Physical scale integration (coupled use)

John Prospathopoulos, Jake Badger, Patrick Volker, George Sieros, Panagiotis Chaviaropoulos, Pierre-Elouan Rethorè

8-7-2013

Agreement n.:	FP7-ENERGY-2011-1/ n°282797
Duration	January 2012 to June 2015
Co-ordinator:	DTU Wind Energy, Risø Campus, Denmark

Support by:

Document information

Document Name:	Physical scale integration (Coupled use)
Document Number:	D1.2
Author:	John Prospathopoulos (CRES)
Date:	8-7-2013
WP:	WP1
Task:	Task1.3

Table of contents

1 EXECUTIVE SUMMARY

EERA-DTOC project aims at developing and integrating new software tools for optimal design of offshore wind farm clusters. The design of wind farm clusters requires integration of two different scales, the wind farm scale resolved by the microscale models (resolution on the order of meters) and the cluster scale resolved by the mesoscale models (resolution on the order of hundreds or thousands of meters). Uncertainties in the offshore wind farm cluster modelling stem from both scales: The large spatial extent of clusters on the one hand and the need for detailed representation of the flow within the wind farms on the other hand (including the appropriate setting of boundary conditions).

The task is to match and pair wake models from wind farm to cluster in a proper way, so that the information can be transferred from the one scale to the other with the least possible uncertainty. This implies an accurate simulation of the interaction between neighboring wind farms in the cluster scale, which affects the speed deficit and the power production of the downstream installations. In the present study such a coupling is realized using the CRES-flowNS microscale RANS solver and the Weather and Forecast Research, WRF, mesoscale model a very widely used community mesoscale model, which already has an implementation of a parameterization of wind turbine wakes. The Horns Rev offshore wind farm experiencing a wind of 8m/s from 270^o (hub height) is the simulated test case.

The main concept is the estimation of the wind turbine thrusts with the microscale model (wind farm scale) and the transfer of this information to a mesoscale model (cluster scale). Two coupling approaches are validated and tested, the first one is aggregation of wind turbine thrusts on the basis of the whole wind farm and the second is aggregation of thrusts on the basis of the mesoscale grid cells. A first validation is performed by applying the microscale model to a coarse (mesoscale) mesh and comparing the results with those provided on the fine (microscale) mesh. Aggregation of turbine thrusts on the basis of the mesoscale grid cells realizes a more accurate spatial distribution of the turbine thrusts, resulting in a better reproduction of the vertical profile of the velocity deficit.

Application of the two coupling approaches is made on transferring the wind turbine thrusts estimated by the CRES-flowNS microscale model to the WRF mesoscale model. It is found that whether aggregation is made on the basis of mesoscale grid or the whole wind farm is significant for the wake inside the wind farm. However, downstream of the wind farm, differences are reduced and predictions using the whole wind farm aggregation concept seem to agree well with the measurements. A sub-mesoscale-grid vertical wake expansion is proved to capture the wake behavior inside the wind farm and the near wind farm wake. Without the vertical wake expansion the wake deficit tends to be too concentrated in the vertical direction, which results in a too strong deficit. However, moving downstream of the wind farm into the far wake, the difference caused by including sub-mesoscale-grid vertical wake expansion, or not, becomes much less pronounced.

2 INTRODUCTION

Due to the growing demand for offshore wind energy capacity, interactive wind farm clusters will unavoidably appear at favorable locations. The design of such clusters poses new challenges regarding the siting of the neighboring wind farms. The target of the EERA-DTOC project is to develop and integrate new software tools for optimal design of offshore wind farms and clusters. A significant issue is the interaction between neighboring wind farms which affects the speed deficit and the power production of the downstream installations. In order to quantify this interaction the wind farm and the cluster scale must be coupled through numerical simulation. The main objective of this task is to use the information provided by the wind farm model as input to the cluster model in a proper way, so that the total wake effect of a wind farm is captured correctly by the cluster model

A wind farm scale model operates at rather fine resolution, on the order of meters, and belongs in the category of the so-called microscale models. A large number of such models have been developed and applied for the simulation of wind farms with varying degree of complexity from the engineering ones like the amended GCL [1] or the known and straightforward WAsP model [2] to the moderately complex Ainsle-based WindFarmer [3] and the more complex WAKEFARM [4] and FUGA [5] models, that are based on the parabolized and linearized Navier–Stokes equations respectively. Advanced 3D RANS solvers like Fluent, 3D–NS [6] and CRES-flowNS [7] have also been applied for offshore and onshore wind farms in complex terrain. In the context of the UpWind project [8], many of these models were used to simulate the large offshore wind farms of Horns Rev [8,9] and Nysted [8]. Predictions were compared with measurements for the western wind directions at various sector widths around 270º and assessment turned out to be extremely difficult due to the large uncertainties of the measurement data due to the atmospheric conditions. In general, wake losses in the centre of large wind farms offshore were larger than modeled suggesting that further validation and calibration of the models was necessary. The latter is the objective of Task 1.1 of the EERA-DTOC project.

A cluster scale model should simulate the collective impact of multiple wakes from several wind turbines. Its resolution is on the order of thousands of meters and in that sense it belongs in the category of the so-called mesoscale models as for example [10]. The mesoscale model cannot explicitly model the individual turbines wakes, yet the microscale model alone cannot model influences of mesoscale circulations (at scales of several kilometres), such as coastal winds, convective systems, and orographic forced flow which may have a strong influence on the wake behaviour. The basic idea is that information from microscale wake models is passed in some form to the mesoscale models. The Weather and Forecast Research [11], WRF, a very widely used community mesoscale model, already has an implementation of a parameterization of wind turbine wakes [10] by applying a thrust, via the prognostic velocity tendency equation.

In the context of Task 1.3, the EERA-DTOC project aims at coupling the results of a microscale model with the mesoscale model in order to simulate the interaction between neighboring wind farms in the cluster scale. To this end, the CRES-flowNS microscale model and the WRF mesoscale model are used. First, a description of the two models is given (Section 3). Then, the different approaches of coupling are presented (Section 4). Results of the coupled use of the models are given in Section 5 by simulating the Horns Rev offshore wind farm for the western wind direction. The microscale model is also applied with a cluster scale mesh to assess the effect of the different approaches. Conclusions are summarized in Section 6 and suggestions for future work are made.

