INTERNATIONAL ENERGY AGENCY

TASK 31
Benchmarking of wind farm flow models

Progress Report to ExCo 68
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Introduction

This progress report summarizes the status of the new IEA Task 31, approved by the ExCo66 in October 2010, and provides a draft work plan discussed during the kick-off meeting of the 5-7 October 2011.

Objectives

Task 31 aims at defining quality-checked procedures for the simulation of wind and wakes. The working methodology will be based on the benchmarking different wind and wake modeling techniques in order to identify and quantify best practices for using these models under a range of conditions. These benchmarks will involve model intercomparison versus experimental data. The best practices will cover the wide range of tools currently used by the industry and attempts to quantify the uncertainty bounds for each types of model.

The stated objectives of this task are:

- To make an inventory of state-of-the-art models for the simulation of wind and wakes for site assessment applications: inputs, model equations, outputs, etc
- To define procedures for the definition of test cases for validation purposes of wind and wake models: requirements on measurement data, filtering processes, metrics, etc
- To identify the most critical aspects of the modeling chain by quantifying the associated uncertainties: boundary conditions, turbulence model, stability, etc
- To define the range of applicability of the models under investigation: site conditions, wind regimes, wind farm size, etc
- To reach consensus on best practice guidelines for the verification and validation of wind and wake models

Members and Participants

More than 70 expressions of interest have been compiled from 17 IEA countries. The group of interest is composed of: wind energy researchers, boundary layer meteorologists, wind energy developers, wind turbine manufacturers, software developers and consultants. The participation of flow model developers and end-users from research and industry is a key aspect of the Task.

Negotiations for securing participation fees are underway with different levels of success.

- Already signed in (7): United States, Spain, Greece, Canada, Italy, Japan, Denmark
- Under negotiation (9): Netherlands, Finland, Norway, Switzerland, Germany, Rep. Korea, Sweden, United Kingdom, China, Ireland

Given that the Task has already been initiated with the kick-off meeting, invoices of 8500€/year will be issued to the countries that have already signed. This would correspond to a scenario of 12 participating countries for a total budget of 100k€/year. If more than 12 countries sign in during the first year, the annual fee will be lowered accordingly.

Task Structure and Organization

As agreed in ExCo66, the general management of the Task is taken care of by O.A.-CENER Javier Sanz Rodrigo. He shall also coordinate the scientific and technical aspects concerning wake-free benchmarks, while O.A.-NREL Patrick Moriarty will coordinate the wakes benchmarks.

The structure of the Task is composed of four work packages:

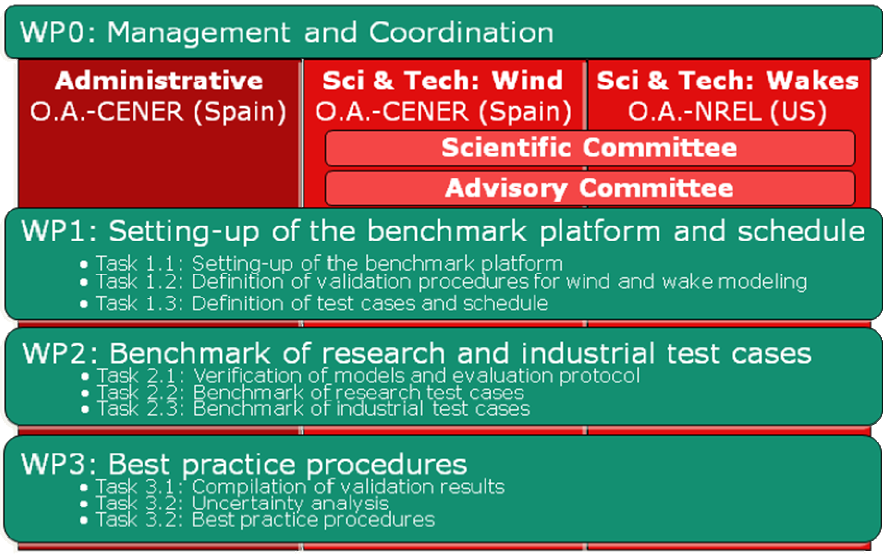

Figure 1: Structure of Wakebench IEA Task

Kick-off Meeting

The **kick-off meeting** was hosted by CENER between the 5th and the 7th of October 2011 (**T0**). The agenda and list of participants is provided in the first annex of this report.

