Final Report Summary - EERA-DTOC (EERA Design Tools for Offshore Wind Farm Cluster)

Executive Summary:
The European Energy Research Alliance – Design Tools for Offshore wind farm Clusters (EERA DTOC) was partly funded by the European Commission. The EERA DTOC project lasted for 42 months. It started in January 2012 and ended in June 2015. The project had 22 partners across Europe and was led by DTU Wind Energy.

The EERA DTOC project aimed to deliver robust and efficient software for planning of offshore wind farm clusters. The user requirements from industrial partners formed the basis for deciding on model integration and functionality. The many models that were available in the EERA consortium have been developed in previous projects, often through national funding. This was the first time a systematic effort to efficiently...
The software has been intensively validated during the project. The validation is based on wind farm production data from several large wind farms. Additionally, new experimental observations from scanning lidar and wind-profiling lidar on a moving platform (ship) as well as high resolution satellite Synthetic Aperture Radar (SAR) images have been applied for validation of wind farm wake models.

The developed tool describes a new design tool based on open interfaces. This enables future integration of other software. The spin-off tool from the project is called Wind & Economy. The tool was used during the project by the partners to model several common test cases, so-called scenarios. These ranged from state of the art current practice for large offshore wind farms near the coast, through cluster scale wind farm planning very far offshore and to strategic planning of a far-future scenario around the year 2030.

Project Context and Objectives:

Project context
The European Energy Research Alliance – Design Tools for Offshore wind farm Clusters (EERA DTOC) project was realized in response to the European Commission’s FP7 Topic: ENERGY.2011.2.3-2: Development of design tools for Offshore Wind farm clusters (Open in call: FP7-ENERGY-2011-1) with funding scheme: Collaborative project.

The objective of this topic was to develop new design tools to optimise the exploitation of individual wind farms as well as wind farm clusters, in view of transforming them into virtual power plants.

The topic asked such design tools to integrate:

- Spatial modelling: medium (within wind farms) to long distance (between wind farms) wake effects
- Interconnection optimisation: to satisfy grid connection requirements and provide power plant system service.
- Precise energy yield prediction: to ease investment decisions based on accurate simulations

Focus would have to be on offshore wind power systems and make optimal use of previously developed models.

The expected impact of the project to be funded was:

- demonstrate the capability of designing virtual wind power plants composed of wind farms and wind farm clusters while minimising the negative spatial interactions, improving the overall power quality output and providing confidence in energy yield predictions;
- contribute to the development of offshore wind power as required by the SET-Plan.

The EERA DTOC consortium, with 22 partners from across Europe, successfully applied and obtained funding from January 2012 to June 2015, i.e. 42 months duration. The budget was 4 million euro, of which 2.9 million euro was contributed by the EC.

In parallel to EERA DTOC, the FP7 ClusterDesign project was funded in the same call. Collaboration between these projects included two major joint workshops.

Main objectives of EERA DTOC
The EERA DTOC project focused on designing wind farm clusters considering:

- Wind farms wake losses;
- Wind farms electrical cabling.

- Its objective was to deliver an integrated tool for the design of individual wind farms and clusters of wind farms;
- The tool is composed of existing models as available throughout Europe;
EERA DTOC targets potential stakeholders such as wind farm developers, consultants, strategic planners and transmission system operators.

The aim of the project was to help developers, strategic planners and other stakeholders in the offshore wind energy business with improved planning of offshore wind farms at cluster scale.

The new design tool focuses on wind farms wake losses and wind farms electrical cabling. Its objective was to deliver an integrated tool for the design of individual wind farms and clusters of wind farms. The tool is composed of existing models from EERA science partners.

Major industry partners in the project guided the effort of the project to ensure maximum benefit seen from the industrial perspective. In this way the project enabled a move from science to business.

The EERA DTOC project aimed to deliver robust and efficient software for planning of offshore wind farm clusters, consisting of a selection of models for different purposes and a central software platform, managing the farm description, editing of wind farm properties, and the invocation of the different tools.

The user requirements from industrial partners formed the basis for deciding on model integration and tool functionality. The many models that were available in the EERA consortium, e.g. WAsP, FUGA, FarmFlow, CorWind or Net-Op, have been developed in previous projects mainly through national funding. This was the first time a systematic effort has been performed to efficiently integrate these models in one software. The software has been intensively validated during the project. This validation was based on wind farm production data from several large wind farms. Additionally, new experimental observations from scanning lidar and wind-profiling lidar on a moving platform (ship) as well as high resolution satellite Synthetic Aperture Radar (SAR) images have been applied for validation of wind farm wake models.

The wind farm wake model evaluation included analysis at the offshore wind farms Horns Rev 1 in the Danish North Sea, Lillgrund in the Swedish Baltic Sea, Rødsand-2 in the Danish Baltic Sea and Alpha Ventus in the German North Sea. For these SCADA data were available. Furthermore the wake model evaluation at the far range (the cluster effect) was investigated at the Rødsand-2 and Nysted twin wind farms and from satellite SAR at several wind farms in the North Sea including wind farms in Belgium, Denmark, Germany, the Netherlands and the UK.

The developed integrated tool is based on open interfaces. This enables future integration of other software. Finally, the tool development led to a commercial spin-off, a new integrated software called Wind & Economy. The developed and integrated tool was used during the project by the partners to model several common test cases, so-called scenarios. These ranged from state of the art current practice for large offshore wind farms near the coast, through cluster scale wind farm planning very far offshore and to strategic planning of a far-future scenario around the year 2030.

Project Results:

The main S & T (Science and Technology) results of EERA DTOC are related to 1) the scientific work on wake model validation to observations, 2) the technological development and implementing several softwares into the tool, and 3) validation and demonstration of the tool mainly through scenarios. The work is thus described with these three headlines: 1) Science, 2) Software and 3) Scenarios.

The Science section introduces the validation work comparing wake models to various observations and comparing wake models to power production from several offshore wind farms. The observations include existing data as well as newly acquired observations during the project period, e.g. the scanning lidar and ship-based wind-profiling lidar data. The wind farm power production data are kindly provided by industrial partners. The annual energy yield of wind farms and uncertainty are reported.

The Software section describes the new design tool for offshore wind farm clusters. It describes a new
design tool based on open interfaces. Various software models are integrated and the functionality of each of the software is briefly introduced.

The Scenario section presents applied use of the new design tool. The tool is able to handle daily situations of today, highly relevant for wind farm developers at present. The tool is also able to handle far-future strategic conditions. Thus to demonstrate clearly the opportunities of the new design tool we present: 1) A development case of today for a large wind farm near the coast and with several wind farms in the vicinity; 2) A development case in the near future far offshore for a cluster of wind farms; 3) A far-future scenario around year 2030 for strategic planning.

SCIENCE
Introduction
The wind farm wake modelling is addressed from several microscale and mesoscale models and coupling of micro- and mesoscale modelling. We focus on benchmarking of the different models based on data from several offshore wind farms. Further we focus on energy yield assessment and uncertainties and losses. Mesoscale modelling of the wind climate is investigated through comparison to satellite winds.

First, we benchmarked the existing wind-farm-scale wake models of the EERA-DTOC partners. The ultimate goal of this task was to provide guidelines for the industry users on which model to use in a specific context and how to quantify the uncertainty of the results produced by the wind farm flow models. In order to draw this conclusion benchmark campaigns on offshore wind farms Horns Rev 1 in the Danish North Sea and Lillgrund in the Swedish Baltic Sea were carried out. The task was done in parallel to the IEA Task 31 WakeBench work. Later also Rødsand-2 and Alpha Ventus wind farm have been used for wake model comparison. Finally, satellite data of wind farm wakes are investigated.

The results of the first two benchmarking campaigns indicate that many of the models significantly over-predict the maximum wake losses in comparison with the measurements. This is particularly the case for the CFD models that accurately simulate the wake shape, and less so for more empirically-based models. However, recent findings of the project indicate that the discrepancy between the measurements and model results could be attributed to the high level of uncertainty of the wind direction measurement. This high uncertainty causes the analysis of the measured data to produce artificially low power losses in the wake center because of the direction variability.

The approaches outlined in the report to model wind farm wakes at cluster scale describe application of two different mesoscale models in two different modelling frameworks (idealised and realistic). The influence that the wind turbines exert in the resolved atmospheric flow is represented using three different methods: 1) The wind turbines are represented by increasing the surface roughness; 2) The wind turbines constitute an elevated sink of momentum and a source of turbulent kinetic energy and; 3) A novel approach that represents the wind turbines as an elevated sink of momentum allowing for a vertical expansion of the wake. The different approaches are in broad agreement providing similar results with a microscale approach under neutral atmospheric conditions.

