Final report

1.1 Project details

Project title	EUDP 11-II,WakeBench - Benchmarking of Wind Farm Flow Models
Project identification (program abbrev. and file)	64011-0308
Name of the programme which has funded the project	EUDP 11-II
Project managing company/institution (name and address)	DTU Wind Energy
Project partners	N/A
CVR (central business register)	30 06 09 46
Date for submission	Jan 2015

1.2 Short description of project objective and results

English:
The EUDP-WakeBench project aims at supporting the participation of DTU to the IEA-Task 31: "WakeBench" and thereby investigating how to properly calibrate, validate and benchmark wind farm flow models both onshore and offshore. DTU has had a leading role on many of the activities organised within the IEA task. The main results of the project are a better understanding of how to properly compare wind farm flow models with wind farm and meteorological mast measurements. These results are important, as they can lead to a reduction of the uncertainties associated to the prediction of wind farm power production over its lifetime, and thereby a reduction of the risks and costs associated to planning wind farms.

Dansk:
EUDP-WakeBench projekt sigter mod at støtte deltagelse af DTU til IEA-task 31: "WakeBench" og dermed at undersøge, hvordan man kan bedst kalibrere, validere og benchmark vindmøllepark flow modeller både onshore og offshore. DTU har haft en fremtrædende rolle på mange af de aktiviteter der var organiseres inden for IEA-task 31. De vigtigste resultater af projektet er en bedre forståelse af, hvordan man kan korrekt sammenligne vindmøllepark flow modeller med vindmøllepark og meteorologimasten målinger. Disse resultater er vigtige, da de kan føre til en reduktion af usikkerheden forbundet til forudsigelse af vindmøllepark elproduktion i sin levetid, og dermed en reduktion af risici og omkostninger forbundet med planlægning af vindmølleparker.

1.3 Executive summary
DTU has actively participated in the IEA-Task 31 project, which was about benchmarking wind farm flow models. The goal in such a benchmarking is to assess how precise a wind farm flow model can predict the power production of a wind farm in specific wind conditions, and for the total energy production over a whole year. These types of models are typically used by wind farm planners to predict how much energy the wind farm can produce, and are therefore critical to estimate the economical viability of a wind farm project. DTU has over the years developed many different types of wind farm flow models [16]. Benchmarking

those models is critical as it gives an idea to the user how accurate the prediction of the model will be. This information can be used in the financial risk assessment of a wind farm flow models, and might actually play a key role in the realisation of the project. The IEA-Task 31 gathered participants both from the academia and the industry from all over the world. It consisted in a series of workshop during which, and in-between, test cases were organised to benchmark different types of wind farm flow models on different existing datasets.

One of the major breakthroughs of the project was when DTU understood how the uncertainty of some measurements were affecting the interpretation of the measurements, and thereby were also affecting their comparison with the models. This leaded to a series of investigations on how the measurements uncertainties propagate through the models, and how this should be taken into account in the benchmarking context. This is a critical result as it shifted the focus of the research from the purely physical modelling effort that was done until now, to an uncertainty quantification effort, of estimating the uncertainty of the inputs and outputs of the models. This is an important discovery because until now researchers were trying to improve the physics of the models without being able to prove that their improvements were actually increasing the predictive capability of their tools. This result is a stepping-stone on which the wind energy research community can further improve the wind farm flow modelling capabilities, and thereby reducing the uncertainty and risks associated to developing future wind farms.

1.4 Project objectives

The project objectives are to firstly to establish a series of international benchmarks for wind farm flow models. Secondly, to create protocols to fairly compare models and measurements together. Thirdly, to quantify the uncertainty associated to the wind farm flow models prediction using those measurements. Finally to establish guidelines on how to use the models both to participate to the benchmarks and also to predict wind farm performance under various conditions. The objectives of the project where clearly defined by the related IEA-Task, and did not change throughout the project. The deliverables of the project were identical to the IEA-Task deliverables.