The work plan was discussed and approved by the active participants in the kick-off meeting. In particular, the following items were discussed:

- Definition of the **Scientific Committee (SC)**, composed of experienced researchers who should provide scientific direction to the Task and act as reviewers of the benchmarks in order to ensure quality-checked results
- Definition of an **Advisory Committee (AC)**, composed of industrial partners who should monitor and provide advice the SC on the implementation of the program
- Definition of **Working Groups (WG)** around test cases and benchmarks: Up to ten WG have been identified with associated partners
- Definition of a **schedule** of benchmarks for the first year of the project (M12)
- Discussion on organizational procedures around the ***Windbench*** platform and networking activities through webinars

Windbench Platform

The *Windbench* model evaluation web platform is under construction at CENER. It will be ready by the end of 2011. The tool is based on the administration of user accounts to form groups around the virtual workspace of each benchmark. The information from the users, models, test cases and benchmarks will be compiled with standardized questionnaires approved by the SC. A user's guide was presented in the kick-off meeting. During the duration of WP1 the contents and functionalities of the platform will be iterated based on the feedback of the end-users.

Work Plan

As preparatory work before the kick-off meeting, the O.A.s circulated an **Exploratory Questionnaire** (attached in the second Annex) among the group of interest. The idea was to collect opinions about intended participation in the Task, as well as exploring the availability of potential test cases. Thirty questionnaires were received, 25 of them showing interest for active participation in benchmarks distributed in working groups (Table 1).

Table 1: Interested participants per working group

Working Group		Interest (#/25)
1	Flow over flat terrain	13
2	Flow over hills in wind tunnel	5
3	Flow over hills in the field	9
4	Flow in and above forest canopies	7
5	Flow over Mountains	9
6	WT Wakes. Theoretical verification	12
7	WT Wakes. Wind tunnel experiments	11
8	Small wind farms / Individual WT	15
9	Large wind farms	16

An additional WG was proposed during the meeting on "Requirements for Validation Experiments". The objectives of WG10 would be to develop the criteria required for the inclusion of an experimental dataset into the benchmarking database, model evaluation methodology and the definition of the needs of future experimental test cases to make a more complete benchmark approach. In principle, but not exclusively, the new test cases will be based on wind tunnel experiments upon request of the Wakebench network.

Within each WG new test cases have been proposed and have been included in the test case survey. The schedule of benchmarks will be planned on a 6-monthly basis corresponding to the frequency of progress (ExCo) meetings. Initial benchmarks have been selected for the first semester (Table 2). These benchmarks will initiate discussions in each WG and will allow participants to get acquainted with the use of the Windbench platform.

Table 2: List of initial benchmarks per working group

WG	Test Case	Benchmarks due in M8
1	Monin-Obukhov	Quasy-steady surface layer profiles at different stabilities
	Leipzig	Quasy-steady ABL in neutral conditions
2	POSTECH 2D hills	Isolated 2D hills with and without flow separation
	POSTECH 2D hills	Hill-hill interaction using the same hill geometries of previous
3	Askervein	Askervein 210. Isolated hill, historical reference
	Askervein	Askervein different wind directions
	Bolund	Revisit blind test simulations, now calibration is allowed
4	CSIRO homogeneous forest	1D profile in and above modelled forest canopy
	CSIRO 2D Furry hill	Isolated 2D hill covered by modelled forest canopy
	Bradley's roughness change	Smooth <--> Rough transition in the field
6	Theory	Self-similar turbulent circular wake (possibly with swirl)
	Theory	Infinite wind farm
7	University of Minnesota	Single or multiple turbines with different stability
8	Sexbierum	Single WT in flat terrain and neutral atmosphere
9	Lillgrund	Offshore, 48x2.3MW, 3.3Dx4.3D, gap in the middle

Actions due in M6

In brief, the following list of actions have been identified for the initial semester of the IEA Task 31.

- Assign roles: SC members, AC members, Test Case Managers (TCM) and Benchmark Managers (BM) for the initial benchmarks
- Definition of WGs and organization of initial WG meetings
- Review list of test cases and benchmarks
- Identify missing experiments to be considered within WG10 for wind tunnel data and to guide the call for test cases from industry
- Initiate discussion on the "Model Evaluation Protocol for Wind Farm Modeling" deliverable
- Resolve IP issues in test cases data
- Windbench up and running with uploaded information for the initial benchmarks
- Setting up of communication and dissemination strategy: webinars, Linkedin network, Task webpage, dissemination events.

