FARMFLOW

EXTENSIVELY VALIDATED AND DEDICATED MODEL FOR WIND FARM CONTROL

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INTRODUCTION

In a wind farm, turbines affect each other through their wakes, decreasing their power production and increasing the structural loading (wear and tear) of their components. It is still a common practice to operate wind turbines individually, each maximizing its own power production. Such strategy ignores the wake effects and is thus not optimal for maximizing power output at wind farm level. This triggered TNO researchers to develop a new, cooperative approach called active wake control (AWC). Patents for the potentially game-changing technology were granted already in 2003. AWC deals with mitigating the wake effects by coordinated control at farm level. AWC boosts the annual energy production (AEP), elongates turbine lifetime, and hence contributes to lowering the levelized cost of wind energy.

To maximize the potential benefits from AWC, it is essential to optimize the AWC strategy by making use of an accurate model for the wake effects. To this end, TNO has developed the cutting-edge software tool FarmFlow: a 3D parabolised CFD code, that achieves very accurate results at acceptable calculation time. FarmFlow allows to optimize and predict the effects of different AWC strategies, such as induction control (achieved by power down-regulation), wake redirection (achieved by yaw misalignment), or combination of these. In various benchmark studies in the past, FarmFlow proved to provide often the highest accuracy for large offshore wind farms in comparison with other wake models.[1]

Recent model improvements brought FarmFlow predictions even closer to real-life measurements. For validation of the newly improved model, FarmFlow results are compared with measurements from different wind farms and wind tunnel experiments. The validation results include velocity deficits in single wakes, power deficits in both single and multiple wakes, annual energy productions of wind turbines in an offshore wind farm, and deflected and reduced wakes behind wind turbines with yaw misalignment. This report summarizes the results from these validation studies.

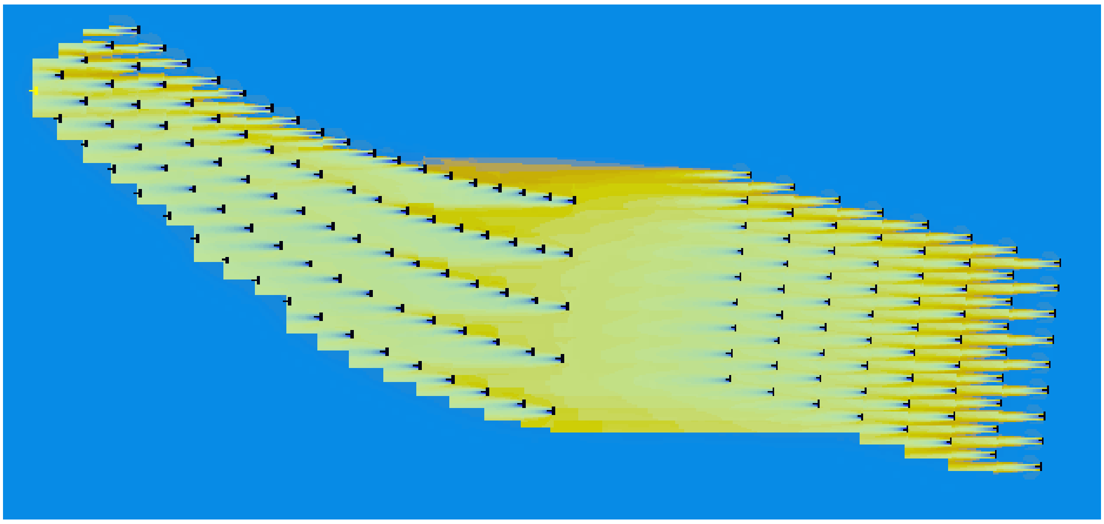

Figure 1: FarmFlow simulation of wakes in a cluster of wind farms

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[1] Réthoré, Pierre-Elouan; Hansen, Kurt Schaldemose; Barthelmie, R.J.; Pryor, S.C.; Sieros, G.; Prospathopoulos, J.; Palma, J.M.L.M.; Gomes, V.C.; Schepers, G.; Stuart, P., Benchmarking of wind farm scale wake models in the EERA - DTOC project, Proceedings of the 2013 International Conference on aerodynamics of Offshore Wind Energy Systems and wakes (ICOWES2013), Denmark,

FARMFLOW MODELING

WAKE MODEL

FarmFlow makes use of a wake model that solves the Reynolds Averaged Navier Stokes (RANS) equations in three dimensions. The free stream axial velocity and turbulence intensity are modelled as a function of height, based on the friction velocity, the surface roughness and the Monin-Obukhov length. The RANS equations are parabolized in streamwise direction so that the solution can be obtained very efficiently by “marching” in the stream-wise direction. The streamwise pressure gradients in the near wake region are obtained from an inviscid calculation and prescribed as a source term in the RANS equations. These pressure gradients are pre-calculated from a panel method with an actuator disk model in which the wake is represented by discrete constant strength vortex rings. Because these pressure gradients are only a function of the axial force coefficient in inviscid flow, a database has been created with 2D (axisymmetric) pressure gradients as a function of the axial induction factor. This way the wake model includes the near wake region while still benefiting from the computationally very efficient marching procedure.

The effect of turbulent processes occurring in the wake are simulated with a two-equation turbulence model that determines the turbulent kinetic energy k and its rate of dissipation ε. A known problem with the standard k-ε turbulence model is overestimated wake recovery in the near wake region due to neglecting the delay of turbulent kinetic energy production in the simplified flow field described by the time averaged equations. Studies with high fidelity dynamic LES simulations have shown that tip vortices in the near wake region reduce shear and impede exchange of momentum, while the process of turbulent mixing becomes significant after the tip-vortex breakdown. FarmFlow addresses these phenomena by discerning three wake regions for the turbulence model: the near wake, transition, and the far wake.

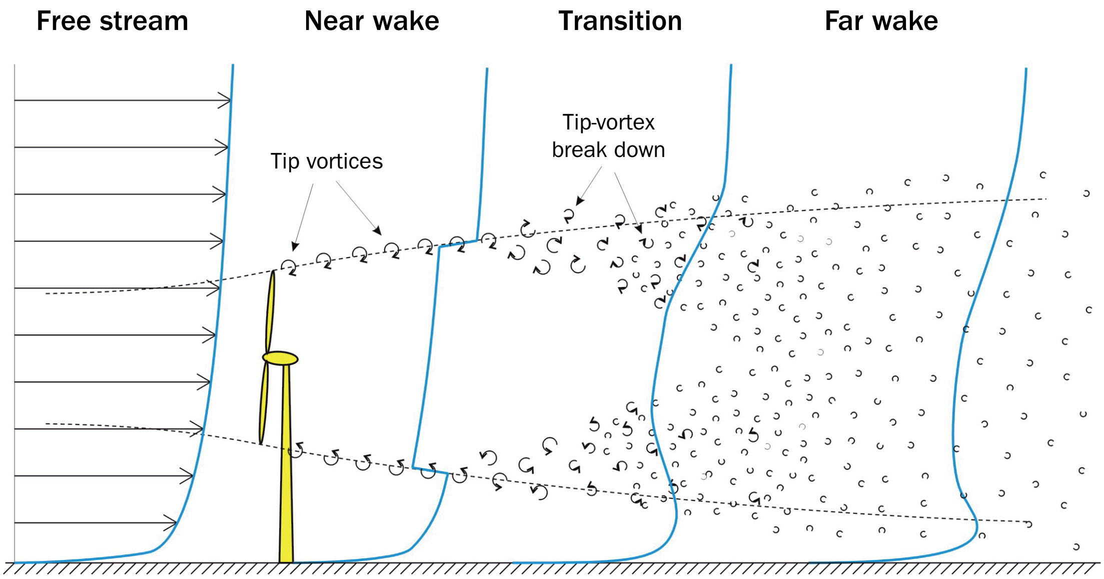


Figure 2: Turbulence development in a wind turbine wake

In the near wake region the turbulence production is strongly limited because of the shear-reducing tip vortices. In the transition region the turbulence dissipation rate is slightly adapted and in the far wake the standard k-ε turbulence model is applied. The length of the near wake region and the adapted turbulence dissipation rate in the transition region depend on the rotor inflow conditions, and have been calibrated on basis of a huge amount of available experimental data.

