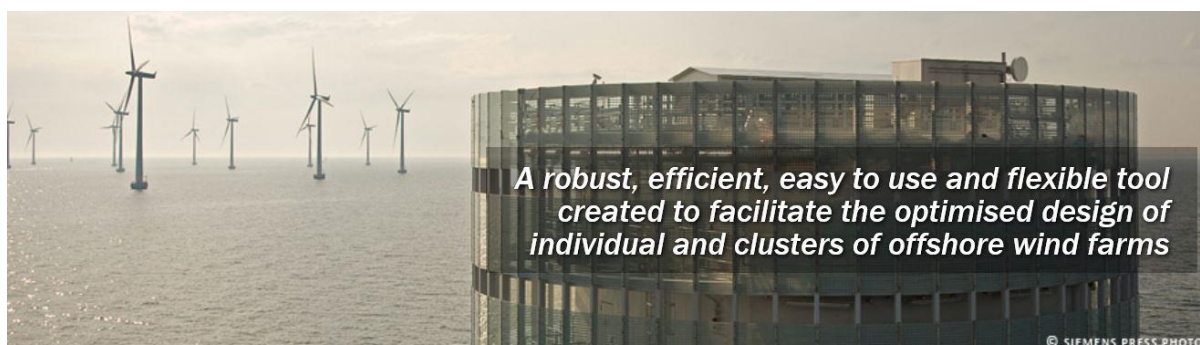


EERA DTOC final summary report

Charlotte Bay Hasager and Gregor Giebel (editors)

June, 2015



Agreement n.:

FP7-ENERGY-2011-1/ n° 282797

Duration

January 2012 to June 2015

Co-ordinator:

DTU Wind Energy, Risø Campus, Denmark

Supported by:



The EERA-DTOC project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 282797.

PROPRIETARY RIGHTS STATEMENT

This document contains information, which is proprietary to the "EERA-DTOC" Consortium. Neither this document nor the information contained herein shall be used, duplicated or communicated by any means to any third party, in whole or in parts, except with prior written consent of the "EERA-DTOC" consortium.

Document information

Document Name:	EERA DTOC final summary report
Document Number:	D7.20
Author:	Charlotte Hasager and Gregor Giebel, DTU (editors) Diletta Zeni, Sharon Wokke, EWEA (lay-out)
Date:	June 2015
WP:	7
Task:	

Table of contents

1	FOREWORD	5
2	EXECUTIVE SUMMARY	6
3	INTRODUCTION	7
3.1	Introduction	7
3.2	Background	7
3.3	Report structure	9
4	SCIENCE	10
4.1	Introduction	10
4.2	Wake modelling micro- meso and coupling	11
4.3	Long term uncertainty on net energy yield	14
4.4	WRF intercomparison to meteorological data and satellite data	17
4.5	Horns Rev-1 wind farm	18
4.6	Lillgrund wind farm	21
4.7	Rødsand-2 (farm to farm)	23
4.8	Alpha Ventus wind farm including lidar experiments	26
4.9	Satellite SAR wind farm far-field wakes	29
4.10	Summary	30
5	DTOC SOFTWARE	32
5.1	Introduction	32
5.2	User requirements	32
5.3	DTOC Software	33
5.4	Models and model chains	33
5.5	Software from partners	34
5.6	How to get started with DTOC	42

5.7	Summary	46
6	SCENARIOS	48
6.1	Introduction	48
6.2	Base Scenario (Race Bank)	48
6.3	Near future Scenario (Dogger Bank)	50
6.4	Scenario far-future 2030	55
6.5	Summary	59
7	CONCLUSION	61
8	ACKNOWLEDGEMENTS	62
9	APPENDIX A: PARTNERS	63
10	APPENDIX B: LIST OF PARTICIPANTS	64
11	APPENDIX C: LIST OF PEER-REVIEWED PUBLICATIONS, PRESENTATIONS AND ARTICLES	70

1 FOREWORD

Peter Hauge Madsen

As coordinator of the project Design Tools for Offshore wind farm Clusters (DTOC) I have found it extremely useful to base the scientific developments on the partnership in the European Energy Research Alliance (EERA). The expertise of these has contributed excellently to move forward in a highly cross-disciplinary way, and the project has benefitted enormously from the knowledge and models developed in national efforts. The industrial partners have set a truly ambitious target for the integrated software and we have been able deliver this in collaboration. It is my impression that the scientific achievements of the project and the spin-off tool are both highly relevant in the near future for the planning of new offshore wind farm clusters. The approach, whereby the end-users identify the needs and set the target, and the research groups bring existing national science, and they in collaboration bridge the research gaps and further develop and validate a common cross-disciplinary design tool, should be a model for future European initiatives.

2 EXECUTIVE SUMMARY

Charlotte Hasager and Gregor Giebel

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 integrate the software has been performed.

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.

3 INTRODUCTION

3.1 Introduction

Peter Hauge Madsen, Charlotte Hasager, Gregor Giebel

EERA DTOC was a project of the European Energy Research Alliance on Design Tools for Offshore Wind Farm Clusters. It received funding from the European Commission's FP7 programme.

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;

This EERA DTOC *final* report is public and targets potential stakeholders such as wind farm developers, consultants, strategic planners and transmission system operators.

3.2 Background

Peter Hauge Madsen, Charlotte Hasager, Gregor Giebel

The European Energy Research Alliance – Design Tools for Offshore wind farm Clusters (EERA DTOC) project was realised 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). 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 workshops¹.

¹ Websites: EERA DTOC: www.eera-dtoc.eu, ClusterDesign: www.cluster-design.eu

The EERA DTOC project was led by DTU Wind Energy. Appendix A lists the partners of EERA DTOC and Appendix B lists the participants. Figure 3.1 shows the participants at two project meetings.



Figure 3.1 The consortium at the kick-off meeting January 2012 at DTU Wind Energy, Risø, Denmark (above) and project meeting January 2015 at CRES in Athens, Greece (below).

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 project web-site www.eera-dtoc.eu contains detailed information on the project structure, presentations and publications of results.

3.3 Report structure

Charlotte Hasager, Gregor Giebel

This report consists of three major parts: **Science**, **Software** and **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 peer-reviewed publications published from EERA DTOC are listed in Appendix C.

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.

Finally, conclusions are drawn and perspectives for the future are outlined.

“The opportunity to build experience with novel measurement techniques likely to become standard in the future, e.g. multiple scanning lidars, is a valuable outcome of cooperation in such EU-funded projects.

We believe that as more offshore concession areas are developed, changes to business cases of existing farms will become evident – calculation of the magnitude of this impact for refinancing and sales of assets will become increasingly important to the industry. The reporting of clear findings on the impacts of meso-scale wake meander on neighbouring wind farms, wind farm deficit regions in disturbed and undisturbed inflow conditions, and clear recommendations on the aggregation of turbine thrusts on meso-scale grid scale are important outputs to aid industry in improved design of offshore farms and clusters.

We see some clear complementarity between EERA-DTOC and ClusterDesign outputs. While EERA-DTOC focusses on inter farm cabling, ClusterDesign toolbox focusses more on intra farm cabling. While EERA-DTOC focusses on flow variability due to other farms, the ClusterDesign toolbox focusses on turbine load responses due to such variability. There is definitely scope to take the best of each project output and develop a tool that better satisfies the offshore cluster design tool requirements defined by IRPWind.”

3E

4 SCIENCE

4.1 Introduction

Pierre-Elouan Réthoré, Elena Cantero, Rebecca Barthelmie, Takis Chaviaropoulos, Ana Palomares, Hauke Beck

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 (see Section 4.5 and 4.6 respectively). 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 (see Section 4.7 and 4.8 respectively). Finally, satellite data of wind farm wakes are investigated (see Section 4.9).

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 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 (AEP_{NET}) 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.

4.2 Wake modelling micro- meso and coupling

Pierre-Elouan Réthoré, John Prospathopoulos, Takis Chaviaropoulos, Ana Palomares, Patrick Volker, Jake Badger

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) realises 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 (Figure 4.1).

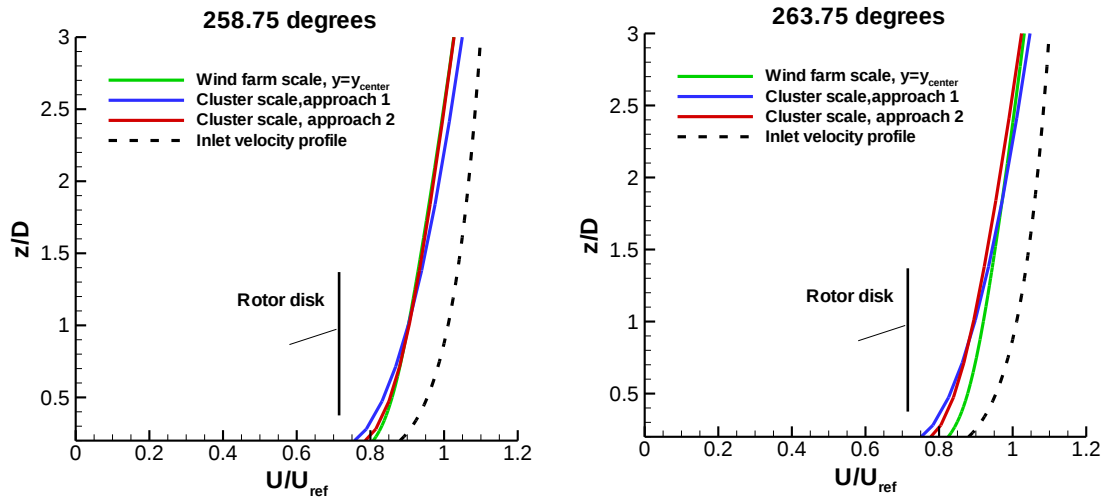


Figure 4.1: Comparison of the velocity profiles provided by the microscale model for the wind farm and the cluster scale meshes, 35 rotor diameters downstream of the Horns Rev 1 wind farm. The lateral position is located at the center of the wind farm ($y = y_{\text{center}}$). Results are shown for two wind directions: 258.75°, 263.75°.

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 (Figures 4.2c, d). In addition, the concept of a sub-mesoscale-grid vertical wake expansion was considered in the WRF model (WRF-CRES-EWP) (Figure 4.2a). It was proved that such a model was necessary to capture the wake behaviour inside the wind farm and the near wind farm wake (Figure 4.2b). However, in the far wake, the difference caused by including sub-mesoscale-grid vertical wake expansion, or not, becomes much less pronounced (Figures 4.2b, c). 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.

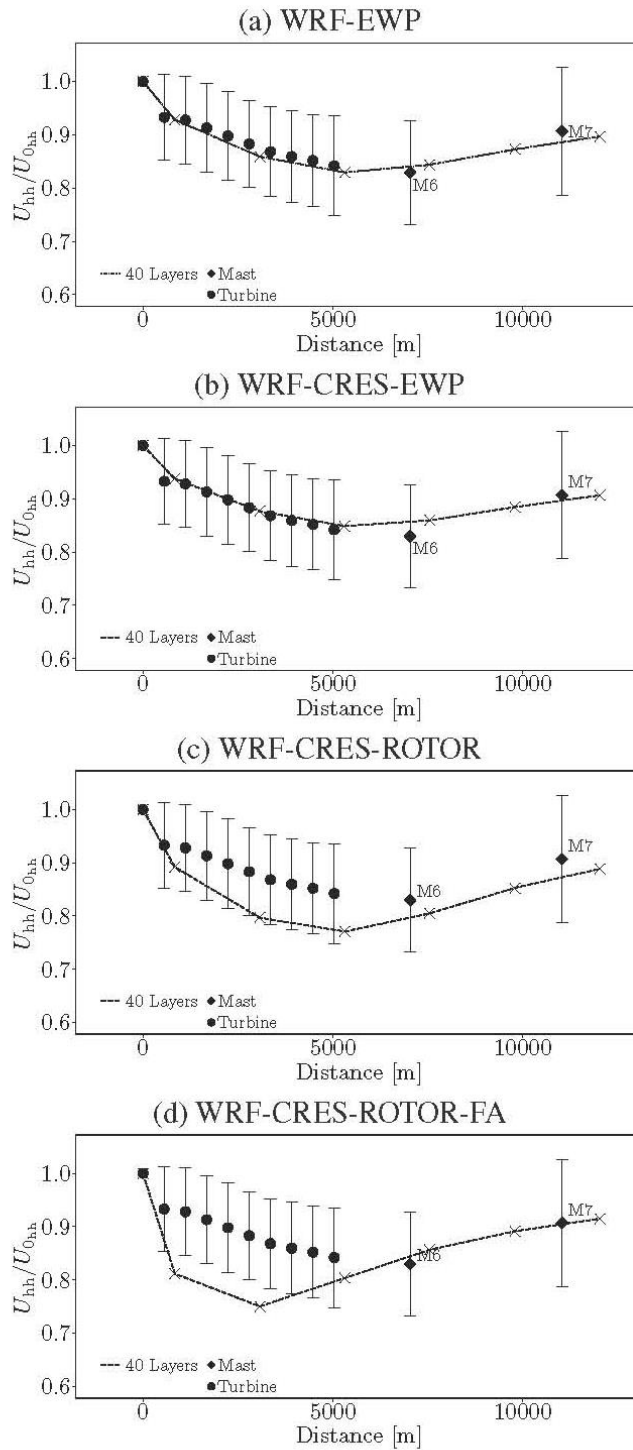


Figure 4.2: Recovery validation plots for the different wake parameterizations used: (a) WRF-EWP, (b) WRF-CRES-EWP, (c) WRF-CRES-ROTOR and (d) WRF-CRES-ROTOR-FA. The x-axis is the distance in meters from the first turbine row, the y-axis is the wake horizontal wind speed expressed as a fraction of the inflow wind speed, both at hub height, i.e. for first row turbines the value is 1. The black dots are measurements based on wind turbine power or from anemometers at mast 6 (M6) and mast (M7) downwind of the wind farm.

4.3 Long term uncertainty on net energy yield

Elena Cantero, Ana María Palomares, Jorge Navarro, Pedro Ángel Jiménez, Javier Sanz, Giorgos Sieros, Peter Stuart, Tom Young, Matthias Wächter, Allan Morales, Patrick Milan, Pierre-Elouan Réthoré

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 AEP_{NET} 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 AEP_{NET} calculations was performed. Besides, the possibility of integrating these methods into a general code was analysed.

“EERA-DTOC represents a fantastic collaboration which has allowed theory and industrial experience to come together. Wind & Economy will be an invaluable planning tool for the industry, helping to maximise site usage.”
EWEA

4.3.1 INTRODUCTION

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 AEP_{NET} from the Gross Annual Energy Yield, it is necessary to take into account different losses that must be applied to the initial gross value, Figure 4.3 shows the main steps.

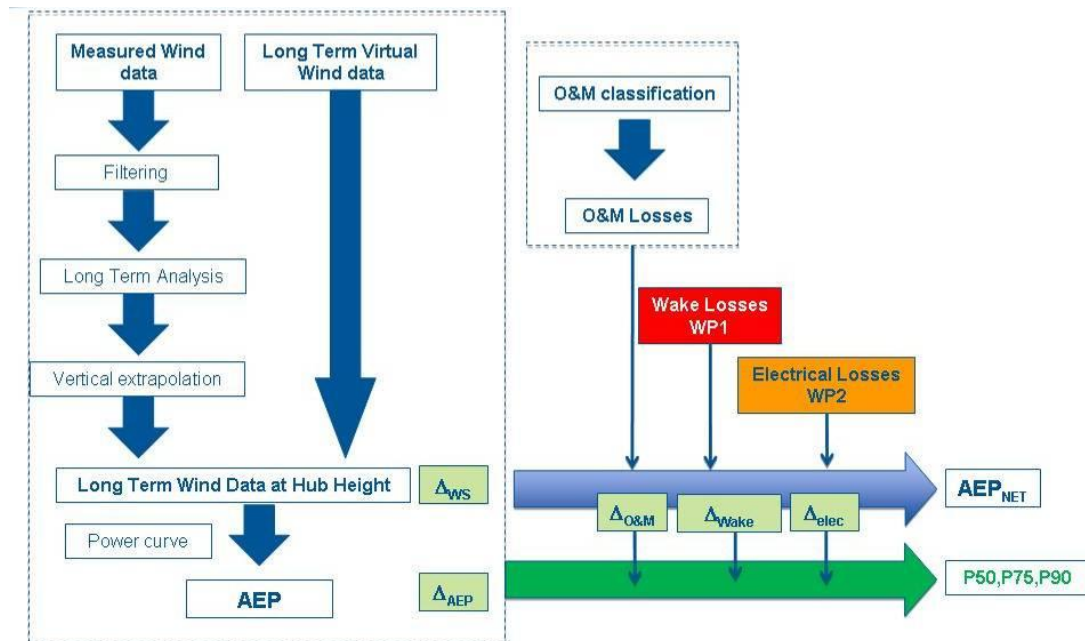


Figure 4.3: The main components in an offshore wind resource assessment

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 AEP_{NET} uncertainty. An accurate estimation of the expected AEP_{NET} 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 AEP_{NET} estimation process, that avoid the fact that different consultants can give very different numbers for the same location.

4.3.2 NET ANNUAL ENERGY PRODUCTION ASSESSMENT

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 AEP_{NET} .

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 AEP_{NET} 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 AEP_{NET} can be estimated from the AEP.

4.3.3 UNCERTAINTIES ESTIMATION

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.

4.3.4 CONCLUSION

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.

4.4 WRF intercomparison to meteorological data and satellite data

Ioanna Karagali, Patrick Volker, Ana Palomares, Jorge Navarro, Elena Cantero, Pedro Correia

QuikSCAT (QSCAT) 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. All statistics between WRF and QSCAT shown in Table 4.1 are derived by matching the QSCAT value of speed or direction at a specific point with the corresponding WRF value of the closest time and grid point, for the entire area and period of WRF runs, unless otherwise stated.

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.

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 statistics are shown in Table 4.1 (DTU_{FD}-QSCAT). Because the WRF domain is very large compared to the Dogger Bank area, a second comparison was performed (DTU_{DB}-QSCAT) only for the area around the wind farm, i.e. two QSCAT grid cells compared to the closest WRF grid points.

Table 4.1: Statistics of point-by-point comparisons between WRF and QuikSCAT for the wind speed (U) and direction (Dir), for the Race Bank (CENER runs) and Dogger Bank (DTU runs) wind farm areas.

Datasets	Mean bias		Standard Deviation		Root Square Error		Correlation coefficient r		Number of match-ups	
	U m/s	Dir deg	U m/s	Dir deg	U m/s	Dir deg	U m/s	Dir deg	U	Dir
CENER _{RB} -QSCAT	0.08	5.20	2.43	29.14	2.43	29.60	0.76	0.95	29486	26052
DTU _{FD} -QSCAT	0.41	10.11	2.62	29.8	2.66	31.54	0.77	0.94	884597	786227
DTU _{DB} -QSCAT	0.78	9.58	2.57	78.93	2.69	79.49	0.78	0.65	2519	2220

4.5 Horns Rev-1 wind farm

Kurt S. Hansen, Pierre-Elouan Réthoré

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. Tables 4.2a and b list the benchmark simulation matrix.

Table 4.2a: Benchmark simulation matrix

EERA-DTOC	Flow sector			Stratification			Turbulence			Spacing			Park efficiency
	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3	4.1	4.2	4.3	5.1
WASP (NOJ)		1	1							1	1	1	
NOJ(BA)	1	1	1				1			1			
FarmFlow	1	1	1				1	1	1	1	1	1	
FUGA	1	1	1				1			1			
GCL(BA)	1	1	1				1	1	1	1			
DWM/HAWC2	1	1	1	1	1	1	1	1	1	1	1	1	
CRESflowNS	1	1	1	1	1	1	1	1		1		1	1 ^a
Ainslie	1	1	1				1	1	1				
RANS	1	1	1				1			1	1	1	
NOJ/Penã	1	1	1	1	1	1	1	1	1	1	1	1	1
GCL(GU)	1	1	1				1	1	1	1	1	1	1
sum	10	11	11	3	3	3	10	7	6	10	6	7	3

1^a Amended GCL calibrated with CRESflowNS

Table 4.2b: Models participating in the Horns Rev benchmark.