3 NUMERICAL MODELS

3.1 Microscale modeling

3.1.1 CRES-flowNS solver

The microscale model used in this study is Each farm is the inhouse RANS solver CRESflow-NS [7]. It implements the k-ω turbulence model for closure and the actuator disk theory for the simulation of the embedded wind turbines and has been applied to the simulation of single wind turbine wakes, as well as small and large wind farms in flat and complex terrain [12,13]. The momentum equations are numerically integrated introducing a matrix-free pressure correction algorithm which maintains the compatibility of the velocity and pressure field corrections. Discretization is performed with a finite volume technique using a body-fitted coordinate transformation on a structured curvilinear mesh. Convection terns are handled by a second order upwind scheme bounded through a limiter, whereas centred second order schemes are employed for the diffusion terms. Velocity-pressure decoupling is prevented by a linear fourth order dissipation term added into the continuity equation. The *k-ω* turbulence model has been suitably modified for neutral atmospheric conditions [14]:

$$\alpha = 0.3706, \quad \beta = 0.0275, \quad \beta_* = 0.033, \\ \sigma = 0.5, \quad \sigma_* = 0.5 \tag{1}$$

Stratification is considered through an additional production term *f·G* added to each one of the *k* and *ω* transport equations to account for the buoyancy effect [3]. The production term *G* is given from the following relationship [15]:

$$G = -\mu_t \left(\frac{\partial U}{\partial z}\right)^2 \cdot \frac{Ri}{f_m}, \quad Ri = \zeta \frac{0.74 + 4.7\zeta}{(1+4.7\zeta)^2}, \quad f_m = 1 + 5\zeta, \quad \zeta = z / L \tag{2}$$

where μ_t is the eddy viscosity and *Ri* is the Richardson number. The *f* function is estimated for the *k* and *ω* equations (f_k and f_ω) respectively, so that the simplified momentum and transport equations for constant pressure (*dp/dx=0*) are fulfilled. After a proper mathematical analysis, the following functions f_k and f_ω are derived for the *k* and *ω* transport equations:

$$f_k = 1 + 4.9\zeta, \quad f_\omega = -14 \cdot (1 + 1.28\zeta) \quad \text{for stable conditions} \tag{3}$$

$$f_k = 1 - 1/Ri, \quad f_\omega = \frac{1/Ri - 1}{\sigma \cdot \beta^* \cdot \kappa^2 / \beta^{1.5} - 1} \quad \text{for unstable conditions} \tag{4}$$

3.1.2 Wind turbine simulation

According to the actuator disk approach, the rotor of each wind turbine is simulated as a disk discretized by a number of control volumes. Each control volume acts as a momentum sink through the actuator force calculated using the following relationship:

$$F = 0.5\rho\, U_{ref}^2\, C_T\, \Delta S \tag{5}$$

where *ρ* stands for the air density, U_{ref} is the reference wind speed for the thrust coefficient calculation, C_T is the thrust coefficient and *ΔS* is the surface area of the control volume. One of the major challenges in the actuator disk theory is the determination of the reference velocity for thrust calculation.

The most accurate way is to calculate the velocity at the position of each wind turbine as if the specific turbine was absent. In offshore wind farms, wind turbines are mostly installed in parallel rows, so turbine rows can be considered instead of single turbines. A parabolic procedure is then applied: The run starts ignoring the presence of the turbines to estimate the reference velocities at the positions of the first row. When a certain convergence criterion is fulfilled for the velocities at those positions, the actuator disks are activated at the first row. The simulation continues and the reference velocities are estimated at the second row. This procedure is repeated until all turbine rows are added. Namely, a successive activation of turbine rows occurs when a certain convergence criterion is fulfilled for the velocities at the specific positions of that row.

3.1.3 Computational domain and boundary conditions

The wind farm is enclosed in a computational domain with assumed known inflow conditions, corresponding to the downstream conditions of the affecting upstream installations. If there is no upstream installation free stream logarithmic profiles for neutral or stratified conditions are applied to the inlet boundary according to the similarity theory [16]. The outflow and the side boundaries are positioned sufficiently far so that Neumann conditions can be applied for the velocities and the *k,ω* turbulence quantities. The inlet and outlet boundaries are positioned *10D* and *30D* upstream and downstream of the first and last wind turbine rows respectively. The side boundaries are positioned *10D* away of the closest wind turbine and finally the top boundary is positioned nearly *30D* above sea level. Logarithmic wall functions are implemented for the first grid point above the sea level.

The mesh is kept fine close to the wind turbine rotors in the horizontal *x, y* directions with a minimum grid spacing close to *0.1D*. Between the turbine rotors successive coarsening and refinement of the grid lines occurs using geometrical progression. In the vertical direction the mesh is constructed fine close to the sea level with the first grid line at a distance of about *0.007D*. A fine mesh is also constructed in the area of each W/T rotor disk, using 15 grid points along the rotor diameter.

3.2 Meso-scale modeling

Mesoscale models are designed to forecast weather phenomena with typical length scales down to 5 km. Therefore, to limit computational costs, a coarse horizontal resolution in the order of kilometres is required. The vertical resolution is in the Planetary Boundary Layer (PBL) typically in the order of decametres to allow the vertical temperature and moisture structure to be resolved sufficiently. Mesoscale models are intended to resolve, similar to Reynolds Averaged Navier-Stokes (RANS) models, only the mean flow, whereas the turbulence part of the spectrum is completely modelled. The basic assumption is the scale separation of the resolved mesoscale processes and the unresolved turbulent ones, since no explicit filtering is applied. This means that the solution will not converge to the expected value with horizontal grid refinement, since from a certain horizontal scale onwards double counting will take place. Mesocale models are generally non hydrostatic and fully compressible. This means that they contain a prognostic equations for all three wind velocity components and a complete continuity equation. Furthermore, they contain a prognostic equation for the temperature as well as for all moisture components. Finally, the pressure is obtained via the equation of state. The time step used in the prognostic equations is determined by the Courant number, which is a function of the advection velocity and the horizontal grid size. The lower boundary values, are over land provided by soil (diffusion) models and over water they are generally obtained from reanalysis data.

4 COUPLING BETWEEN WIND FARM AND CLUSTER SCALE

4.1 Cluster scale to wind farm scale

The work of this Task is focused on finding a method to correctly pass the information provided by a wind farm (microscale) model to a cluster scale (mesoscale) model. However, it should be noted that significant information regarding the boundary conditions of the microscale model can be provided by a mesoscale model. Microscale models usually use a steady state approach where the inlet velocity and turbulence profiles follow the logarithmic relationships of the similarity theory. Although the inlet boundaries are positioned far enough from the wind farms, such an approximation could be significantly different from the real situation, due to various mesoscale effects of the broader topography, such as coastal winds, convective systems and orographic forced flow. In this connection, a mesoscale model could be used to provide more accurate velocity and turbulence profiles for the boundaries of the computational domain where the microscale model is applied. For example several time-averaged velocity profiles over a certain time period can be calculated along a plane representing the inlet boundary of the microscale computational domain. Then, these profiles would be interpolated to the finer mesh used by the microscale model. In this way, the mesoscale information is passed to the microscale model, which otherwise could not take into account the above mentioned mesoscale effects.