The simulations tend to underestimate the wind speed deficit associated with the wake near the wind farm (less than 4 km downstream). There is a better agreement between the models and observations at larger downstream distances (more than 4 km). This indicates that mesoscale simulations have the potential to model the impacts that large offshore wind farms within a cluster exert among each other. In this direction, results indicate that dynamical impact of wind farm wakes moving on to neighbouring downstream wind farms may add considerable variability to wind farm production.
Finally, we devised a way to match and pair wake models from wind farm to cluster level in a proper way, so that the information can be transferred from the one scale to the other with the least possible uncertainty. 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. 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 behaviour 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.

Wake data are difficult to compare directly with models because their properties inherently comprise the wake width due to the turbine rotor width that expands as it moves downstream and the wake becomes wider but less deep, and the meander component that arises mainly from atmospheric turbulence. Typically, wake models have not included the dynamic component. Nonetheless the use of data from wind farms is a critical component of wake model evaluation. It is also the key to correctly quantify the freestream flow.

The aim of the work on energy yield consists of providing means to produce an accurate assessment of the expected net energy yield from wind farms and clusters of wind farms as well as the associated uncertainty by integrating results from the wake and the electrical work. The work aims at checking methodologies and techniques used in the assessment of the Net Annual Energy Production (AEPNET) of offshore wind farms and the associated uncertainties. Given the lack of available data from operational wind farms, it is challenging to validate the proposed methodologies, especially regarding uncertainty quantification which is very case-specific.

Wake modelling micro- and mesoscale and coupling
The main concept for the coupling between the wind farm and the cluster scale 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 (approach 1) and the second was aggregation of thrusts on the basis of the mesoscale grid cells (approach 2). The simulated test case was the Horns Rev offshore wind farm for the western wind directions and mean wind speed of 8 m/s. The CRES-flowNS and WRF were used as micro- and mesoscale models respectively.

The two coupling approaches were first validated by applying the microscale model at both micro- and mesoscale 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 (approach 2) 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 (WRF-CRES-ROTOR) or the whole wind farm (WRF-CRES-ROTOR-FA) 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 (WRF-CRES-EWP). It was proved that such a model was necessary to capture the wake behaviour 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.

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 microscale modelling, 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.

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.

Long-term uncertainty on net energy yield
This task included two main objectives: the identification of long term uncertainty components for the Net Energy Yield estimation and the preparation for interface protocol.

The first step before any uncertainty analysis is to perform a data quality control procedure, in which the entire database (observational and numerical data) will be checked in detail through a set of sequential quality control tests which will be case specific to take into account the particularities of the variable/parameter being checked. Regarding the uncertainty on numerical data (model’s output), different sources of uncertainty can affect the estimation of a climatological variable and it can be increased during the downscaling step. This calls for a quantification and understanding of the uncertainty that stems from the application of any given downscaling technique.

Regarding the uncertainty analysis on energy yield estimation, some significant advances have been made during the last years at the IEC-61400-12-1 standard (Power Performance Measurements of Electricity Producing Wind Turbines), IEA Recommended Practices 11 on Wind Speed Measurement and use of Cup Anemometer as well as at the MEASNET guidelines for Wind Resource Assessment.

There are many other sources of uncertainty (wake and electrical losses, unavailability, power curve, etc.) and the objective was to integrate the corresponding uncertainty models into the tool, in order to determine the long term uncertainty estimates for the Net Energy Yield estimation and its confidence levels.

Nevertheless, the main conclusion was that there are not any rules or agreement regarding both the losses and uncertainty calculations, and the differences in the methods used for these calculations can lead to
very important disagreements in the final AEPNET Figures. A questionnaire on the procedures for losses and uncertainties calculation has been answered by different partners and an extensive bibliographical research has been carried out. Then, a review on the procedure, inputs, and outputs for the code integration of the different methods used for the steps, losses and uncertainties in the AEPNET calculations was performed. Besides, the possibility of integrating these methods into a general code was analysed.

The Gross Annual Energy Yield of a wind farm or cluster is the energy production of the wind farm (cluster) obtained by calculating the predicted free stream hub height wind speed distribution at each turbine location, and the manufacturer’s supplied turbine power curve.

In order to calculate the AEPNET from the Gross Annual Energy Yield, it is necessary to take into account different losses that must be applied to the initial gross value. Every wind resource assessment is an uncertain process. Besides, the determination of the power curve and power production of a wind turbine is also potentially subject to error, which causes uncertainty. Furthermore, the loss factors calculation is an uncertainty process. All these different sources of uncertainties must be accounted for in calculating the overall AEPNET uncertainty. An accurate estimation of the expected AEPNET is essential for possible investors in a wind energy project (wind farm or cluster).

All described above evidence the need for an agreement on the procedures for calculating the losses and uncertainties in the AEPNET estimation process, that avoid the fact that different consultants can give very different numbers for the same location.

The first step to calculate The Gross Annual Energy Yield (AEP) of a wind farm or cluster is a wind resource site assessment. Then, the results will be combined with the wind turbine(s) power curve to get the AEP value. Finally, the different loss factors will be applied to the AEP in order to calculate the AEPNET.

The wind resource assessment is based on the calculation of standard values, like the mean and maximum wind speed, wind roses, wind speed distribution and Weibull fit, seasonal and daily evolution, turbulence analysis, etc. Nevertheless, the most important variable for the AEPNET estimation is the hub height level wind speed at the location of each turbine of the wind farm (cluster). The steps for such estimation are: Quality control analysis of the data base, wind speed distribution and Weibull parameters estimation, long term extrapolation and hub height extrapolation. It is possible to integrate a quality control procedure into the code, although it needs an expert to check the process and there is not an agreement on the methods. Regarding the wind speed distribution and extrapolation, different methods that could be integrated into the code exist, although there is not an agreement on the best ones to use.

Once the wind resource at a site has been determined (i.e. the wind speed at the hub height), it is combined with a selected power curve to yield an estimate of the energy production of the wind turbine (wind farm or cluster). The Annual Gross Energy (before accounting for losses) can be obtained from the power output for each wind speed interval and the number of hours in a year for each wind speed interval. To compensate for the inaccuracies in the modelling approach and basic input data, as well as the individual turbines, wind farms and clusters performance, it is advisable to use “factors of safety” to adjust, or discount the final output.

Two blocks determine the factors of safety are losses and uncertainties. Estimation of energy losses is challenging and requires a great amount of observational and modelling experience. Instead, in most cases, standard values are assumed, based on previous consultants’ experience. Nevertheless, an appropriate estimation of the losses should be carried out in order to avoid the differences in the total amount energy estimation numbers given by different consultants and to increase its accuracy.
Six main sources of energy loss for wind farms are considered: Availability and electrical losses, wake effect, turbine performance, environmental losses and curtailments. Once all the losses are calculated, the total AEPNET can be estimated from the AEP.

Regarding the loss factor uncertainty, the analyses presented within the energy assessments typically assume that the turbines will perform exactly to the defined availability and power performance levels because such levels are usually covered by specific warranty arrangements. However, it is increasingly the norm to assign a moderate uncertainty to the estimated availability, loss factor and power performance factors, to reflect that small deviations from expected availability and power performance levels may not be sufficient to trigger damage payments under the warranty. Among all these uncertainties, the power curve uncertainty is typically significantly larger than the other ones. When power curves for wind turbines are measured by the manufacturer, several factors contribute to the uncertainty in this measured power curve. In practice, all the individual uncertainty components are considered independent, and the overall uncertainty is calculated as the root-sum-square of these individual uncertainty values, regardless the error source.

There is a great variety of methods for each step in the Net Energy Yield estimation process. Even though the same method is used for one of these steps, the results can greatly differ, depending on the inputs and assumptions applied. Each calculation (step) in the Net Energy Yield estimation process has an associated uncertainty. One of the most important uncertainty sources is the wind data base itself, and every wind resource analysis should start from a quality control analysis, in which agreed rules should be applied.

The main conclusion is the need for an agreement on the procedures for the Net Energy Yield estimation, including its uncertainty and losses, which avoid the great differences among the numbers given by different consultants. In practice, most uncertainties and loss factors are assumed as standard values, from consultants’ experience, but this practice should be avoided, because their estimation depends on the particular site and project, and could lead to important errors that trigger unintended consequences for risk estimation.

It is difficult to integrate the different procedures for the Net Energy Yield estimation into a code, since each method allows for different options and inputs, which should be provided by experts. Nevertheless, it should be possible but, at the moment only for some of these procedures.