Chronogram

Three workshops/annual meetings are foreseen, each one associated with specific milestones and deliverables of the Task.

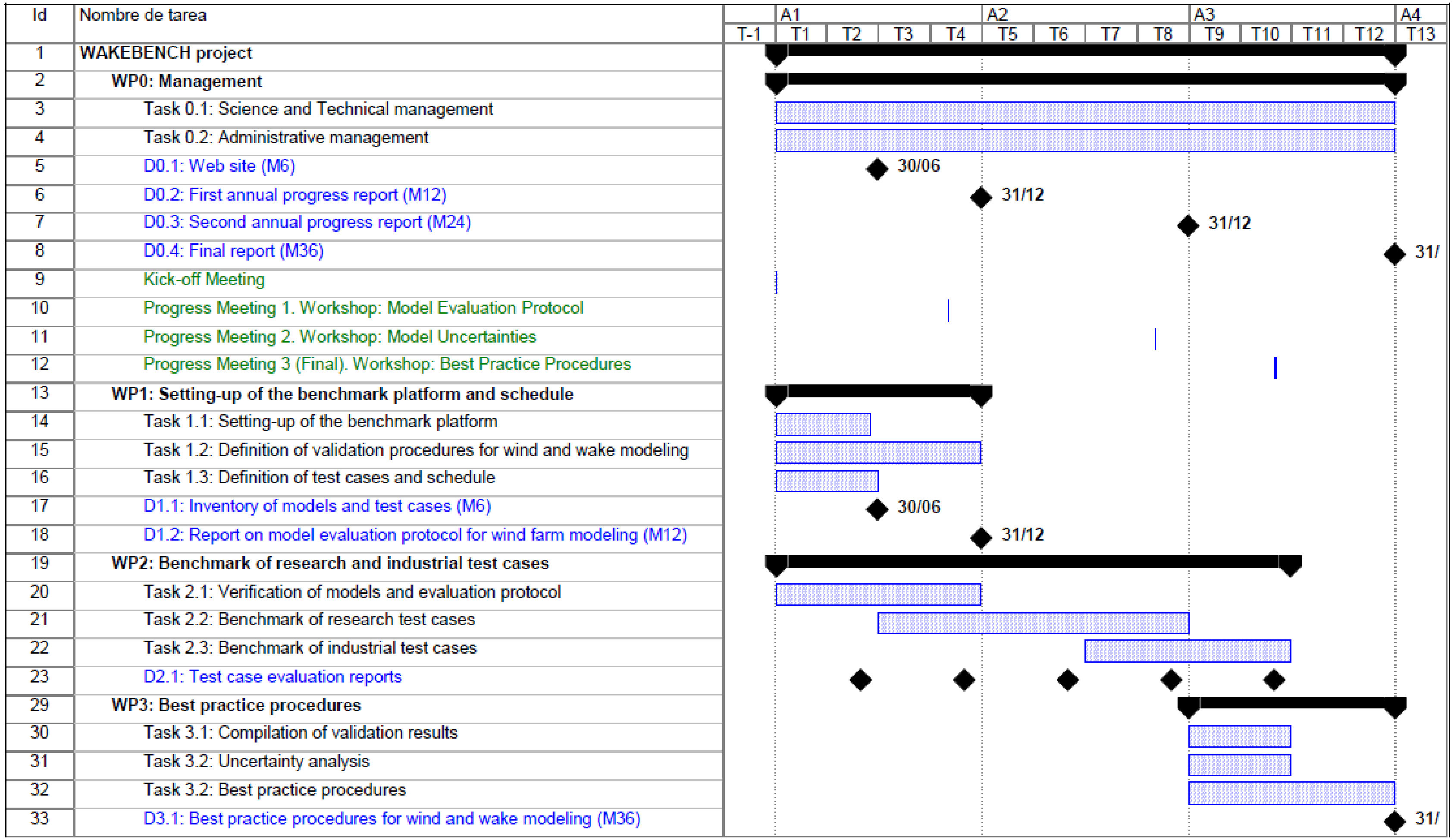

Figure 2: Gantt chart with the chronogram of the Task

Progress meetings will be held every 6 months just before the ExCo meetings. The spring meetings will be carried out using teleconferencing (webinars) to report of the progress and discuss the results of ongoing benchmarks. Autumn meetings, in person, will be used to discuss key aspects of the Task in a workshop format:

- Kick-off: state-of-the-art and work plan definition (M0, CENER, Pamplona, Spain)
- Workshop on model evaluation protocol (M12, NREL, Colorado, US)
- Workshop on model uncertainties (M24, venue to be defined)
- Workshop on best practice procedures (M33, venue to be defined)

Reports and Deliverables

Annual progress reports will give an overview of the follow-up of the project. Within each Work Package a number of deliverables will be elaborated in order to summarize the most important results. These reports/deliverables will be composed by the Operating Agents based on the inputs and reviews from the Participants. The planned deliverables are given in Table 3.