4.2 Wind farm scale to cluster scale

A CFD microscale model such as CRESflow-NS is capable of estimating the wind turbine thrusts in a wind farm and the detailed flow field around the wind turbines. Different approaches can be developed on how this information is transferred to a mesoscale model. This also depends on the capabilities of the mesoscale model regarding the implementation of the microscale information. Figure 1 shows two indicative meshes for the micro- and meso- scale models respectively in the xy-directions. As a result of the different scales the whole wind farm may be included in few numerical cells of the mesoscale model. In the vertical direction, mesoscale models use a finer discretization which means that more grid lines can be encountered in the space between the ground and the top height of the wind turbines.

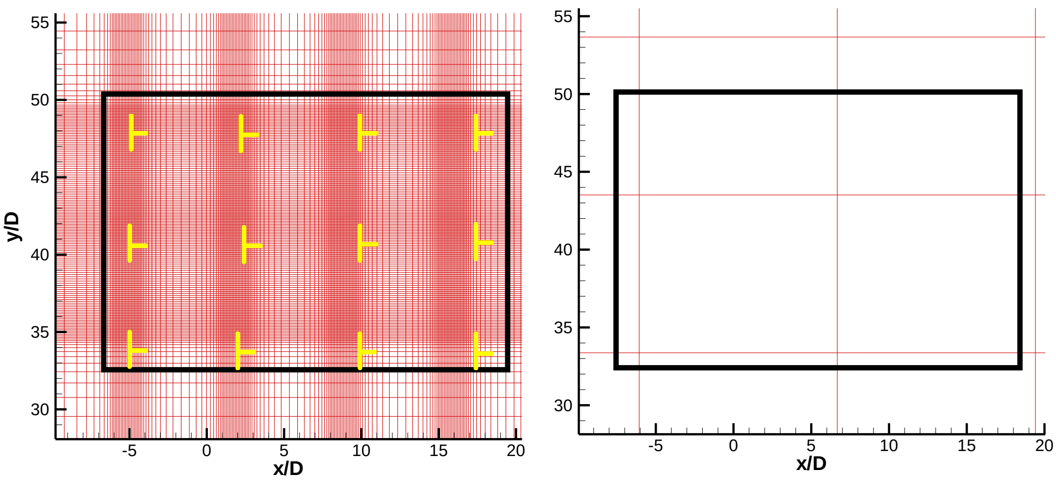

Figure 1: Indicative meshes for the wind farm scale (microscale) and the cluster scale (mesoscale) model. The black box indicates the extent of the wind farm. Wind turbines are marked with yellow color.

There are two general ways the turbine thrusts can be expressed. According to the first, the thrust is given as a single turbine thrust value with no information about its distribution in space. According to the second way, the whole flow field is available and the effective distribution of thrust for a given volume can be obtained via momentum theory. Although the second way seems to be more detailed, it is more sensitive to numerical errors due to the discrete cells used in the application of the momentum theory, and the interpolation made from the fine microscale to the coarse mesoscale mesh. In addition, this way bears a complication, if the wind farm covers several mesoscale grid cells. In that case, the inflow and outflow velocities of the grid cells, could be used to determine wake related thrust, but would include the effects of the continued expansion of wakes caused by turbines upwind of the grid cell in question. This is a problem, because the mesoscale wake parameterization should only address the representation of wakes caused by turbines in a single grid cell. For these reasons, the first way was followed in the present study. Again, there are two different approaches on how the turbine thrust information is transferred to the mesoscale mesh. The first approach sums up the turbine thrusts on the basis of the whole wind farm, whereas the second sums up the turbine thrusts on the basis of the mesoscale grid cells. Both approaches were applied in the present study and are further analyzed below.

4.2.1 1st approach: Sum up thrusts on the basis of the whole wind farm

According to this approach an equivalent thrust is evaluated to represent the effect of the wind farm on the downstream velocity field. This thrust acts as a momentum sink on the coarse mesoscale mesh. There are two ways to estimate the total thrust. The first is to simply sum up the thrusts of the individual wind turbines as they have been estimated from the microscale model. The second is to apply the momentum theorem to a volume surrounding the wind farm using the velocities predicted by the microscale model. A total thrust representing the effect of the wind farm is estimated which corresponds to the velocity deficit due to the presence of the wind farm (see Figure 2).

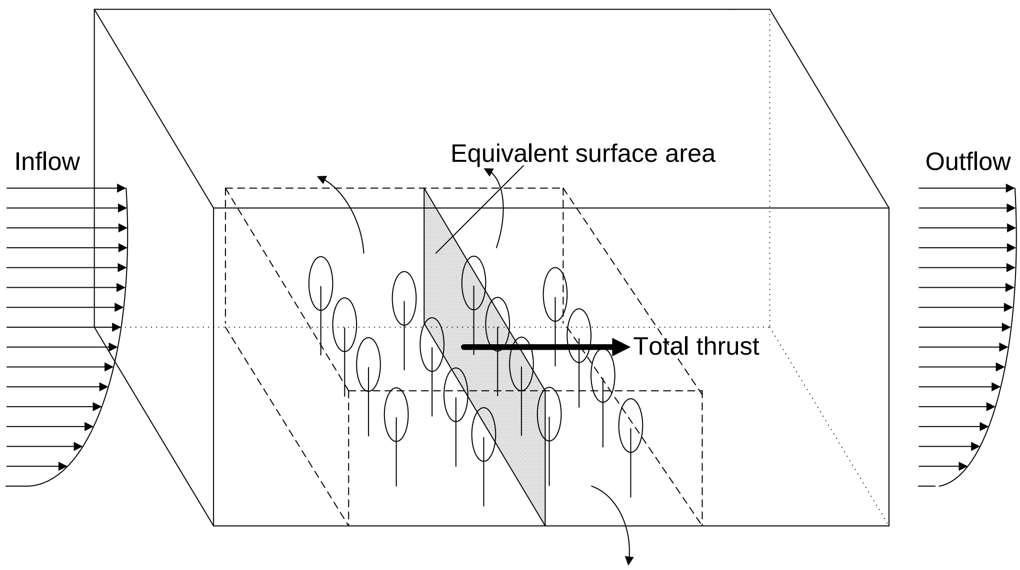

Figure 2: Calculation of the total thrust and the equivalent thrust coefficient by applying the momentum theorem to a volume surrounding the wind farm

The second method was found to be inaccurate because the estimated value of thrust was affected by the size of the volume used for the application of the momentum theorem. This can be attributed to numerical errors in the calculation of fluxes due to the non-uniform implemented mesh. The mesh is constructed fine close to the turbines to better simulate their wakes and is coarsened following a geometrical progress outwards. This results in large numerical cells at the sides of the oblong which is used as control volume. Because of the non-accurate estimation of the total thrust the first method of simply summing up the individual turbine thrusts was adopted.