The wake model in FarmFlow enables the simulation of yaw misalignment with accurate prediction of the most important effects on the wake: a deflected wake with narrower shape and reduced velocity deficit. Active Wake Control (AWC) is a wind farm controlling concept that uses yaw misalignment to deflect wakes away from downstream turbines in order to increase the total energy production of the wind farm and to reduce fatigue loading of the wind turbines.

SINGLE WAKE DEFICITS IN VARIOUS ATMOSPHERIC CONDITIONS

For a single wake model benchmark with field data in 2018, high quality lidar measurements of single wakes in various atmospheric conditions became available for participants in the EU H2020 project CL-WindCon. FarmFlow was one of the models included in the benchmark. The inflow wind field was measured with a nacelle mounted forward facing lidar, a mast upstream of the test turbine (IEC compliant) that measured the wind speed and direction (with cups, sonics and vanes) and the temperature gradient, and with a vertical lidar (Windcube V2) that measured the vertical wind profile. The wakes were measured with a Windcube 200s scanning lidar at the tower base. The test turbine is operational in a wind farm in South Texas, and has a rotor diameter of 116 m and a hub height of 80 m. For the dominant wind direction, this turbine is exposed to free stream wind conditions.

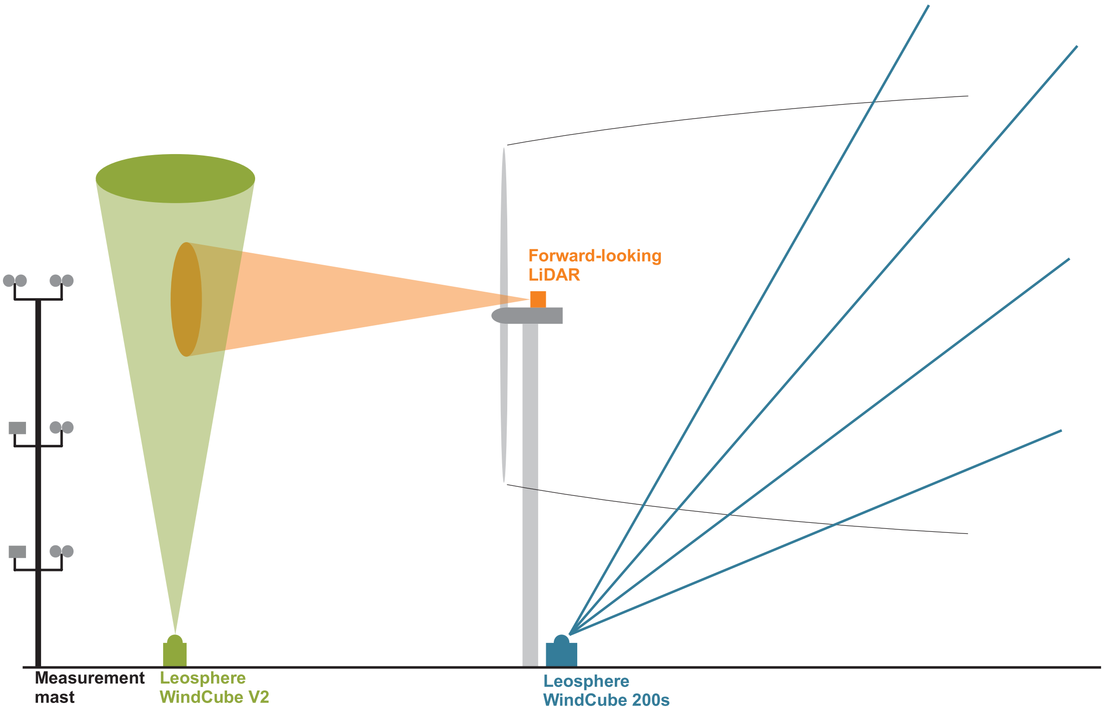


Figure 3: Instrumental setup

As a follow up to this benchmark study, a significantly improved near wake turbulence model has been developed for FarmFlow. With this renewed model, the most important shortcomings of the previous model were addressed. In this section, the measured single wakes are compared with results from the old and new FarmFlow model. Figures 4 and 5 show the hub-height velocity deficit profiles from the lidar compared to FarmFlow results with the old and new near wake model for neutral, stable and unstable conditions respectively. The hub-height velocity deficits are plotted at four downstream distances between 3.4 and 11 rotor diameters (D) for normal operation and wind speeds of 6-8 m/s. It is clear that results with the new near wake model show much better agreements with the lidar data. For all three atmospheric conditions FarmFlow predicts the wake diameter, the wake centre velocity and the upspeeding effect very accurately.

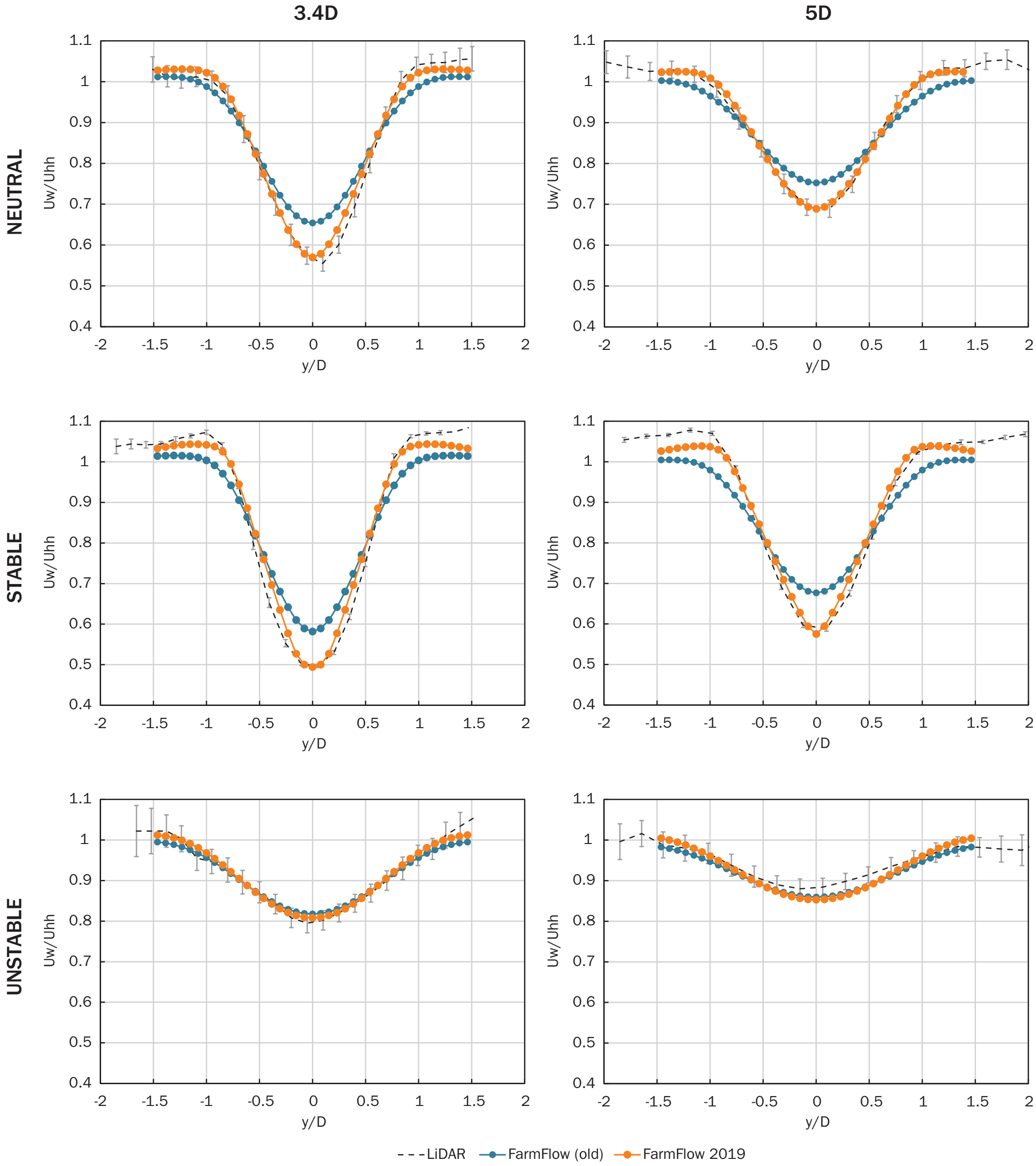


Figure 4: Hub-height velocity deficit profiles for 6-8 m/s at 3.4D and 5D distance downstream for neutral, stable and unstable atmospheric conditions