Institute	Model Name	Inflow	Hub WS	Turbine	Wake acc	Wake flow
DTU WE	SCADA	Processed wind farm SCADA measurements				
DTU WE	FUGA	Log law	7P	PTC	Linear	FUGA
DTU WE	GCL	Log law+TI	16P	PTC	Linear	GCL
DTU WE	DWM	Mann	> 100P	HAWC2	Max.	DWM
DTU WE	NOJ	Homog.	Mosaic	PTC	RSS	NOJ
Indiana Uni	WASP/NOJ	Homog.	Mosaic	PTC	RSS	NOJ+GPR
RES-LTD	Ainslie	Homog.+TI	1P	PTC	ARL	Ainslie+GPR
CRES	CRESflowNS	Log law	1P	PTC	Elliptic $k-\omega$	
Porto Uni	RANS	Log law	1P	PTC	Elliptic $k-\epsilon$	
ECN WE	FarmFlow	Stability	1P	PTC	Vortex + Parabolic $k-\epsilon$	

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, Figure 4.4, 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 established 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.

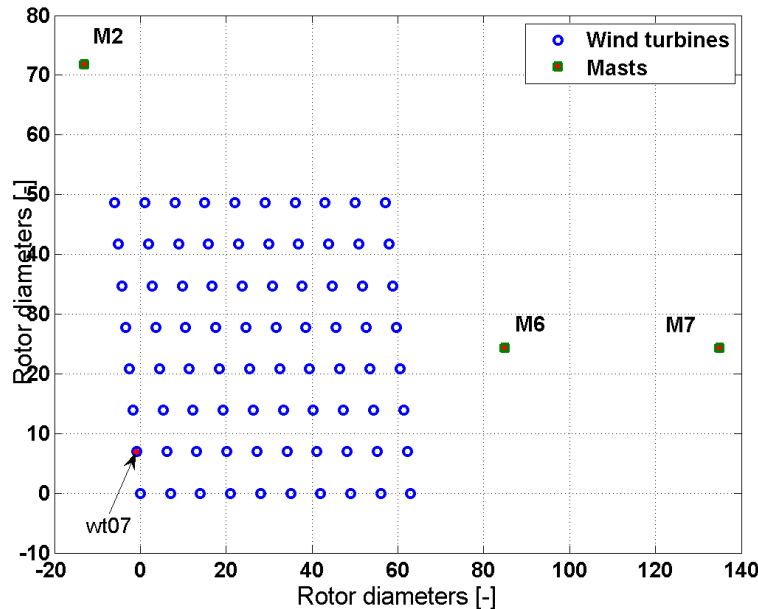


Figure 4.4: Layout of Horns Rev offshore wind farm including meteorological mast M2, M6 & M7

One flow case is used to determine the power deficit along a row of turbines. The power deficit between wt07 and the downstream turbines in row7 in the direction 270° , with an averaging window of $D = 5$ and 30° are illustrated in Figure 4.5 a and b. The wind direction is measured, using the nacelle position of wt07. The wind speed is measured using an inversed power curve using the power production of wt07. When directly aligned in 270° , the wind turbines have a spacing of 7 rotor diameters.

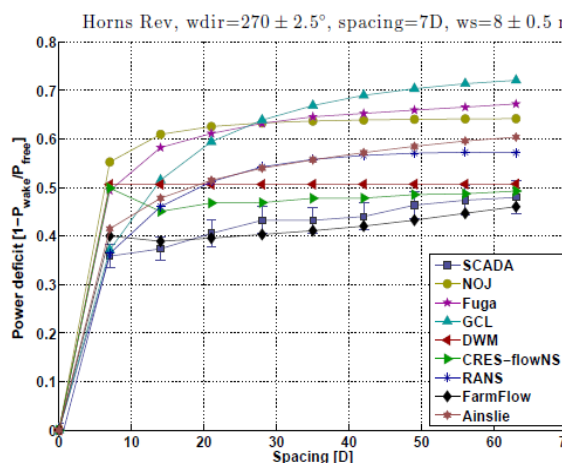


Figure 4.5a: Power deficit along a row of turbine with and inflow wind direction bin of $\Delta=5^\circ$

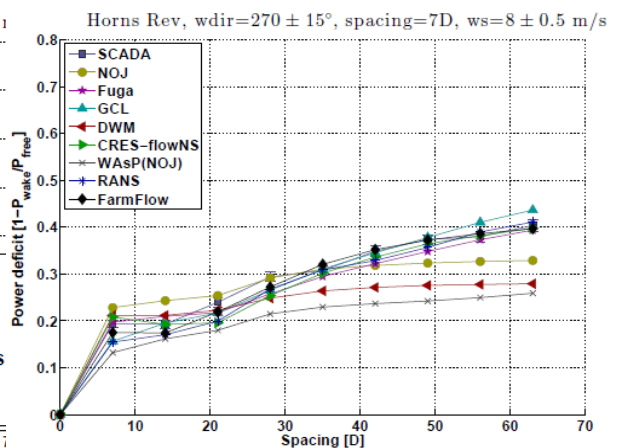


Figure 4.5b: Power deficit along a row of turbine with and inflow wind direction bin of $\Delta=30^\circ$

As a general trend, most models seem to over-predict the wake deficit for small wind direction averaging window (Δ), and have a closer prediction to the largest Δ . Some of the models, like GCL and RANS have a close estimate of the first turbine downstream, and then seem to deviate gradually from the SCADA points for $\Delta=5^\circ$ (Figure 4.5b). In both Δ s, FarmFlow seems to

consistently match closely the shape of the SCADA points. Most models, except NOJ, WAsP/NOJ and DWM, seem to be very close to the SCADA point shape in $\Delta = 30$.

Another flow case is a determination of the 360 degree park efficiency for $\Delta = 5^\circ$. The park efficiency plot in Figure 4.6 illustrates the four distinct narrow deficit sectors along the main directions inside the Horns Rev wind farm. The deficits sectors are well captured with all three participating models, but both CresFlowNS and NOJ over estimates the negative efficiency peaks compared to the SCADA results.

The results of the Horns Rev benchmarking campaign indicate that many of the models significantly overpredict the maximum wake losses in comparison with the measurements. This is particularly the case for the CFD models that simulate the wake shape exactly, 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.

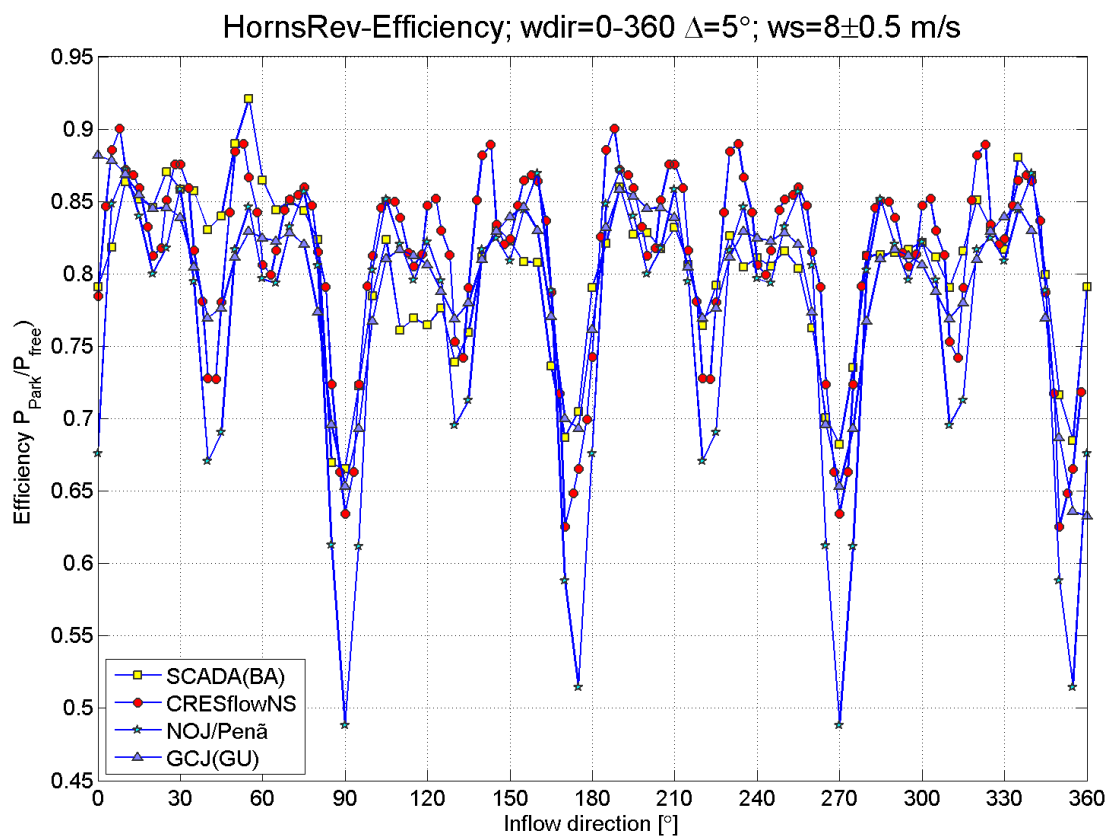


Figure 4.6: Park power efficiency @ 8 m/s as function of inflow direction.

4.6 Lillgrund wind farm

Kurt S. Hansen, Pierre-Elouan Réthoré

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. See Table 4.3.

Table 4.3: Simulation matrix for Lillgrund benchmark.

EERA-DTOC		Complete rows		Missing turbine(s)		Turbulence		Park
Institution/model		Row:3-120deg	Row:B-222deg	Row:5-120deg	Row:D-222deg	TI-3.3D	TI-4.3D	Efficiency
DTU	FUGA	1	1	1	1	1	1	1
CRES	CRESflowNS	1	1	1	1			
ECN	FarmFlow	1	1	1	1	1	1	1
DTU	GCJ-BinAve	1	1	1	1	1	1	1
DTU	GCJ-GauUnc	1	1	1	1	1	1	1
DTU	NOJ-BinAve	1	1	1	1			1
DTU	NOJ-GauUnc	1	1	1	1			1
DTU	NOJ(Penā)	1	1	1	1	1	1	1
RES-LTD	AD/Ainslie	1	1	1	1	1	1	1
CENER	GCJ-GauUnc	1	1	1	1	1	1	1
sum		10	10	10	10	7	7	9

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 layout of the wind farm is shown in Figure 4.7. 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.

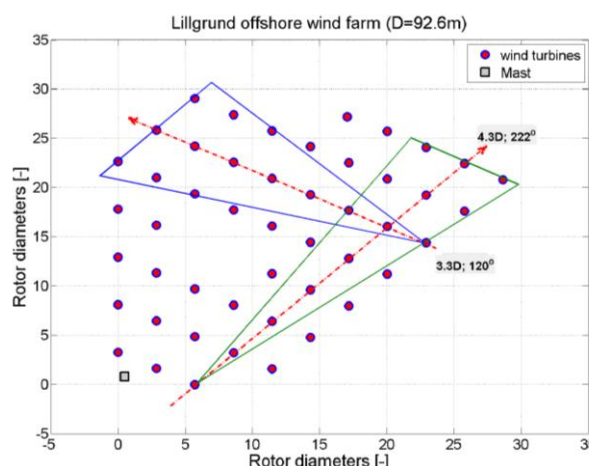


Figure 4.7: Lillgrund offshore wind farm layout with two principal spacings 3.3D and 4.3D.

The initial flow case is the single wake case. The first test case is between A03 and B03 for a wind direction of 120° and 3.3D spacing, Figure 4.7. The SCADA and model results are shown in Figure 4.8 where a group of 5 models agrees very well with SCADA results. The second test case is between B08 and B07 for a wind direction of the 222° and 4.3D spacing. The SCADA and model

results demonstrate a smaller peak value, but the distribution of model results are identical to 3.3 D spacing.

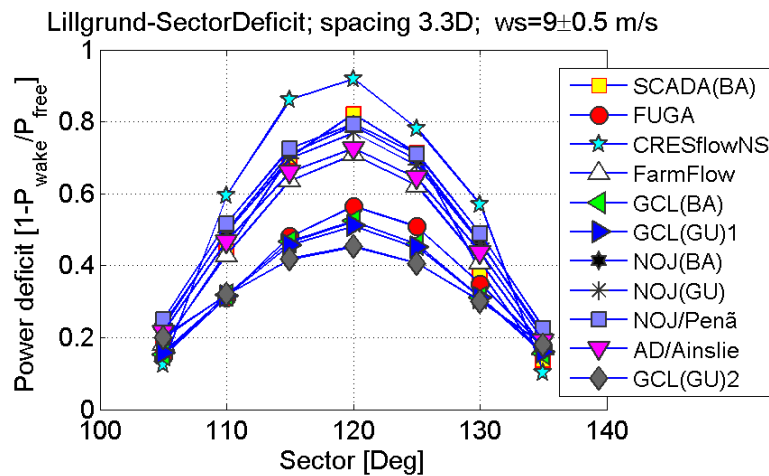


Figure 4.8: Lillgrund WF, sector wise deficit for 3.3 D spacing.

The final flow case is the determination of the park efficiency for $\Delta = 3^\circ$. The park efficiency plot in Figure 4.9, 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.

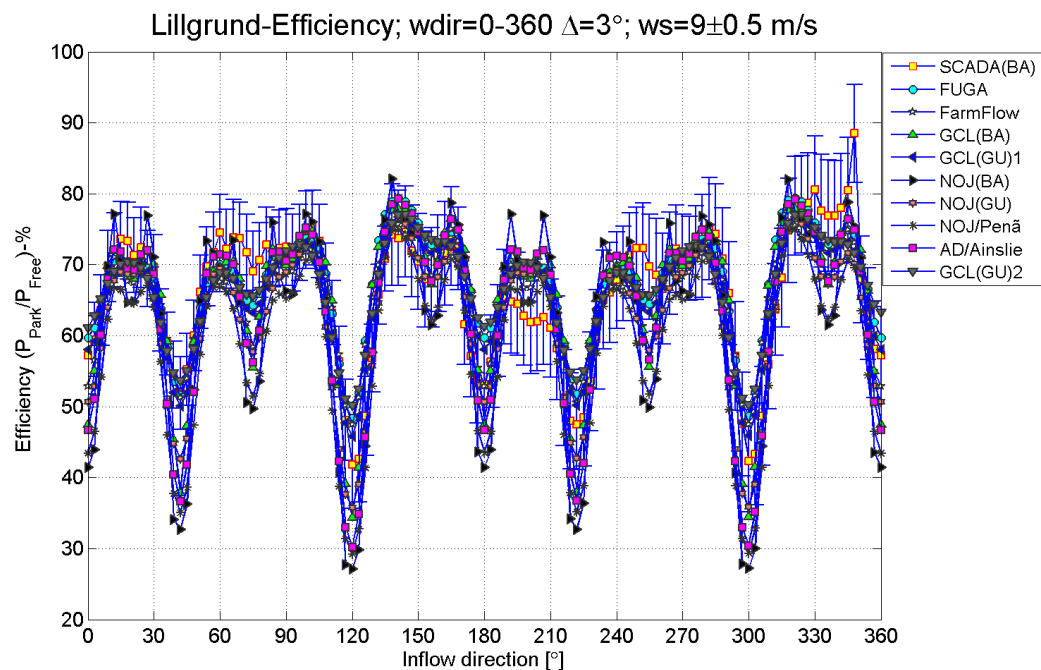


Figure 4.9: Park efficiency for Lillgrund WF, $\Delta=5^\circ$, $U=9$ m/s and 0 - 360° inflow.

This 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.

4.7 Rødsand-2 (farm to farm)

Kurt S. Hansen, Pierre-Elouan Réthoré, Sarah Ruth Schmidt

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, Figure 4.10. 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.

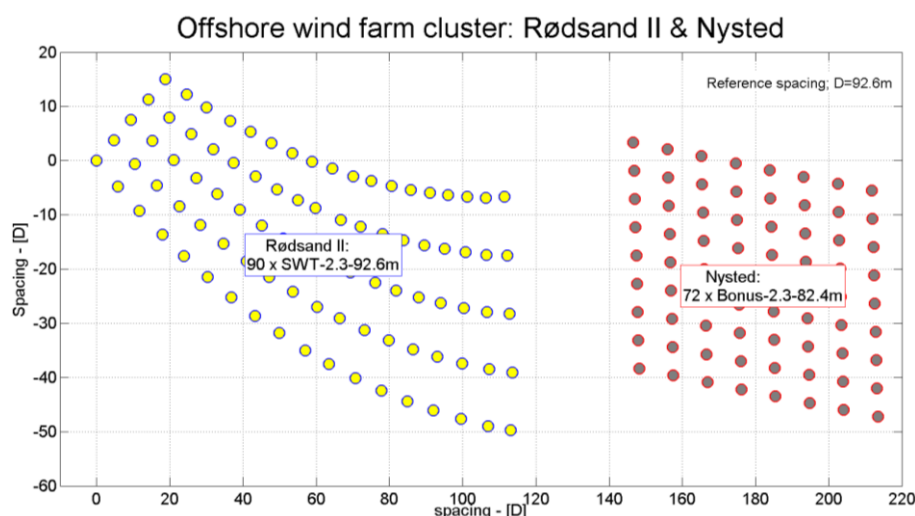


Figure 4.10: Layout of Rødsand II and Nysted wind farms.

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 (Figure 4.11). 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, Figure 4.12. The size of the zone increases and moves downstream for increasing inflow direction e.g., where the wind farm operates in partly wake conditions.

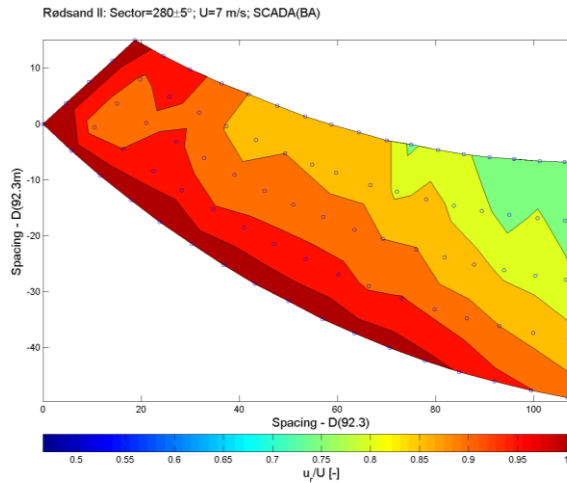


Figure 4.11: Normalised wind speed for undisturbed inflow from direction 280°, west.

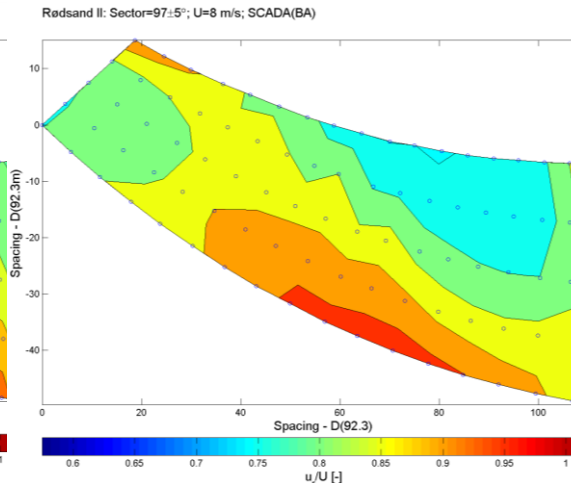


Figure 4.12: Normalised wind speed for a disturbed inflow sector, influenced by the Nysted wind farm.

Table 4.4: Simulation matrix for Rødsand II and Nysted WF.