1.5 Project results and dissemination of results

The project followed a cycle of design of benchmarks, benchmark runs, and discussion of benchmark results roughly every 6 months. DTU participated actively in most of the benchmarks both as a benchmark manager, reviewer and participants. The benchmarks were first distributed through emails during the first phase of the project. In the second phase of the project CENER had setup a website (i.e. windbench.net [11]) that helped centralize the benchmarking activity.

Every 6 months or so a workshop was organised in several locations in the world (one in Spain, USA, China, Germany and two in Denmark). DTU hosted two of those workshops in June 2013 and June 2014 as there was then related independent international conferences organised on Lyngby campus, where many participants of the IEA task were present. Over the course of these 3 years, this project coordinated the participation to these workshops of 6 researchers (Pierre-Elouan Réthoré, Kurt Hansen, Alferdo Pena Dias, Andreas Bechmann, Niels Sørensen and Andrey Sogachev); 5 PhD students (Paul van der Laan, Tilmann Koblitz, Tuhfe Göçmen Bozkurt, Juan Pablo Murcia and Ewan Machefaux), 1 post-doc (Søren Juhl Andersen) and 1 MSc student thesis (Mathieu Gaumont). Furthermore, the results of this project and associated IEA task were disseminated at several topically related international workshops and conferences independently organized (Torque 2012 and 2014, International Conference on aerodynamics of Offshore Wind Energy Systems and wakes 2013, The NREL Wind Energy System Engineering workshop 2013, The Wind Farm Data Management And Analysis conference 2013, the Uncertainty Quantification in Computational Fluid Dynamics Workshop 2014, And the summer school on Uncertainty Quantification 2014).

The project and IEA-task were also used as a dissemination platform to other related project, such as the EU-FP7 EERA-DTOC that had a similar benchmarking activity planned [4]. The two projects collaborated to design common benchmarks cases (e.g. the Horns Rev and Lillgrund benchmark cases [5]).

The results and deliverables of this project were also connected to the related IEA-Task. The main IEA deliverables are the benchmarking website [11], one final report [10] and two open access conference papers [1,2], that summarize the activity and results of the IEA-task 31. DTU actively contributed to write the three documents and contributed to test the website platform. The final report [10] presents in detail a model evaluation protocol for wind farm flow models. It is inspired from a similar Verification and Validation (V&V) protocol defined by the American Institute for Aerospace and Astronautics (AIAA) [12]. The two papers present the scientific results of the benchmarks in two parts, the wind flow models and the wind farm flow models.

One of the major scientific discovery of this project was that some of the measurements uncertainties were "corrupting" the comparison of the models with the measurements. In particular the wind direction uncertainty was found to have a dramatic effect on how the measurements should be interpreted. Until this discovery this uncertainty had been disregarded, and the results of the wind farm flow models were directly compared with the wind farm power measurements. This leaded to misleading results were the models result appeared to underpredict the power performance of the wind farms. For many years research was then focused on trying to increase the physical realism of the wind farm flow models to try to capture this effect. Our discovery showed that by propagating the uncertainty of the measured wind direction through the models to its power estimate, we were able to obtain similar results as the power measurements. This is a major step forward to understand how to accurately predict wind farm performance, and to be able to benchmark, validate and estimate the uncertainty of wind farm flow models. This major finding was presented in several international conferences and workshops and was published in a scientific journal in open access [6].

The following sub-sections are extracts from the major deliverables of this project, summarizing their topic of discussion:

1.5.1 Executive summary from "WAKEBENCH Model Evaluation Protocol for Wind Farm Flow Models" [11]

"Wakebench" was initiated in 2011 to establish an international forum for networking and research collaboration in the field of wind farm flow modeling. The objective is to gather industrial, governmental and academic partners to develop and define quality-check procedures, as well as to improve atmospheric boundary layer and wind turbine wake models for use in wind energy. The working methodology is based on collaborative model intercomparison benchmarking of atmospheric boundary layer (ABL) and wake models, in order to identify and quantify best practices for using these models under a range of operational conditions, both onshore and offshore, from flat to very complex terrain.
A model evaluation protocol (MEP) is developed as basis for a framework considered by the wind community as mutual reference for activities related to verification and validation. The MEP is integrated on a web-based portal for model benchmarking (www.windbench.net), which contains a repository of test cases, an inventory of models and a set of online tools for peer reviewing, discussion and reporting.
While the scope is focused on microscale wind farm flow models, the protocol can be applied, to a large extend, to other types of models. Indeed, validation follows the building-block approach that was originally developed for generic computational fluid dynamic models 0. This methodology analyzes a complex system, consisting in this case of a wind farm layout and the corresponding siting and environmental conditions, by subdividing it into subsystems and unit problems to form a hierarchy of benchmarks with a systematic increase of complexity 0. This allows isolating individual or combined elements of the model-chain to evaluate the potential impact on the full system performance. The process typically imply analyzing idealized conditions using theoretical approaches, parametric testing in control environment with scaled-down models in wind tunnels and field testing of scaled or full-scale prototypes in research conditions as well as operational units in industrial conditions. This incremental physical complexity is typically associated with decreasing levels of data quality and resolution because of practical as well as economical limitations. Hence, an important part of the

protocol is dedicated to defining procedures for the generation of these validation datasets, to make sure they are of sufficient quality and consistency with the target models to allow a fair evaluation. Some examples of model evaluation have been included based on results from Wakebench benchmarks.
Another essential aspect of the evaluation process is the definition of fit-to-purpose metrics to assess the performance of models on variables of interest for the target application. This allows going beyond the graphical visualization of model performance to actually quantifying it and determining if minimum quality acceptance criteria are met considering the intended uses of the model.
A chapter on data provision and licensing procedures is also included as part of the data management that deals with different levels of accessibility from public to fully private data. Following open-access philosophy, a benchmark process is proposed that progressively facilitate data transfer from research and industry to the public domain.
A best-practice guidelines report is released together with this protocol, as technical annex for those topics of the protocol that deserve more room and with especial focus on the standardization of flow modeling and evaluation methodologies.
This document is referenced as 1st edition because the intention is to update it in the future as the scientific scope is extended to other neighboring models, as well as to further validation and uncertainty quantification procedures.

1.5.2 Abstract of "IEA-Task 31 WAKEBENCH: Towards a protocol for wind farm flow model evaluation. Part 1: Flow-over-terrain models" [2]

The IEA Task 31 Wakebench is setting up a framework for the evaluation of wind farm flow models operating at microscale level. The framework consists on a model evaluation protocol integrated on a web-based portal for model benchmarking (www.windbench.net). This paper provides an overview of the building-block validation approach applied to flow-over-terrain models, including best practices for the benchmarking and data processing procedures for the analysis and qualification of validation datasets from wind resource assessment campaigns.
A hierarchy of test cases has been proposed for flow-over-terrain model evaluation, from Monin-Obukhov similarity theory for verification of surface-layer properties, to the Leipzig profile for the near-neutral atmospheric boundary layer, to flow over isolated hills (Askervein and Bolund) to flow over mountaneous complex terrain (Alaiz). A summary of results from the first benchmarks are used to illustrate the model evaluation protocol applied to flow-over-terrain modeling in neutral conditions.

1.5.3 Abstract of "IEA-Task 31 WAKEBENCH: Towards a protocol for wind farm flow model evaluation. Part 2: Wind farm wake models" [3]

Researchers within the International Energy Agency (IEA) Task 31: Wakebench have created a framework for the evaluation of wind farm flow models operating at the microscale level. The framework consists of a model evaluation protocol integrated with a web-based portal for model benchmarking (www.windbench.net). This paper provides an overview of the building-block validation approach applied to wind farm wake models, including best practices for the benchmarking and data processing procedures for validation datasets from wind farm SCADA and meteorological databases. A hierarchy of test cases has been proposed for wake model evaluation, from similarity theory of the axisymmetric wake and idealized infinite wind farm, to single-wake wind tunnel (UMN-EPFL) and field experiments (Sexbierum), to wind farm arrays in offshore (Horns Rev, Lillgrund) and complex terrain conditions (San Gregorio). A summary of results from the axisymmetric wake, Sexbierum, Horns Rev and Lillgrund benchmarks are used to discuss the state-of-the-art of wake model validation and highlight the most relevant issues for future development.