The next step is to transfer the estimated total thrust to the mesoscale model. On the basis of the whole wind farm aggregation an equivalent thrust coefficient can be determined by selecting an equivalent surface area. A reasonable strategy is to select the equivalent surface area as shown in Figure 2, namely a yz-intersection of the surrounding volume which surrounds all the rotors visible from the upwind side of the farm. The estimated thrust is introduced to the coarse mesoscale mesh as a momentum sink to the numerical cells which are located closest to the middle of the wind farm (Figure 3)

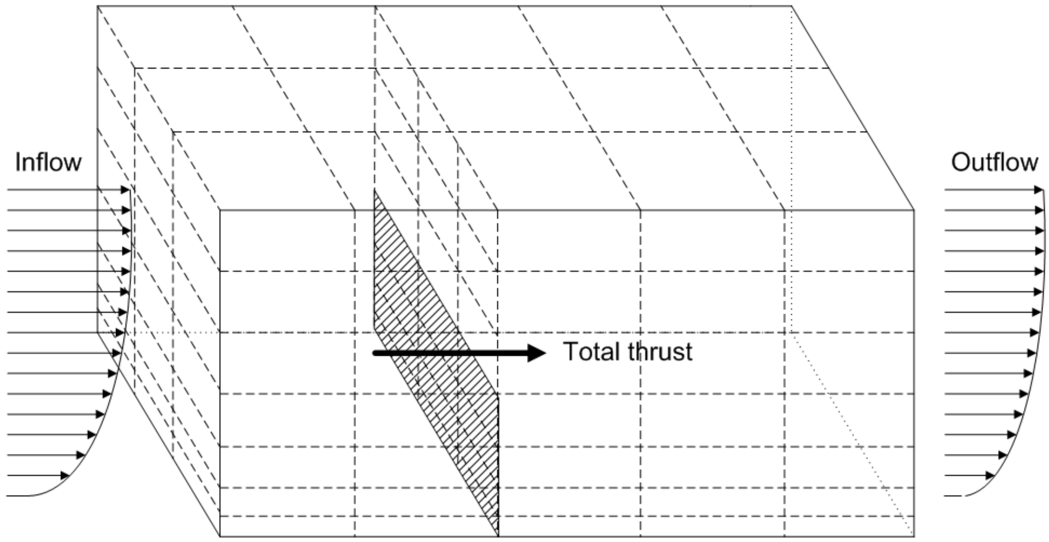

Figure 3: Coupling between the wind farm and the cluster scale models. The total thrust estimated from the wind farm model is applied to the numerical cells of the cluster scale model. The lineal surface represents the equivalent surface area.

4.2.2 2nd approach: Sum up thrusts on the basis of the mesoscale grid cells

According to the 2nd approach the estimated thrusts from the microscale model are properly distributed to the cells of the mesoscale mesh taking into account the percentage of the rotor swept area that belongs to this cell. This percentage expresses the contribution of the wind turbine thrust to the numerical cell. The concept is illustrated in Figure 4. The total contribution to the cell is calculated by summing up contributions from all wind turbines and is added as a sink term to the momentum equations of the meso-scale model.

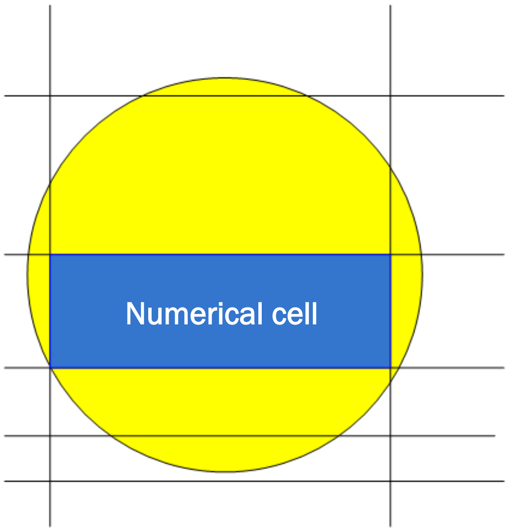

Figure 4: Calculation of the percentage of the rotor swept area (yellow) that belongs to the numerical cell (blue)

Based on this concept, the WRF-WF mesoscale model expresses the presence of wind turbines as a turbine number density per grid cell and rated power is prescribed. Exact turbine position is not needed and there is no interaction of one turbine wake on another turbine, within a grid cell, i.e. all turbines experience the same hub height wind speed. In addition the turbines are parameterized as turbulent kinetic energy sources. A new wind turbine wake parameterization, called WRF-EWP [17], imposes a wind turbine wake velocity deficit vertically distributed according to a diffusion based model for wake expansion. The presence of wind turbines is determined by a turbine number per grid cell and power and thrust curves (i.e. power and thrust as function of hub-height wind speed) can be employed. As in WRF-WF, exact turbine position is not needed and there is no interaction between turbines inside the same grid cell.

5 RESULTS

The Horns Rev offshore wind farm was used as a test case for the application of the two coupling approaches. It comprises 80 VESTAS V80 wind turbines (hub height=70m, diameter=80m), arranged in a regular array of 8 by 10 turbines, with a spacing of 7 diameters in both directions covering an area of 5x3.8 km^2. The layout of the wind farm is shown in Figure 5, where it can be seen that the direction of the N-S columns is 353°. The diagonal wind turbine spacing is either 9.4 D or 10.4 D. The simulated cases refer to an inflow mean velocity of 8m/s and an inflow turbulence intensity of 7%, at hub height.

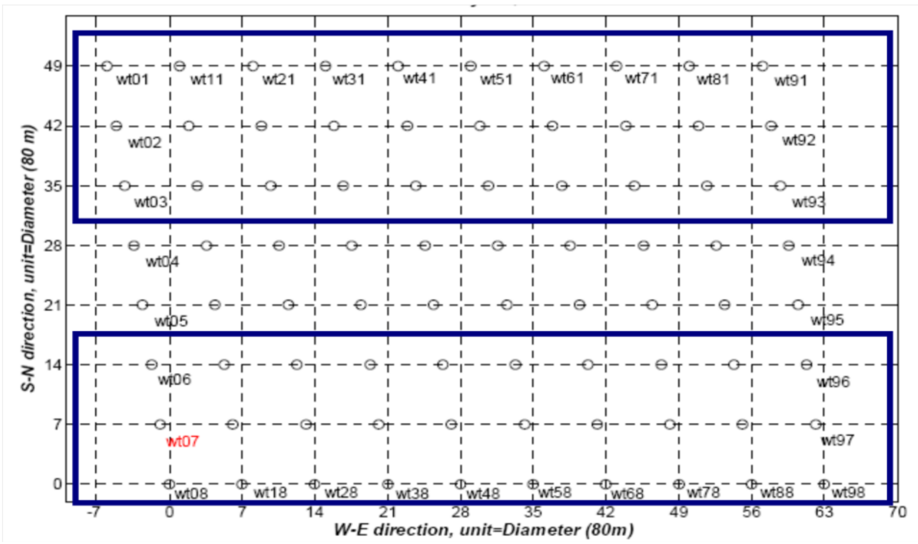

Figure 5: The layout of the Horns Rev wind farm. Internal spacing between wind turbines is 7D (diameters) in both directions. The blue boxes show the two simulated parts of the wind farm. The northern part is used for wind directions 270°-286.25° and the southern part is used for wind directions 253.75°-268.75°