Table 3: Planned deliverables and milestones

	WP	Deliverable	Due Month
D0.1	0	Web site	M6
D0.2	0	First annual progress report	M12
D0.3	0	Second annual progress report	M24
D0.4	0	Final report	M36
D1.1	1	Inventory of models and test cases	M6
D1.2	1	Report on model evaluation protocol for wind farm modeling	M12
D2.1	2	Test cases reports	M6-M30
D3.1	3	Best practice procedures for wind and wake modeling	M36

Methods of Review and Evaluation of the Work Progress

The following key milestones are defined for the follow-up of the progress of the project.

Table 4: List of milestones

	WP	Deliverable	Outcome	Month
M0.1	0	Kick-off Meeting	Confirmation of the consortium and validation of the work programme	M1
M0.2	0	Web-page operational	Website of the project (D0.1)	M6
M1.1	1	Benchmark web platform operational	Initial test cases implemented	M6
M0.2	0	1st Progress Meeting	Workshop on evaluation protocol. Planning of test cases	M11
M1.2	1	Evaluation protocol defined	Protocol report	M12
M0.3	0	2nd Progress Meeting	Workshop on research test cases. Evaluation of uncertainties. Planning of test cases.	M23
M0.4	0	Final Meeting	Workshop on industrial test cases. Best Practice Procedures	M30

Annex 1: Kick-off meeting Agenda and List of Participants

Wednesday 5 October 2011			
9.00-9.30		Registration	
9.30-11.00		Overview of Wakebench	J.Sanz Rodrigo, CENER, Spain; P. Moriarty, NREL, US
11.00-11:20		Coffee break	
11.20-13.00		Technical Presentations 1	
	20'	Quality assurance of wind assessment microscale models	H. Holmes, UniHH-ZMAW, Germany
	20'	Modeling of rotor aerodynamics and forested regions at ETS, Canada	C. Masson, ETSMTL, Canada
	20'	Considerations on CFD computations	Claude Abiven, Natural Power, UK
	20'	CFD Wind and Wake flows in complex terrain and offshore	D. Cabezón, CENER, Spain
	20'	Wind simulation in Japan	I. Makoto, UniTokio-RCAST, Japan
13.00-14.00		Lunch break	
14.00-15.40		Technical Presentations 2	
	20'	Use of actuator disc model for wake calculation	F. Castellani, UNIPG, Italy
	20'	Overview of wake models at Risø-DTU	A. Bechmann, Risø-DTU, Denmark
	20'	Overview of wind and wake models at INSEAN	L. Greco, INSEAN, Italy
	20'	Overview of wake models at WERC	C. Gundling, UW-WERC, United States
	20'	Overview of wake models at NREL	P. Moriarty, NREL, United States
15.40-16.00		Coffee break	
16.00-17.40		Technical Presentations 3	
	20'	A parabolic model to simulate multiple wind turbine wake interaction and meandering e	A. Crespo, UPM, Spain
	20'	LES actuator line simulations of wakes and wind farms	J.N. Sørensen, MEK-DTU, Denmark
	20'	LES model adapted for the simulation of the flow conditions in the offshore test site alph	G. Steinfeld, ForWind, Germany
	20'	Wake projects in the Nordic Consortium; optimization of large wind farms	S. Ivanell, GHO, Sweden
	20'	Validation of LES wake models using wind tunnel data	Yu-Ting Wu, EPFL, Switzerland
20.30-23.30		Dinner	