WRF model comparison to satellite data

QuikSCAT was a satellite mission carrying the SeaWinds scatterometer to measure wind speeds, referenced to a height of 10m above the surface assuming neutral atmospheric stability. For a direct comparison of the wind speed between WRF and QuikSCAT, the WRF friction velocity was used along with Charnock’s model for the surface roughness and assuming neutral atmospheric stability to estimate the Equivalent Neutral Wind (ENW) at 10m above the surface.

CENER has provided one year (352 days) of hourly WRF simulations, spanning different calendar years. From this dataset, 563 hourly fields were used for comparisons with observations of 10 meter ocean-surface winds from the QuikSCAT mission. The mean bias on wind speed was 0.08 m/s for 29,486 samples and 5.2 degrees for 26,052 samples.

DTU Wind Energy has provided almost 2 years of hourly WRF simulations, starting on Jan 11, 2006 and finishing on December 31, 2007. From this dataset, 1431 hourly fields were compared to the 10 meter ocean-surface winds from QuikSCAT. The mean bias on wind speed was 0.41 m/s for 884,597 samples and 10.11 degrees for 786,227 samples.
Horns Rev 1 wind farm benchmark
Previous offshore wind farm wake benchmarks have been carried out during the past decade as part of the ENDOW and UpWind projects. New and refined models are now available for the industry, combined with the better understanding and refined processing of the wind farm SCADA data makes it relevant to initiate a new benchmark based on the Horns Rev wind farm within the EERA-DTOC project. The initial benchmark focused on the basic flow cases, which includes simple wake between a pairs of turbines, flow along a straight row of turbines with fixed spacing and park efficiency. Eleven wake models were benchmarked.

The Horns Rev wind farm (HR) has a shared ownership by Vattenfall AB (60%) and DONG Energy AS (40%) located 14 km from the west coast of Denmark. The wind farm has a rated capacity of 160 MW comprising 80 wind turbines, which are arranged in a regular array of 8 by 10 turbines, with a spacing of 560 m in both directions equal to 7 diameters. The layout of the wind farm is not rectangular, while the direction of the N-S columns is 353°. The diagonal wind turbine spacing is either 9.4 D or 10.4 D. The wind farm comprises VESTAS V80 turbines, which are 2 MW pitch controlled, variable speed wind turbines with a diameter of 80 m and 70 m hub height. The wind farm has been in operation since 2004 and the SCADA statistics from 2005 – 2007 is available for the wake analysis.

The dataset for the current wake analysis was limited to three years, from 2005 to 2007 and includes the SCADA data from the 80 wind turbines and the two downstream wake masts (M6 & M7). Due to the local wind rose, the wake analysis shall be concentrated to westerly and easterly inflow sectors centered at 270° and 90° respectively. Because M6 & M7 are located inside the wind farm wake for the 270° sector, a flow reference has been establish based on wt07 (located in the most western row of the wind farm) in terms of wind speed derived from electrical power and wind direction derived from the calibrated wind turbine yaw position.

The results of the Horns Rev benchmarking campaign indicate that many of the models significantly over-predict the maximum wake losses in comparison with the measurements. This is particularly the case for the CFD models that simulate the wake shape precisely and less so for more empirically-based models. However, recent findings obtained within this project indicate that the discrepancy between the measurements and model results could be caused by a high uncertainty and residual spatial and temporal variability in the measurement and estimation of the wind direction. This high uncertainty causes the analysis of the measured data to produce artificially low power losses in the wake center because of direction variability. This finding challenges the traditional methods of comparing wind farm SCADA measurements with wind farm flow models.

Lillgrund wind farm benchmark
The second benchmark focused on closely spaced wind turbines, speed recovery due to “missing” turbines and park efficiency. The Lillgrund wind farm has been selected for the benchmarking due to the small internal spacing. 31 flow cases have been identified, which all are validated against the SCADA data obtained from the wind farm. Ten wake models were benchmarked.

The Lillgrund wind farm (HR) is owned by Vattenfall AB and is located in Øresund, 6-8 km from the swedish west coast and south of Malmö, with small water depth. The wind farm has a rated capacity of 110 MW comprising 48 wind turbines, which are arranged in an irregular array. The wind turbines are erected with a spacing of 3.3 & 4.3 D along the main directions 120/222°. The mast, with a height of 65m, was installed prior to the wind farm installation, to document the wind conditions and moved closer to the
wind farm in 2007. The wind farm comprises SWT-2.3-93 turbines, which are 2.3 MW pitch controlled, variable speed wind turbines with a diameter of 92.3 m and 65 m hub height. The wind farm has been in operation since 2007 and the SCADA statistics measured in the period 2008 – 2012 has been made available for the wake analysis.

One of the flow case is the determination of the park efficiency for $\Delta = 3^\circ$. The park efficiency plot illustrates the nine distinct deficit sectors in the wind farm. The distinct deficits sectors are so well captured by all 9 models such that it is difficult to distinguish between the models.

The Lillgrund benchmark demonstrates a good agreement between wake model results and measurements as all models were able to predict the increased deficit between closely spaced turbines. The speed recovery due to some “missing” turbines has been well reproduced. The linear relation between peak deficit and turbulence has been well reproduced by most of the models and the park efficiency at 9 m/s for 0 - 360° inflow has very well reproduced, compared to the SCADA measurement.

Rødsand-2 wind farm benchmark (including Nysted wind farm) farm to farm cluster effects

The cluster performance, defined as the wake effect between two wind farms has been simulated and validated. This is the first benchmark on multiple wind farms, modelling the large-scale effects of more than 150 wind turbines. The validation has been performed on two large wind farms, separated with a distance of 33 rotor diameters. For easterly flow conditions the upwind (Nysted) wind farm consists of wind turbines installed on straight rows with a spacing of 11D, while the downwind (Rødsand II) wind turbines are located on arches with variable spacing between 5-7 D. The sideways displacement of the wind farms is approximately 10D, which limits the inflow sector with visible cluster effects. Ten wake models were benchmarked.

Identification of flow cases are purely based on SCADA data, recorded on the Rødsand wind farm where the inflow conditions are derived from a partly undisturbed wind turbine, due to lack of met mast measurements.

The SCADA analysis conclude that centre of the deficit for a wind farm with variable spacing and undisturbed inflow is located 80-90 diameters downstream from the inflow turbines. Furthermore, the location of the zone with maximum deficit is not very sensitive to the inflow direction and the maximum deficit inside the zone is 20 – 25 %. The SCADA analysis of disturbed inflow concludes that the zone with maximum deficit is distinct and located only 5-10D downstream from the WF inflow area. The size of the zone increases and moves downstream for increasing inflow direction e.g. where the wind farm operates in partly wake conditions.

The initial benchmark was the simulation of undisturbed inflow to the Rødsand II wind farm to demonstrate the model ability to handle wind turbines with variable spacing. The main focus is the benchmark on simulating the combined cluster effect between Nysted and Rødsand-2. The flow cases, identified with wind speed and sector, have been simulated and validated towards the SCADA results. The validation confirms that a distinct triangular deficit zone appears 5-10D into the wind farm, when the wake encompasses the downwind wind farm. The deficit zone, representing 20-30% speed reduction, increases and moves downstream for increasing inflow direction (partial cluster effect), and the external wake effect disappears outside a flow sector of ±15°.

The benchmark demonstrates that most of the models were able to predict the cluster performance when the Rødsand-2 operates partly or completely in the wake of Nysted WF. Furthermore, the park efficiency has been calculated for a limited inflow sector 77-117° where the Rødsand operates partly in wake of Nysted WF and compared to the measured park efficiency. The modelled park efficiency levels vary with
±5% and all models predicts the minimum efficiency to be located in the sector 97-107°.

Alpha ventus wind farm including lidar experiments

Measurements with a long-range multi-lidar system (ForWind Oldenburg) and a ship-based lidar system (Fraunhofer IWES) have been performed at the German offshore test field ‘alpha ventus’ as part of the wake model verification activities of EERA DTOC. Mainly, the inflow and wake flow in the vicinity of the wind farm were measured to obtain data for validation of the different wake models.

The Alpha Ventus wind farm is composed of twelve wind turbines of 5MW each (total 60MW). Although it has a smaller size to ‘BARD Offshore 1’, however, it was expected to be useful in estimating wake length and general characteristics that could be extrapolated to larger sized wind farms.

Measurements were performed with the multi-lidar system of ForWind-Oldenburg from July 2013 until January 2014. In this time period, three campaigns were carried out. Datasets were made available for defining test cases to validate microscale and mesoscale wake models.

The first campaign aimed at assessing the performance of the multi-lidar system. For this purpose, data from the offshore meteorological mast at the research platform FINO1 has been used. Furthermore, the measurement strategy was designed to allow a comparison between multi-lidar and ship-lidar measurements above 100 m in free flow conditions. The second and third campaigns were dedicated to measuring inflow and wake flow quasi-simultaneously.