EERA-DTOC		Rødsand II		Nysted	
Institution/Models		RS; 270-290°	RS; 77-117°	NY; 270-290°	NY; 77-117°
DTU	SCADA(BA)	15	13	20	15
CRES	CRESflowNS	15	-	-	-
UPORTO	AD/RANS	10	9	-	9
ECN	FarmFlow	20	15	-	15
DTU	NOJ/Penã	15	15	-	-
DTU	NOJ(GU)	15	15	-	-
DTU	FUGA/SO	-	15	-	-
Ciemat	WRF/UPM	18	12	-	6
CENER	CFDWake	4	-	-	-
DTU	Meso/PV	-	15	-	-
DTU	RANS/f _p C	-	11	-	11

The 10 models, Table 4.4 in the benchmark includes both RANS models, mesoscale models and engineering models and 245 different flow cases have been modelled.

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 II.

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 (Figure 4.13). 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 $\pm 15^\circ$.

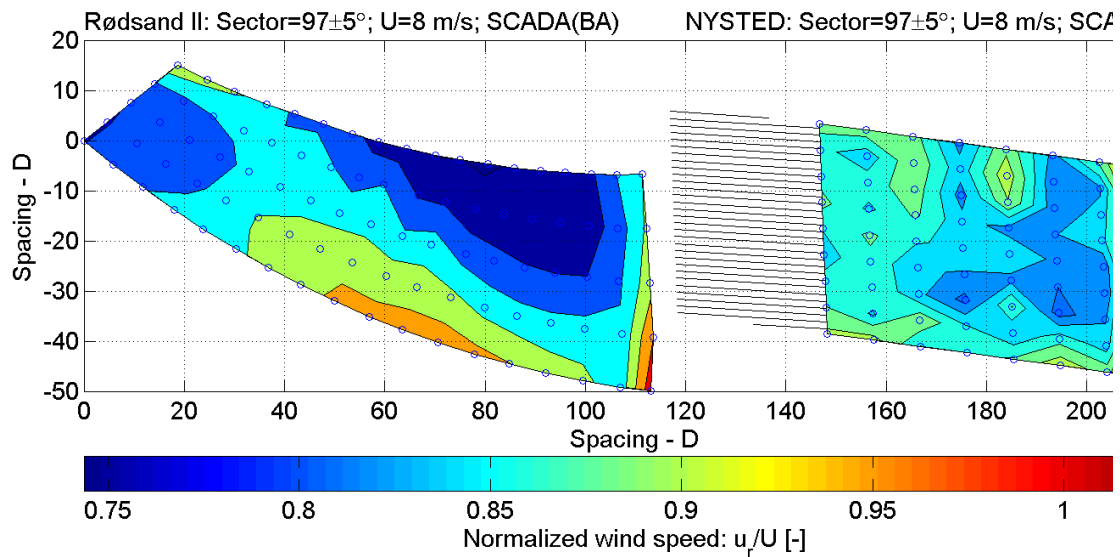


Figure 4.13: Measured normalised wind speed for $WD=97^\circ$ & $U=8$ m/s.

The benchmark demonstrates that most of the models were able to predict the cluster performance when the Rødsand II operates partly or completely in the wake of Nysted WF. Furthermore, the park efficiency has been calculated for a limited inflow sector $77-117^\circ$ where the Rødsand operates partly in wake of Nysted WF and compared to the measured park efficiency. The modelled park efficiency levels vary with $\pm 5\%$ and all models predicts the minimum efficiency to be located in the sector $97-107^\circ$ (Figure 4.14).

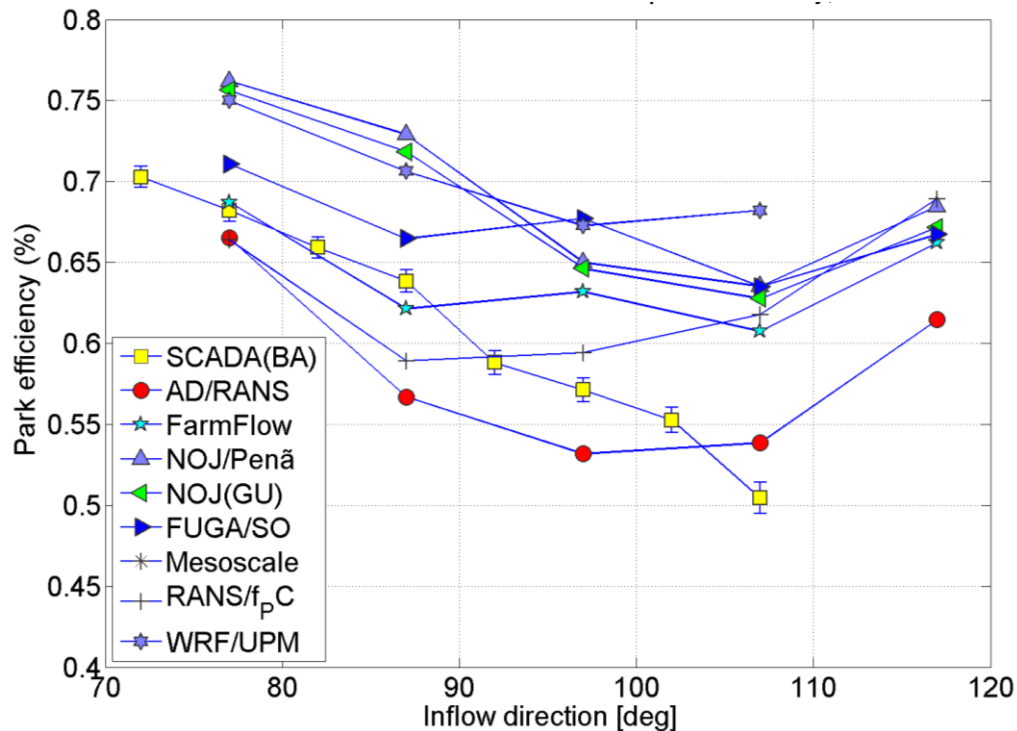


Figure 4.14: Rødsand II sector wise park efficiency at 8 m/s.

4.8 Alpha Ventus wind farm including lidar experiments

Hauke Beck, Juan José Trujillo, Gerrit Wolken-Möhlmann, Ilona Bastigkeit, Julia Gottshall, Alfredo Peña, Jose Palma, Vitor Gomes

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 31st 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.

4.8.1 COMPARISON OF SCANNING LIDAR, SHIP-LIDAR AND FINO1 MEASUREMENTS

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.

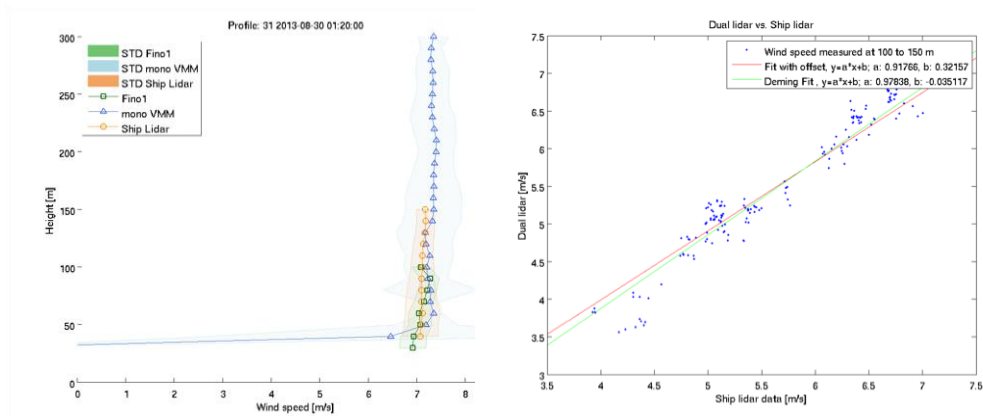


Figure 4.15: {left} Comparison of measured and processed wind speed profile of ship-lidar system (orange), multi-lidar system (blue) and FINO1 (green) including standard deviation of a single 10min average. {right} Correlation of wind speed of ship-lidar system and multi-lidar system of a single 10min average time period within the range of 100 m - 150 m.

The exemplary results presented here (Figure 4.15) 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.

4.8.2 MICROSCALE INFARM WAKE MEASUREMENTS

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 (Figure 4.16) 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.

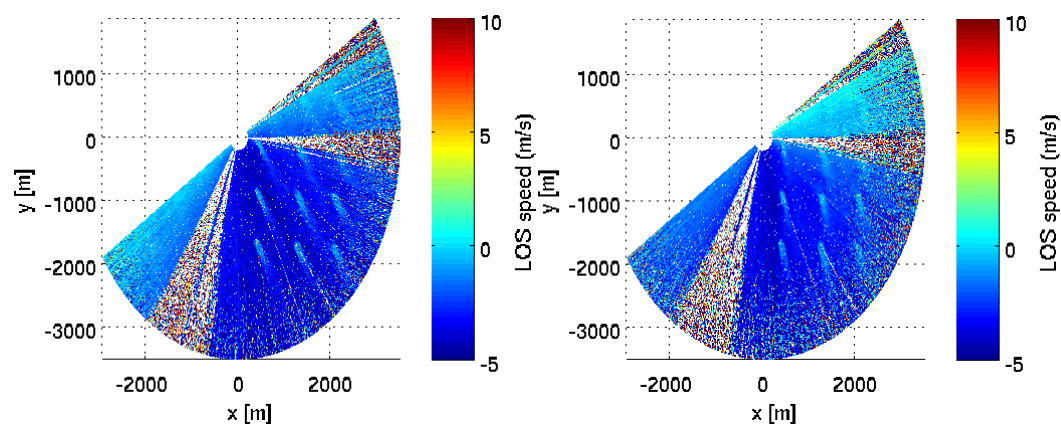


Figure 4.16 Exemplary visualisation of the wind speed in 'alpha ventus' from infarm wake measurements performed by a lidar on FINO1 within the second long range lidar measurement campaign.

4.8.3 SHIP-BASED LIDAR MEASUREMENTS

Julia Gottschall, Gerrit Wolken-Möhlmann

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. Figure 4.17 shows the used measurement system and the ship it was operated from.

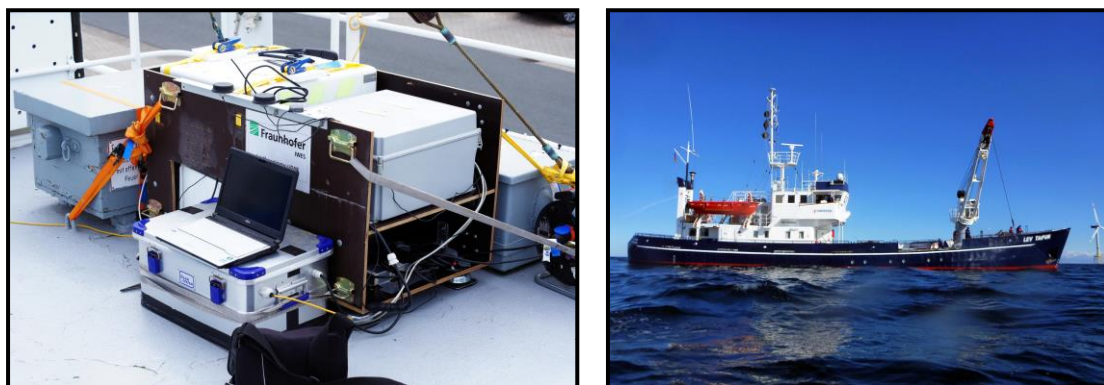


Figure 4.17: Left: ship-lidar system comprising lidar and motion sensors, installed in a frame onboard the vessel LEV Taifun; right: support vessel LEV Taifun during measurements in proximity to FINO1 and alpha ventus.

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 atmospherical 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 $k-\epsilon$ 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 in Figure 4.18. The wake deficit behind the four rows of turbines is both clear in observations and in model results.

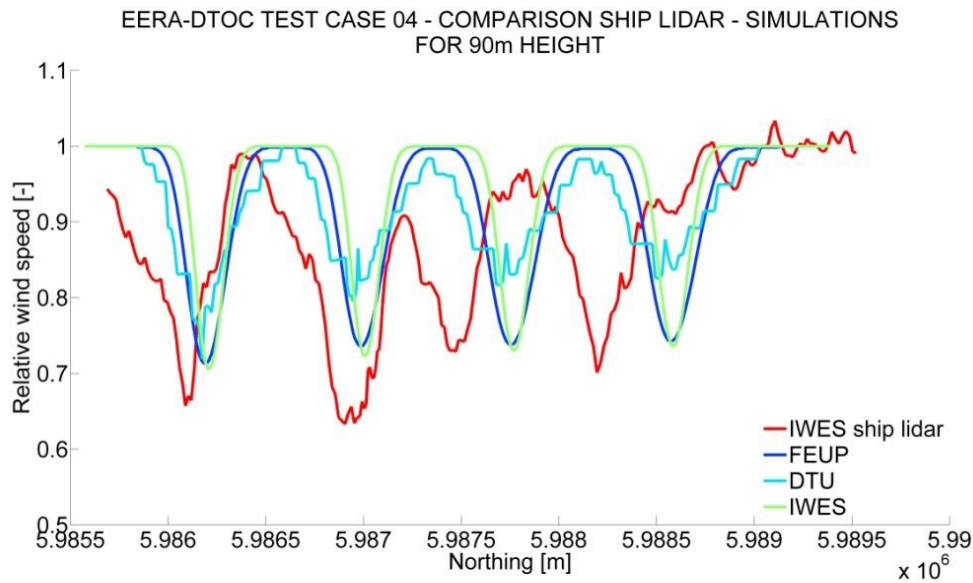


Figure 4.18: Comparison of relative wind speed at 90m height in the wake of ,alpha ventus' for averaged test case inflow condition.

4.9 Satellite SAR wind farm far-field wakes

Charlotte Hasager, Romain Husson, Pauline Vincent, Merete Badger, Alfredo Peña, Patrick Volker, Jake Badger, Ana Palomares, Elena Cantero, Alessandro Di Bella

4.9.1 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 (Figure 4.19).

The synthetic aperture radar (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 result is shown in Figure 4.20. The winds are from south east with a value around 3-4 m/s at 10 m above sea level.

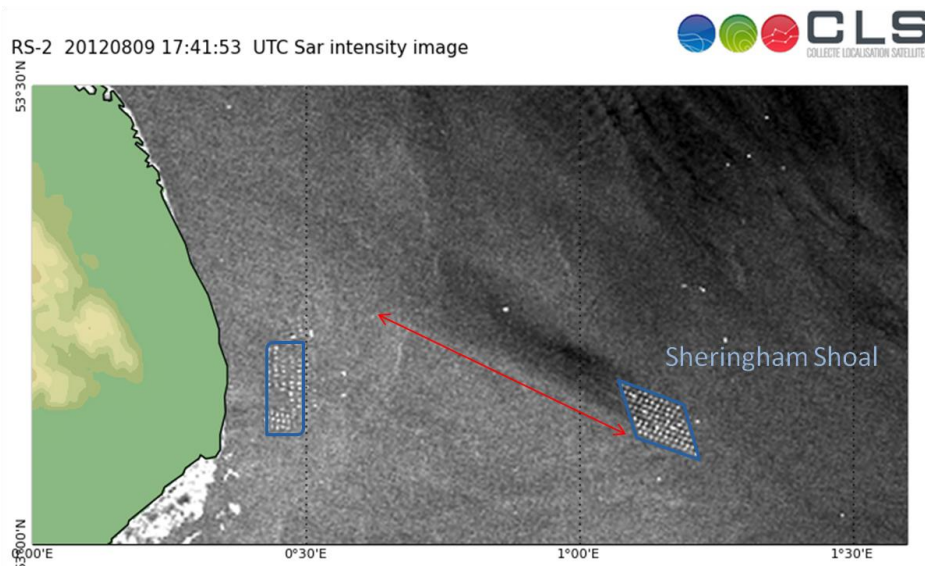


Figure 4.19: Wind farm wake on Sheringham Shoal seen in RADARSAT2 intensity image.

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 (Figure 4.20). 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.

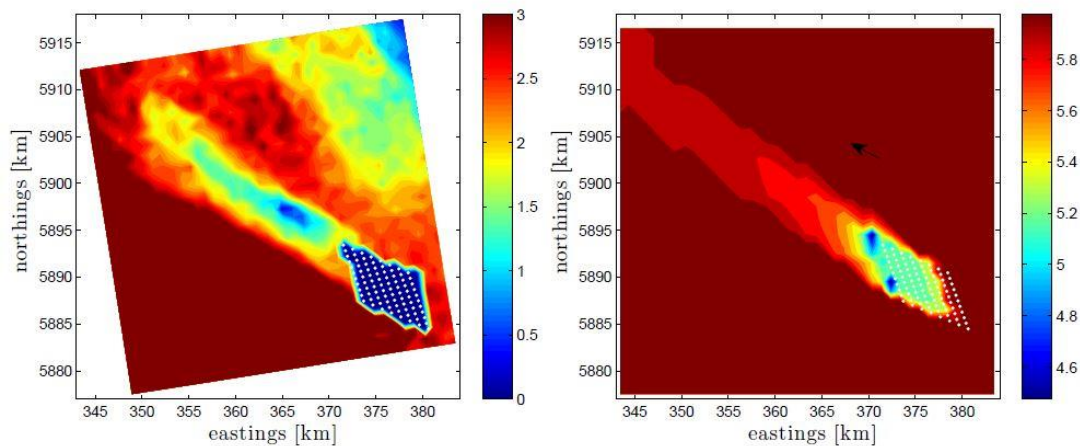


Figure 4.20: Satellite 10-m SAR wind retrieval and (left) modified Park wake results at 81.75 m (right) for the Sheringham Shoals wind farm. The colorbar indicates the wind speed in m s^{-1} . The wind direction used for the modeling is indicated with the black arrow and is from the southeast.

Another example of long wind farm wakes observed from SAR is shown in Figure 4.21. 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 shown in Figure 4.22.

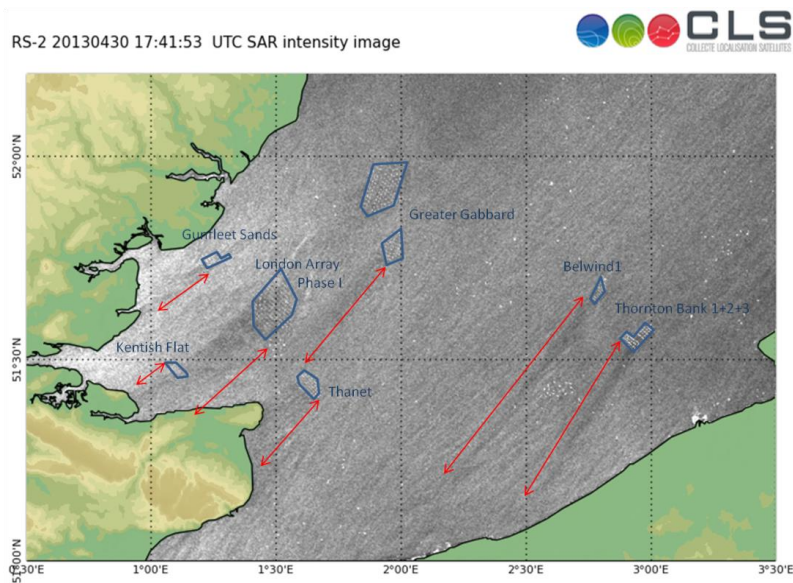


Figure 4.21 RADARSAT-2 intensity map of the southern North Sea observed 30 April 2013 at 17:41 UTC. The blue lines outline wind farms and the red arrows the wind farm wake. From Hasager *et al.* 2015 in *Energies*.