Thursday 6 October 2011			
9.00-10.20		Windbench: a web-based tool for the management of model validation benchmarks	J. Sanz Rodrigo (CENER)
10.20-10.40		Missing validation experiments and instrumentation needs	J. Naughton, UW-WERC, United States
10.40-11.00		Coffee break	
11.00-13.00		Workshop: Test Cases and Working Groups for ABL	J. Sanz Rodrigo (CENER)
	30'	Overview of Riso-DTU's non-wake test cases	A. Bechmann, Risø-DTU, Denmark
		Discussion	J. Sanz Rodrigo (CENER)
13.00-14.00		Lunch break	
14.00-15.40		Workshop: Test Cases and Working Groups for wakes	
	20'	Generation of validation data from wind tunnel experiments and Lidar field tests	V. Lungo, EPFL, Switzerland
	30'	Measurement of speed deficit and turbulence in wind turbine wakes in the field	K.S. Hansen, MEK-DTU, Denmark
		Proposals from industry (Please bring a short description of your potential test cases)	L. Terzi, Sorgenia, Italy
		Discussion	P. Moriarty (NREL)
15.40-16.00		Coffee break	
16.00-17.00		Workshop continues	
17.00-17.30		Conclusions: Work programme	J. Sanz Rodrigo (CENER), P. Moriarty (NREL)

Friday 7 October 2011	
9.30-13.00	Visit to Alaiz Test Site

WAKEBENCH kick-off meeting			October 2011			
List of Participants			Wednesday 5		Thursday 6	Friday 7
			9:00 - 18:00	20:30 Dinner	9:00 - 18:00	9:00 - 13:00 Alaiz
Christian Masson	ETS - Montreal University	Canada	OK	OK	OK	
Shiu Yeung Hui	DONG Energy	Denmark	OK	OK	OK	OK
Kurt S. Hansen	DTU-MEK	Denmark	OK	OK	OK	OK
Jens N. Sorensen	DTU-MEK	Denmark	OK	OK	OK	
Charlotte Hasager	Riso-DTU	Denmark	OK	OK	OK	OK
Andreas Bechmann	Riso-DTU	Denmark	OK	OK	OK	OK
Jens Madsen	Vattenfall	Denmark	OK	OK	OK	OK
Jeroen Dillingh	VTT	Finland	OK	OK	OK	OK
Claude Abiven	Natural Power	France	OK	OK	OK	OK
Sandrine Aubrun-Sanches	Orleans University	France				
Herbert Schwartz	Anemos-Jacob	Germany	OK	OK	OK	OK
Beatriz Canadillas	DEWI	Germany	OK	OK	OK	OK
Gerald Steinfeld	ForWind	Germany	OK	OK	OK	OK
Heather Holmes	Hamburg University - ZMAW	Germany	OK	OK	OK	OK
John Prospathopoulos	CRES	Greece	OK	OK	OK	OK
Brian Hurley	Wind Site Evaluation	Ireland	OK	OK	OK	OK
Luca Greco	CNR-INSEAN	Italy	OK	OK	OK	OK
Stefano Zaghi	CNR-INSEAN	Italy	OK	OK	OK	OK
Ludovico Terzi	Sorgenia	Italy	OK	OK	OK	OK
Massimiliano Burlando	University of Genoa	Italy	OK	OK	OK	OK
Francesco Castellani	University of Perugia	Italy	OK	OK	OK	OK
Makoto IIDA	University of Tokyo	Japan	OK		OK	OK
Peter Eecen	ECN	Netherlands			OK	
Lorenzo Lignarolo	Technical University of Delft	Netherlands	OK	OK	OK	OK
Lene Sælen	GexCon	Norway	OK	OK	OK	
Arne R. Gravdahl	Windsim	Norway	OK	OK	OK	OK
Jose Laginha Palma	Porto University	Portugal	OK	OK	OK	OK
Vitor Costa Gomes	Porto University	Portugal	OK	OK	OK	OK
Miguel Marques	INEGI	Portugal	OK	OK	OK	OK
Mikel Illarregi	Acciona	Spain	OK		OK	OK
Julián Alberdi	Acciona	Spain	OK		OK	OK
Daniel Ortiz	Barlovento Recursos Naturales	Spain	OK		OK	
Anselmo Barrios	Barlovento Recursos Naturales	Spain	OK		OK	
Javier Sanz Rodrigo	CENER	Spain	OK	OK	OK	OK
Daniel Cabezón	CENER	Spain	OK	OK	OK	OK
Ignacio Martí	CENER	Spain	OK			
Raquel Izuriaga	CENER	Spain	OK		OK	OK
José Maza	Enel Green Power	Spain	OK	OK	OK	OK
José Manuel Ramírez	Gamesa	Spain	OK	OK	OK	OK
Alejandro Abascal	Iberdrola Renovables	Spain	OK	OK	OK	
Jon López de Maturana	Suzlon Spain	Spain	OK		OK	OK
Antonio Crespo Martínez	Universidad Politécnica de Madrid	Spain	OK	OK	OK	
Miriam Marchante	Vestas Mediterranean	Spain	OK	OK	OK	
Stefan Ivanell	Gotland University	Sweden	OK	OK	OK	OK
Valerio Iungo	EPFL	Switzerland	OK	OK	OK	OK
Yu-Ting Wu	EPFL	Switzerland	OK	OK	OK	OK
Simon J. Watson	Loughborough University	United Kingdom	OK	OK	OK	OK
Holly Hughes	DNV Renewables	United States	OK	OK	OK	
Justin Wolfe	E.ON	United States	OK	OK	OK	OK
Rebecca Barthelmie	Indiana University	United States				
Pat Moriarty	NREL	United States	OK	OK	OK	OK
Raul Bayoan Cal	Portland State University	United States	OK	OK	OK	OK
Leo P. Chamorro	University of Minnesota	United States				
Jonathan W. Naughton	University of Wyoming - WERC	United States	OK	OK	OK	OK
Chris H. Gundling	University of Wyoming - WERC	United States	OK	OK	OK	OK
		TOTAL	**51**	**43**	**51**	**41**