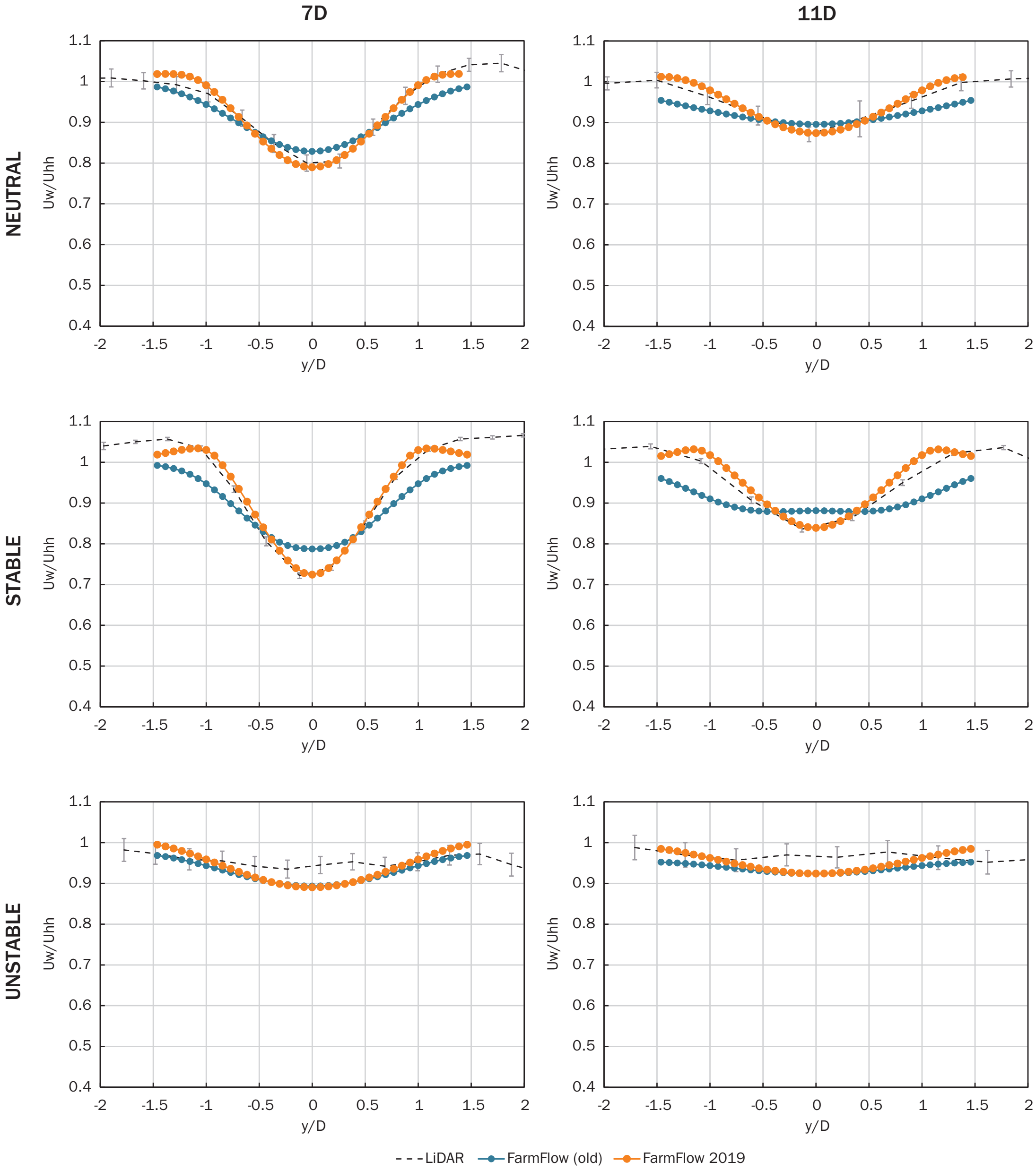


Figure 5: Hub-height velocity deficit profiles for 6-8 m/s at 7D and 11D distance downstream for neutral, stable and unstable atmospheric conditions

HORNS REV OFFSHORE WIND FARM

WIND FARM LAYOUT

The Horns Rev wind farm is located 14 km from the west coast of Denmark. The wind farm comprises 80 Vestas V80 wind turbines arranged in regular arrays of 8 by 10 turbines with an internal spacing of 7 rotor diameters, see Figure 6. The two diagonal spacings are 9.4 and 10.4 rotor diameters. The 2MW wind turbines are pitch controlled with a rotor diameter of 80 m and 70 m hub height. Meteorological measurements are performed on three met masts. Instrumentation on a height of 62 m is installed on met mast M2, 2 km north west of the wind farm. East from the wind farm, two met masts are installed at a distance of 2 km (M6) and 6 km (M7), both with instrumentation at 70 m height.

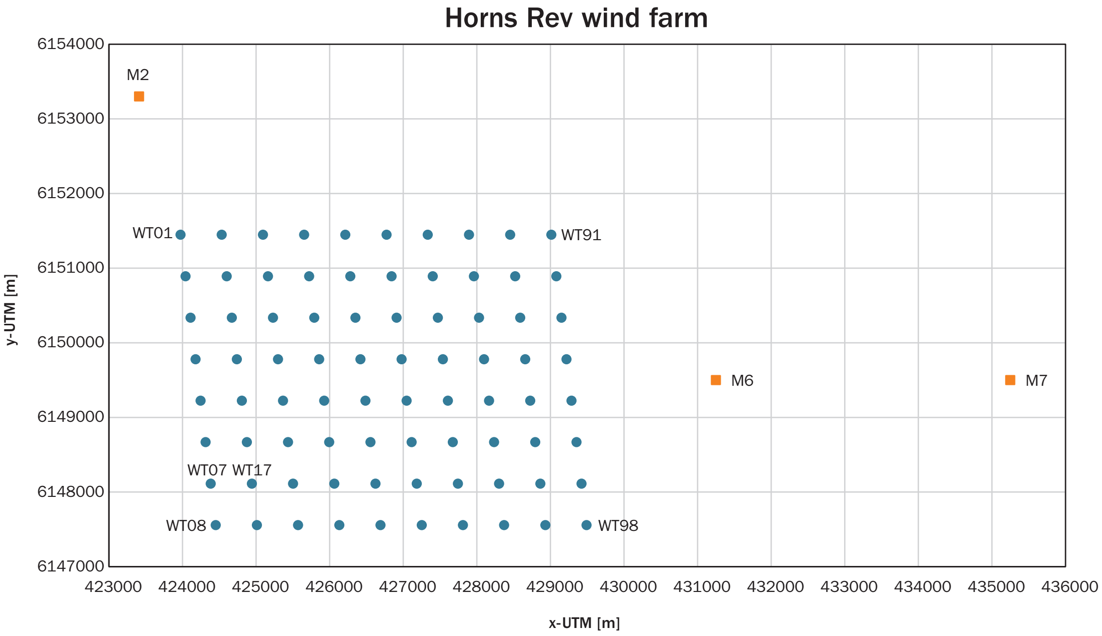


Figure 6: Layout of the Horns Rev offshore wind farm

SINGLE WAKE POWER DEFICIT

For wind directions between 250° and 290°, turbine wt07 is exposed to free stream wind conditions, while turbine wt17 is exposed to the wake of turbine wt07. The measured normalized power deficit of turbine wt17 ($1 - P_{WT17}/P_{WT07}$) is plotted in Figure 7, including error bars representing the standard deviations of the 5° averaged results. In order to reduce scatter, the measurements have been averaged using a 5° moving window of the wind direction. Also for the FarmFlow results this 5° moving window technique is used.