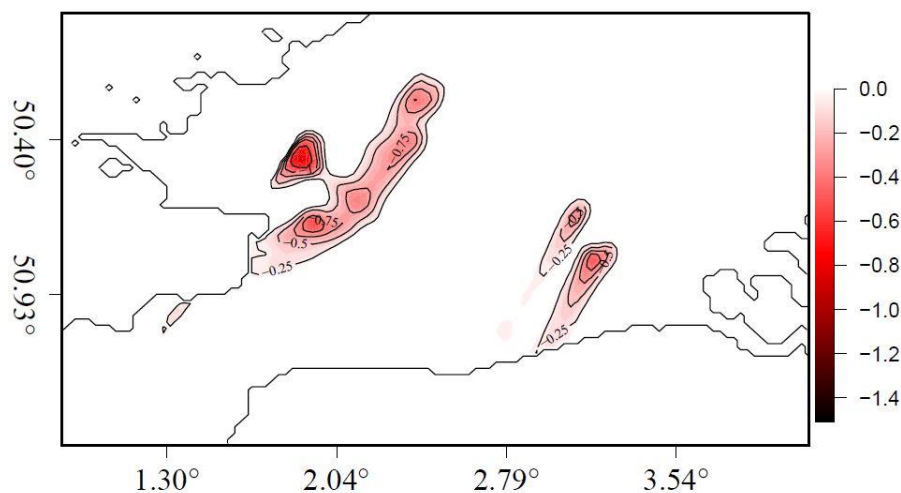


Figure 4.22 WRF wake model results on velocity deficit in m s^{-1} at 10 m AMSL at 30th April 2013 at 18:00 UTC at the wind farms London Array, Greater Gabbard, Thanet, Belwind1 and Thornton Bank. From Hasager *et al.* 2015 in *Energies*.

4.10 Summary

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.

5 DTOC SOFTWARE

5.1 Introduction

Gregor Giebel, Igor Waldl

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.

5.2 User requirements

Peter Stuart, Jan Matthiesen

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.

"Working with the top wind power research institutions throughout Europe in a collaborative environment is a unique way to get close to cutting edge scientific knowledge. As such, the EERA-DTOC project represents an exciting step towards the future of layout design within offshore wind technology."
Iberdrola Renovables

5.3 DTOC Software

Gregor Giebel, Igor Waldl

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.

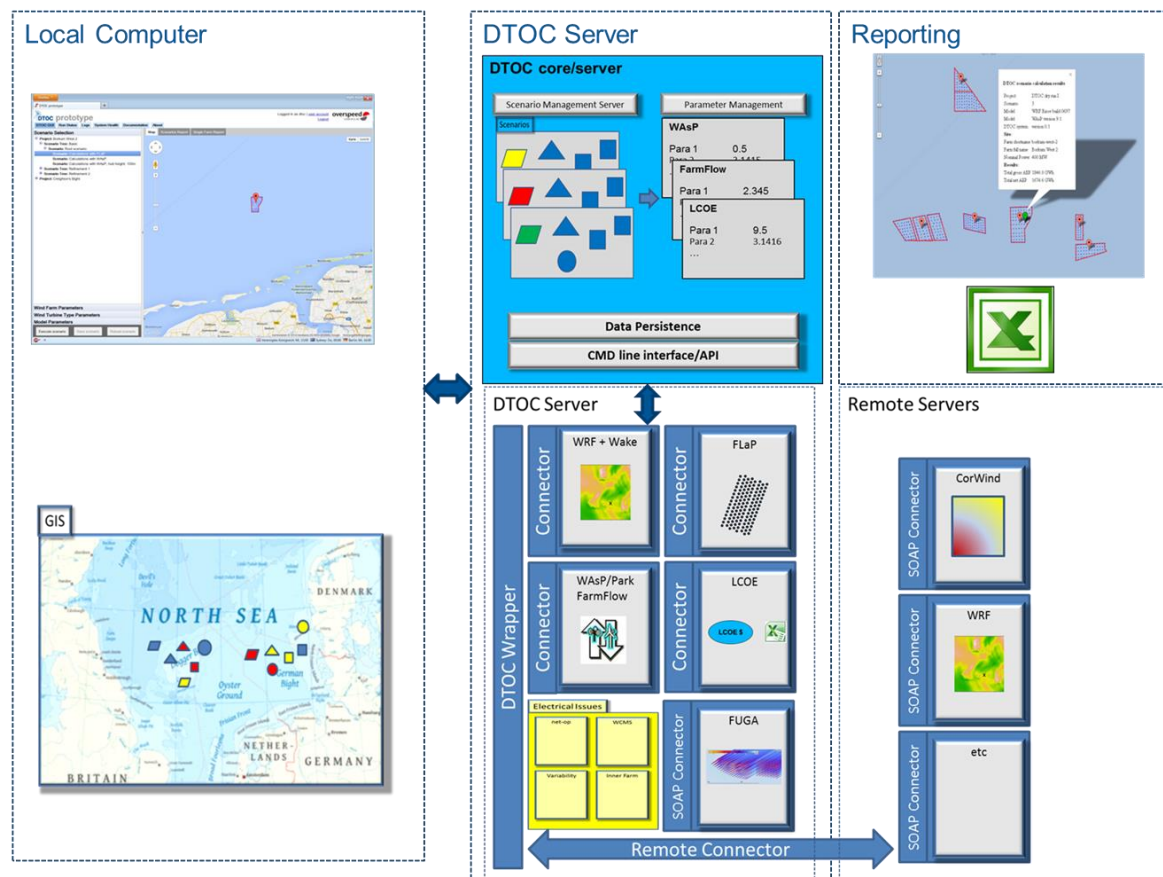
5.4 Models and model chains

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.

Figure 5.1 shows what the total system looks like. On the left, the activity on the local computer is shown. Besides a web browser, a GIS tool is used locally. User rights management is an integrated part of the DTOC platform. In the reporting, the end user should have a good guess about the cost price of the produced wind power, and an idea of the sensitivities of that price.



5.5.1 CorWind

Nicolaos Antonio Cutululis

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 (Figure 5.2). It includes historical time series from year 2000.

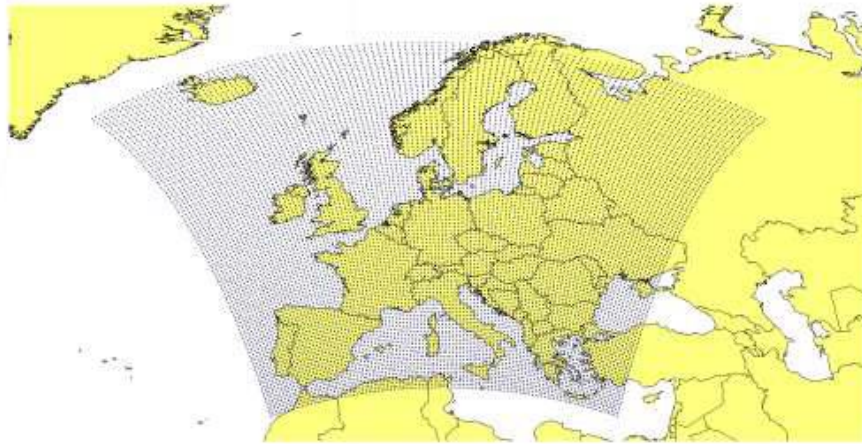


Figure 5.2: Weather database domain of CorWind.

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. The CorWind main structure is given in Figure 5.3:

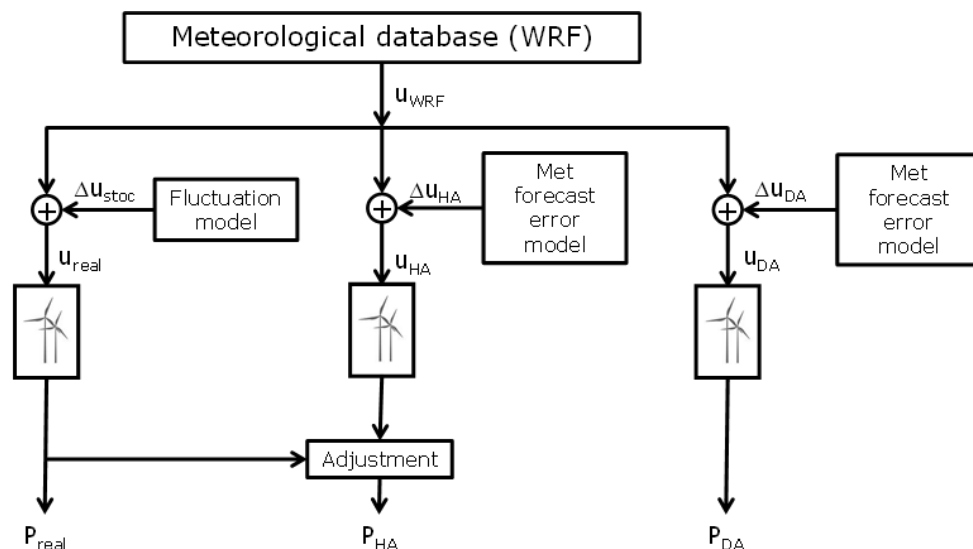


Figure 5.3: CorWind main structure.

For power system studies, the interesting output from CorWind is the generation pattern of the wind power, which is illustrated as Ppos in Figure 5.4. The Figure also shows day-ahead and hour-ahead prognoses generated with CorWind based on a model for randomly generated wind speed forecast errors.

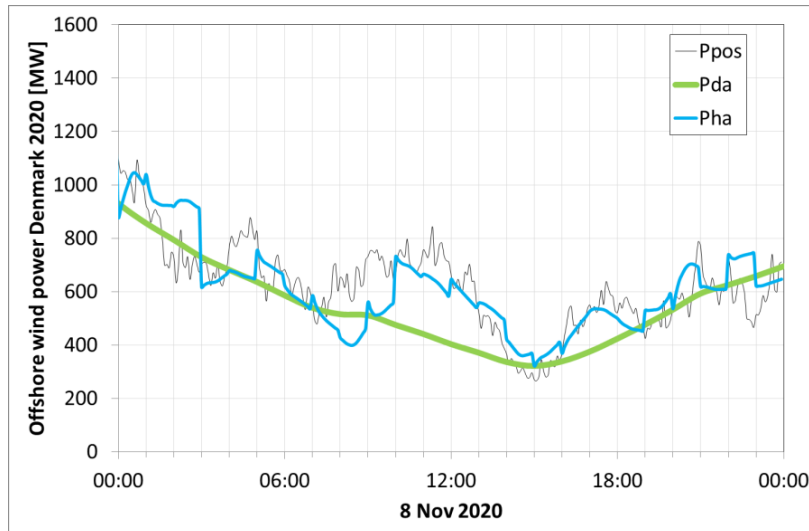


Figure 5.4: Example illustrating CorWind simulation of consistent time series for real wind power (Ppos) and prognoses daily and hourly (Pda and Pha)

5.5.2 FUGA

Alfredo Peña, Søren Ott

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.

5.5.3 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.

5.5.4 LCOE

Igor Waldl

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.

5.5.5 NET-OP

Harald Svendsen

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 (see Figure 5.5).

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.

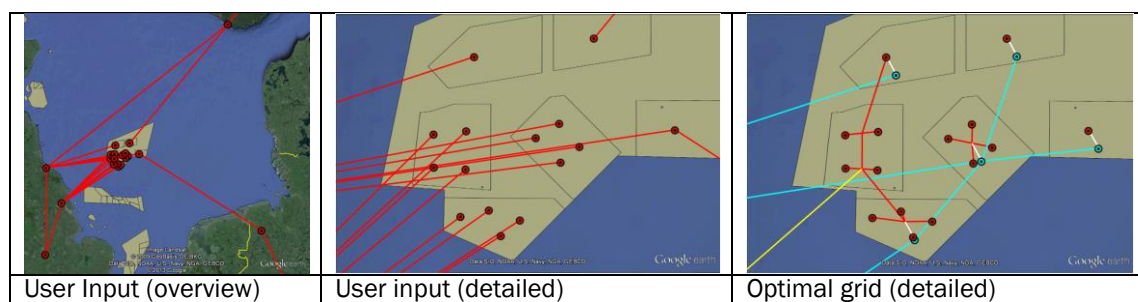


Figure 5.5. Net-Op overview

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.

5.5.6 QGIS

QGIS is a cross-platform Open Source Geographic Information system with an international support community of enthusiastic users, developers and supporters. See <http://www.qgis.org/en/site/index.html>

5.5.7 WASP

Alfredo Peña

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, which may be summarised as follows:

Analysis

Time-series of wind speed and direction → observed wind climate (OWC)

Observed wind climate + site description → regional wind climate (wind atlas data sets)

Application

Regional wind climate + site description → predicted wind climate (PWC)

Predicted wind climate + power curve → annual energy production (AEP) of wind turbine

Wind farm production

Predicted wind climates + WTG characteristics + wind farm layout → wind farm wake losses

Annual energy productions + wake losses → net annual energy production of entire wind farm

5.5.8 WRF (CIEMAT)

Ana Palomares

Weather Research and Forecasting model (WRF) is used at three partners (CIEMAT, CENER and DTU Wind Energy). The set up at each partner is described in Sections 5.5.9, 5.5.10 and 5.5.11.

Physical background

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.

The wind turbine drag parameterization scheme is based on Blahak and it works with the MYNN planetary boundary layer (PBL) scheme and modifies the turbulent kinetic energy (TKE) field.

The setup of WRF at CIEMAT

WRF gets its boundary conditions from the ERA-Interim Reanalysis product. A number of subgrid scale processes are parameterised by WRF. The shortwave and longwave radiation schemes follow the works by Dudhia and Mlawer, respectively. Microphysical processes are represented with the WRF single moment six class scheme, whereas the cumulus effects are parameterised only in the outermost three domains. The air-sea momentum flux is parameterised following the work by Charnock. The effects of the turbulent vertical mixing within the planetary boundary layer are parameterised using a 1.5 order scheme that predicts the turbulent kinetic energy and advects it with the wind. The scheme is based on the work by Mellor and Yamada but includes a better formulation of buoyancy effects and a master length scale that depends on atmospheric stability. The effects of the wind turbines over the atmospheric flow are parameterised following the work by Fitch et al. The wind turbines are represented as an elevated sink of momentum and a source of turbulent kinetic energy that responds to the wind speed according to a specified function approximating the effects of the turning rotors on the flow. The scheme is comprehensively documented in the work by Fitch et al. This method has been shown to produce a realistic representation of wind farm wakes but a comprehensive evaluation of its performance has not yet been performed.

Main advantages

The effects of wind turbines are represented by imposing a momentum sink on the mean flow; transferring kinetic energy into electricity and turbulent kinetic energy (TKE). The parameterisation improves upon previous models, basing the atmospheric drag of turbines on the thrust coefficient of a modern commercial turbine. In addition, the source of TKE varies with wind speed, reflecting the amount of energy extracted from the atmosphere by the turbines that does not produce electrical energy.

Possible limitations

High computational cost and the great amount of parameterisations and different wind farm designs.

5.5.9 WRF (CENER)

Elena Cantero, Pedro Correia

Also at CENER, the WRF model is used, with version 3.6 of the ARW solver, which includes a wind farm parameterisation option (Fitch scheme). Real wind turbine positions and characteristics, power curves, thrust coefficients are defined for each individual turbine and used in the simulations.

One typical year, based on the best annual mean methodology developed at CENER and representative of the last ten years, is simulated, using the ERA Interim data as input. Three, two-way nested domains with horizontal resolutions of 27km, 9km and 3km in the innermost domain are created and centered in the area of interest.

The physical options used are WRF Single-Moment 3-class simple ice scheme as microphysics, the RRTM scheme for long wave radiation, the Dudhia scheme for the short wave radiation, the MYNN scheme as surface layer and planetary boundary layer scheme, the Noah Land-Surface Model as surface physics and the Kain-Fritsch (new Eta) scheme as cumulus option.

Two individual runs are performed, in which the wind farm parameterization is activated (turbines taken into account) or deactivated (control run, without wind turbines). By obtaining the reference

state of the atmosphere (control run) and comparing it with the wakes simulation, it is possible to obtain the wind speed deficit due to the presence of the wind farms and ascertain the impact on the surrounding region.

5.5.10 WRF (DTU WIND ENERGY)

Patrick Volker, Jake Badger

The Weather Research & Forecast (WRF) model is an open-source local area weather forecast model. It uses the Reynolds Averaged Navier-Stokes (RANS) equations to simulate the flow in time. It also includes equations to predict the temperature, moisture components (water vapor, cloud, rain, ice, etc.) and pressure. Mesoscale models have been developed to predict the weather patterns over relatively large areas. To limit the computational costs, the model equations have been adapted to a relatively coarse horizontal grid-spacing on the order of kilometres. In the vertical direction, the model spacing is finer to resolve the important vertical structure of the temperature, moisture components and wind speed in the boundary layer. Processes that remain unresolved due to the coarse on the mesoscale model grid size, such as turbulence, micro-physics, radiation, eventually convection, etc., are parametrised. The WRF model contains a large variety of state-of-the-art parametrisations. Because it is a limited area model, it needs every time-step to be forced from the lateral and lower boundaries for the entire simulation period. Usually reanalysis data is used for this purpose (and to define the initial atmospheric state). The WRF model includes also modules that are capable to interpolate reanalysis data to the lateral and lower boundaries of the WRF model domain. The WRF model has furthermore the option to nest several domains with an increasing horizontal resolution inside each other. This feature allows to reduce the total domain size, which should be large enough to fill the gap in resolution between that of the reanalysis and the mesoscale model.

5.5.11 EeFARM-II

Edwin Jan Wiggelinkhuizen

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.

5.5.12 FARMFLOW

Gerard Schepers

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 $k-\epsilon$ 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. An example can be seen in Figure 5.6.

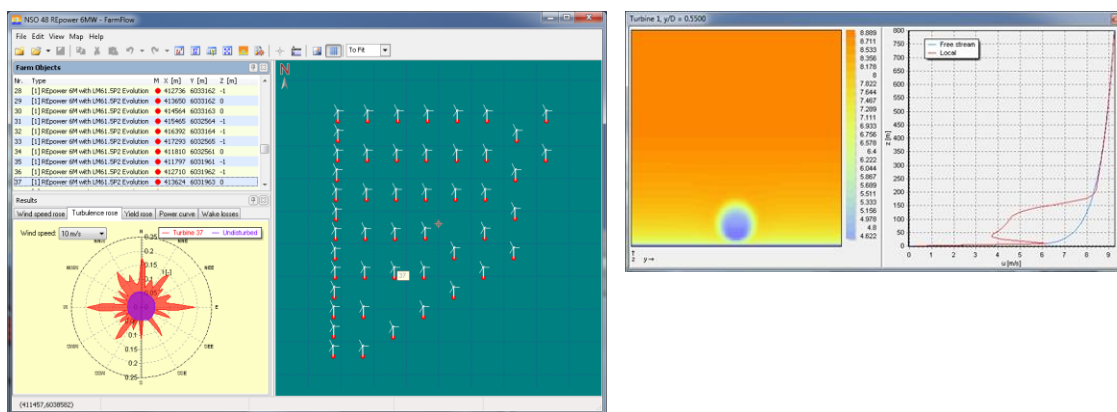


Figure 5.6. Graphical user interface of FarmFlow.

5.5.13 WIND CLUSTER MANAGEMENT SYSTEM (WCMS) FOR DTOC

Lothar Löwer, Tobias Hennig

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 undispachable and therefore considered as losses due to (forecast) uncertainty. Figure 5.7 summarises the approach.

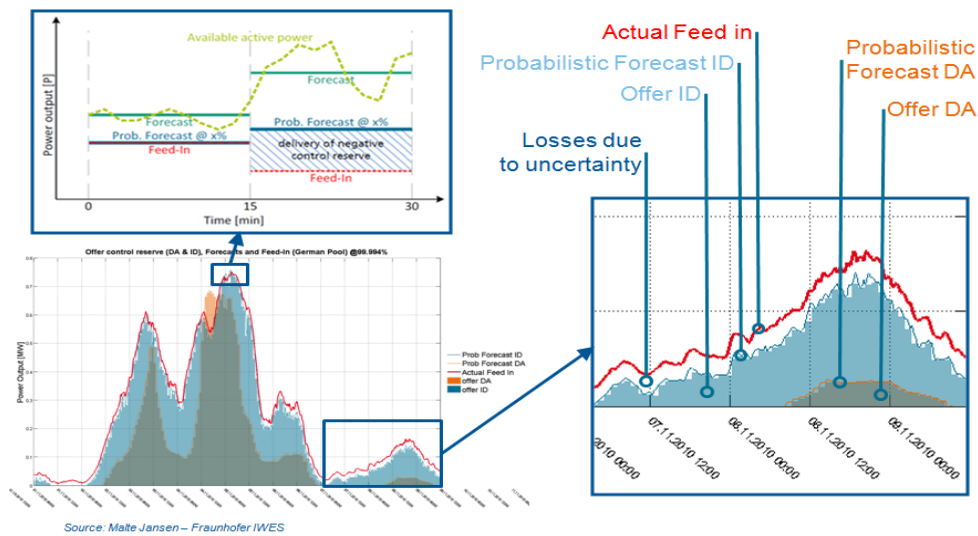


Figure 5.7: Reserve and balancing power calculation (Images source: Malte Jansen, Fraunhofer IWES).