Annex 2: Exploratory Questionnaire

IEA Task 31 WAKEBENCH
Exploratory Questionnaire

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Abstract This questionnaire is addressed to potential participants of the new IEA Task 31 WAKEBENCH. The information requested will allow an initial profile of the participants, their priorities and their future involvement in the Task.

1. Introduction

WAKEBENCH is a new IEA Task on Benchmarking of Wind Farm Flow Models, which aims at defining quality-checked procedures for the simulation of wind and wakes. The working methodology will be based on the benchmarking of different wind and wake modeling techniques in order to identify and quantify best practices for using these models under a range of conditions. These benchmarks will involve model intercomparison versus experimental data. The best practices will cover the wide range of tools currently used by the industry and attempts to quantify the uncertainty bounds for each type of model.

A questionnaire is addressed to interested participants in order to configure a draft work plan which will be discussed during the kick off meeting: 5-7 October 2011, Pamplona (Spain).

2. Objectives

The objectives of the questionnaire are:

- Define the profile of the network
- Assess the adequacy of the proposed research strategy
- Identify the individual priorities of the participants
- Survey the models available within the network
- Identify test cases needs

3. Methodology

The methodology of the questionnaire is mostly based on multiple-choice questions in order to simplify the analysis. Please don't hesitate to extend your answers further whenever necessary by filling up the "Please specify..." fields.

Please fill in the questionnaire and send it back to jsrodrigo@cener.com and Patrick.Moriarty@nrel.gov no later than the **21st of September 2011**.

4. Participants

The questionnaire is distributed to all the persons that expressed interest in participation in the Task. Not filling out this questionnaire will mean that the interest is merely informative and no active participation is sought.

5. Questionnaire

Your profile….

Considering the working conditions of IEA Tasks, it is important that from the very beginning we are able to assess the available resources within the network and the level of commitment of the different participants.

The roles within the network can be easily divided in two categories: model developer and end-user. While the model developer would be generally more interested in analyzing individual aspects of the model chain in detail with dedicated experiments, the end-user will be more interested in participating in test cases with a more practical orientation on sites that represent more closely their daily activities. These two levels of participation correspond to the classification of research and industrial test cases.

Even though the separation is well recognized by the different players, it is highly recommended that some overlap is done between the two groups. This is especially important for the end-users to develop a more comprehensive approach to future advanced use of their models. Participating in benchmarks on research test cases together with model developers will allow end-users to understand better the possibilities and limitations of their models. On the other hand, model developers can receive first-hand feedback from the user and assess user-dependencies (i.e. robustness) of the model by accompanying end-users from research to industrial test cases.

If the interaction between model developers and end-users is sufficiently developed, it should be easier to reach consensus on the definition of the best practice guidelines for the use of wind farm models, which is the main deliverable of the Task. An essential aspect in this process will be the objective evaluation of the benchmark setting up and model intercomparison results. This is taken care of by the *Scientific Committee* (SC), a group of experts with sufficient experience to judge the appropriateness of each benchmark and the quality of the results versus the intended use of the models. The SC will be responsible for the drafting of the Task deliverables, making use of the results of the different benchmarks.