Two ship-lidar based measurement campaigns were performed from August 27th till August 31th 2013 and October 4th to October 9th 2013 by the Fraunhofer IWES. The main objective of the first measurement campaign was the testing of the system hardware and measurement parameter, verification of the ship-lidar correction methods as well as first near-wake measurement tests. Main intention of the second ship campaign was the measurement of wakes in different downstream distances to the wind turbines. As a reference, wind data from FINO1 meteorological mast (met mast) was used.

The measurements during the long-range lidar campaigns are heavily based on vertical wind speed profiles at different positions around or within the wind farm. Mainly, they are related to the process of measuring wind speed along a vertical line at some remote points in space. Therefore they are called ‘remote’ or ‘virtual mast’. The advantage for offshore applications is the possibility of ‘moving’ around the measurement target at convenience. However, their usage is relatively new and there is no standard definition of its implementation. Likewise, the applied ship-based velocity-azimuth display (VAD) measurements by Fraunhofer IWES were novel in its application, wherefore an inertial comparison with the meteorological mast FINO1 were performed.

The exemplary results show a good agreement of the new measurement methodologies against the standardised measurements with cup anemometers wherefore a sufficient accuracy of the measurements discussed in the following sections can be assumed.

The second long range lidar campaign aimed at measuring the wind field inside the wind farm. For this,
standard scanning techniques were applied based on so-called Plan-Position-Indicator (PPI) scans. Mainly, the lidars were scanning with a constant elevation inside the wind farm. The results show details of the individual wakes and their merging inside the wind farm. The measurement data is available for validation of microscale wind farm models in a test case basis.

Ship-based lidar measurements in the wake of an offshore wind farm were carried out by Fraunhofer IWES. Different datasets were collected to support the validation of the integrated design tool.

During the measurement campaign – from 4-9 October 2013 – 36 different tracks through the wake of the Alpha Ventus wind farm were performed for downwind distances from 2 km to 10 km, inflow wind speed between 4 ms-1 and 11 ms-1 and inflow angles from 180° to 320°. The data were corrected applying the complete correction algorithm.

In a first consideration averaged inflow conditions, like the wind speed profile, wind direction at 90m height and atmospheric turbulence intensity at 90 m, measured by the meteorological measurement mast FINO1 in the time from 05.10.2013 9:50h till 10:30h were used as input parameters for the different simulations. These conditions changed slightly in the 40min of measurement. In a first approach these changes were not taken into account and representative mean values were used instead.

Three models were used to simulate the measured wake situation in test case. A modified version of the Park wake model, also implemented in the Wind Atlas Analysis and Application Program (WAsP), is here used for one part of the wake calculations. The second used model is based on the CFD code VENTOS®/2. It is a finite volume implicit solver for the Reynolds averaged Navier-Stokes (RaNS) equations for non-stratified flows, with a two-equation k–ε turbulence model. It is geared specifically towards the solution of wind flow problems over complex terrain. The third numerical model is a further development by the Fraunhofer IWES of the wind farm layout code FLaP which has original been developed by the University of Oldenburg.

On the basis of the ship trajectory and the measured heights ranging from 40 m to 140 m, the wind speed was extracted from the corresponding points of the simulations. A comparison of the ship-lidar measurements and the wake model simulations can be found. The wake deficit behind the four rows of turbines is both clear in observations and in model results.

Satellite Synthetic Aperture Radar (SAR) wind farm far-field investigation
Case study at Sheringham Shoals
The satellite RADARSAT2 image from 9th August 2012 at 17:41:53 UTC shows the presence of a 35 km-long wind farm wake on Sheringham Shoal in the North Sea. It is the intensity image where the darker area is due to lower wind speed. The SAR image has been observed from emitted microwave radiation at C-band (wavelength around 5 cm). The backscattered signal from the natural ocean surface is dominated by surface winds. The bright objects observed are ships and wind turbines mainly. For the ocean surface, the roughness of the sea appears darker for lower wind speed and brighter for higher wind speed because the backscatter from capillary and short-gravity waves at the surface of the ocean relates to surface wind speed. More wind produces more short waves. The backscatter may be used to retrieve wind speed using
geophysical modal function. The winds are from south east with a value around 3-4 m/s at 10 m above sea level.

A modified version of the Park wake model, also implemented in the Wind Atlas Analysis and Application Program (WAsP) is here used for wake calculations. The main difference between this modified version and that in WAsP is that the former does not take into account the effects of the ‘ground reflecting back wakes’ and so it only takes into account the shading rotors both directly upstream and sideways. The comparison is fairly good for the shape and length of the wind farm wake but the wind speed levels are different. The winds in the SAR image are below cut-in, so it is necessary to use a (slightly) higher wind speed in the wake model to achieve a wake result.

Case of several wind farms in the North Sea

Another example of long wind farm wakes observed from SAR is at Belwind wind farm the wake is around 55 km long, at Thornton Bank 45 km, at London Array 15 km, at Thanet 14 km and at Kentish Flat 10 km (but probably continues inland). The WRF wake model is used for simulation of the case. The model simulation includes the largest wind farms (London Array, Greater Gabbard, Thanet, Belwind1 and Thornton Bank). The velocity deficit at 10 m at 30th of April 2013 at 18:00 UTC is calculated. Comparison between satellite observations and wake modelling shows fairly good agreement.

Summary on wind farm wake validation

The EERA DTOC wind farm wake validation has been demonstrated at Horns Rev 1, Lillgrund and Rødsand-2 using SCADA data. Many wake models have been compared and the results show overall good agreement between SCADA data and models. The far-field wakes observed at Alpha Ventus with novel techniques are less clear to interpret and compare to wake models. This is due to both natural variability in winds and the measurements from lidar that need careful processing. For the ship-based lidar the movement of ships should be accounted for. For scanning lidar the exact timing and position of all beams should be carefully adjusted. Finally, the wake at longer distances is not necessary steady in time and space. The satellite data investigated show long wake and this can in part also be modelled by wake models.

DTOC SOFTWARE

Introduction

At the beginning of the DTOC project, the EERA consortium members had about 20 different software tools potentially available for integration. Those tools included meteorological mesoscale models (WRF and Skiron), wake models (PARK, Flap, FUGA, FarmFlow and some CFD tools), wind resource assessment tools (WAsP and others), models for the calculation of electrical flows and networks (eeFarm, WCMS, NetOp) and other specialised models like CorWind for the calculation of the correctly correlated wind output of a region of wind farms. The different tools ran on a variety of different platforms, from PCs to supercomputers. The development and usability status was very heterogeneous, from fully commercial products to researcher tools. Therefore, the first item on the agenda was to find out which models are in a status that they may be integrated, how the final tool should look like and work, and how all those models could work together in different model chains. These were developed based on the user requirements which were analysed in detail together with the end-user partners of the project.

User requirements

The user requirements were clarified early in the project (within 4 months) based on a workshop and a questionnaire. The design and model selection have guided by this. There are two main user groups: a)
Developers and b) Strategic planners of offshore wind farms. The associated users are: a) Consultants, b) Research institutions, c) Manufacturers, d) System Operators.

The user stories have been included in the three application scenarios (See Chapter 6) such that all user stories will be considered in minimum one of the scenarios but more often in several scenarios.

• As a developer, I can determine the optimum spacing, position, turbine model and hub height of turbines within an offshore wind farm.

Software supports the comparison of many design scenarios. Comparative reporting enables selection of optimised configurations.

The comparative score is the Levelised Cost of Energy (LCoE) in €/kWh.

Software

One of the design parameters was to establish open interfaces between the tool and the partner softwares, in order to enable a seamless data transfer and a modular approach for the DTOC platform. This includes formats defined for static data, meteorological data, wind resource data, energy production data and electrical grids, i.e. the different data sets, which exist as input and output of DTOC models.

The development of these formats is based on existing formats, end-user requirements, user stories, and the dry-run results, and a review by the respective DTOC partners. These formats and interfaces are defined on base of existing professionally proven formats and altered to meet the requirements of describing the DTOC application cases. This also includes non-functional requirements such as compatibility, portability, ease of use, being lightweight, simplicity etc. Static data is stored in XML formats, which are mostly derived from the formats used operationally in DTU’s WAsP and in the wind power forecasting platform ANEMOS. Gridded data is stored in netcdf format. Time series data is stored in the Depri format, which is a format proven in various commercial and research applications in the wind energy sector.

Models and model chain

Together with the interfaces connecting the individual softwares from a data perspective, the three topic-oriented WPs worked out the conceptual model coupling, and the data flow.