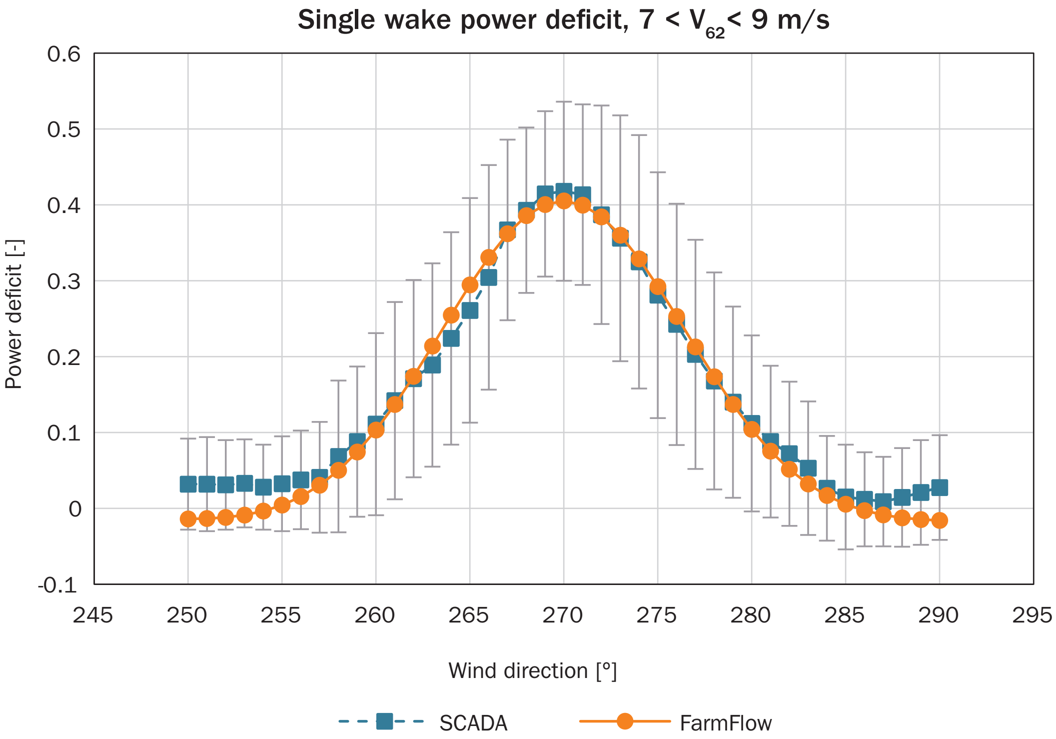
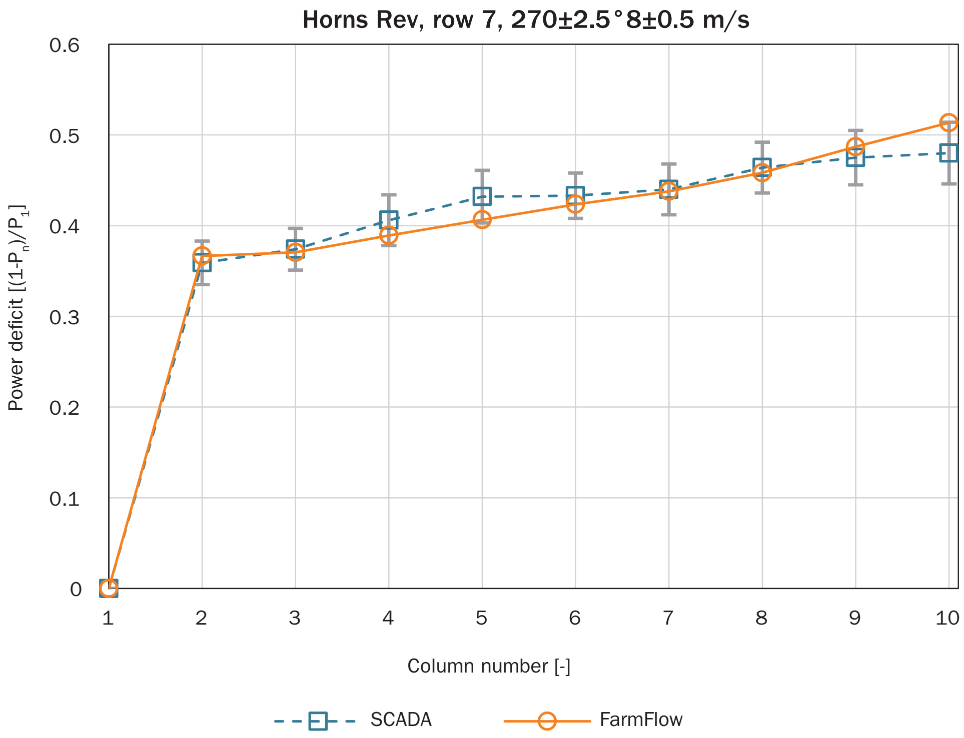


Figure 7: Power deficit of turbine wt17 due to a single wake from turbine wt07 as a function of the wind direction for wind speeds between 7 and 9 m/s at neutral conditions

ARRAY POWER DEFICIT

For a wind direction sector of 270° with a narrow and wide averaging sector of ±2.5° and ±15° respectively, the power deficit of the 7th row is compared with results from FarmFlow in Figure 8. The turbulence intensity is measured at met mast M7, 6 kilometers downstream of the wind farm. The wind direction is measured using the nacelle position of wind turbine WT07 and the wind speed is determined from the power curve of WT07. Measurements have been selected for a wind speed range of 8 ±0.5 m/s at an average turbulence intensity of 0.07. In both the narrow and wide averaging sectors, FarmFlow consistently matches closely the shape of the SCADA points.



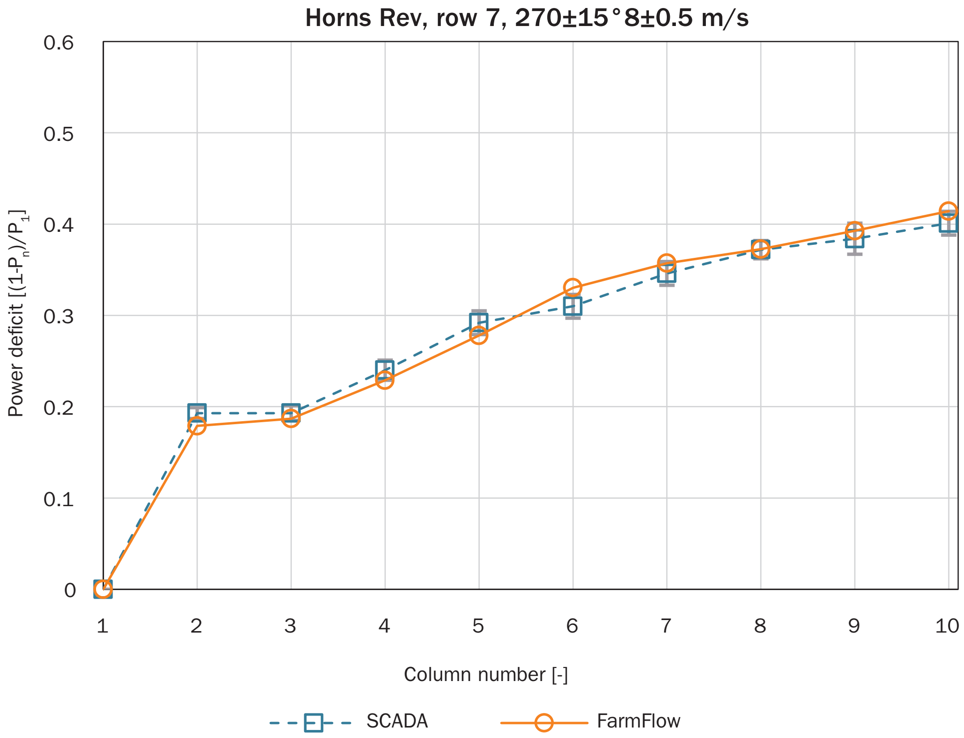


Figure 8: Power deficit in a row of turbines for a narrow (top) and wide (bottom) averaging window of 5° and 30° respectively