Each test case will produce a number of benchmarks that will be managed online in the *Windbench* validation web platform by a *Test Case Manager* (TCM) under the supervision of two representatives of the SC. The SC will make sure that the benchmark is documented with all the required information that would be generally requested in a journal paper. The contents of this quality control is a fundamental aspect of the model evaluation protocol developed in the first phase of the project.

1. What is the main activity of your organization related to the scope of Wakebench?

   ☐ Wind energy developer
   ☐ Wind turbine manufacturer
   ☐ Consultant
   ☐ Researcher
   ☐ Other. Please specify...

2. How many years of experience do you have as...

   Model developer: years
   Model user: years

3. Explain why the Wakebench Task is important for your organization

   Please specify...

4. How would you describe your intended participation in Wakebench? Please select all that apply.

☐ I want to be informed about the progress of the Task
☐ I want to participate as stakeholder in progress meetings in order to give my opinion about the progress of the project
☐ I want to participate as test case manager, providing test case data and managing the progress of the benchmarks associated to the test case(s)
☐ I want to provide test case data but I'd rather leave the management of the benchmarks to a delegate within the network (by default, the Operating Agent)
☐ I want to participate in model intercomparison benchmarks by running simulations with my model(s) and participating in the evaluation and reporting of the results
☐ I want to participate in the Scientific Committee acting as reviewer of the benchmarks and participating in the drafting of the Task deliverables
☐ Other. Please specify...

Your models….

The Task is primarily concerned with models that are able to simulate the flow field within a wind farm, i.e. the most relevant spatial and temporal scales range from meters to kilometers and from seconds to minutes. Hence, from the meteorological perspective, the modelling scope can be categorized within the microscale range. At this level, the application of the models is focused on wind farm energy yield and site assessment where the main output variables are: the wake-free mean wind speed and turbulence intensity, the gross energy yield, the mean wind shear, the added turbulence intensity and the wake-induced power deficit that contributes to the net energy yield.

In this context, for practical reasons, most of the microscale models are focused on simulating the mean flow field, i.e. the steady state response of the system, which is subsequently integrated with the wind climate distribution to obtain the annual energy production (AEP). Hence, from the flow model validation perspective, most of the test cases are devoted to the steady-state regime.

Concerning wake models, the interest is mostly placed on the far wake, where the most frequent wake-turbine interactions take place in a wind farm. This domain is also convenient for a simplification of the wake model which may only require as input data such as the rotor dimensions, the power curve and the thrust curve as input data, all easily accesible from the wind turbine manufacturer.

Beside the mean flow field, in site assessment it is necessary to have access to the turbulence field. Turbulence modelling is often greatly simplified in order to reduce the computational expense of wind farm models. The standard approach in CFD-based models is to rely on the Reynolds Averaged Navier Stokes (RANS) approximation with eddy-viscosity closure of first order (k-l, k-ε,k-ω, etc), i.e. turbulence is assumed as an isotropic flow quantity.

Finally, concerning the state of the atmosphere (atmospheric stability), classical models assume neutral stratification as a fair simplification in windy sites. This simplification comes along with the limitation of limited measurements of atmospheric stability in wind assessment campaigns.

Notwithstanding the practical use of wind farm models, the Task is open to participation of more elaborated model approaches that can provide some insight into the limitations of current practices:

- From steady-state to transient regimes
- From averaged to time-resolved turbulence modelling: LES models
- From isotropic to Reynolds-stress transport modelling: RSM models
- From far wake to near wake models: BEM models

- From neutral to stratified models: stability dependent turbulence schemes
- From microscale to mesoscale models: very large wind farms

As the model chain includes less simplifications validation test cases become more demanding in terms of input and validation data. Besides computational effort, finding appropriate validation test cases constitutes the most difficult obstacle for the development of state-of-the-art wind farm models.

5. What type of models do you intend to use in the benchmarks?

Name:	Please specify...
Sofware:	Commercial, wind specific linearized model
Regime:	Steady
Turbulence closure:	RANS eddy-viscosity model
Turbulence model:	Please specify...
ABL Range:	Surface layer
Stability:	Yes
Stability model:	Please specify...
Forest:	Yes
Forest model:	Please specify...
Wakes:	Yes
Rotor model:	Actuator disk
Wake model:	Linearized (semi-empirical)
Range:	Single wake
Specific features:	Please specify...
Remarks:	Please specify...