The access to the DTOC platform on the central server is realised by a web interface and accessed via a standard internet browser. This interface has been realised using the Google Web Toolkit, so it is based on a quite generic approach and should be independent of the specific web browser used by the end-user. In addition, Geographical Information Systems may be connected via standardized OGC data base interfaces.

Editing geographic features like turbine positions, cable layout, etc., are implemented via a GIS interface, as most end users employ some form of GIS (Geographical Information System) already. For moving turbines, laying cables, or dealing with water depths for example, the current project is accessed via a GIS system running locally on the client computer (the open-source QGIS system has been tested) and modified there. The data exchange with the DTOC platform is realised using the open standard “OGC SQL extensions”. This means that the GIS is running locally on the client computer, but the data is still exchanged online with the central DTOC server via an OGC data base.

The software from partners available in the novel Wind & Economy tool, the EERA DTOC spin off is described below. The software in DTOC1.0 are CorWind, Fuga, WAsP and WRF from DTU Wind Energy, Grid code compliance from UStrath, Net-Op from SINTEF, WRF from CENER and CIEMAT, QGIS open
source and LCOE from several partners. Tools expected in DTOC2.0 are EeFarm 2 and FarmFlow from ECN and WCMS from Fraunhofer IWES.

CorWind

CorWind is an advanced tool developed at DTU Wind Energy Department to simulate wind power variability. It is based on a database of meteorological data simulated by DTU Wind Energy using WRF. The meteorological database has 1 hour resolution in time and 30 km spatial resolution and covers all Europe. It includes historical time series from year 2000. In order to include wind speed fluctuations which are not captured by the WRF model with this resolution, CorWind adds randomly generated correlated fluctuations to the WRF (Weather model) data. CorWind uses power curves to convert wind speeds to power, and the simple power curve approach has been extended with a method to include the shut-downs and start-ups due to extreme weather conditions. For power system studies, the interesting output from CorWind is the generation pattern of the wind power. The results include day-ahead and hour-ahead prognoses generated with CorWind based on a model for randomly generated wind speed forecast errors.

WAsP

WAsP is the wind energy industry-standard PC-software for bankable wind resource assessment and siting of wind turbines and wind farms. There are currently more than 4300 users in over 110 countries and territories, who use WAsP for all steps from analysis of wind and terrain effects to estimation of wind farm production.

WAsP is a PC-program for the vertical and horizontal extrapolation of wind climate statistics. It contains several physical models to describe the wind flow over different terrains and close to sheltering obstacles. WAsP is an implementation of the so-called wind atlas methodology.

Fuga

Fuga is a new wake model for offshore wind resource estimation. Key features are prediction of shadowing from neighbouring farms and effects of atmospheric stability from moderately stable over neutral to unstable.

The annual energy production is calculated by wind climates specific for each turbine site as extracted from a WAsP workspace file - so please note that a WAsP workspace file is a prerequisite for working with Fuga. Statistics of atmospheric stability are prescribed in an additional file.

Grid code compliance

The Grid Code compliance assessment of offshore wind farm clusters is conducted offline using the software NET-OP and PSS/E. The tool NET-OP provides the optimal electrical connection (grid layout) for a cluster of wind farms and generates an output file that is later used in PSS/E to conduct power systems studies (power flows and transient stability) to assess grid code compliance. However, as NET-OP does not provide a dynamic model of the electrical configuration, it is necessary to do some manual work and build the dynamic model in PSS/E. This task includes preparing the single-line model (including generation, both conventional and wind, transmission and loads) and populating the model with the appropriate electrical parameters in order to conduct steady state and dynamic studies. Once the electrical model is build, a methodology to assess grid code compliance is applied. This involves applying disturbances in different locations of the network and observing the dynamic performance of the configuration and how it complies with the requirements in a particular grid code. At this stage, most of the focus has been on assessing the Fault-Ride Through (FRT) capabilities. The ENTSO-E, E.On and GB Grid Codes have been considered during this task.
LCoE

For benchmarking different wind farm variants, a Levelized Cost Of Energy (LCOE) model has been defined, designed and implemented. The cost model is detailed enough to allow a meaningful comparison of design options, but at the same time it is flexible and simple enough to be of practical use. It is possible to interface with more detailed and advanced cost models. A discount rate and Net Present Value (NPV) is used to work out the NPV of lifetime costs and NPV of lifetime production.

The LCOE model takes the energy production of the wind farm as input together with a number of parameters describing the economic figures like turbine and foundation costs, discount rates, installation costs, OPEX, etc. The model is implemented as a JAVA module and running integrated in the DTOC platform. The results of the calculation are presented together with the energy production values in the DTOC reporting.

Net-Op

Grid connection of offshore wind farms differs from grid connection of onshore wind farms in several significant ways. Firstly, the offshore location means that power transmission has to be through subsea cables, something which adds costs and constraints. Secondly, there is in most cases no pre-existing offshore electricity grid that offshore wind farms can connect into. And thirdly, the long distances to onshore connection points for many planned wind farms brings with it technological challenges, but also new possibilities regarding grid layout; when distances are large it is increasingly relevant to consider the wind power grid connection in tandem with power trade possibilities.

These considerations are at the core of the Net-Op design approach. It takes into account the possibility of trade with different prices at onshore connection points and optimises the grid from a socio-economic point of view, finding the solution whereby demand is covered by the cheapest possible mode of production. The Net-Op tool takes a high-level perspective, avoiding technical and financial details. It is aimed at long-term planning at a high-level by users such as government and government agencies, transmission grid operators and academia. It is fairly easy to use and requires a relatively modest amount of input data. The Net-Op optimisation takes into account the variability in wind power generation and power system demand/prices, sampling from correlated time series to get a statistically representative set of operating points. The main output is the grid layout specifying the number of cables on each allowable connection, whether it is ac or dc, and the cable capacity. The problem is formulated as a mixed integer linear programming problem. Net-Op does not consider the wind farm internal grid design.

QGIS

QGIS is a cross-platform Open Source Geographic Information system with an international support community of enthusiastic users, developers and supporters.

WRF

Weather Research and Forecasting model (WRF) is used at the partners (CIEMAT, CENER and DTU Wind Energy).

The regional atmospheric models or limited area weather models have undergone a large development during the last decades. This has been partially possible due to the large increase in the computational capabilities. The WRF model is the regional model used to simulate the atmospheric evolution in this investigation. WRF is a numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. The model is public domain and concentrates the efforts of various public institutions of the U.S. and overseas. The model numerically solves the Euler equations of motion applied to a fully compressible atmosphere. It is a non-hydrostatic model which allows for high
horizontal resolution in a simulation. WRF has a large number of parameterizations to represent unresolved physical processes such as the turbulent mixing within the planetary boundary layer, radiation transfer, cumulus, microphysics, soil processes, etc.

**EeFarm**

EeFarm-II has been developed to study and optimise the electrical performance of wind farms. The program is used to determine the energy production, electrical losses, component failure losses and the price of the produced electric power of a wind farm. The program consists of a component library, a component data base, and a postprocessor. The component library contains steady state models of turbines, generators, transformers, AC and DC cables, PWM (pulse width modulated) and thyristor converters and of an inductor, statcom and chopper. EeFarm-II is programmed in MATLAB -Simulink. EeFarm-II calculates the voltage, current, active and reactive power of the main electrical components in a wind farm. The calculation starts at the turbines and proceeds in the direction of the high voltage grid. EeFarm-II calculations require component parameters (typically resistances, capacitances and inductances) and budget prices which are stored in a component database. Ideally the parameters and budget prices should be supplied by component manufacturers and should be updated regularly. A database with manufacturer supplied component parameters is included; budget prices however are not included due to confidentiality agreements. EeFarm-II was originally developed by ECN and Delft University of Technology in MATLAB. To improve user-friendliness, it was completely rebuilt in MATLAB-Simulink, exploiting the advantages of the Simulink graphical user interface and MATLAB data structures.

**FarmFlow**

For the accurate calculation of wind turbine wake effects in (large) offshore wind farms, ECN has developed the software tool FarmFlow. FarmFlow calculates the time-averaged flow velocities and turbulence intensities inside a wind farm. The wake model in FarmFlow is a 3D parabolised Navier-Stokes code, using a k-ε turbulence model to account for turbulent processes in the wake. A boundary layer model is used for the calculation of the free stream wind speed. For the deceleration and expansion of the near wake, FarmFlow uses an axisymmetric vortex wake model to calculate the stream wise pressure gradients, which are prescribed as a source term in the flow equations. Given a year averaged distribution of wind speeds and wind directions the yearly energy yield of a wind farm can be determined.