5.1 Application of the CRES-flowNS microscale model

In order to simulate the 270°±15° sector of western wind directions, 12 sub-sectors of 2.5° were considered. For each one of the sub-sectors the mean wind direction was simulated, e.g. for the sub-sector 270°-2.5°, the simulated mean wind direction was 268.75°. Next, two sub-domains of the Horns Rev wind farm, marked with blue lines in Fig.5, were considered. The first one including rows 1-3 was used for the simulation of the wind directions 268.75°-283.75° and the second one including rows 6-8 was used for the simulation of the wind directions 256.25° -266.25°. It was found that when the first sub-domain was used, rows 1-3 were not affected by the wind turbine wakes from rows 4-8. In addition, the flow field at the 4th-8th rows was similar to the flow field at the 3rd row. In the same way, when the second sub-domain was used, rows 6-8 were not affected by the wind turbine wakes from rows 1-5 and the field at the 1st-5th rows was similar to the flow field at the 6th row. Thus, simulation of one sub-domain instead of the whole wind farm is acceptable and saves significant computational cost.

CRES-flowNS was used by applying the successive activation procedure of the wind turbine rows, which are the N-S columns in this case. The relative velocity errors between the current and the previous time step were calculated at the three wind turbine positions of each column. When their maximum value became lower than $5 \cdot 10^{-6}$ the next wind turbine column was activated. For the wind direction of 273.75°, the convergence of the momentum equations is shown in Figure 6. The peaks correspond to the activation of each wind turbine column. After the activation of the last wind turbine column, the reference velocities of all wind turbines were known. Thrusts were then estimated using Eq.(5).

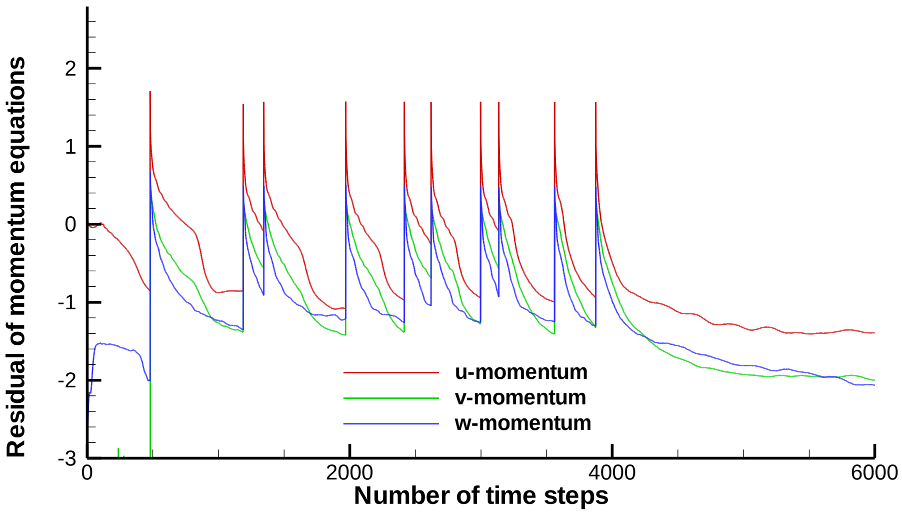

Figure 6: Convergence of the momentum equations for the 273.75º wind direction. The appearance of peaks indicate the activation of each wind turbine column

5.2 Validation of the two coupling approaches using the microscale model

In order to validate the two coupling approaches, the microscale model was applied to a coarse mesh (cluster scale) implementing the thrust information from the wind farm scale simulation. According to the first approach, the total thrust is estimated by summing up the thrusts of the individual wind turbines and is applied to the middle cells of the coarse mesoscale mesh through an equivalent thrust coefficient. The equivalent thrust coefficient is calculated through Eq.(5) using the equivalent surface area of Figure 2. According to the second approach the contribution of each wind turbine to a certain numerical cell of the mesoscale mesh is found by calculating the percentage of the rotor swept area belonging to that cell (Figure 4). The total thrust contribution to a specific cell is calculated by summing up the contributions from all wind turbines, and is applied as a sink term to the discretized momentum equation. The velocity profiles derived from the two coupling approaches at the mesoscale mesh are compared with the velocity profile derived at the microscale mesh, 35 diameters downstream of the Horns Rev wind farm. The lateral position (y-coordinate) is located at the center of the lateral wind farm extent.

The comparison is shown in Figure 7 for 6 wind directions (253.75º, 258.75º, 263.75º, 276.25º, 281.25º and 283.25º). The inlet velocity profile and the vertical extent of the wind turbine rotor have been also plotted in the same figure. At a first glance, it can be said that the velocity deficit downstream of the wind farm (difference between the inlet velocity profile and the calculated velocity profiles) is reasonably captured by both coupling approaches. A more careful observation indicates that the shape of the velocity profile is better reproduced using the second coupling approach. This is more pronounced for the south-western wind directions (253.75º, 258.75º and 263.75º) and is a result of the fact that the spatial variation of thrust is taken into account only by the second approach. Therefore, the velocity deficit provided by the first approach is uniformly distributed in space which is depicted in the vertical profiles at the extent of the rotor disk. On the other hand, the second approach performs a vertical distribution of thrust which is capable of affecting the velocity profile in a non-uniform way. Therefore, it should be preferred provided that the mesoscale model is capable of implementing such a non-uniform thrust distribution to the numerical cells. WRF is such a type of model and its results of different thrust implementations are presented in the next section.