EWTW

WIND FARM LAYOUT

The research wind farm at the ECN Wind Turbine Test Site Wieringermeer (EWTW) is located next to the lake IJsselmeer, in the North East of the Province Noord- Holland in the Netherlands. In 2008, EWTW comprised 4 prototype turbines (numbered P1-P4, see Figure 9) and the research wind farm consisting of five Nordex N80 turbines (numbered R5-R9) oriented in a single line directed 95-275° with respect to north, with a mutual distance of 3.8D. The research turbines are variable speed and pitch controlled, with a rotor diameter and hub height of 80 m. A meteorological mast (MM3) is located at a distance of 2.5D from research turbine R6 and 3.5D from R5.

Figure 9: ECN Wind Turbine Test Site Wieringermeer with 5 research turbine (R5-R9)

In the years 2005-2007 wind characteristics and power production in wake conditions have been measured in the research wind farm of EWTW.

POWER DEFICITS

Figure 10 shows the single, double, triple, and quadruple power loss profiles (normalized with the free stream power production from the first turbine) of the research turbines for wind speeds in the range 6-8 m/s, as a function of the wind direction.

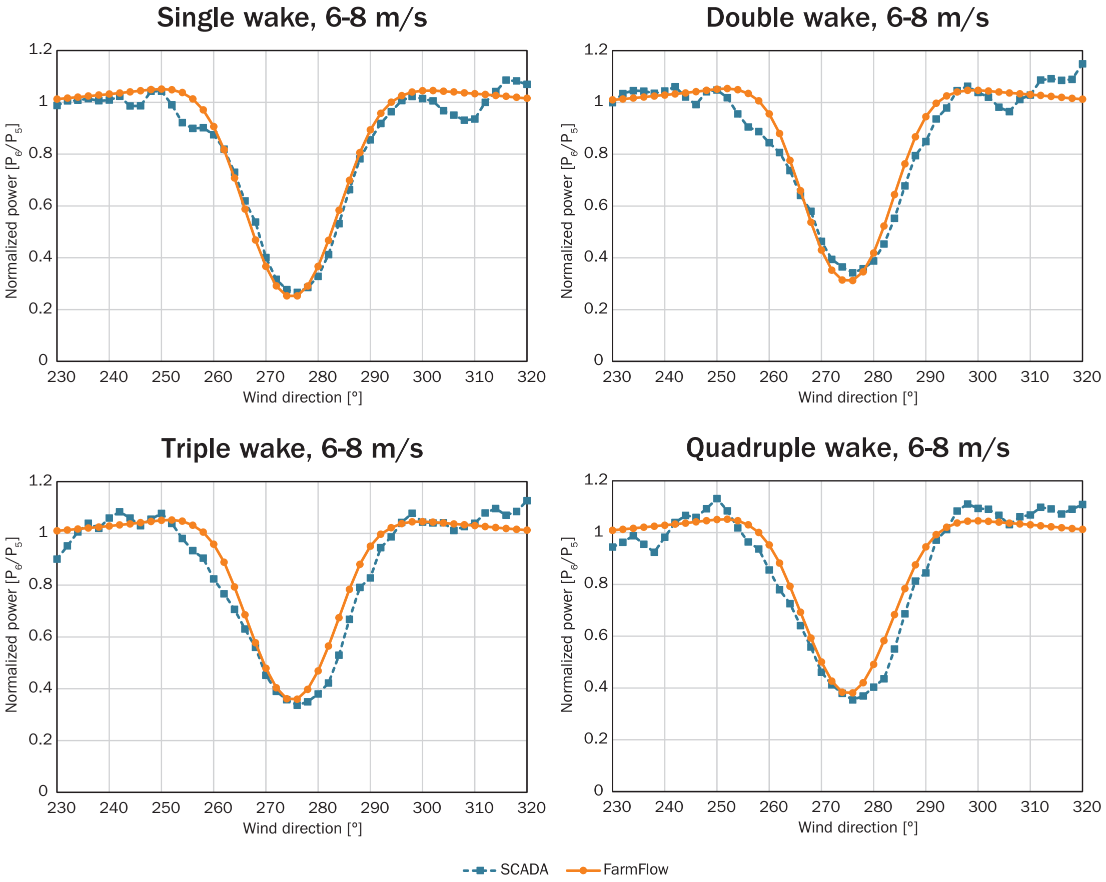
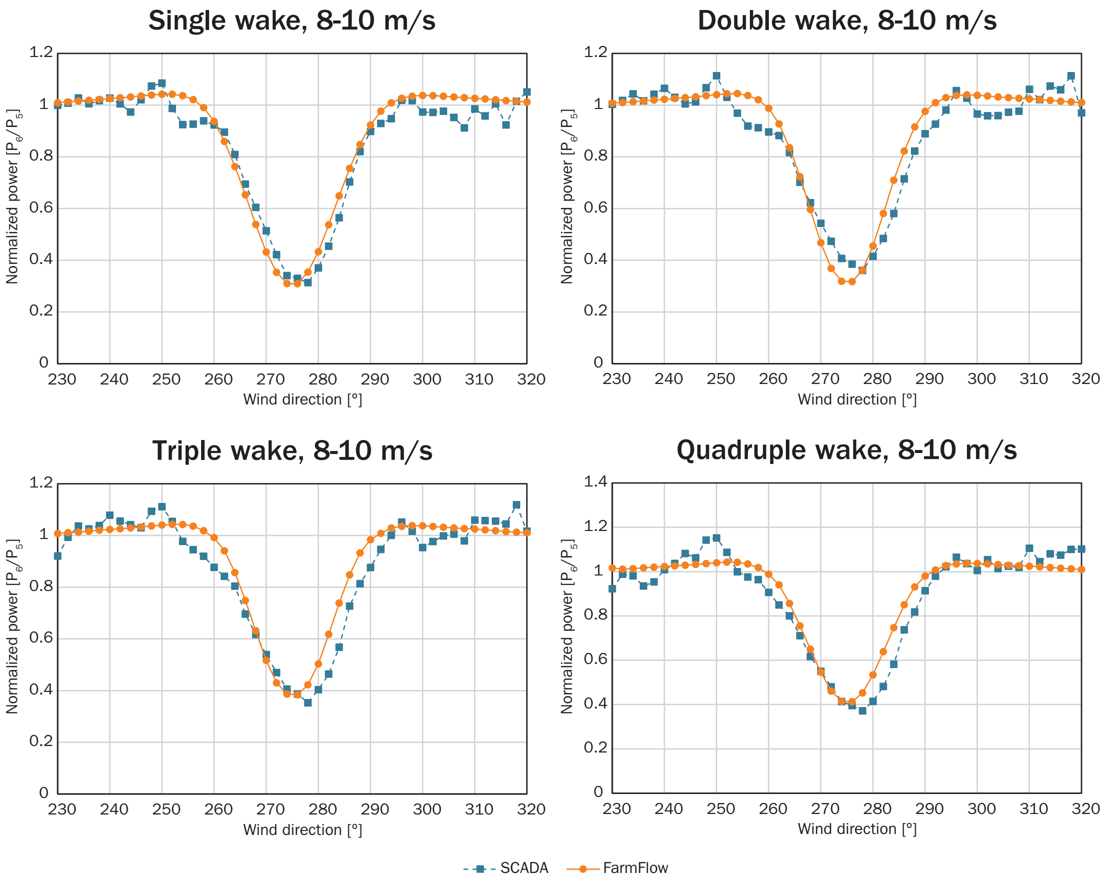


Figure 10: Power deficits of single, double, triple and quadruple wakes at 6-8 m/s wind speed

For the single wake, FarmFlow matches the measured wake deficit nearly perfectly. The largest power loss occurs in single full wake. In multiple wakes there is more turbulent mixing causing faster recovery. For the triple and quadruple wakes it seems that the grow in diameter of the profiles are a little bit larger than predicted by FarmFlow. The wider triple and quadruple wake profiles are probably the result of wake deflection due to asymmetric (half-wake) conditions, which is not (yet) modelled in FarmFlow.