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.

5.6 How to get started with DTOC

Gregor Giebel, Igor Waldl

5.6.1 PRINCIPLES

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. Examples of this can be seen in Chapter 7. The tool structure is shown in Figure 5.8 and the work flow to optimise through comparing LCOE is shown in Figure 5.9.

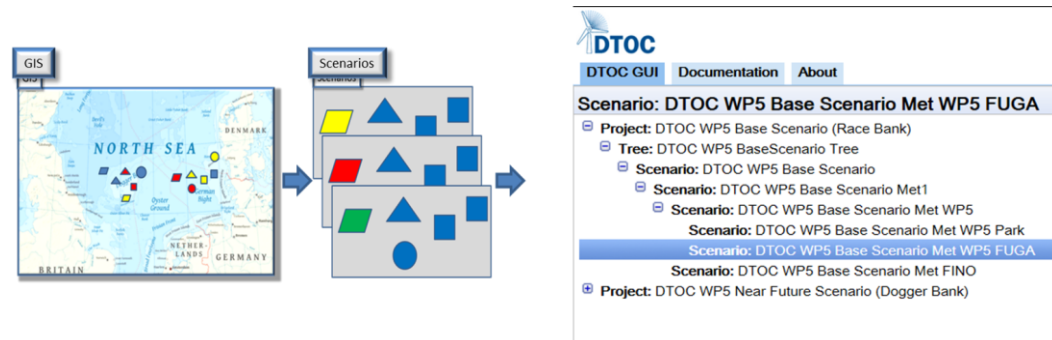


Figure 5.8. Organizing variants of a wind farm or wind farm cluster as scenarios. The different scenarios themselves are again organised in a tree structure.

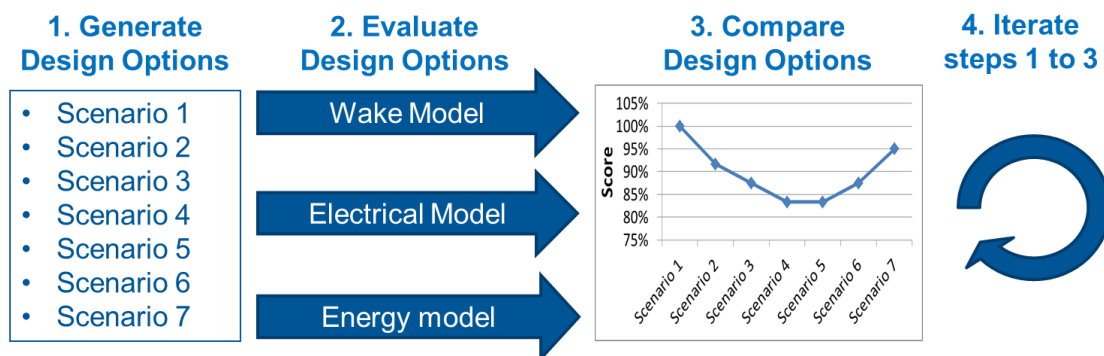


Figure 5.9: Work flow for the DTOC-tool based optimization process.

Web interface overview is shown in Figure 5.10. Figure 5.10 shows a typical view on the DTOC web interface. 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. Results are shown in Figure 5.11.

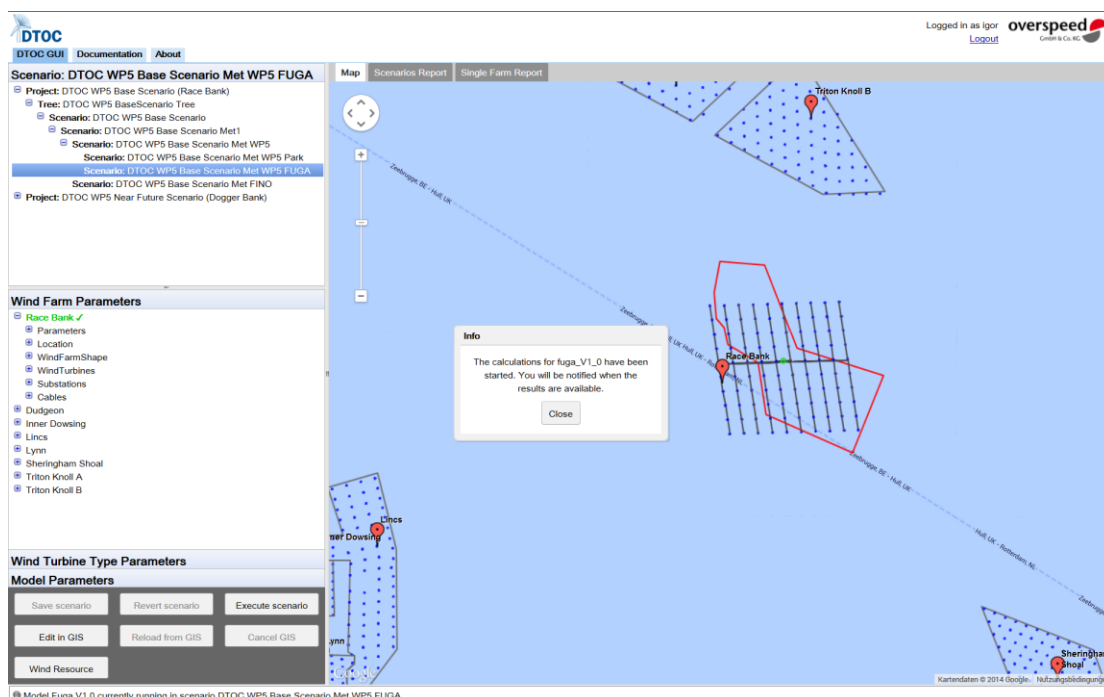


Figure 5.10: Overview of the DTOC web interface (accessed via web browser).

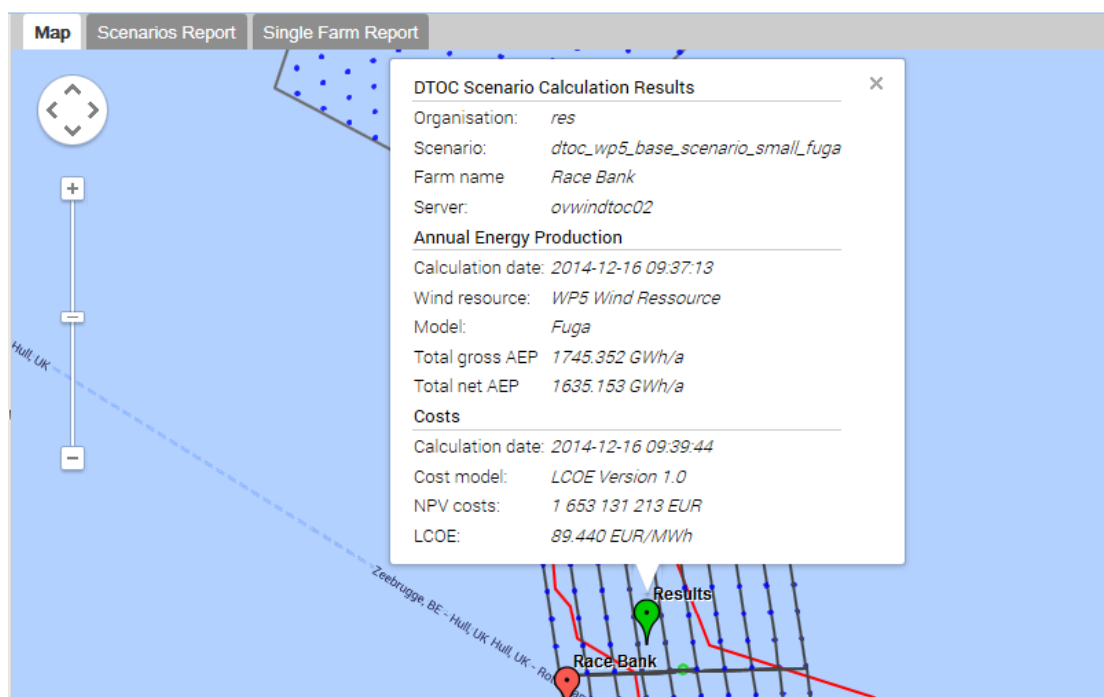


Figure 5.11: Showing the model calculation results including AEP and LCOE for a specific wind farm scenario.

After the calculations are finalised, the calculation results are shown on as comparative reporting (Figure 5.11).

DTOC Energy Production Report

23.04.2014

EON, 2014

Reference LCOE: 13.5 ct/kWh

Reference Scenario: BWII - WAsP

	Scenario Shortname	BWII - WAsP *	BWII - FLAP	BWII - WAsP 100m
Comment		Calculations with WAsP	Calculations with FLAP	Calculations with WAsP, hub height: 100m
	Last Update	2014.04.22 14:30	2014.04.22 16:30	2014.04.23 11:05
Turbines				
	Turbine Manufacturer	Areva	Areva	Areva
	Turbine Type	M5000	M5000	M5000
	Nominal Power [kW]	5000	5000	5000
	Rotor Diameter [m]	116	116	116
	Hub Height [m]	90	90	100
Farm				
	Number of Turbines	80	80	80
	Nominal Power Wind Farm [MW]	400	400	400
Results				
	AEP Gross [GWh/a]	1'758.2	1'747.6	1'846.1
	AEP Farm [GWh/a]	1'613.8	1'600.9	1'702.6
	AEP Net [GWh/a]	1'495.0	1'483.1	1'577.1
	Capacity Factor [%]	46.1%	45.7%	48.6%
	Wind Farm Efficiency	91.8%	91.6%	92.2%
	Availability	96.0%	96.0%	96.0%
	Electrical Losses	3.50%	3.50%	3.51%
	LCOE [Cent/kWh]	13.5	13.4	14.2
	LCOE [%]	+100.00%	+99.20%	+105.50%
	delta LCOE [%]	+0.00%	-0.80%	+5.50%

Figure 5.12: Concept for comparative reporting. A number of scenarios is selected and the calculations are shown in a comparative table. LCOE results are benchmark with reference to one selected reference scenario.

5.6.2 GIS INTEGRATION

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 this interface (Figure 5.13).

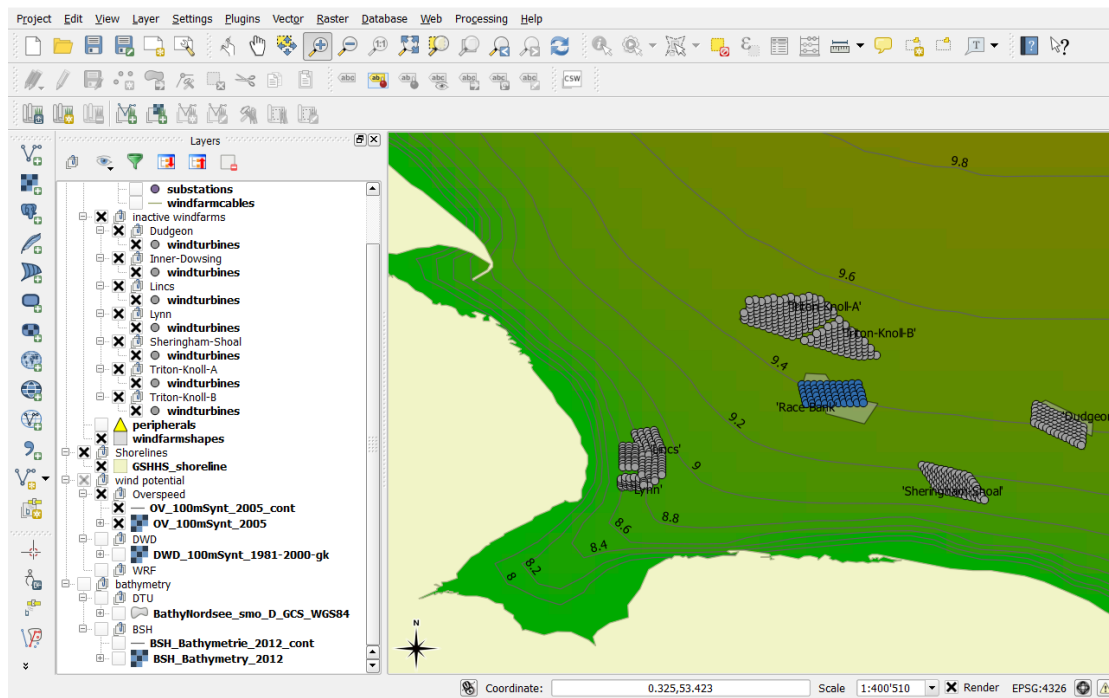


Figure 5.13: GIS view of the selected scenario. The wind turbines of the target wind farm (blue dots) and the surrounding cluster can be identified. In addition, different background information is organised in this GIS project (water depth, wind climate, shoreline, etc.), here showing the wind climate overview map in m/s.

5.7 Summary

Gregor Giebel, Igor Waldl

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.

“High certainty about the actual wind resource and short wind farm development times are essential contributions to our goal, significantly reducing the cost of offshore wind energy.”
Overspeed

6 SCENARIOS

6.1 Introduction

Gerard Schepers

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 realised 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 upscaled 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.

6.2 Base Scenario (Race Bank)

The base scenario is performed at the location of the planned Race Bank wind farm at the Eastern coast of England, see <http://www.4coffshore.com/windfarms/race-bank-united-kingdom-uk18.html> and <https://mapsengine.google.com/map/edit?hl=nl&mid=zBjDdqwg1tDE.klnbPPDGvF7U> which shows this farm to be planned 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 (Jason Jonkman NREL reference turbine, February 15, 2007, NREL/NWTC). The resulting power and C_{DAx} curves from this description were calculated by ECN and included in the EERA-DTOC tool.

The suggested layout of the target farm is given in Figure 6.1 The present wind farm lay-out 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. In Figure 6.1 the distance of the main wind farm lines is 5.1 rotor diameters but scenarios will be considered with different distances between the turbines.

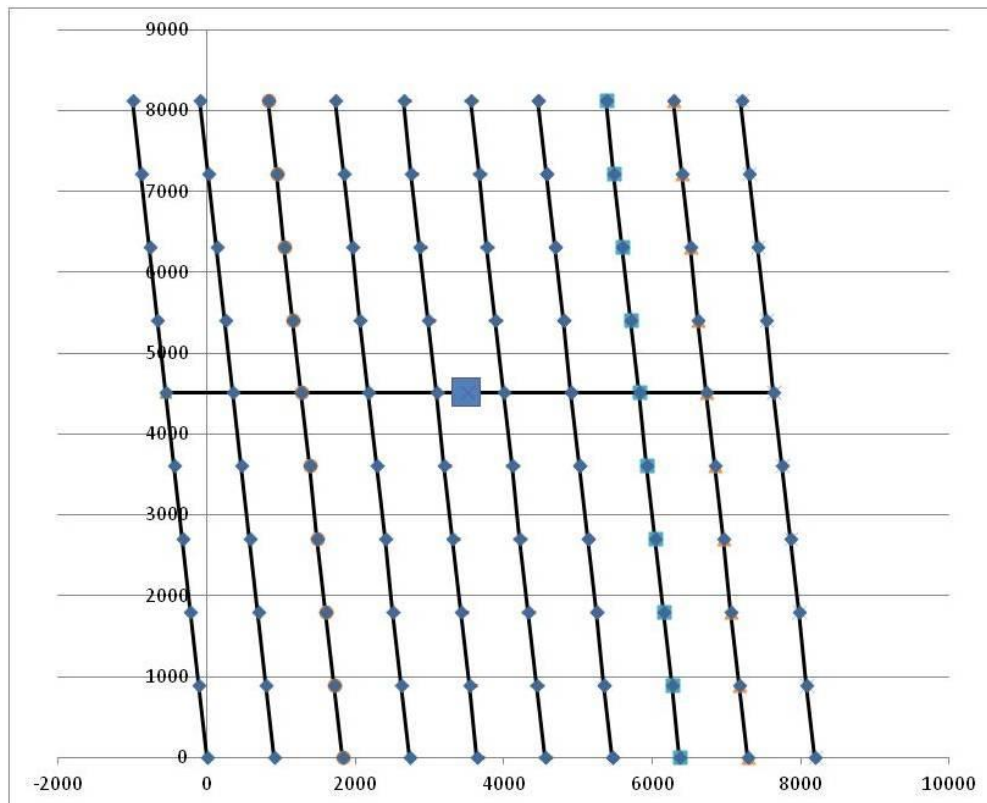


Figure 6.1: Layout of wind farm with the lay-out of electrical cables and transformers. In this case the distance between the turbines is 5.1D but different distances can be used.

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 scenario could consist of investigating several basic intra-array infrastructures.

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).

More information on these farms can be found from <http://www.4coffshore.com/windfarms/>
The wind data has been produced by CENER using WRF (see Section 5.5.9).

The base scenario for Race Bank was evaluated for the user story 3.1, i.e. a wind farm developer can determine the wake effects of neighboring wind farm clusters on a single wind farm (meso and/or micro). This scenario was initially evaluated using the standard wind farm layout and all existing wind farms around, for the different combinations of the wind resource (WRF or Fino1 meteorological data from years 2004-2008) and the wake modeling (Fuga vs WASP-Park), always including the Levelised Cost Of Energy (LCOE) model.

6.3 Near future Scenario (Dogger Bank)

Gerard Schepers, Wei He

The near future farm is located at the Dogger Bank East of North England in relatively shallow waters (18 to 63 meters). Dogger Bank is part of the UK Crown Estate Round 3 area (8,660 km², the largest of the Round 3 zones) with distances between 125 and 290 kilometres off the east coast of Yorkshire, UK.

The development consortium Forewind has defined several projects, each divided in phases of 1.2 GW: Creyke Beck A and B, Teesside A and B (where Teesside C and D are planned for a later stage). The whole estimated capacity of Dogger Bank could add up to 9GW.

Figure 6.2 shows approximate locations of Creyke Beck A and B and Teesside A and B projects. 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.