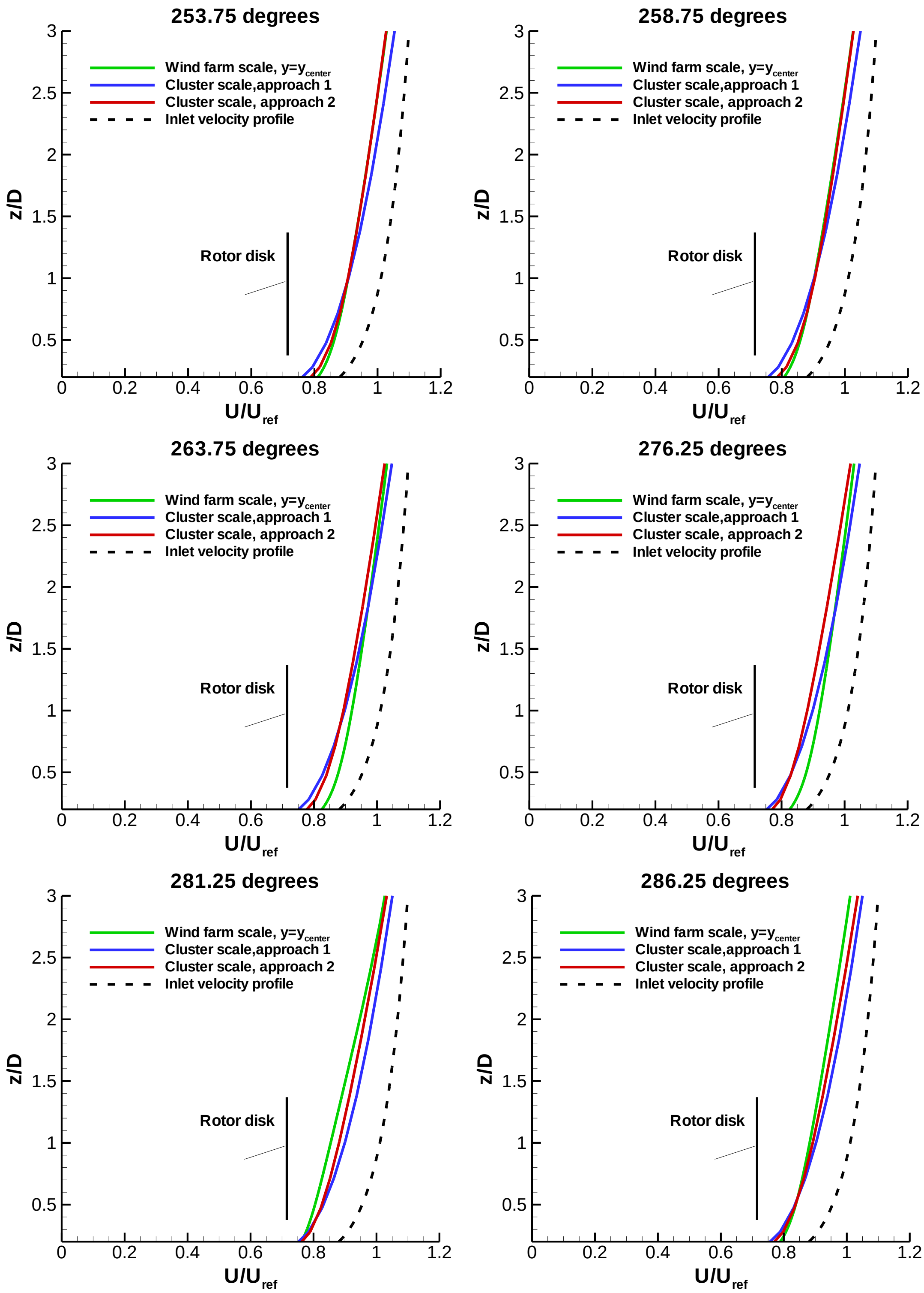

Figure 7: Comparison of the velocity profiles provided by the microscale model for the wind farm and the cluster scale meshes, 35 diameters downstream of the Horns Rev wind farm. The lateral position is located at the center of the wind farm ($y = y_{center}$). Results are shown for six wind directions: 253.75º, 258.75º, 263.75º, 276.25º, 281.25º and 286.25º

5.3 Coupling with the mesoscale model

Coupling between the wind farm and cluster scale is realized using the WRF mesoscale model. The estimated wind turbine thrusts by the microscale model CRES-flowNS are transferred to WRF for the Horns Rev wind farm case experiencing a wind of 8m/s from 270° (hub height). Implementation is made using three different variations of a mesoscale model wind farm wake parameterization. An original wake parameterization, without micro-meso scale coupling, serves as reference parameterization for comparison.

The reference parameterization WRF-EWP [17] uses the nominal wind turbine thrust curves instead of the microscale information. It applies a diffusion based vertical wake expansion model to account for the wake variation inside the large mesoscale numerical cells. The other parameterizations feature the inclusion of the microscale model CRESflow-NS results. WRF- CRES-EWP and WRF-CRES-ROTOR parameterizations use the second coupling approach described in section 4.2.2, which is turbine thrust aggregation on the basis of the mesoscale grid. Their difference consists in the fact that WRF- CRES-EWP uses the sub-mesoscale-grid vertical wake expansion model of WRF-EWP, whereas no sub-mesoscale-grid wake expansion is considered in WRF-CRES-ROTOR. WRF-CRES-ROTOR-FA parameterization follows the first coupling approach described in section 4.2.1 which is wind turbine thrust aggregation on the basis of the whole wind farm (along the wind direction axis). No sub-mesoscale-grid wake expansion is included. In practice, all the parameterizations, except WRF-CRES-ROTOR-FA, impose a thrust on 6 (3 along wind direction x 2 normal to wind direction) mesoscale grid points, covering the horizontal extent of the farm. For the WRF-CRES-ROTOR-FA parameterization thrust is imposed on 2 (1 along wind direction x 2 normal to wind direction) grid points.

In Figure 8 the results from the mesoscale model parameterizations are compared with the measurements from the wind farm. The measurements refer to wind speed within the range 7.5 – 8.5 m/s and wind direction within the range 255–285° [19]. In comparison to WRF-EWP (Fig. 8a), WRF-CRES-EWP (Fig.8b) gives a slightly smaller wake deficit. Both parameterizations show good agreement with the measurement data, and lie well within the error bars. WRF-CRES-ROTOR (Fig. 8c) predicts a larger wake deficit inside the wind farm, on the lower bounds of the error bars of the measurement data. Downstream of the wind farm, the difference compared to WRF-EWP is less pronounced, however the velocity deficits are still larger. WRF-CRES-ROTOR-FA (Fig. 8d) predicts a very strong deficit inside the wind farm, below the lower bounds of the error bar. Downstream of the wind farm the difference is much reduced and agreement with measurement at masts M6 and M7 is good.

By comparing the two coupling approaches, WRF-CRES-ROTOR and WRF-CRES-ROTOR-FA, it is concluded that aggregation on the basis of mesoscale grid or the whole wind farm has a large impact on the mesoscale modelled wake within the wind farm. When imposing the total thrust of the wind farm at a single grid point, the maximum wake deficit is too large compared to measurements. However, downstream of the wind farm, differences are reduced and predictions using the whole wind farm aggregation concept seem to agree well with the measurements. Comparison between WRF-CRES-EWP and WRF-CRES-ROTOR shows that the sub-mesoscale-grid vertical wake expansion is a necessary feature to capture the wake behavior inside the wind farm and the near wind farm wake. Without the vertical wake expansion the wake deficit tends to be too concentrated in the vertical direction, which results in a too strong deficit. However, moving downstream of the wind farm into the far wake, the difference caused by including sub-mesoscale-grid vertical wake expansion, or not, becomes much less pronounced. It should be reported that the thrust predictions of the microscale model were provided through a single simulation of the 270°. An alternative is to provide a mean thrust derived from averaging the results of the 12 simulations in the 270°±15° wind sector. In the context of Task 1.1, it has been demonstrated that such an averaging procedure results in lower wind speed and power deficits. This could have a correction effect on the predictions of the WRF-CRES-ROTOR and WRF-CRES-ROTOR-FA models.