Figure 11 shows the single, double, triple, and quadruple power loss profiles (normalized with the power of the first turbine in the row) of the research turbines for wind speeds in the range 8-10 m/s. Due to lower thrust coefficients at these higher wind speeds, the wake effects are slightly smaller in comparison with Figure 10. Other than that, the same conclusions on the comparison between measured and simulated power losses can be made.


Single wake, 8-10 m/s

Double wake, 8-10 m/s

Triple wake, 8-10 m/s

Quadruple wake, 8-10 m/s

Figure 11: Power deficits of single, double, triple and quadruple wakes at 8-10 m/s wind speed

For the maximum power deficit in full wake conditions, Figure 12 shows the power deficits as a function of the turbine position in the row for low wind speeds (6-8 m/s) and above rated wind speed (14-16 m/s). Here it is found that only at low wind speeds the maximum power deficit occurs in the single wake condition (i.e. for the turbine in position 2). Above rated wind speeds, the thrust coefficient decreases with wind speed, which causes stronger wake production by the next turbine in the row. These two different trends are very well predicted by FarmFlow.

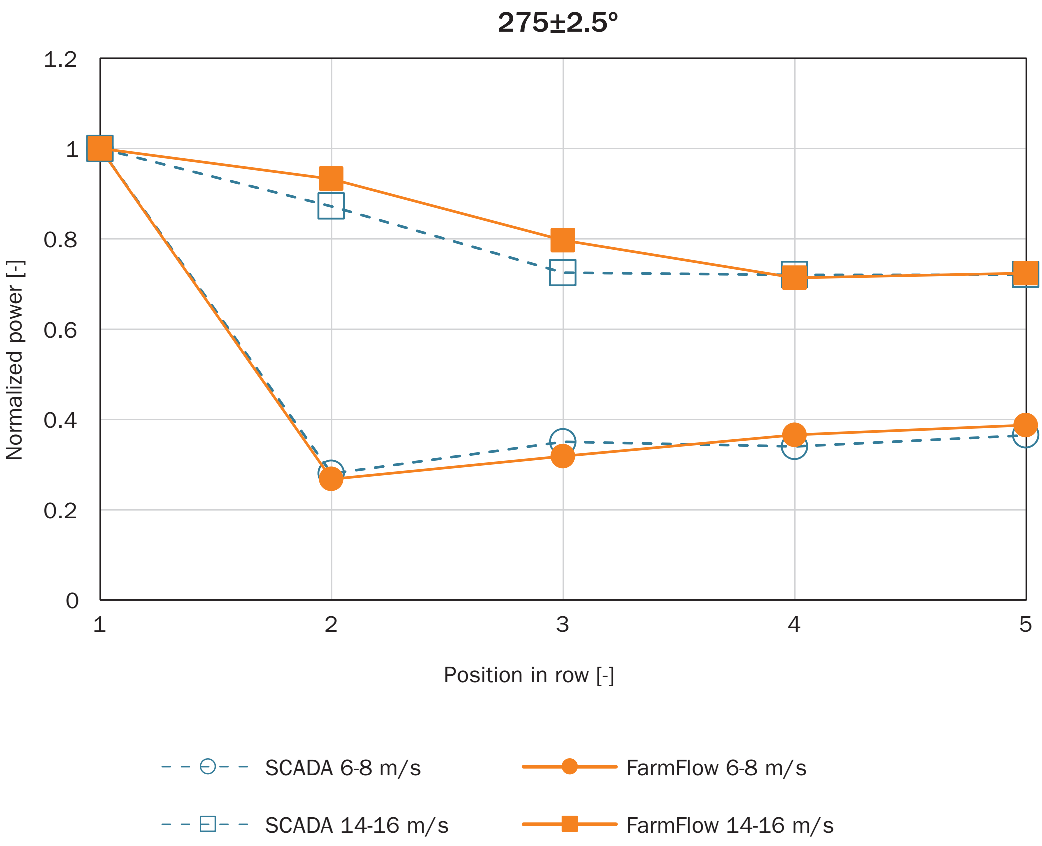


Figure 12: Power deficits of the EWTW research turbines in full wake at 6-8 and 14-16 m/s wind speed

Comparisons of the power deficits as a function of the wind speed between 3 and 16 m/s in full single, double, triple, and quadruple wake are shown in Figure 13. Above 6 m/s the SCADA data and FarmFlow results agree very well. At lower wind speeds the SCADA are not reliable: according to the measurements, the Nordex turbines still produce power in full wake conditions when the free wind speed is already below the cut-in wind speed of 3.5 m/s. This means that the SCADA data deviates from the power curve that is used in FarmFlow for wind speeds below 6 m/s.