**Wind Cluster Management System (WCMS)**

The Design Tool for Offshore Clusters- Wind Farm Cluster Modelling & Simulation (DTOC-WCMS) is designed to estimate the provision of system services. It has been adapted from an existing operational version known as Wind Cluster Management System (WCMS).

This simulation consists of the cluster behaviour and the cluster control. The cluster simulation is a steady-state load flow simulation of the wind farms, their connections to offshore substations and the connections to the grid on land (by HVAC or HVDC technology). The cluster control provides the intrinsic required control commands (set-points) for the individual wind farms within the cluster in order to fulfil requirements for power plant system services at the connection point(s) on land.

The wind power plants (WPP) are considered dispatchable units that can be committed to provide a service or to schedule active power to the power system either day-head or intraday. In this context, the forecasted power for the WPP are used to create schedules of power that can be used either as a reserve or allocated as active power scheduled day-head -both based on the day-head forecast- or as balancing power schedules, based on intraday forecasts. The differences between the addition of those schedules and the real active power production are considered as undispatchable and therefore considered as
losses due to (forecast) uncertainty. In addition WPP can also provide voltage support by providing reactive power and reactive current on different time scales.

The run flow of the DTOC-WCMS is basically divided in three main blocks or modes:
1. Check/planning mode: The "check" mode calculates the load flows for maximum power output of the WPP (rated power) and in low wind conditions (minimum generation). This calculation allows knowing if the utilised grid layout is able to accommodate the power flows, detecting possible congestion and overload.
2. Reserve mode: in this mode, the provision of reserve, balancing power and active power provision for the day-ahead market (based on schedules) is investigated.
3. Voltage mode: using the grid layout and the wind power time series the maximum reactive power contribution of all WPP in a cluster to the onshore nodes is calculated. This calculation allows knowing how much reactive power can be provided to the onshore nodes by a cluster.

The congestion detection is automatically implemented for each calculation due to the fact, the best option in terms of electrical losses reduction and component utilization reduction is selected.

DTOC TOOL
A central concept of the DTOC tool is the organisation of wind farm variants as scenarios and scenario trees. The single scenario is a fine-grained project variant, distinguished by all project parameters and the employed model chain including the model parameters. Scenarios can be cloned or duplicated, and inherit the settings from the higher level scenario.
This philosophy supports one of the central user stories: As a developer I can determine the optimum spacing, position, turbine model and hub height of turbines within an offshore wind farm.
The DTOC software supports the generation and comparison of the calculation results of many design scenarios. Comparative reporting of those results enables then the selection of optimised configurations. Web interface overview is available. On the top left, projects and the scenario trees can be organised. Below are the wind farm parameters (plus wind turbine type and model parameters) managers. In the right frame, the currently selected scenario is shown, including wind turbines, wind farm shapes and cabling configuration. In the lower left frame, the action buttons for model calculations, GIS interaction and wind climate management are situated. In addition, a message box is shown indicating that there is a model run which has been started recently. In the status bar at the lower end of the browser window, the model run status is shown.
As mentioned above, the editing of geographical properties is implemented by the integration of a local GIS, again based on open interface standards. Communication between local GIS and the DTOC platform is realised via online read and write access to a geographical data base. In addition, turbine properties like hub height and turbine type may also be altered via GIS interface.

The EERA-DTOC tool and its commercial variant, the Wind&Economy tool (wind-and-economy.com) allow developers and strategic planners to quickly scan and compare the LCOE of a large number of possible wind farm layouts with state-of-the-art models in an integrated work flow. The tools thereby take into account the wakes within the wind farm, and the mesoscale wake effects of surrounding or even future wind farms. From the tool, a dedicated WRF run can be started at one of the three collaborating institutes. The effect of bathymetry is parameterised, and the electrical cabling losses may be incorporated.
The large-scale electrical infrastructure (transformers, HVDC cables to shore etc.) can also be determined and optimised, using the Net-Op tool in an offline mode. The grid compliance of the resulting layout can be determined.

The software is intended to be used in-house at offshore developers, or probably as a service for strategic planners.

Compared to other existing wind farm design software, the DTOC/Wind&Economy tool shows the following unique selling points:

• Clear workflow for layout, variation and comparison of variations in wind farm layout, called scenarios;

• Integrated comparative reporting;

• Multi-user approach and user rights management;

• Includes economic calculations for benchmarking different layout scenarios via the LCOE; Seamless integration of leading edge models for wind climate and wind farm interaction calculations;

• Validation of integrated models with offshore applications;

• Integration of state-of-the-art wind farm wake models, supporting the effects of large scale wind farms and long distance wakes;

• Consideration of the non-uniform wind climate over large sea areas, including the change of wind climate by existing or planned other offshore wind farms;

• Coupling to GIS software for editing of locations and properties;

• Consideration of limitations and other exploitation by GIS approach.

SCENARIOS

In the EERA-DTOC project the integrated offshore wind farm design tool as delivered is demonstrated for the industry by means of likely use cases or scenarios. The likely scenarios are defined for the Northern European Seas where governments are planning clusters of wind farms. Requirements in the scenario definition are that industry itself plays an important role in them.

In this respect, it is obvious that the value of the EERA-DTOC tool could best be demonstrated by a comparison with measurements but it should then be realized that the intended clusters for which the tool is developed are still mainly in the planning phase by which measurements to validate the tool are lacking. However, by the calculation of likely scenarios, the industrial usefulness of the tool can still be tested where moreover an ‘expert view’ on the results will be carried out in order to check their degree of reality.
Three types of scenarios have been defined: The ‘base and the near future scenario’, are scenarios which are still relatively close to the present state-of-the-art wind farm (clusters). This is in particular true for the base scenario which is described as a scenario which reflects ‘the current way of thinking’. The near future scenario is exploring the near future (i.e. a time line of 5 years after its definition in early 2014) e.g. through the use of very large upsampled turbines. Moreover a far future scenario has been defined which considers a time line until 2030 when large wind farm clusters are defined with several relatively unconventional options like floating turbines, HVDC grids and assuming an offshore grid infrastructure already exists. Several parties carried out calculations with the software. Thereto a test matrix has been defined with which the user stories and scenarios were divided over the partners.

For the base scenario (Race Bank) IWES, DTU, RES, Fraunhofer, UPorto were running the following user stories:

- “As strategic planner or developer I can determine the wake impact of individual wind farms within a cluster on each other (just meso)”
- “As a developer I can determine the wake effects of neighbouring wind farm clusters on a single wind farm (meso- and microscale modelling)”
- “As a developer I can determine the wake effects due to turbines within a wind farm”
- “As a developer I can determine the net energy yield of a wind farm”

For the near future scenario (Dogger Bank) ECN, DTU, CRES, Fraunhofer were running user stories

- “As a developer I can determine the wake effects of neighbouring wind farm clusters on a single wind farm (meso scale and micro scale modelling)”
- “As a developer I can determine the optimum spacing, turbine model and hub height of turbines within off-shore farms”
- “As a developer I want to use wind farm lay-out scenarios of my target wind farm with respect to nr of turbines, turbine types, thrust curves etc.”

The far future scenario (year 2030) was run off-line by SINTEF and UStrath. All parties were asked to report the results of their calculations in a prescribed format so that a consistent and comparable set of user reports has been obtained.

Race Bank scenario (base scenario)
The base scenario is performed at the location of the planned Race Bank wind farm at the Eastern coast of England 27 km from the North Norfolk coast. The capacity is 580 MW and it will be composed of 94-116 turbines in the range of 5-6.15 MW. The water depths are between 6 and 23 m. The present scenario assumes the farm to consist of 100 UPWIND (NREL) 5MW reference turbines as it reflects the current state of the art wind turbine technology which is one of the conditions for the base scenario. A full description of the selected turbine is available from the former EU FP6 project Upwind. The resulting power and CDAx curves from this description were calculated by ECN and included in the EERA-DTOC tool.

The suggested layout of the target farm includes 10x10 wind turbines where one main ‘wind farm line’ is oriented in the East-West direction and the other main wind farm line slightly skewed compared to the North-South direction. The electrical lay-out of the farm consists of 20 grid lines connecting 5 turbines to a central substation. However this infrastructure should be seen as a starting point. Part of the optimisation
The Race Bank wind farm is surrounded by several other wind farms which are either in operation already or they are in the planning phase. These surrounding farms are added into the tool. Moreover rotor characteristics of the actual turbines from the adjacent wind farms were found from manufacturers brochures or based on best guesses. In this respect it should be realised that the influence of the detailed characteristics of the turbines in the adjacent wind farm are slightly less critical in view of the fact that these turbines are far away from the RaceBank farm under consideration.