1.5.4 Abstract of "Wake Modelling and Review of Wind Turbine Wake Models Developed in Technical University of Denmark, DTU" [13]

Wind turbine wakes are one of the most important concepts in the wind farm aerodynamics since they decrease the power production and increase the loading towards downstream. Their physical importance imposes the necessity of having a 'good' wake model to properly develop wind power plant-level control strategies, predict the performance and understand the fatigue loads. In this report, five of the widely used wake models (N.O. Jensen, G.C. Larsen, Dynamic Wake Meandering, Fuga and Ellipsys 3D LES and RANS) that were developed in Technical University if Denmark, DTU, is described. In order to understand the idea behind each model, the progress of wake modelling has been analyzed in terms of its sub-components providing a wider range of understanding. The models are analyzed and compared using Sexbierum wind farm (onshore) and Lillgrund (offshore) cases to identify the target of their application.

1.5.5 Abstract of "Evaluation of the wind direction uncertainty and its impact on wake modeling at the Horns Rev offshore wind farm" [6]

Accurately quantifying wind turbine wakes is a key aspect of wind farm economics in large wind farms. This paper introduces a new simulation post-processing method to address the wind direction uncertainty present in the measurements of the Horns Rev offshore wind farm. This new technique replaces the traditional simulations performed with the 10 min average wind direction by a weighted average of several simulations covering a wide span of directions. The weights are based on a normal distribution to account for the uncertainty from the yaw misalignment of the reference turbine, the spatial variability of the wind direction inside the wind farm and the variability of the wind direction within the averaging period. The results show that the technique corrects the predictions of the models when the simulations and data are averaged over narrow wind direction sectors. In addition, the agreement of the shape of the power deficit in a single wake situation is improved. The robustness of the method is verified using the Jensen model, the Larsen model and Fuga, which are three different engineering wake models. The results indicate that the discrepancies between the traditional numerical simulations and power production data for narrow wind direction sectors are not caused by an inherent inaccuracy of the current wake models, but rather by the large wind direction uncertainty included in the dataset. The technique can potentially improve wind farm control algorithms and layout optimization because both applications require accurate wake predictions for narrow wind direction sectors.

1.6 Utilization of project results

The project results are already utilised now, as we now have an increased confidence in the wind farm flow models. Several associated publications have started to use the methodology defined within this project to benchmarks the wind farm flow models and validate their use [7, 8].

Also, some of the issues related to the uncertainty propagation of wind direction are already included in software packages such as FUGA, which is already in used by the wind industry to design the future wind farms.

Furthermore, the realization of the importance of uncertainty quantification in the benchmarking and validation of wind farm flow models has sparked a departmental wide interest, were many different similar initiatives have arised. Such as the recent Forskel project RUNE, that aims at investigating the uncertainty of wind ressource estimation in near shore regions; or the EUDP project Online WASP that also include some dimensions of uncertainty quantification of wind ressource estimation.

In a similar context as this project, a new PhD student has been hired in another project (i.e. the Korean Topfarm project, a joint project between Denmark and Korea). His task is to continue the investigation of how to consistently quantify the uncertainty associated to wind farm flow models predictions.

1.7 Project conclusion and perspective

While this EUDP project has now been finalised, the associated IEA-Task 31 has been accepted by the IEA-ExCo for another 3 years. DTU is planning to lead one of the three work packages, on the topic of uncertainty quantification in the task extension, and will join CENER and NREL as the leading institutions of the IEA-Task. DTU will therefore apply for funding again to continue its successful participation in IEA-Task 31.

Annex

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