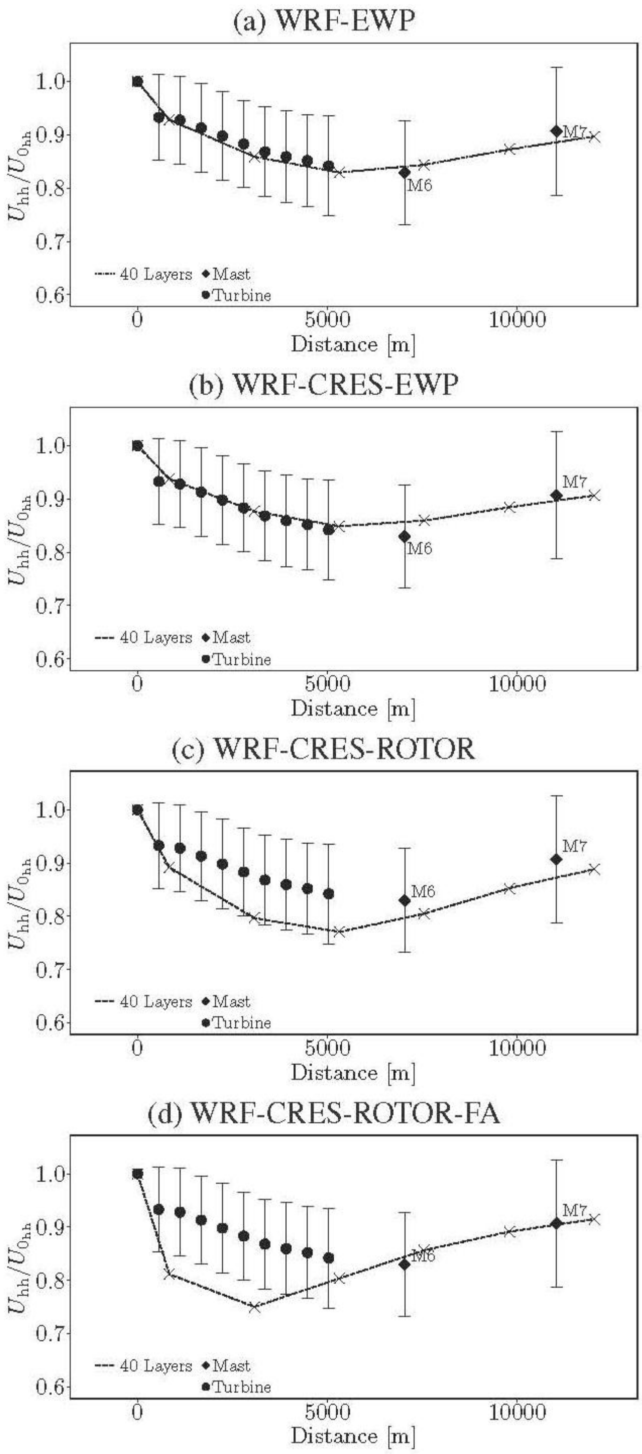

Figure 8: Recovery validation plots for the different wake parameterizations used: (a) WRF-EWP, (b) WRF-CRES-EWP, (c) WRF-CRES-ROTOR and (d) WRF-CRES-ROTOR-FA. The x-axis is the distance in meters from the first turbine row, the y-axis is the wake horizontal wind speed expressed as a fraction of the inflow wind speed, both at hub height, i.e. for first row turbines the value is 1. The black dots are measurements based on wind turbine power or from anemometers at mast 6 (M6) and mast (M7) downwind of the wind farm.

6 CONCLUSIONS AND FUTURE WORK

In the context of Task 1.3, the coupling between the wind farm and the cluster scale was investigated. The main concept was to estimate the wind turbine thrusts using a microscale model (wind farm scale) and then transfer this information to a mesoscale model (cluster scale). Two coupling approaches were validated and tested, the first one was aggregation of wind turbine thrusts on the basis of the whole wind farm and the second was aggregation of thrusts on the basis of the mesoscale grid cells. The simulated test case was the Horns Rev offshore wind farm for the western wind directions and mean wind speed of 8m/s. The CRES-flowNS and WRF were used as micro- and meso- scale models respectively.

The two coupling approaches were first validated by applying the microscale model at both micro- and meso- scale meshes. It was shown that the velocity deficit in the far wake downstream of the Horns Rev wind farm was reasonably captured by both approaches. Aggregation of turbine thrusts on the basis of the mesoscale grid cells realizes a more accurate spatial distribution of the turbine thrusts, resulting in a better reproduction of the vertical profile of the velocity deficit. This was more pronounced in the simulation of the south-western wind directions.

The estimated wind turbine thrusts using the CRES-flowNS microscale model were implemented to the WRF mesoscale model by using the two coupling approaches. It was found that aggregation on the basis of mesoscale grid or the whole wind farm had a large impact on the mesoscale modelled wake within the wind farm. However, downstream of the wind farm, differences were reduced and predictions using the whole wind farm aggregation concept seemed to agree well with the measurements. In addition, the concept of a sub-mesoscale-grid vertical wake expansion was considered in the WRF model. It was proved that such a model was necessary to capture the wake behavior inside the wind farm and the near wind farm wake. However, in the far wake, the difference caused by including sub-mesoscale-grid vertical wake expansion, or not, becomes much less pronounced. As a general conclusion, aggregation of turbine thrusts on the basis of the mesoscale grid cells including a wake expansion model is the more accurate approach to capture the wake inside the wind farm and the near wake downstream. In the far wake, the simpler approach of aggregation on the basis of the whole wind farm works equally well, even without a wake expansion model. Nevertheless, more comparisons are necessary to confirm that the findings of this study are valid in other offshore wind farm cases.

Furthermore, the CRES-flowNS estimated turbine thrusts, used in the simulations of the WRF model, were derived from the simulation of the mean wind direction only (270°). In the context of Task 1.1 of the EERA-DTOC project it was demonstrated that, averaging the CFD predictions from the simulations of several wind directions inside a sector, results in a significantly lower mean velocity deficit than that of the mean direction simulation. This is depicted in Figure 9, where the mean power deficit along the wind turbine rows of the Horns Rev wind farm is plotted through averaging over different sectors. Thus, inclusion of the averaged wind turbine thrusts over the 270°±15° sector should also be tested in the mesoscale model.