The neighbouring farms are:
- Lincs 270 MW wind farm consisting of 75 Siemens SWT 3.6 120 turbines at a distance of 25.5 km and 246.5 degrees from Race Bank;
- Linn and Inner Dowsing 97,2 MW wind farm, consisting of 27 SWT 3.6 107 turbines at a distance of 31.21 km and 238.364 degrees from Race Bank;
- Triton Knoll 200-300 MW wind farm consisting of turbines in the range from 3.6 to 8 MW (unknown yet since the farm is still in the planning phase. The farm is located approximately 18.2 km and 165.815° degrees from Race Bank;
- Sheringham Shoal 316.8 MW farm consisting of 88 Siemens SWT 3.6 107 turbines at a distance of 26.693 km and 131.259 deg. from Race Bank;
- Dudgeon 360-400 MW wind farm consisting of Siemens SWT 6.0 154 turbines at a distance of 37.259 km and 94.242 deg. from Race Bank (in planning phase).

The wind data has been produced by CENER using WRF.

The wind farm under consideration is then suggested to be located at the Creyke Beck A site, which is the most Southerly project 131 km from the shore at its closest point and it consists of 100 turbines with a rated power of 10MW as described below. The surrounding farms are given by the above mentioned projects Creyke Beck B, Teesside A and Teesside B. These surrounding farms are assumed to have a similar layout with the same 10 MW wind turbine types as the Creyke Beck A farm.
The lay-out of the near future scenario target wind farm is similar to the 10x10 wind farm for the base scenario. The difference with the base scenario lies, apart in the different location, in the 10 MW turbines as used in the wind farm making it a 1 GW wind farm. 10 MW turbines are not on the market yet and therefore the INNWIND.EU reference turbine is utilised. The data of this turbine are already made publicly available by DTU.

The surrounding wind farms (Creyke Beck B, Teesside A and B) are assumed to have a similar lay-out and the same types of turbines. The lay-out of all farms together with the turbine characteristics of the INNWIND.EU turbine are already included in the EERA-DTOC tool.

The wind climate in this area has been calculated by both CIEMAT and DTU. Thereafter DTU Wind Energy used the WRF model to estimate a two year wind climate, from January 2006 to December 2007.

A 'preliminary scenario' has been calculated based on this near future scenario using the ECN toolkit combination FarmFlow - EeFarm-II. The purpose of the preliminary scenario was to test the scenarios defined in EERA-DTOC and to show the potential of a combined aerodynamic-electrical tool in quantifying investment costs, electric performance and levelised transport costs given a specific choice of wind farm layout and cable topology. The investment costs from model EeFarm scale more or less directly with cable length, but the net energy production increases slowly with increasing spacing distance. Hence investment costs keep on rising with distance but there is hardly any increase in energy production anymore for large distances indicating that an optimum distance should exist in the levelised cost of energy where the increase in investment costs from the increase in distance is not balanced anymore by the increase in energy production.

Far-future scenario (year 2030)
The context of the scenario is a post 2030 situation where many offshore wind farms have already been installed and an offshore grid infrastructure is in place, which connects the countries around the North Sea. In this far future scenario, three new wind farm clusters are considered.

The main aim of the far future scenario is to demonstrate the usefulness of the EERA-DTOC tool for long-term, strategic planning. This means planning by e.g. government, regulators, seabed owners, transmission grid owners and scientists concerned about making optimal recommendations and decisions. The scenario therefore addresses specifically the user stories related to "strategic planning". From a wind farm developer point of view this may be somewhat removed from their direct needs – however, also for such users it may be useful to study a far future scenario in order to provide input to their long term planning.

The data files and documentation provided based on the outcomes of Net-OP tool are utilised to examine the compliance of the far future wind clusters with grid codes. The examined benchmark system represents the major regions that are going to be connected directly or indirectly to the three far future wind clusters. This system is inspired from the outcome of Net-OP tool, which recommended certain pattern to connect the three clusters.

For the sake of simplicity, the wind generation is modelled by a single aggregate machine of type 4 (Full rated converter wind turbine generator) at each bus. Likewise, conventional generation is modelled as a
single generator with a capacity equals the generation capacity of the entire region of the bus (the parameters source reactance and resistance are assumed to be 0.3 and 0.06 per unit respectively). The generation capacities at each bus and aggregate load at each region is estimated. To initialise the power flow, a limitation is applied on wind generated power through assuming that the capacity factor of any wind power plant is not exceeding 50%. The implemented case studies are selected to investigate the impact of integrated new wind clusters on voltage response of connected grids during severe faults. The methodology provided in (add footnote1) is applied. The fault is initiated at time = 0s and the simulations continues for 4s.

The reactive current grid requirement is fulfilled by the wind clusters where the reactive current is always higher than the red threshold. However, the reactive power slightly violates the code limit after the fault is almost cleared. It is worth mentioning that the applied codes are dealing with wind farms at certain point of common coupling in an AC grid. But in the given case, there are several wind farms which form the wind cluster. In addition they are linked through HVDC corridors. Thus, the reactive capability mainly depends on the reactive limits of the DC link inverter not on the wind turbines installed in the wind clusters. It is expected that after fifteen years, special codes will be needed to deal with such advanced renewable energy integration. The steep drops and peaks are most probably caused by the numerical solution obtained from the mathematical methods implied by the PSS®E.

Finally, the active power provided by the wind clusters to Bus 101 in the second case study (Nordic code dip) is highlighted. The active power flows continuously even during the dip. However, it suffers a moderate drop (i.e. the reactive power increases during the dip). Afterwards, it stabilises at a new value after the dip ends.

Summary
Several parties carried out calculations with the software. Thereto a test matrix has been defined with the user stories and scenarios to be calculated. All parties were asked to report the results of their calculations in a prescribed format so that a consistent and comparable set of user reports has been obtained.

One of the main obstacles for a thorough testing was formed by remote access problems, since firewall problems prevented many users to run the tool from their offices. These problems could sometimes be solved through workarounds, but this turned out to be a time consuming procedure. Together with the fact that testing of the tool started later than originally anticipated, this made that not all planned scenarios and user stories from the test matrix could be covered.

Generally speaking the users reported positive experiences, with easy installation (apart from the firewall problems) and a steep learning curve. The QGIS was sometimes mentioned to have long runtimes.

Most results which have been obtained were believed to be realistic. In many cases a comparison was made between Fuga and WAsP leading to a reasonable to good mutual agreement. Interfacing to other tools was however not possible yet from the EERA-DTOC tool by which the users who wanted to run other models than Fuga and WAsP had to run these cases off-line.

Very interesting was a study on the near future scenario in which the production was compared of a wind
farm consisting of INNWIND.EU turbines and the production of the farm where the turbines were replaced by low induction (and higher diameter) AVATAR turbines. The farm with AVATAR turbines led to a higher gross energy production (as expected from the larger turbine) but also to lower wake losses which are attributed to the design concept (low induction) of the AVATAR turbine. The results of this study will be communicated to the AVATAR project.

Moreover, a large number of observations were made which sometimes led to improvement of the tool, e.g.:

- Too little detail in output results (largely solved);
- Expiry of licences without notice (solved);
- The use of an unconventional turbine (i.e. the AVATAR turbine) leads to unrealistic results (solved);
- The user story which investigates the effect of different turbine heights led to unrealistic cost variations, since the effect of tower height on turbine costs is not included yet;
- Some functionality did not work on Unix, Mac (solved);
- Some puzzling results on the gross energy yield (still under investigation);
- It was found that the wind resource has to be changed at least once in the wind resource manager to get the correct wind resource even if other wind data are pre-selected in the GUI. This is an initialisation/ misconfiguration problem (users have been informed about this);

CONCLUSION

The European Energy Research Alliance – Design Tools for Offshore wind farm Clusters (EERA DTOC) was partly funded by the European Commission. The EERA DTOC project lasted for 42 months. It started in January 2012 and ended in June 2015. The project had 22 partners across Europe and was led by DTU Wind Energy.

The EERA DTOC project aimed to deliver robust and efficient software for planning of offshore wind farm clusters, consisting of a selection of models for different purposes and a central software platform, managing the farm description, editing of wind farm properties, and the invocation of the different tools. The user requirements from industrial partners formed the basis for deciding on model integration and tool functionality. The many models that were available in the EERA consortium, e.g. WAsP, FUGA, FarmFlow, CorWind or Net-Op, have been developed in previous projects mainly through national funding. This was the first time a systematic effort has been performed to efficiently integrate these models in one software.

The software has been intensively validated during the project. This validation was based on wind farm production data from several large wind farms. Additionally, new experimental observations from scanning lidar and wind-profiling lidar on a moving platform (ship) as well as high resolution satellite Synthetic Aperture Radar (SAR) images have been applied for validation of wind farm wake models.