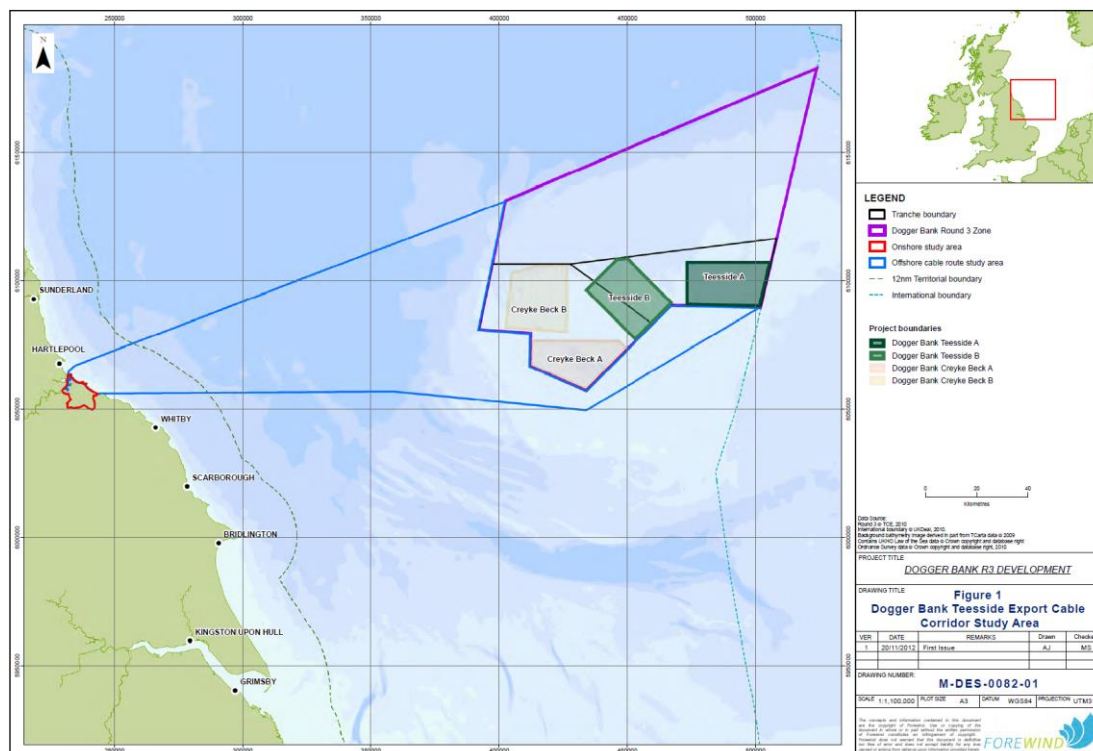


Figure 6.2: Location of Dogger Bank projects (Source Forewind, 2012).

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. A detailed description on the turbine including a power curve and C_{Dax} curve as needed in many wake models can be found at: <http://dtu-10mw-rwt.vindenergi.dtu.dk/>.

The surrounding wind farms (Creyke Beck B, Teesside A and B) are assumed to have a similar layout and the same types of turbines. The layout 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. Thereto DTU Wind Energy used the WRF model to estimate a two year wind climate, from January 2006 to December 2007. The most inner, third, domain contained the Dogger-Bank area in the centre and it stretched over around 725km in the West-East and the South-North direction and a 3km grid-spacing. This domain has for every time-step been run twice, once without and once with wind farm. The simulation without wind farm is used for the model evaluation. In the wind farm simulations we included all wind turbines from the Creyke Beck B and Teesside B wind farms. The third domain was nested (without feedback) within two other domains, that served to downscale the coarse resolution reanalysis data set to 3km. The second and first domain had a 9km and 27km horizontal grid-spacing. For all the domains the number of vertical levels was set to 51. The boundary data for the first domain was from the ERA-Interim Reanalysis and the lower Sea-Surface-Temperatures were taken from the Optimum Interpolation Sea Surface Temperature (OISST) data-set. The two year wind climate has been obtained from 72, 11 days simulations. From every simulation, the first day has been considered to be a spin-up period and was therefore discarded. For the computation, we used the DTU Wind Energy cluster where one single 10 day simulation took between 7 and 8 hours, which results in a total of around 540 hours. Since the simulations are independent, it was possible to simulate the whole period in 3 days, when using around 16% of the cluster's capacity. In the post-processing time-series, as well as observed and generalised wind roses are generated. The validation of the model against QuikSCAT is described in Section 4.4. In that section, we summarise also the WRF model schemes that have been used for the simulations.

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. Thereto the distance between the turbines in the target wind farm Creyke Beck A was chosen to be variable between 3.65 and 10 rotor diameters in order to investigate the net wind farm production (i.e. the wind farm production which includes both the electrical as well as the aerodynamic losses) as function of inter-turbine distance and assess the net wind farm production against the costs for the electrical infrastructure as function of inter-turbine distance.

In these preliminary calculations an estimated wind climate was assumed based on a typical North Sea wind climate. It is noted that at a later stage the wind climate became available from WRF calculations.

In Figure 6.3 the net energy yield (i.e. the energy yield which includes aerodynamic and electrical losses) per year as calculated by EeFarm-II for all 10 rows of wind turbines is plotted. As can be seen, the rows of wind turbines in the middle of the wind farm have a lower energy yield than the rows of wind turbines at the edges of the wind farm. As expected this effect is more pronounced for the wind farm with more closely placed wind turbines.

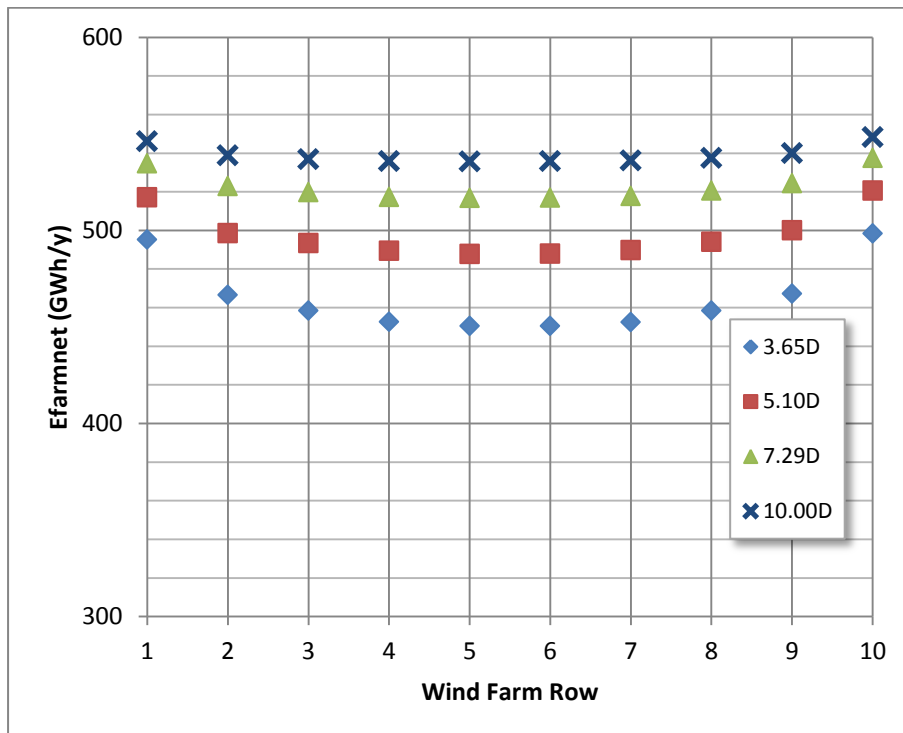


Figure 6.3: Net energy yield per year for each row of wind turbines for different wind turbine spacing distances.

In Figure 6.4 investment costs of the electrical infrastructure is given as function of distance and Figure 6.5 shows the net energy production. It can be seen that the investment costs 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.

It is noted that the investment costs of the electrical infrastructure are seen as the main cost variable when considering distance changes between the turbines. Another contribution might come from the costs of occupied area. When these costs are known they can easily be included in the present tool.

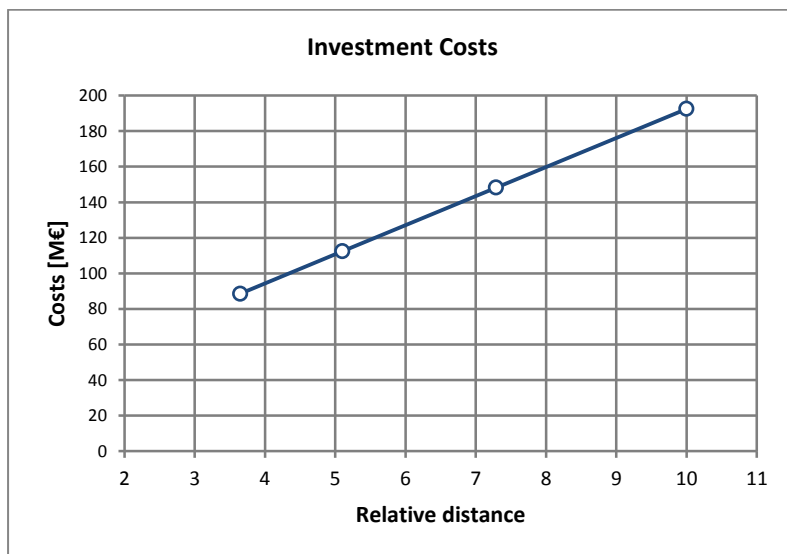


Figure 6.4: Investment cost as function of wind turbine spacing distance.

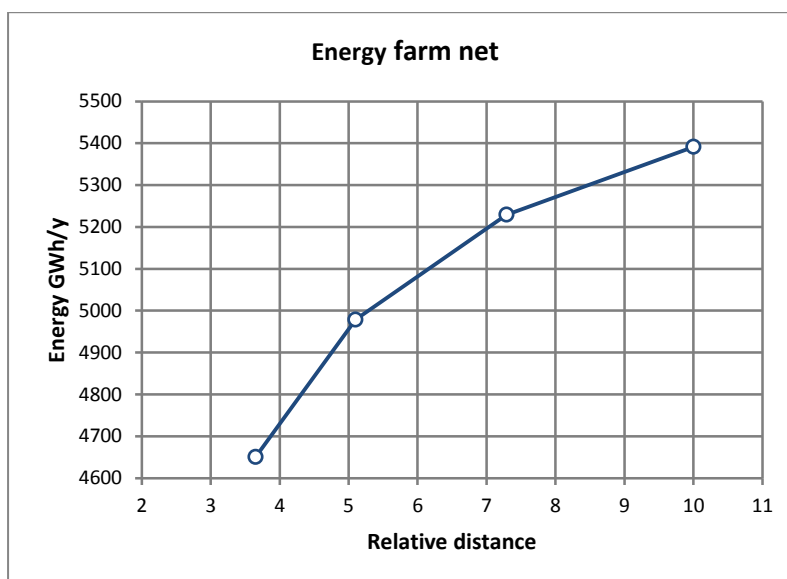


Figure 6.5: Net wind farm energy yield as function of wind turbine spacing distance.

In order to assess the optimal distance between the turbines the LCOE has been determined based on the following assumptions:

- Average discount rate: 7.8%
- Economic lifetime: 12 years
- Availability: 95%
- Capex: 3,876 MEuro/MW for 5.1D distance
- The capex vary with the variation of electrical investment costs as function of distance based on the results from Figure 4.
- Opex: 0.107 MEuro/MW/year

The result is given in Figure 6.6, **Error! Reference source not found.** showing an optimum distance of 9.2 rotor diameter between the turbines.

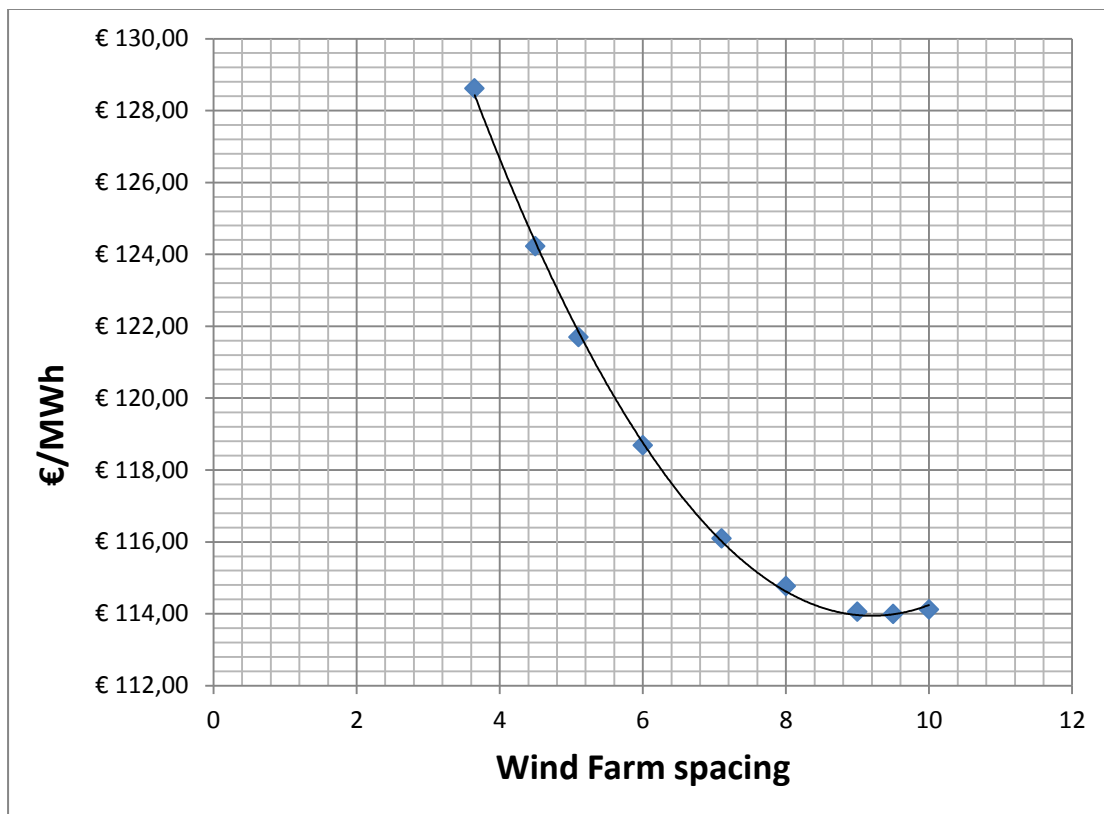


Figure 6.6: LCOE as function of wind farm spacing based on FarmFlow-eeFarm results.

The previously defined user stories and the global definition of scenarios then formed the starting point of the calculations.

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 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 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 was run off-line by SINTEF and Strathclyde, see section 6.4

- Iberdrola was planning to run its own calculations but could not finish them in time.

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.

“Finally, it's all about economics and risks. That's why we supported the integration of economic tools into EERA-DTOC project. Overall, the project demonstrated how academia and industry can work effectively together”

 Carbon Trust

6.4 Scenario far-future 2030

6.4.1 NET-OP CALCULATIONS

Harald Svendsen

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, as illustrated below (left). The red dots and lines represent potential new wind farm clusters and connections. One particular wind farm cluster (A) is singled out for more detailed analyses (shown in cyan in the Figure 6.7). Another one (B) has a location, which is not precisely given, and instead left as part of the scenario analyses to determine. Results are shown in Figure 6.8.

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.

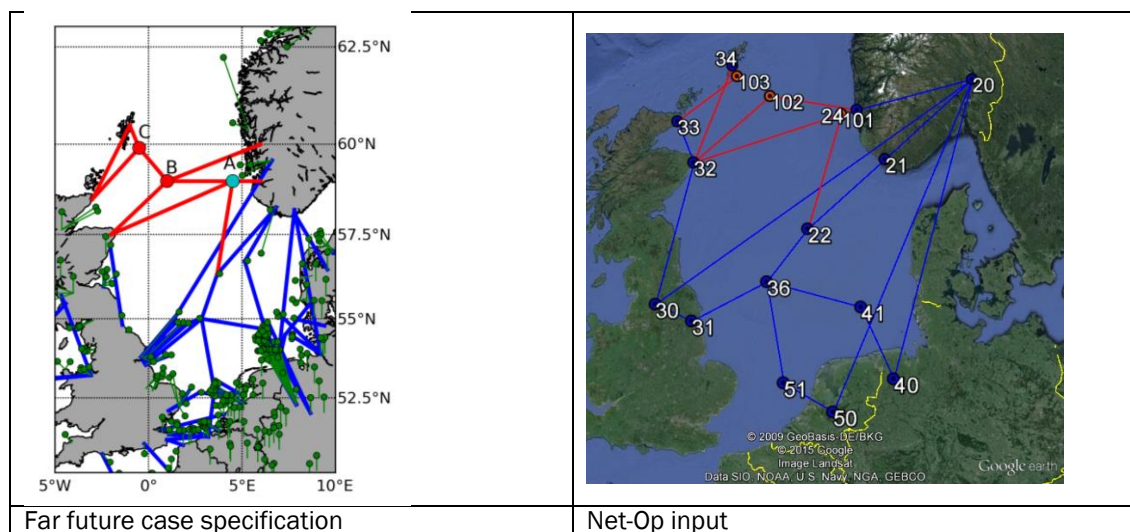


Figure 6.7: The far future scenario definition.

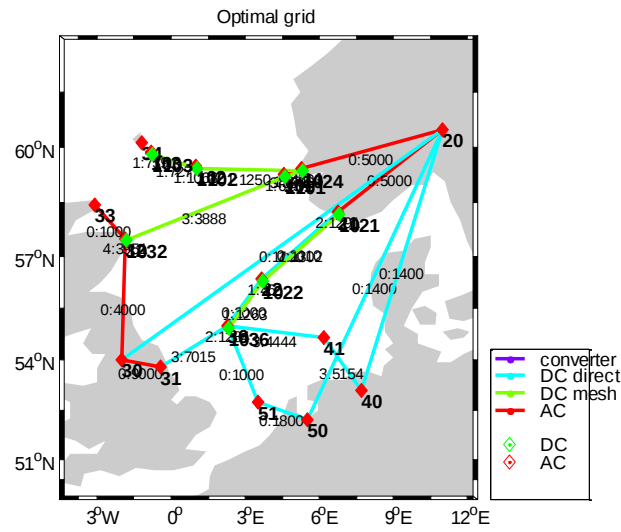


Figure 6.8: Results of Net-Op for the far future scenario.

6.4.2 VERIFICATION OF GRID CODE COMPLIANCE FOR FAR FUTURE WIND CLUSTERS

Ayman B. Attya, Olimpo Anaya-Lara, Pablo Ledesma

Introduction

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 as shown in Figure 6.8.

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). Table 6.1 describes the generation capacities at each bus, and Table 6.2 displays the aggregate load at each region. 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%.

Table 6.1 Aggregate conventional and wind generation at different buses

Aggregate generation, MW		Wind aggregate generation, MW	
Bus 20- Norway	31900	Bus 30- UK	58320
Bus 30- UK	82630	Bus 101- Wind cluster A	1200
Bus 33- Scotland	1000	Bus 102- Wind cluster B	1200
Bus 40- Germany	128900	Bus 103- Wind cluster C	1200

Table 6.2 Aggregate loads at different buses

Aggregate load, MW	
Bus 20-Norway	17352
Bus 30-UK	49772
Bus 33-Scotland	49
Bus 40-Germany	72146

In this initial report only the Nordic sector, which includes the future clusters, is considered in the simplified system shown in Figure 6.10. The geographical presentation of the whole system provided by Net-OP tool is displayed in Figure 6.11 where the bordered part is the simplified system described in Figure 6.10.

