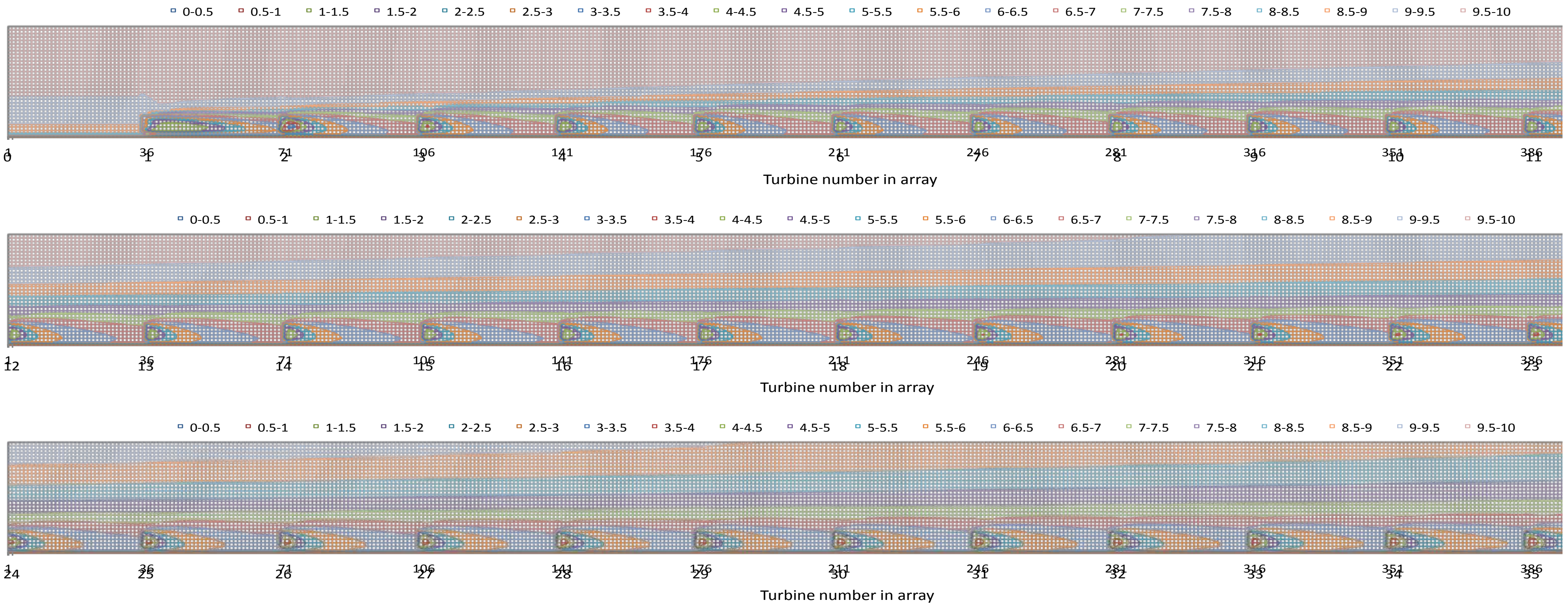

Figure 3. The wind speed profile along a row of 35 wind turbines separated 7 rotor diameters. The color code indicates the wind speed in metre per second.