The developed integrated tool is based on open interfaces. This enables future integration of other software. Finally, the tool development led to a commercial spin-off, a new integrated software called Wind & Economy. The developed and integrated tool was used during the project by the partners to model several common test cases, so-called scenarios. These ranged from state of the art current practice for large offshore wind farms near the coast, through cluster scale wind farm planning very far offshore and to strategic planning of a far-future scenario around the year 2030.
Potential Impact:
The potential impact of the EERA DTOC project is through the commercial spin-off software (tool) called “Wind & Economy” as well scientific work presented publically. The exploitation plan for the tool is outlined.

Spin-off tool “Wind & Economy”
Optimised offshore windfarms

One of the most challenging tasks for wind farm developers, the optimisation of wind power plants in the middle of large offshore wind farm clusters, is tackled by the new software tool Wind & Economy which was presented at the EWEA offshore conference in Copenhagen in March 2015. In large offshore clusters, like the German Bight and Dogger Bank, the regional wind climate itself changes by the influence of the big number of turbines, and the wake effects of the big arrays are much more pronounced than known from onshore installations.

EU R&D project

Wind & Economy is a spin-off from the EU-funded R&D project DTOC, Design Tools for Offshore Wind Farm Clusters. This project initiated and led by the European Energy Research Alliance (EERA), brought together models from leading edge research and practical needs and experiences of high-impact industry partners.

Levelised costs of energy

With the Wind & Economy software, wind farm developers have access to a tool which may model the large scale effects of wind farm clusters and large wind farms in order to optimise the wind farm layout with respect to energy production and economics (levelised costs of energy), including turbines and infrastructure costs. In order to offer simple integration with existing wind farm design work flows, a conventional GIS is closely integrated into the software product.

Strengths of Wind & Economy

A big advantage of the close cooperation of researchers, end-users and software developers is the seamless coupling of meteorological, wind farm effect and economical models which are not only from leading edge research and optimised for large offshore wind clusters, but are also verified with actual off-shore applications and measurements. Other highlights of the Wind & Economy software include the support of strategic planners for defining areas for new offshore clusters, optimisation of the onshore grid connections, and the simulation of ancillary services like balancing power and voltage support from offshore wind farms, thus supporting the integration of the large amount of power into the electricity supply systems.

Properties and specific selling points of Wind & Economy
• Addressing wind farm developers and strategic planners;
• Supporting the users in their goal, efficient optimisation of the layout of offshore wind farms and efficient planning of large offshore areas;
• With respect to
  o Wind climate turbine selection
  o Turbine spacing and placing
  o Electrical infrastructure
  o Interaction between wind farms in clusters with respect to energy production
  o Wind resource
  o Limitations of usage
  o Grid connection;
• Clear workflow for layout, variation and comparison of variations in wind farm layout, called scenarios;
• Integrated comparative reporting;
• Multi-user mode;
• Includes economic calculations for benchmarking different layout scenarios via the LCOE;
• Seamless integration of leading edge models for wind climate and wind farm interaction calculations;
• Validation of integrated models with offshore applications;
• Integration of state-of-the-art wind farm wake models, supporting the effects of large scale wind farms and long distance wakes;
• Consideration of the non-uniform wind climate over large sea areas, including the change of wind climate by other existing or planned offshore wind farms;
• Coupling to GIS software for editing of locations and properties;
• Consideration of limitations and other exploitation by GIS approach.

Intellectual Property Rights (IRP)
During the project, it has been a focus to keep the IPR definitions clear and explicit.
The current IPR status is:

Interfaces and file formats: Open

DTOC platform: Overspeed

Calculation models (wakes, electric, wind resource): The respective modeller or public domain

Overspeed will lead the marketing and sales activities of the platform. As product, a combination of the DTOC platform and the models FUGA, WASP, WRF and CorWind (remote) has been defined and is marketed via the brand Wind & Economy.

Exploitation activities
Actually, the exploitation activities already started at the end of 2014, leading to a side-event at the Copenhagen EWEA offshore event in March 2015 and an exhibition stand. In addition, a new web page was set up for Wind & Economy and it is updated constantly.

From the software development point of view, the current product is an advanced prototype, requiring approximately 12 person months of additional work for a real end-user suitable version. To finance this
development, Overspeed is looking for an external investor/business angle with an investment of approximately 300,000 EUR (including management and intensive marketing).

Further public exposure to attract future customers will be the EWEA Annual Event in Paris, November 2015.

The tentative time schedule is as follows:
- Exposé to potential investors July 2015
- Financial close with an investor September 2015
- Version 1.0 November 2015
- Presentation on the EWEA Annual Event in Paris November 2015
- Discussion and business plan for Wind & Economy onshore May 2016

In total, the consortium, the lead partners, the External Advisory Board and the project reviewers see a large potential for the exploitation of the final software product.

While smaller national projects may extend the integration of single purpose models, future funding in the framework of EU R&D projects may also lead to structural extension to new application fields, like O&M strategies and wind farm operations.

In recent weeks, there have been activities to acquire additional funds from national funding bodies:
- Integration of the Fraunhofer wind farm model FLaP-FOAM, Germany, BMWi;
- Advanced optimisation of wind farm structure, Germany, BMWi;
- Dedicated applications for strategic planners including Denmark, (Innovationfund Denmark, proposal), and sea bed conditions

The main dissemination activities of EERA DTOC
Dissemination has the aim of increasing awareness on the project activities and communicating and disseminating its main findings.

The Communication and Dissemination Plan was delivered in month 3 and, together with the Targeted Mailing List (TML), was sent to the project coordinator in Period 1- the TML being also sent to the Project Officer. Worth mentioning is that the TML is constantly updated and currently counts more than 800 contacts.

The project identity was created in month 2, consisting of: Logo, Word template for letters and reports, Power point presentation template.

The project website was set up by EWEA to provide public information about the project goals, status and major deliverables to all stakeholders interested in the development and final results of the project. The website was delivered in Month 3, available at www.eera-dtoc.eu. The project website is being regularly updated with news about the project, such as forthcoming events, public deliverables or other findings. The website also consists of an internal part, hidden to the general public, to which all project partners can access (login required) and share useful information on the project progress. The EERA-DTOC web-site will be hosted at EWEA until February 2017.

Two seminars have been organized during the lifetime of the project. The first one, due for month 2, took place in Copenhagen during the annual event ‘EWEA 2012’ on Tuesday 17 April 2012, while the second
seminar, due for month 18 (mid-project), took place in Frankfurt on 19 November 2013 during the EWEA Offshore conference. Both seminars proceedings are available.

Three workshops have been organized during the project lifetime. The first workshop took place in London on 06 June 2013, in cooperation with EERA-DTOC’s twin project Cluster Design. The second workshop was organized on 24 September 2014 in Amsterdam, once again in cooperation with Cluster Design. The final workshop took the form of the final event during the fair ‘EWEA Offshore 2015’ in Copenhagen, Denmark, on March 10. Proceedings of the workshops are available.

During EWEA Offshore 2015 the spin-off tool “Wind & Economy” was launched on a EERA DTOC exhibition stand during the conference and exhibition 10-12 March 2015.

Beyond the project life time an event is now schedule for the EWEA 2016 conference in Paris. It will be a joint side event for EERA-DTOC and IRPWind on Wednesday 18 November from 10.30 – 13.00.

The side-event announcement is as follows:

“The goal of the workshop is to present the audience with concrete, ready-to-apply results of the EERA-DTOC project and first results and goals of the EERA-IRPWind programme.

The DTOC (Design Tool for Offshore wind farm Cluster) project has resulted in a spin-off software called Wind & Economy that optimizes wind farm design for cost of energy, taking into account the wind climate of clustering wind farms, wake information and grid design considerations. This session will show you how to use it for your wind farm planning.

The IRPWind (Integrated Research Programme Wind) aims to reduce the time to market of research and development efforts through efficient cooperation. The key topic is integration. In 3 sessions, we present and discuss open data sharing in wind energy, how forecasting will change the future energy market and how the research community can help kick-start your R&D initiatives, both financially and content-wise.

EERA DTOC and IRPWind are part of the research activity of the European Energy Research Alliance Joint Programme Wind (EERA JP Wind) that promotes cooperation in wind research between 41 European research institutes. “

In 2016 EERA DTOC plan to attend the final public meeting for the twin project ClusterDesign. Date and place is to be confirmed.

The EERA DTOC project has been very active in presenting the project results throughout the entire project. The Clause 39 given to the project enabled us to strive for Open Access publication as one of the first projects. This effort means that all documents are in open access.

The list complete list of presentations and publications is available in digital form.

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Related documents

final1-d7-20-eera-dtoc-final-summary-report-web-version.pdf