In terms of future work it would be also interesting to investigate how the flow field predictions of a CFD microscale model could be used to simulate the vertical wake expansion in the mesoscale grid cells. The difficulty in this concept lies in the interaction between the wakes of the neighbouring wind turbines.

The final target of the microscale user is to produce a look-up table for thrust versus wind speed and wind direction which can be used as input to the mesoscale model. Such a table requires more than a hundred of simulations which is considerably computational cost for CFD simulations of large wind farms. To this end, an engineering model like the amended GCL [20] could be used, calibrated with the available predictions of the CFD model, to simulate the rest of wind directions. The amended GCL model can also be calibrated using a times series information provided by the application of the mesoscale model on the wind farm area (without wind turbines). In that way, it can include possible mesoscale effects on the wind speed and direction throughout the extent of the wind farm.

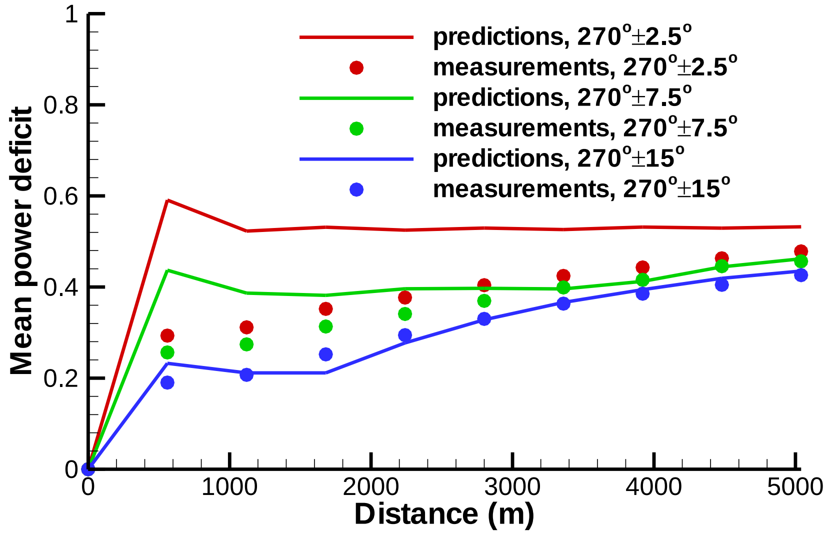

Figure 9: Mean power deficit along the rows 2 to 7 of the Horns Rev wind farm [18], obtained by averaging the power output from wind turbines wt02 to wt97 within each row. Predictions and measurements are plotted for three different flow sectors around the 270° wind direction. Calculations have been performed with CRES-flowNS.

7 REFERENCES

[1] J.W.M. Dekker, J.T.G. Pierik (Editors), ”EuropeanWind Standards II”, ECN-C–99-73, 1999

[2] Troen, I., Petersen, E.L., *European Wind Atlas*, Risø National Laboratory, Roskilde, Denmark, 1989:656

[3] Schepers, J.G., *ENDOW: Validation and Improvement of ECN's Wake Model*. ECN:ECN-C-03-034: Petten, The Netherlands, 2003: 113

[4] Crespo, A., Hernandez, J., Fraga, E., Andreu, C., “Experimental validation of the UPM computer code to calculate wind turbine wakes and comparison with other models”, *Journal of Wind Engineering and Industrial Aerodynamics*, 1988, 27, pp. 77-88

[5] Ott, S., Berg, J., Nielsen, Morten, ”Linearised CFD Models for Wakes”. Technical Univ. of Denmark, Risoe National Lab. for Sustainable Energy. Wind Energy Div. Risoe-R-1772(EN) ISBN 978-87-550-3892-9. Available online.

[6] Rados, K., Larsen, G., Barthelmie, R., Schelz, W., Lange, B., Schepers, G., Hegberg, T., Magnusson, M., “Comparison of wake models with data for offshore windfarms”, *Wind Engineering*, 2002, 25, pp. 271-280

[7] Chaviaropoulos, P. K. and Douvikas, D. I., “Mean-flow-field Simulations over Complex Terrain Using a 3D Reynolds Averaged Navier–Stokes Solver,” *Proceedings of ECCOMAS '98*, 1998, Vol. I, Part II, pp. 842-848

[8] R.J. Barthelmie, S.T. Frandsen, O. Rathmann, K. Hansen, E.S. Politis, J.Prospathopoulos, J.G. Schepers, K. Rados, D. Cabezón, W. Schlez and A.Neubert, "Final Report UpWind, Work Package 8, Deliverable D8.7", Risoe-DTU, Roskilde, 2011

[9] Barthelmie, R.J., Hansen, K, Frandsen, S.T., Rathmann, O., Schepers, J.G., Schlez, W., Phillips, J., Rados, K., Zervos, A., Politis, E.S., and Chaviaropoulos, P.K., “Modelling and Measuring Flow and Wind Turbine Wakes in Large Wind Farms Offshore”, *Wind Energy*, Vol. 12, No. 5, pp. 431-444, 2009

[10] Fitch, A., Olson, J., Lundquist, J., Dudhia, J., Gupta, A., Michalakes J., and Barstad, I.,”Local and mesoscale impacts of wind farms as parameterized in a mesoscale NWP model”, Monthly Weather Review, 2012.

[11] Skamarock, W., Klemp J., Dudhia J., Gill, D., Barker, D., Duda M., Huang X., Wang W., and Powers, J,., ”A Description of the Advanced Research WRF Version 3”, NCAR Technical note, 2008.

[12] Prospathopoulos, J.M., Politis, E.S., Rados, K.G., Chaviaropoulos, P.K., "Evaluation of the effects of turbulence model enhancements on wind turbine wake predictions", Wind Energy, 2011, 14, pp.285-300.

[13] Politis, E.S., Prospathopoulos, J.M., Cabezon, D., Hansen, K.S., Chaviaropoulos, P.K, Barthelmie,R.J., "Modeling wake effects in large wind farms in complex terrain: the problem, the methods and the issues", Wind Energy, 2012, 15, pp.161-182

[14] Prospathopoulos, J.M., Politis, E.S., Chaviaropoulos, P.K., "Modelling Wind Turbine Wakes in Complex Terrain", *Proceedings of EWEC 2008*, Brussells, Belgium, pp. 42-46

[15] Stull, R. B., “An introduction to boundary layer meteorology”, ISBN 90-277-2768-6 ed. Kluwer Publications Ltd, 1988

[16] Panofsky H.A., Dutton J.A., Atmospheric Turbulence, Models and Methods for Engineering Applications, John Wiley & Sons, 1984.

[17] Volker P. J. H., Badger J., Hahmann A. N., Ott S. ”Implementation and Evaluation of a Wind Farm Parametrisation in a Mesoscale Model”, to be submitted to Boundary Layer Meteorology

[18] Hansen, K. ”WP1.1 Wake model performance validations Horns Rev offshore wind farm” Report: Eera-Dtoc, 2013..