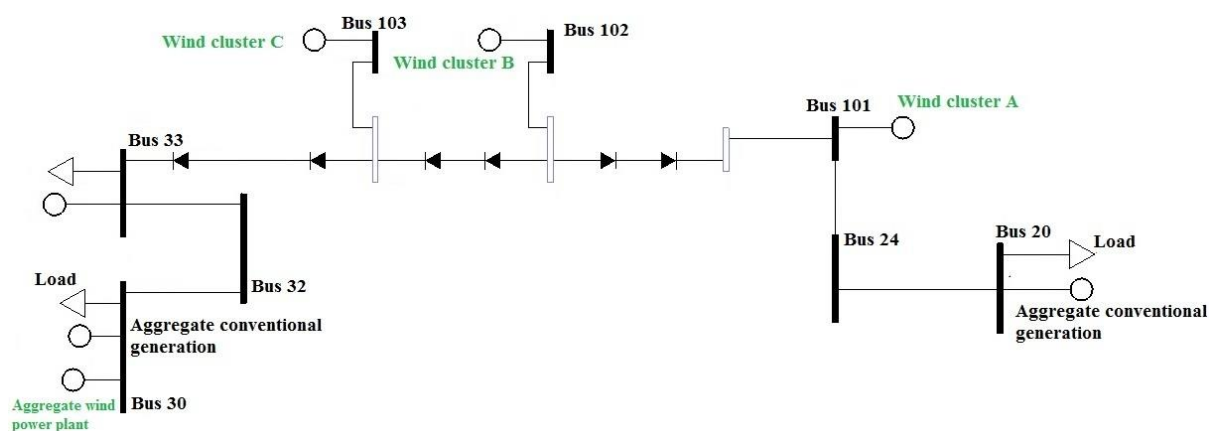


Figure 6.10: Benchmark system single line diagram

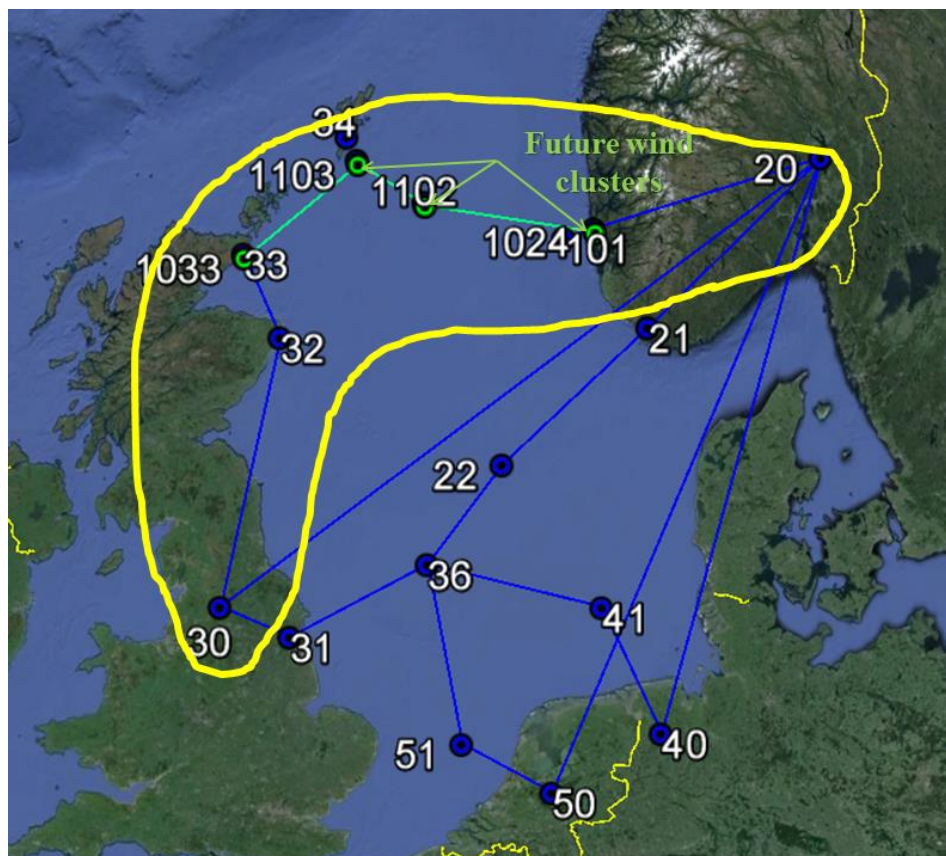


Figure 6.11: Geographical layout of the system provided by Net-OP tool

6.4.3 CASE STUDIES

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.

6.4.4 RESULTS AND DISCUSSION

The reactive current grid requirement is fulfilled by the wind clusters as shown in Figure 6.12, 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 as shown in Figure 6.13. 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 in Figure 6.13 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. As shown in Figure 6.13, 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.

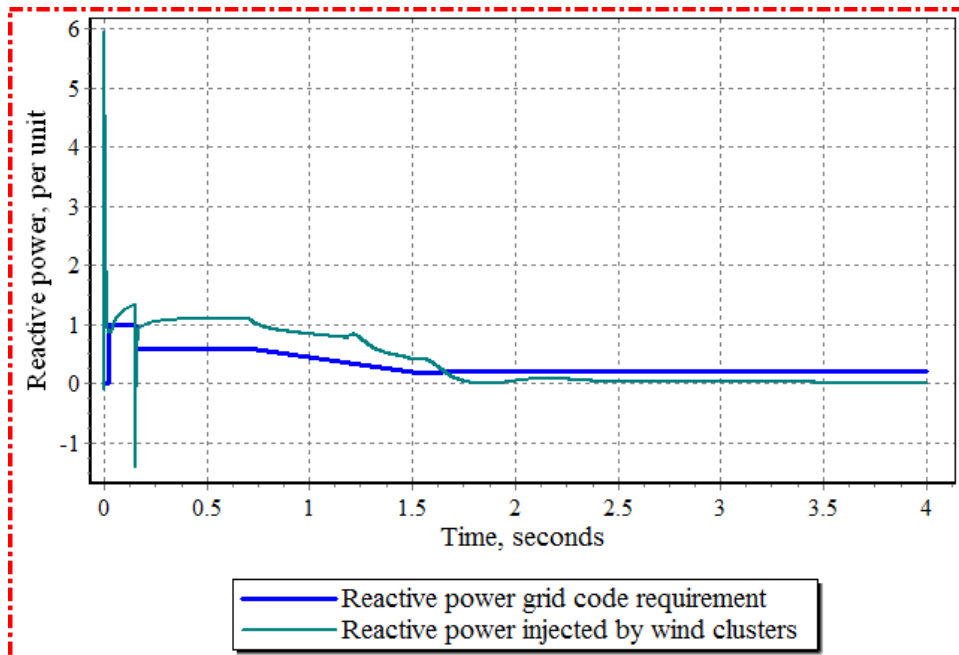


Figure 6.12: Reactive power code requirements and actually injected (Eon voltage dip at Bus 20)

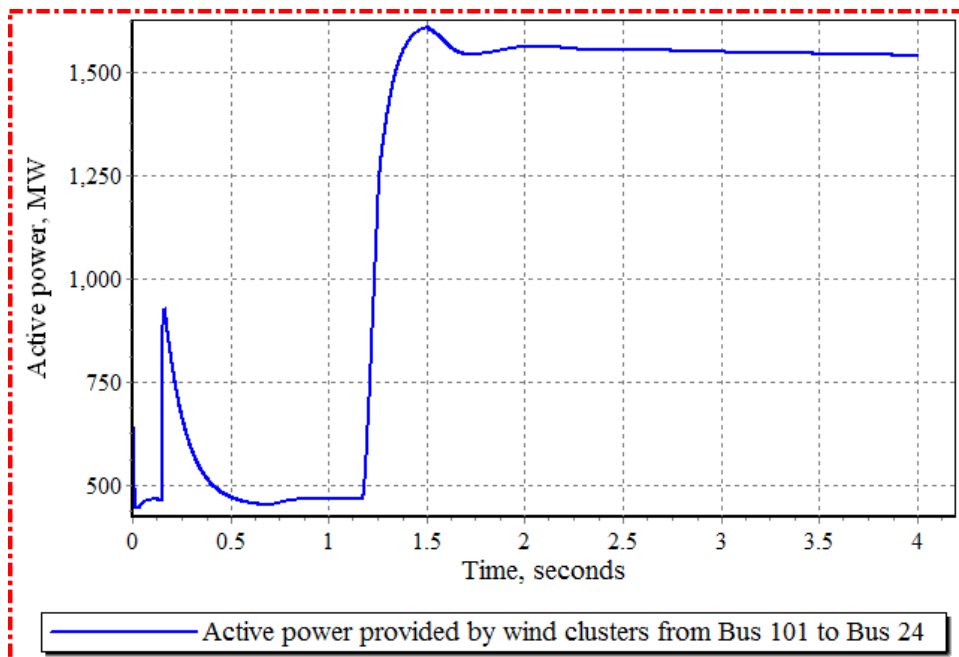


Figure 6.13: Active power provided by wind clusters at Bus 101 (Nordic voltage dip at Bus 20)

6.5 Summary

Gerard Schepers, Wei He, Olimpo Anaya-Lara, Harald Svendsen

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);

7 CONCLUSION

Charlotte Hasager, Gregor Giebel, Gerard Schepers, Igor Waldl

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.

“EERA-DTOC begins to bridge technical and economic considerations that merit much tighter integration and research attention as electricity markets adapt and change. It is to be hoped this platform will serve as a basis for further work of this nature.”
Oisin Brady

8 ACKNOWLEDGEMENTS

Support from the European Energy Research Alliance - Design Tools for Offshore wind farm Clusters (EERA DTOC) project FP7-ENERGY-2011-1/ n°282797 is acknowledged. Satellite images from RADARSAT-2 from Data and Products © MacDonald, Dettewiler and Associates Ltd and Envisat ASAR data from the European Space Agency are acknowledged. We acknowledge SCADA data from RAVE from alpha ventus and SCADA data from DONG energy, Vattenfall and E.On from Horns Rev 1, Lillgrund and Rødsand-2 offshore wind farms.

9 APPENDIX A: PARTNERS



10 APPENDIX B: LIST OF PARTICIPANTS

Name	Short bio	Photo
Alfredo Peña	M.Sc. and PhD, senior scientist at DTU Wind Energy works with wake modelling and wind profiles.	
Alice Ely	Wind energy expert works at RES. CFD expert.	
Ana María Palomares	M.Sc. and PhD, senior scientist at CIEMAT. Task Leader for uncertainty analysis of net energy yield and responsible for CIEMAT.	
Charlotte Bay Hasager	M.Sc. and PhD, senior scientist at DTU Wind Energy. Daily manager of the DTOC project and Task Leader for satellite data used for validation of wind farm wake modelling.	
Diletta Zeni	Project Assistant. Dissemination and Communication at European Wind Energy Association (EWEA).	
Daniel Parades	PhD in Physics. Wind energy expert works at Iberdrola.	
Edwin Wiggelinkhuizen	PhD, works at ECN with the Eefarm model.	
Elena Cantero	Wind Resource expert at CENER. Work Package 3 Leader of the DTOC project.	

Gerard Schepers	M.Sc and PhD, Senior scientist/project manager at ECN, Coordinator of EU and IEA projects. WP 5 Leader of EERA DTOC.		
Gerrit Wolken-Möhlmann	PhD works at Fraunhofer IWES with ship-based wind lidar.		
Gregor Giebel	Senior scientist at DTU Wind Energy, working in wind power meteorology and software development. Leader of Software WP.		
Hans Peter (Igor) Waldl	Director of Overspeed, develops the integration software 'Wind&Economy'.		
Harald Svendsen	PhD, Research Scientist at SINTEF Energy Research. Involved in electrical grids, contact person for the Net-Op model.		
Hauke Beck	M.Sc. and PhD student, research assistant at ForWind Oldenburg. Perform data analysis of scanning lidar.		
Ilona Bastigkeit	Works at Fraunhofer IWES with meteorology for wind energy.		
Ioanna Karagali	M.Sc and PhD, researcher at DTU Wind Energy. On-line DTOC tool testing and validation of WRF with satellite observations.		
Ivan Moya Mallafre	Works at CENER with coordination of activities in wind energy.		

Jan Matthiesen	Head of Innovations at CarbonTrust within the Offshore Wind Accelerator.		
Jake Badger	PhD in Meteorology and expert in mesoscale modelling for wind atlas.		
Jose Palma	Professor at University of Porto and expert in wind energy and aerodynamics.		
John Prospathopoulos	Worked at CRES with aerodynamics and coupling of micro- and mesoscale models (now at NTUA).		
Juan Jose Trujillo	Works at ForWind, Oldenburg wind scanning wind lidar at alpha ventus experiment and data analysis.		
Julia Gottschall	PhD at Fraunhofer IWES and works with floating wind profiling lidar and ship-based wind lidar.		
Kurt S. Hansen	Works at DTU Wind Energy with wake modelling benchmarking using SCADA data.		
Lothar Löwer	Dipl.-Ing. Lothar Löwer at Fraunhofer IWES mainly works on the development of a wind cluster management system (WCMS).		
Marcus Thor	Works at Hexicon with new floating wind farm concepts.		

Mariano Faiella	Dipl.-Ing. Luis Mariano Faiella worked as a Research Engineer at the Department Transmission Networks in Fraunhofer IWES and was WP2 Leader until December 2014.		
Matthias Wächter	PhD works at ForWind, Oldenburg with wind power meteorology.		
Merete Badger	M.Sc. and PhD, senior scientist at DTU Wind Energy. Participating in the satellite based wind farm wake analyses.		
Nicolaos Antonio Cutululis	M.Sc. and PhD, senior scientist at DTU Wind Energy. Participated in EERA DTOC - WP2 mainly as Task Leader for wind power variability and the CorWind software.		
Patrick Volker	PhD and works as post doc at DTU Wind Energy on mesoscale modelling of wake coupled to microscale.		
Pauline Vincent	PhD. Works at CLS with synthetic aperture radar satellite processing on ocean winds.		
Olimpo Anaya-Lara	MSc and PhD, Reader at the University of Strathclyde and leader of the research cluster on dynamics and control of offshore power networks.		
Peter Hauge Madsen	Head of Department for DTU Wind Energy. Coordinator of the EERA DTOC project.		
Peter Stuart	Senior Technical Manager at RES Group.		

Petr Maule	M.Sc. and PhD, research engineer at DTU Wind Energy. Responsible for data exchange between DTU software and DTOC tool.		
Pierre-Elouan Réthoré	Senior Researcher. MSc & PhD from DTU. Leader of WP1. Worked on benchmarking wind farm flow models.		
Rebecca Barthelmie	Professor and Croll Faculty Fellow Sibley School of Mechanical and Aerospace Engineering, Cornell University. Offshore wind energy expert.		
Romain Husson	Works at CLS with synthetic aperture radar processing to ocean winds.		
Sarah-Ruth Schmidt	Wind energy expert, works with project management at E.ON.		
Sara Pryor	Professor Earth and Atmospheric Science, Cornell University. Expert in climate change and winds.		
Sharon Wokke	Senior Project Manager. Planning, administration, and dissemination activities at European Wind Energy Association.		
Søren Ott	PhD in Physics. Senior Scientist at DTU Wind Energy. Developed FUGA wake model.		
Takis Chaviaropoulos	Head of section at CRES in wind energy with expertise in aerodynamics (now at NTUA).		

Vitor Costa Gomes	PhD student at University of Porto and works with CFD model Ventos.		
Wei He	PhD, works in research in wind energy at Statoil.		

“As day-to-day coordinator of the EERA-DTOC project it is with great pleasure that I can announce, following the project evaluation by the consortium, that all partners find that the quality of the reports is as ‘as expected’ or ‘better than expected’, that there were few delays that the work was carried out cost-effectively.

Furthermore, the evaluation showed that the goals and deliverables were clear, that the number of meetings was sufficient and that the communication was efficient and effective. Finally, the two dominant answers to the question ‘What went well in the project?’ were: 1) ‘Very good collaboration’ and 2) ‘Software with a lot of potential was developed’.

Charlotte Bay Hasager, DTU Wind Energy

11 APPENDIX C: LIST OF PEER-REVIEWED PUBLICATIONS, PRESENTATIONS AND ARTICLES

Peer-reviewed journal articles

Badger M., Peña A., Hahmann A.N., Mouche A., Hasager C.B. (2015) [Extrapolating satellite winds to turbine operating heights](#). *Journal of Applied Meteorology and Climatology* (article under review).

Volker P.J.H., Badger J., Hahmann A.N., Ott S. (2015) [The Explicit Wake Parametrisation V1.0: a wind farm parametrisation in the mesoscale model WRF](#). *Geosci. Model Dev. Discuss.*, 8, 3481–3522, 2015 .

Peña, A., Réthoré, P.-E., Laan, M.P.v.d. (2015) [On the application of the Jensen wake model using a turbulence-dependent wake decay coefficient: the Sexbierum case](#). *Wind Energy*, DOI: 10.1002/we.1863.

Hasager C.B., Vincent P., Badger J., Badger M., Di Bella A., Peña A., Husson R., Volker P. (2015) [Using satellite SAR to characterize the wind flow around offshore wind farms](#). *Energies* 2015, 8(6), 5413-5439; doi:10.3390/en8065413.

Peña A., Réthoré P. E., Rathmann O. (2014) [Modeling large offshore wind farms under different atmospheric stability regimes with the Park wake model](#). *Renewable Energy*, vol 70, pp. 164-171, 10.1016/j.renene.2014.02.019.

Costa Gomes V. M., Palma J. M. L. M., Silva Lopes A. (2014) [Improving actuator disk wake model](#). The Science of Making Torque from Wind 2014 (TORQUE 2014) IOP Publishing Journal of Physics: Conference Series 524 [doi:10.1088/1742-6596/524/1/012170](#). Centre for Wind Energy and Atmospheric Flows, Faculdade de Engenharia da Universidade do Porto.

Jiménez P.A., Navarro J., Palomares A.M., Dudia J. (2014) [Mesoscale modelling of offshore wind turbine wakes at the wind farm resolving scale](#). *Wind Energy* 2015:18, p559-566. Published online 2014 DOI: 10.1002/we.1708.

Wolken-Möhlmann G., Gottschall J., Lange B. (2014) [First verification test and wake measurement results using a Ship-LIDAR System](#), *Energy Procedia*, 53, 146-155.

Barthelmie R.J., Pryor S.C. (2013) [Wake model evaluation using data from the Virtual Wakes Laboratory](#), *Applied Energy*, 104, 834-844. doi 10.1016/j.apenergy.2012.12.013.

Hasager C.B., Rasmussen L., Peña, A., Jensen, L.E., Réthoré, P.-E. (2013) [Wind Farm Wake: the Horns Rev Photo Case](#), *Energies*, 6(2), 696-716; doi:10.3390/en6020696.

Peña A., Rathmann O. (2013) [Atmospheric stability-dependent infinite wind-farm models and the wake-decay coefficient](#), *Wind Energy*, DOI: 10.1002/we.1632.

Svendsen, H. G. (2013) [Planning Tool for Clustering and Optimised Grid Connection of Offshore Wind Farms](#), *Energy Procedia*, 35, 297 – 306.

Gaumond M., Réthoré P. E., Ott S., Peña A., Bechmann A., Hansen K. S. (2012) [Evaluation of the wind direction uncertainty and its impact on wake modeling at the Horns Rev offshore wind farm](#), *Wind Energy*. DOI: 10.1002/we.1625.

Peer-reviewed proceedings papers

Hansen K.S., Réthoré P.-E., Palma J., Hevia B., Prospathopoulos J., Peña A., Ott S., Schepers G., Palomares A., Van der Laan M.P., Volker P. (2015) [Simulation of wake effects between two wind farms. Journal of Physics: Conference Series, Visby Wake Conference 2015, vol. 625, Gotland, Sweden, 9-11 June 2015.](#)

Hasager C.B., Vincent P., Husson R., Mouche A., Badger M., Peña A., Volker P., Badger J., di Bella A., Palomares A., Cantero, E., Correia, P.M.F. (2015) [Comparing satellite SAR and wind farm wake models. Journal of Physics: Conference Series, Visby Wake Conference 2015, vol. 625, Gotland, Sweden, 9-11 June 2015.](#)

Prospathopoulos J.M., Sieros G., Chaviaropoulos P.K. (2014) [Numerical Estimation of Power Deficit and Efficiency in Large Offshore Wind Farms](#), *Proceedings of EWEA 2014*, 10-13 March 2014, Barcelona, Spain.

Svendsen H.G., Endegnanew A.G. (2013) [Automated Grid Connection Design Process for Offshore Wind Farm Clusters](#), *Proceedings of EWEA Offshore 2013*, 19-21 November 2013, Frankfurt, Germany.

Badger J., Volker P.J.H., Prospathopoulos J.M., Sieros G., Ott S., Rethore P.-E., Hahmann A. N., Hasager C. (2013) [Wake modelling combining mesoscale and microscale models](#), *Proceedings of International Conference on Aerodynamics of Offshore Wind Energy Systems and Wakes (ICOWES)*, 17-19 June 2013, Lyngby, Denmark.

Barthelmie R.J., Pryor S.C. (2013) [Wake model evaluation metrics and the virtual wakes laboratory](#), *Proceedings of International Conference on Aerodynamics of Offshore Wind Energy Systems and Wakes (ICOWES)*, 17-19 June 2013, Lyngby, Denmark.

Volker P. J. H., Badger J., Hahmann A. N., Hansen K. S. (2013) [Wind-Farm Parametrisations in Mesoscale Models](#), *Proceedings of ICOWES*, DTU, p. 479-489, 2013.