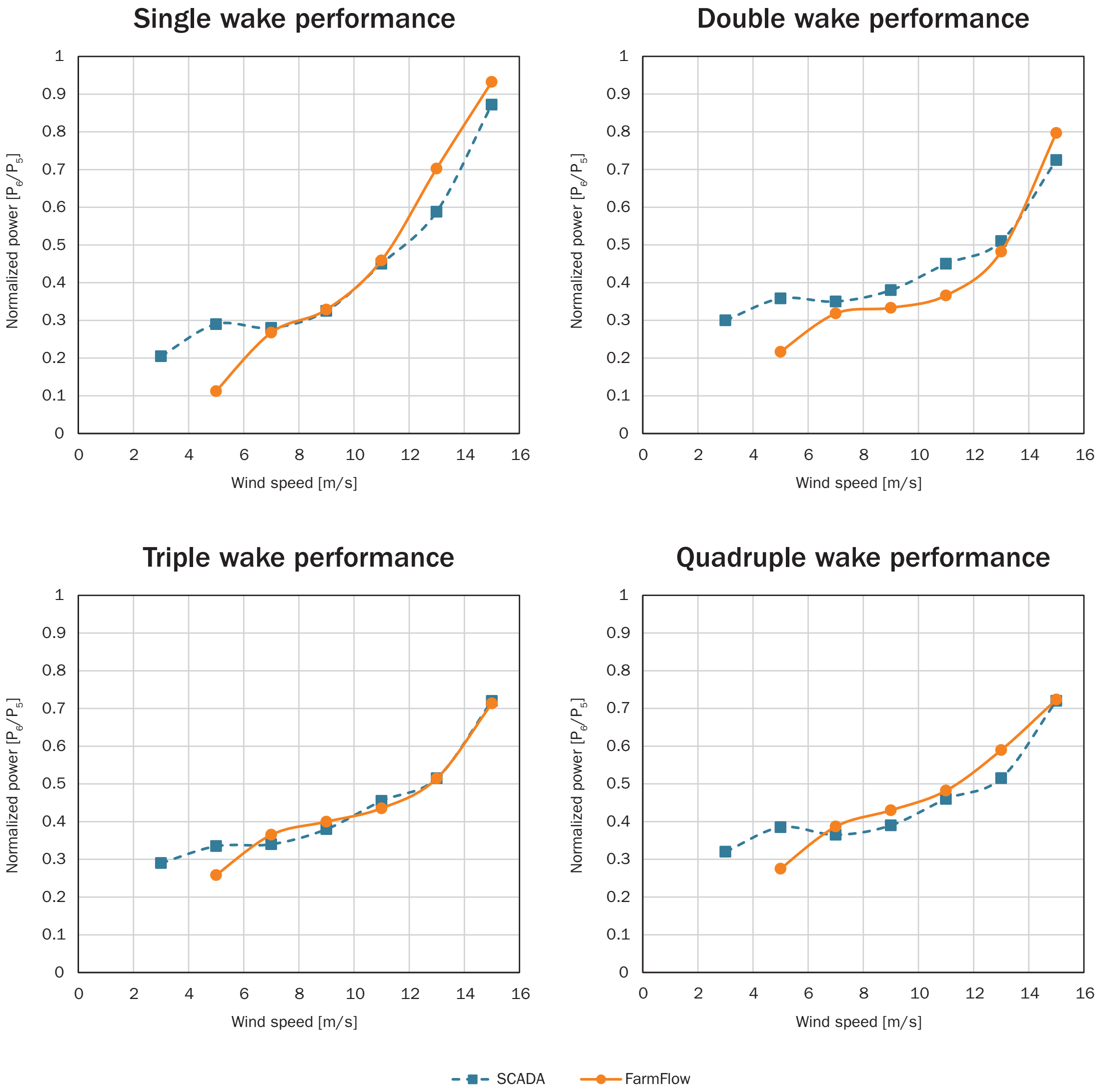


Figure 13: Power deficits of full single, double, triple and quadruple wakes as a function of wind speed.

OWEZ

WIND FARM LAYOUT

The Offshore Wind farm Egmond aan Zee (OWEZ) consists of 36 Vestas V90 3MW wind turbines with a total capacity of 108 MW. The wind farm is located 10 to 18 km off the coasts of Egmond aan Zee, with a size of 27 km^2. Numbering and location of the wind turbines are shown in Figure 14. The wind turbines have a rotor diameter of 90 m, a hub height of 70 m above mean sea level and a capacity of 3 MW.

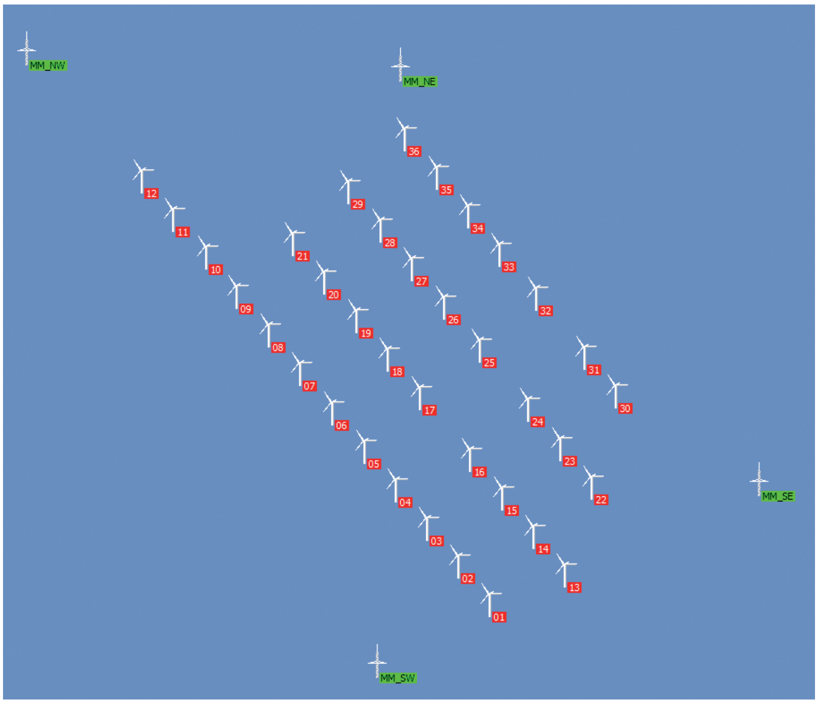


Figure 14: FarmFlow model of OWEZ including 4 virtual met masts on grid points of DOWA time series

ANNUAL ENERGY PRODUCTION

As part of a validation study of the Dutch Offshore Wind Atlas (DOWA), NoordzeeWind has provided times series of OWEZ production data for the period 2008-2010. The wind farm production has been simulated with FarmFlow using DOWA time series in the year 2010 at four grid positions around the wind farm. In the FarmFlow model of OWEZ shown in Figure 14, these grid positions are denoted by virtual met masts.
The time series of OWEZ production data are 10 minute averages. Because DOWA time series contain hourly wind data, production data have been transformed to time series of hourly average productions.

In Figure 15 the average of measured and simulated wind farm power per turbine is plotted as a function of the DOWA wind speed. The graph contains vertical error bars at the observed values that represent the 95% confidence intervals, and a histogram of the data count per wind speed bin.

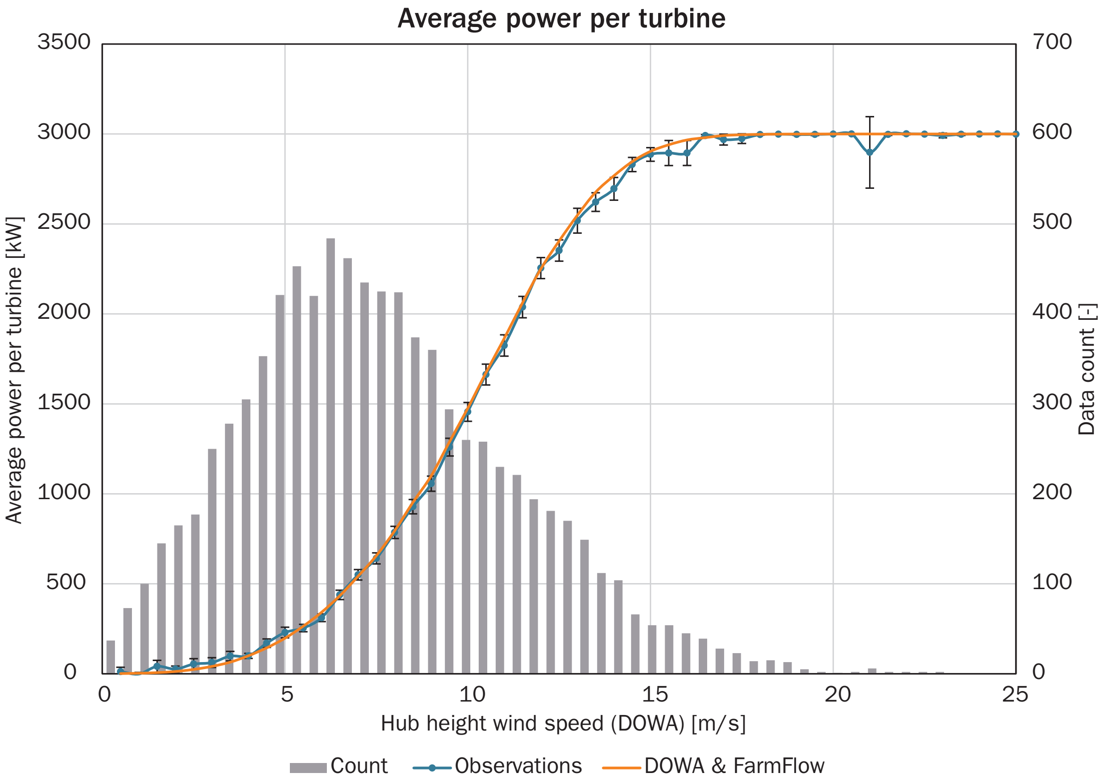


Figure 15: Comparison of the measured and simulated average power production per turbine of OWEZ in 2010, including 95% confidence intervals (error bars) and a histogram of the hourly data points per wind speed bin

Figure 16 shows a comparison of the average power of individual turbines between observations and FarmFlow simulations with DOWA wind, before correction for the average bias. After correction for the average bias, the difference in simulated and measured production is less than 1.8% for 34 of the 36 turbines. The other two turbines produced 2.4% en 2.8% less than the corrected simulated production. Because these two turbines (number 10 and 18) also produce less than neighbour turbines under similar conditions, it is expected that their production is reduced by yaw misalignment or a technical problem.