Réthoré P.-E., Hansen K.S., Barthelmie R.J., Pryor S.C., Sieros G., Prospathopoulos J., Palma J.M.L.M., Gomes V.C., Schepers G., Stuart P., Young T., Rodrigo J.S., Larsen G.C., Larsen T.J., Ott S., Rathmann O., Peña A., Gaumont M., Hasager C. B. (2013) [Benchmarking of Wind Farm Scalewake Models in the EERA - DTOC Project](#), *Proceedings of International Conference on Aerodynamics of Offshore Wind Energy Systems and Wakes (ICOWES)*, 17-19 June 2013, Lyngby, Denmark.

Cantero E., Hasager C. B., Réthoré P.-E., Peña A., Hansen K.S., Badges J., Schepers G., Faiella L. M., Iuga D., Giebel G., Lozano S., Sanz J., Sieros G., Stuart P., Young T., Palomares A. Navarro J. (2013) [Energy Yield Prediction of Offshore Wind Farm Clusters at the EERA-DTOC European Project](#), *Proceedings of EWEA Offshore 2013*, 19-21 November 2013, Frankfurt, Germany.

Prospathopoulos J.M., Chaviaropoulos P.K. (2013) [Numerical Simulation of Offshore Wind Farm Clusters](#), *Proceedings of EWEA 2013*, 4-7 February 2013, Vienna, Austria.

Gaumont M., Réthoré P.-E., Bechmann A., Ott S., Larsen G. C., Peña A., Hansen K. S. (2012) [Benchmarking of wind turbine wake models in large offshore wind farms](#), *The Science of Making Torque from the Wind Conference*, 9-11 October 2012, Oldenburg, Germany.

Oral and Poster presentations

Hasager C.B., Badger M., Karagali I. (2015) [Contribution of EO data to offshore wind energy planning \(poster\)](#). 9th GEO European Projects Workshop (GEOSS), 15-16 June 2015, Copenhagen, Denmark.

Hasager C.B., Vincent, P., Husson, R., Mouche A., Badger M., Peña A., Volker P., Badger J., di Bella A., Palomares A., Cantero E., Correia P.M.F. (2015) [Comparing satellite SAR and wind farm wake models](#) (oral). Visby Wake Conference 2015, 9-11 June 2015, Gotland, Sweden.

Hansen K.S. (2015) [Simulation of wake effects between two wind farms](#), (oral) Presented at the Wake Conference 2015 in Visby, Sweden, June 9 – 11, 2015.

Hasager C., Giebel G., Waldl I., Schepers G. (2015) [Design tool for offshore wind farm clusters](#). (oral) Proceedings of DEWEK 2015, 12th German Wind Energy Conference, Bremen, May 2015.

Hasager C.B. (2015) [Offshore wind resource mapping in Europe from satellites](#) (oral). Seminar at the University of Auckland, Department of Physics, 1 April 2015, Auckland, New Zealand.

Hasager C.B., Badger M., Peña A., Badger J., Di Bella A., Volker P. (2015) [Offshore wind farm wake modelling with focus on cluster scales](#) (oral). EWEA Technology Workshop: Resource Assessment 2015, 2-3 June 2015, Helsinki, Finland.

Wolken-Möhlmann G., Gottschall J., Lange B. (2015) [A detailed analysis of ship-lidar measurements with comparison to FINO1 \(poster\)](#). DEWEK 2015, 19-20 May 2015, Bremen, Germany.

Da Costa Comes V. M. M. G., Palma J. M. L. M. (2015) [Predicting Offshore Wind Farm Cluster Performance Using RaNS-based Actuator Disc Wind Turbine Model](#). PANACM2015. 29 April 2015.

Beck H., Trujillo J. J., Wolken-Möhlmann G., Gomez V. C., Peña A., Schmidt J., Madsen P.H., Hasager C.B. (2015) (oral) [Comparison results of lidar measurements and wind park model simulations](#). Workshop at Servion, 30 March 2015, Österröfeld, Germany.

Beck, H., Trujillo, J. J., Wolken-Möhlmann, Gottschall, J., Schmidt, J., Peña, A., Gomes, V., Lange, B., Kühn, M., Hasager, C.B. (2015) [Comparison of simulations of the far wake of alpha ventus against ship-based lidar measurements](#). (oral) RAVE Offshore R&D Conference, 13-15 October 2015, Bremerhaven, Germany.

Anaya-Lara O., Svendsen H., Wiggelinkhuizen E., Schepers G. (2015) [Scenarios far-future](#) (oral) EWEA Offshore 2015 Event, 10-12 March 2015, Copenhagen, Denmark.

Volker P., Badger J., Hahmann A. N., Hansen K. S., Husson R., Vincent P., Longépé N., Mouche A., Hasager C. B. (2015) [Application of mesoscale models with wind farm parametrizations in EERA DTOC](#). (oral) Roskilde, Denmark. Resource Assessment Session at EWEA Offshore 2015, 10 March 2015.

Hasager C., Giebel G., Waldl H. P., Schepers G. (2015) [Design tool for offshore wind farm clusters](#). (oral) Overall optimised layout design for lowest LCoE Session at EWEA Offshore 2015, 10 March 2015.

Peña A., Hasager C., Husson R (2015) [Far wake wind field comparison between satellite retrievals and microscale model results](#). poster presented at EWEA Offshore, Copenhagen, March 2015.

Giebel G., Waldl I. (2015) [DTOC Software](#) (oral). EWEA Offshore 2015 Event, 10-12 March 2015, Copenhagen, Denmark.

Hansen K.S. (2015) [Wind farm wake verification](#) (oral). EWEA Offshore 2015 Event, 10-12 March 2015, Copenhagen, Denmark.

Madsen P. H., Hasager C.B. (2015) [Project Overview](#) (oral). EWEA Offshore 2015 Event, 10-12 March 2015, Copenhagen, Denmark.

Schepers G., Bot E., Wiggelinkhuizen E., Bulder B. (2015) [Scenarios near-future](#) (oral) EWEA Offshore 2015 Event, 10-12 March 2015, Copenhagen, Denmark.

Matthiesen J. (2015) [Perspectives on EERA-DTOC from Industry Partners](#) (oral). EWEA Offshore 2015 Event, 10-12 March 2015, Copenhagen, Denmark.

Hasager C.B., Badger M., Peña A., Badger J., Volker P., Husson R., Vincent P., Cantero E., Palomares A., Mouche A. (2014) [Offshore wind farm wake study using Envisat ASAR and Radarsat in the North Sea](#) (poster). Earth Observation for Ocean Atmosphere Interactions Science 2014 - Responding to New Scientific Challenges of SOLAS, European Space Agency (ESA) and Surface Ocean Lower Atmosphere Study (SOLAS), 28-31 October 2014, Frascati, Rome, Italy.

Pryor S.C., Barthelmie (2014) [Can climate change impact wind energy? The science of making torque from wind](#), conference. June 2014, Lyngby, Denmark (Poster).

Hasager C.B., Hansen K., Réthoré P.-E. , Volker P. , Palomares A., Prospathopoulos J., Chaviaropoulos T., Sieros G., Schepers G., Ott S., Peña A., Cantero E., Palma J., Pryor S., Barthelmie R., Mouche A., Giebel G., Badger M., Lozano S., Correia P., Rathmann O., Göçmen T., Young T., Rodrigo, J., Madsen, P.H., Maguire, E. (2014) [EERA DTOC wake results offshore](#) (oral). EWEA2014 Annual Conference, 10-13 March 2014, Barcelona, Spain.

Cantero E., Sanz J., Lozano, S., Hasager C.B., Sieros G., Stuart P., Young T., Palomares A., Navarro J., Waechter M., Morales A. (2014) [Energy yield prediction of offshore wind farm clusters at the EERA-DTOC European project](#) (poster). 11th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2014, 22-24 January 2014, Trondheim, Norway.

Wolken-Möhlmann G., Gottschall J., Lange B. (2014) [First verification test and wake measurement results using a Ship-LIDAR System \(poster\)](#). 11th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2014, 22-24 January 2014, Trondheim, Norway.

Schepers G., van Garrel A., Wiggelinkhuizen E. Pierik J. Bot E. (2014) [How aerodynamic and electrical aspects come together in wind farm design](#) (oral). 11th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2014, 22-24 January 2014, Trondheim, Norway.

Da Costa Comes V. M. M. G., Palma J. M. L. M. (2014) [Actuator disk wake model in RaNS](#) (poster). 11th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2014, 22-24 January 2014, Trondheim, Norway.

Madsen, P.H., Hasager, C.B. (2014) [Design Tool for Offshore Wind Farm Cluster](#) (oral invited) 11th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2014, 22-24 January 2014, Trondheim, Norway.

Hansen, K.S. (2014) [Benchmarking of Lillgrund offshore wind farm scale wake models](#) (oral), 11th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2014, 22-24 January 2014, Trondheim, Norway.

C.B. Hasager et al. (2013) [Offshore wind farm clusters – towards new integrated design tool](#) – poster for EWEA Offshore 2013. EWEA Offshore 2013, 19-21 November 2013, Frankfurt, Germany.

Svendsen H. G., Endegnanew A. G. (2013) [Automated grid connection design for offshore wind farm clusters](#) (poster), EWEA Offshore 2013, 19-21 November 2013, Frankfurt, Germany.

Hasager C. B., Mouche A., Longépé N., Badger M. (2013) [Offshore wind farm clusters wakes observed from satellite SAR](#) (poster). ESA Living Planet Symposium, 9-13 September 2013, Edinburgh, United Kingdom.

Badger M., Peña A., Hahmann A.N., Hasager C. B. (2013) [Combining satellite winds and NWP modelling for wind resource mapping offshore](#) (poster). ESA Living Planet Symposium, 9-13 September 2013, Edinburgh, United Kingdom.

Badger J., Volker P., Ott S., Réthoré P.-E., Hahmann A., Prospathopoulos J., Sieros G. (2013) [Wake modeling combining mesoscale and microscale models](#) (oral). International Conference on Aerodynamics of Offshore Wind Energy Systems and Wakes (ICOWES 2013), 17-19 June 2013, Lyngby, Denmark.

Réthoré P.-E., Hansen K.S., Barthelmie R.J., Pryor S.C., Sieros G., Prospathopoulos J., Palma J.M.L.M., Gomes V.C., Schepers G., Stuart P., Young T., Rodrigo J.S., Larsen G.C., Larsen T.J., Ott S., Rathmann O., Pena A., Gaumond M., Hasager C.B. (2013) [Benchmarking of wind farm scale wake models in the EERA-DTOC Project](#) (oral). International Conference on Aerodynamics of Offshore Wind Energy Systems and Wakes (ICOWES 2013), 17-19 June 2013, Copenhagen, Denmark.

Peña A., Réthoré P.-E., Rathmann O. (2013) [Evaluation of the Park wake model under different atmospheric stability conditions at the Horns Rev I wind farm](#), poster presented at EWEA 2013 Conference, 4 - 7 February 2013, Vienna, Austria.

Schepers G. et al. (2013) [Design Tools for Offshore Clusters - including new results on wake bench](#) (oral). EWEA 2013 Conference, 4 - 7 February 2013, Vienna, Austria.

Gaumond M., Réthoré P. E., Ott S., Peña A., Bechmann A., Hansen K. S. (2013) [Evaluation of the wind direction uncertainty and its impact on wake modeling at the Horns Rev offshore wind farm](#). The Second NREL Wind Energy Systems Engineering Workshop, 29-30 January 2013, Broomfield, Colorado, USA.

Svendsen H. G. (2013) [Planning Tool for Clustering and Optimised Grid Connection of Offshore Wind Farms](#), 10th Deep Sea Offshore Wind R&D Conference, 24-25 January 2013, Trondheim Norway.

Réthoré P.-E. (2013) [Wind Farms Design and Optimization Presentation of TOPFARM and EERA-DTOC](#) (oral) The Second NREL Wind Energy Systems Engineering Workshop, 29-30 January 2013, Broomfield, Colorado, USA.

Réthoré P.-E. (2013) [Wind Farms Design and Optimization](#) (oral). The Second NREL Wind Energy Systems Engineering Workshop, 29-30 January 2013, Broomfield, Colorado, USA.

Barthelmie R.J., Pryor S.C. (2012) [Wake model evaluation metrics](#) (oral). IEA Wakebench, NWTC, 8 November 2012.

Faiella M. (2012) [Designing and Operating wind Farm Clusters](#) (oral). International Conference on Grid Integration of Offshore Wind Energy, 10th December 2012, Hamburg, Germany.

Giebel G., Hasager C. B., Madsen P.H., Réthoré P.-E., Faiella M., Cabezon D., Schepers G., Iuga D. (2012) [EERA-DTOC: Design Tools for Offshore wind farm Clusters](#) (poster). EWEA 2012 Conference, 15-19 April 2012, Copenhagen, Denmark.

Hasager C. B., Madsen P.H., Réthoré P.-E., Faiella M., Cabezon D., Giebel G., Schepers G., Iuga D. (2012) [EERA-DTOC – European Energy Research Alliance Design Tool for Offshore clusters - Poster. Making Torque Conference](#). The Science of Making Torque from the Wind Conference, 9-11 October 2012, Oldenburg, Germany.

Technical reports

Charlotte Bay Hasager and Gregor Giebel (editors - June 2015), EERA-DTOC final summary report, EERA-DTOC Technical Report D7.20 (this issue).

Charlotte Bay Hasager, Igor Waldl, Gregor Giebel, Andreas Bechmann, Brian Ohrbeck Hansen, Jake Badger, Poul Sørensen, Nicolaos Cutululis (June 2015), [Exploitation plan](#), EERA-DTOC Technical Report D6.11.

Gerard Schepers, Alfredo Pena, Alice Ely, Ana Palomares, Ayman Attiya, Giorgos Sieros, Gregor Giebel, Harald Svendsen, Ilona Bastigkeit, Ioanna Karagali, Ivan Moya, Olimpo Anaya Lara, Pablo Ledesma, Pedro M. Fernandes Correia, Vitar Gosta Gomez, Wei He (June 2015), [EERA DTOC calculation of scenarios](#), EERA-DTOC Technical Report D5.12.

Gerard Schepers, Igor Waldl, Gregor Giebel, Charlotte Hasager, Rainer Cordsen (May 2015), [The value of the integrated wind farm cluster design tool is demonstrated and reported](#), EERA-DTOC Technical Report D5.13, not available yet.

Hauke Beck, Juan José Trujillo, Gerrit Wolken-Möhlmann, Alfredo Pena Diaz, Vitor Costa Gomes, Jonas Schmidt (February 2015), [Mesoscale effects on wind farm energy yield reported](#), D5.10.

Kurt S. Hansen, Charlotte Hasager (December 2014), [Validation of wake models for \(two\) wind farms](#), EERA-DTOC Technical Report D5.9.

Mariano Faiella, Harald Svendsen, Edwin Wiggelinkhuizen, Olimpo Anaya-Lara, Gerard Schepers (July 2014), [EERA DTOC far future scenario](#), EERA-DTOC Technical Report D5.7.

Garrel A., van Wiggelinkhuizen E.J., Pierik J.T.G., Bot E.T.G., Schepers J.G (ECN Wind Energy), He Wei (Statoil Petroleum AS, July 2014), [Base scenario for clusters simulated](#), EERA-DTOC Technical Report D5.11.

Lothar Löwer, Tobias Hennig, Mariano Faiella (Fraunhofer IWES, March 2014) [Analysis of the availability of power plant system services of a cluster based on its configuration](#), EERA-DTOC Technical Report D2.7.

Gerard Schepers, Wei He, Charlotte Bay Hasager, Mariano Faiella, Edwin Wiggelinkhuizen, Peter Stuart (February 2014), [EERA-DTOC base and near future scenario](#), EERA-DTOC Technical Reports D5.2 & 5.3.

Ana María Palomares Losada, Jorge Navarro Montesinos, Pedro Ángel Jiménez Muñoz, Elena Cantero Nouqueret, Javier Sanz Rodrigo, Giorgos Sieros, Peter Stuart, Tom Young, , Matthias Waechter, Allan Morales, Patrick Milan, Pierre-Elouan Réthoré, Charlotte Bay Hasager (August 2013), [Report on procedures and code integration on the estimation of expected net energy yield and its associated uncertainty ranges for offshore wind farms and wind farm clusters](#), EERA-DTOC Technical Report D3.2.

Nicolaos A. Cutululis, Luis Mariano Faiella, Scott Otterson, Braulio Barahona, Jan Dobschinski (August 2013), [Report on design tool on variability and predictability](#), EERA-DTOC Technical Report D2.8.

Jake Badger, Pedro Angel Jimenez Muñoz, Pedro Miguel Fernandes Correia, Sergio Lozano Galiana, Patrick Volker, John Prospathopoulos, Alexis Mouche, Merete Badger, Gerard Schepers, Ana Maria Palomares Losada, Jorge Navarro Montesinos, Ivan Moya Mallafre, Kurt Hansen, Charlotte Bay Hasager (August 2013), [Benchmark report on wake models at the cluster scale](#), EERA-DTOC Technical Report D1.4.

John Prospathopoulos, Jake Badger, Patrick Volker, George Sieros, Panagiotis Chaviaropoulos, Pierre-Elouan Rethoré (July 2013), [Physical scale integration \(coupled use\)](#), EERA-DTOC Technical Report D1.2.

Elena Cantero Nouqueret, Javier Sanz Rodrigo, Sergio Lozano Galiana, Pedro Miguel Fernandes Correia, Giorgos Sieros, Peter Stuart, Tom Young, Ana María Palomares Losada, Jorge Navarro Montesinos, Pedro Ángel Jiménez Muñoz, Matthias Waechter, Allan Morales, Patrick Milan, Charlotte Bay Hasager, Pierre-Elouan Réthoré, Gerard Schepers (July 2013), [Report on procedure for the estimation of expected net energy yield and its associated uncertainty ranges for offshore wind farms and Wind farm clusters](#), EERA-DTOC Technical Report D3.1.

P.-E. Réthoré, K.S. Hansen, R.J. Barthelmie, S.C. Pryor, G. Sieros, J. Prospathopoulos, J.M.L.M. Palma, V.C. Gomes, G. Schepers, P. Stuart, T. Young, J.S. Rodrigo, G.C. Larsen, T.J. Larsen, S. Ott, O. Rathmann, A. Peña, M. Gaumond and C. B. Hasager (June 2013), [Benchmark report on wake models at the wind farm scale](#), EERA-DTOC Technical Report D1.3.

Harald G. Svendsen (SINTEF Energy Research, February 2013), [Report on tools and results from a case study](#), EERA-DTOC Technical Report D2.3.

Atsede G. Endegnanew, Harald G. Svendsen, Raymundo E. Torres-Olguin (SINTEF Energy Research, Trondheim); Luis Mariano Faiella (Fraunhofer IWES, Kassel, January 2013), [Design procedure for inter-array electric design](#), EERA-DTOC Technical Report D2.2.

Peter Stuart, Gregor Giebel, Charlotte Bay Hasager (June 2012), [EERA-DTOC user requirements](#), EERA-DTOC Technical Report D4.1.

Olimpo Anaya-Lara, Pablo Ledesma (University of Strathclyde, December 2012), [Procedure for Verification of Grid Code Compliance](#), EERA-DTOC Technical Report D2.5.

Peña A, Réthoré P-E, Hasage, CB, Hansen KS (2013), [Results of wake simulations at the Horns Rev I and Lillgrund wind farms using the modified Park model](#). DTU Wind Energy E, no. 0026(EN), pp. 1-43.

Press

- Article in DTU Avisen, April 2014: "[Streamlining project planning of offshore wind farms](#)".
- Article in TPWind newsletter, June 2014: "[EERA-DTOC project aims to optimise offshore wind](#)".
- Article in Wind Watch, June 2014: "[Project aims to optimise offshore wind](#)".
- Article in Wind Directions, November 2013: "[Better wind resource mapping with one click](#)".
- Article in Wind Watch, February 2012: "EU project aims to help offshore wind farm design" (link not available).