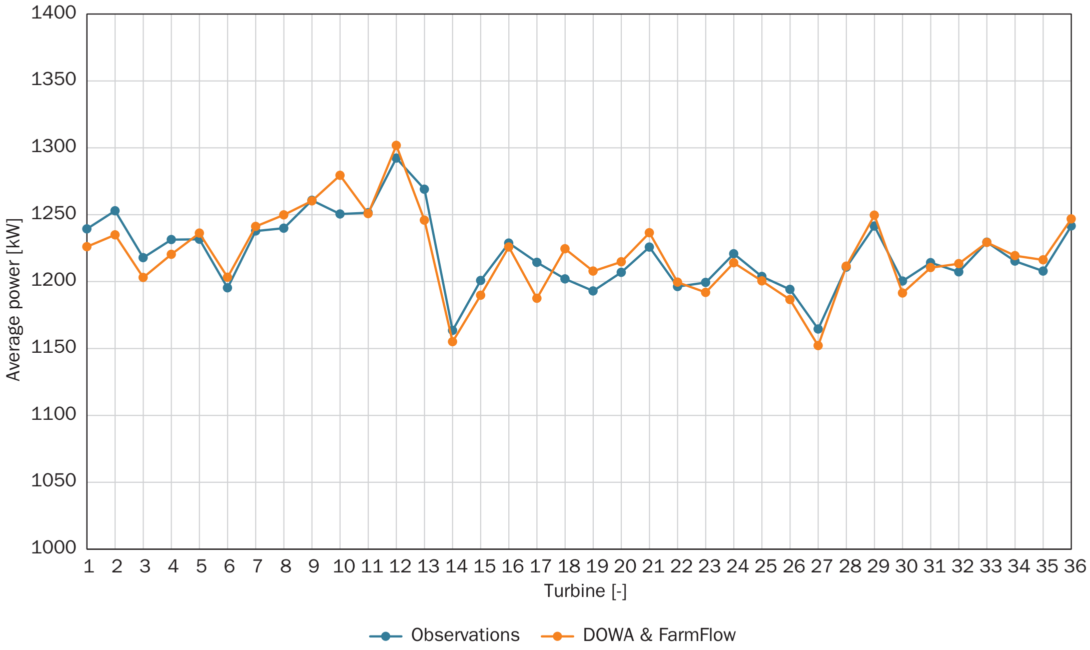


Figure 16: Comparison of the measured and simulated average power productions of individual turbines in OWEZ in 2010

ACTIVE WAKE CONTROL

For validation of the yaw misalignment model, results from FarmFlow have been compared to data from wind tunnel experiments. Recently, in the EU H2020 project CL-WindCon, wind tunnel experiments have been executed in the low-speed turbulent boundary layer wind tunnel at Politecnico di Milano. For the study of wake deflection by yaw misalignment, single turbine measurements have been carried out with a single turbine model with 1.1 m rotor diameter and 0.83 m hub height. The wind conditions are characterized by a turbulence intensity of 6% at an average wind speed of approximately 5.5 m/s.

During normal (un-yawed) operation, the turbine model operates at a rotor power coefficient of 0.37 and a rotor thrust coefficient of 0.79 at the chosen wind speed characteristics. Figure 17 shows comparison of the hub-height velocity deficit profiles between the experiments and FarmFlow simulations at 3D, 7.5D, and 10D with yaw misalignment angles between -40° and 40°. Both regarding the shape of the velocity deficit profile and the amount of wake deflection, there is very good agreement between the measured and calculated profiles in all cases.

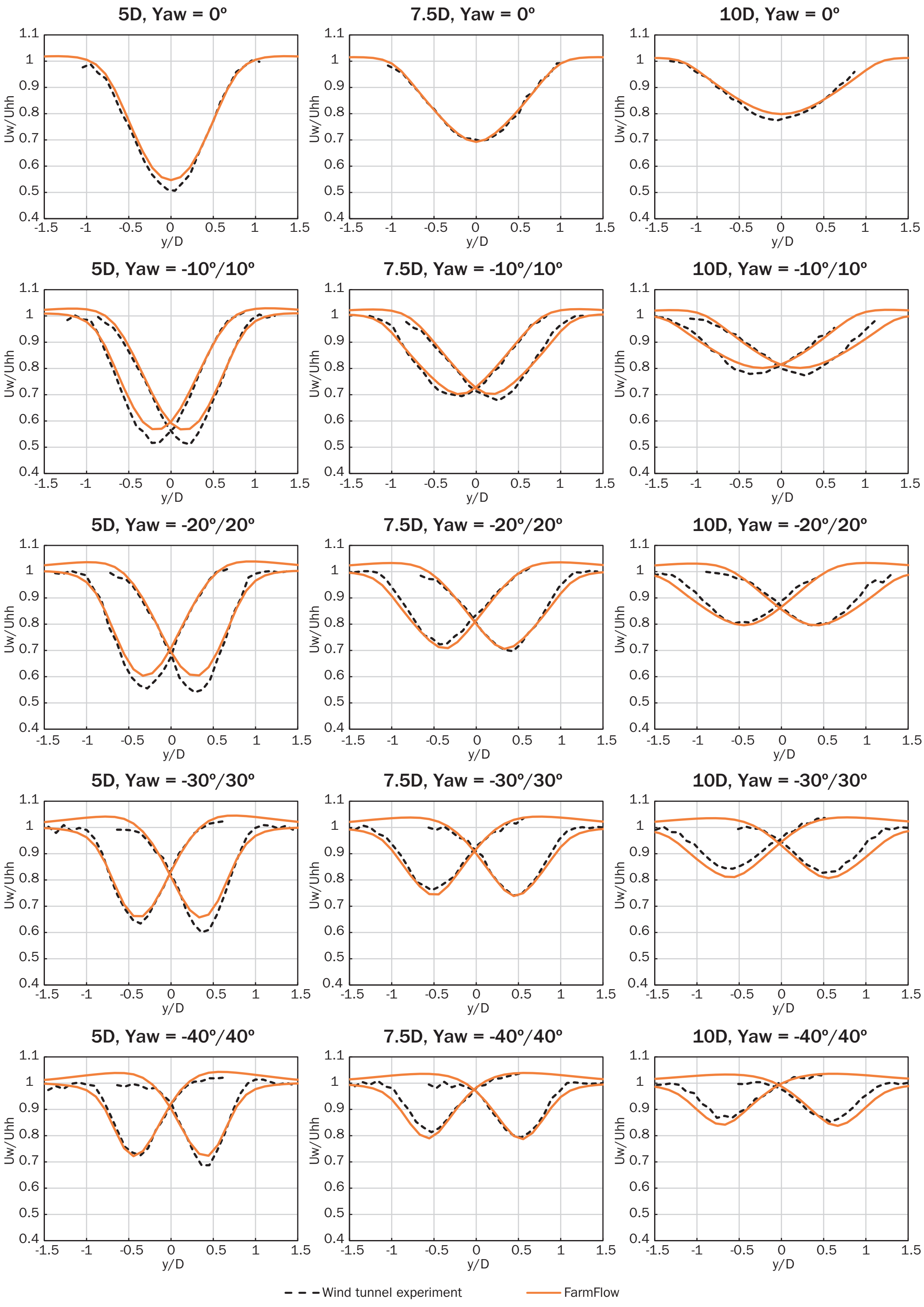


Figure 17: Hub-height velocity deficit profiles at 3D, 7.5D, and 10D distance downstream a scaled turbine with yaw misalignment angles between -40° and 40°

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