Name:	Please specify...
Sofware:	Commercial, wind specific linearized model
Regime:	Steady
Turbulence closure:	RANS eddy-viscosity model
Turbulence model:	Please specify...
ABL Range:	Surface layer
Stability:	Yes
Stability model:	Please specify...
Forest:	Yes
Forest model:	Please specify...
Wakes:	Yes
Rotor model:	Actuator disk
Wake model:	Linearized (semi-empirical)
Range:	Single wake
Specific features:	Please specify...
Remarks:	Please specify...

6. In your opinion, what is the largest limitations of your model(s)?

   Please specify...

7. What input data is required in your model?

   Please specify...

8. How do you use onsite measurements to calibrate your model?

   Please specify...

The model validation strategy...

As baseline, a **building-block approach** will be adopted (AIAA, 1998), wherein the validation process of a complex system is divided in phases of increasing complexity. For a clear understanding of the impact that each element of the model chain has on the evaluation performance, it is essential that the system is divided as much as possible in subsystems and unit problems of simple geometry.

- Unit problems are typically studied in wind tunnels under a control environment where boundary conditions are well defined and high resolution measurements are possible with low uncertainties.
- Sub-system cases are formed based on a combination of unit problems with combined physics and more realistic geometries, still keeping reasonably good knowledge of boundary conditions and measurement uncertainties.
- The complete system constitutes the target application of the model which is typically composed of arbitrary geometry and rather limited measurements.

All the Wakebench work plan will be structured around working groups on model validation benchmarks. The objectives of the next set of questions is 1) to identify your current practices in terms of model validation 2) to identify working groups associated to the most relevant priorities and 2) to let you propose test cases that you miss in the preliminary selection made so far.

9. What validation data have you used for validation? Please specify all that apply

   ☐ I rely on my software provider to take care of model validation
   ☐ Wind tunnel experiments for model validation
   ☐ Field experiments for model validation
   ☐ Measurements from wind resource assessment campaigns
   ☐ Measurements from operational wind farms
   ☐ Other. Please specify...

10. Which type of benchmark are you interested in participating? Please specify all that apply

   ☐ I don't intend to have active participation in any model intercomparison benchmark
   ☐ Benchmarks for model verification (model to model comparison without measurements)
   ☐ Benchmarks on idealized flow conditions (academic test cases based on similarity theories)
   ☐ Benchmarks for model validation based on wind tunnel experiments (research test cases)
   ☐ Benchmarks for model validation based on field experiments (research test cases)
   ☐ Benchmarks for model validation based on operational data (industrial test cases)

11. In order to configure a draft work plan, please indicate the working groups where you would like to take part by checking the benchmarks where you would be interested in providing simulations and/or datasets. Please feel free to propose additional benchmarks not yet listed.

WG1. Quasi-steady atmospheric boundary layer in flat terrain

Objective: Reproduce quasi-steady vertical profiles of velocity and turbulence with different levels of thermal stratification

Description: The models will be tested on empty domains characterized by horizontally homogeneous surface and top boundary conditions in order to show fully developed conditions (no horizontal gradients).

Benchmarks:

- ☐ Model intercomparison of surface layer profiles for a given set of boundary conditions compared with Monin-Obukhov theory
- ☐ Høvsøre: ABL models compared with quasi-steady ensemble-averaged profiles from tall met mast in onshore conditions
- ☐ Fino1: ABL models compared with quasi-steady ensemble-averaged profiles from tall met masts in offshore conditions.
- ☐ Other. Please specify...

WG2. Flow over hills in wind tunnel

Objective: Reproduce speed-up and added turbulence effects with and without terrain induced flow separation in a control environment.

Description: Test flow models on 2D hills with well defined geometries and boundary conditions, under various slopes surface roughness and thermal stratification conditions. The models shall be run at the wind tunnel scale.

Benchmarks:

- ☐ POSTECH 2D Hills: Isolated 2D hills with and without flow separation
- ☐ POSTECH 2D Double Hills: Hill-hill interaction using the same hill geometries of previous benchmark
- ☐ EnFlo 2D Stratified Hill: Isolated 2D hills covered with roughness elements with and without flow separation in neutral and moderately stable conditions
- ☐ CSIRO 2D Furry Hill: Isolated 2D hill covered by a modelled forest canopy
- ☐ Other. Please specify...

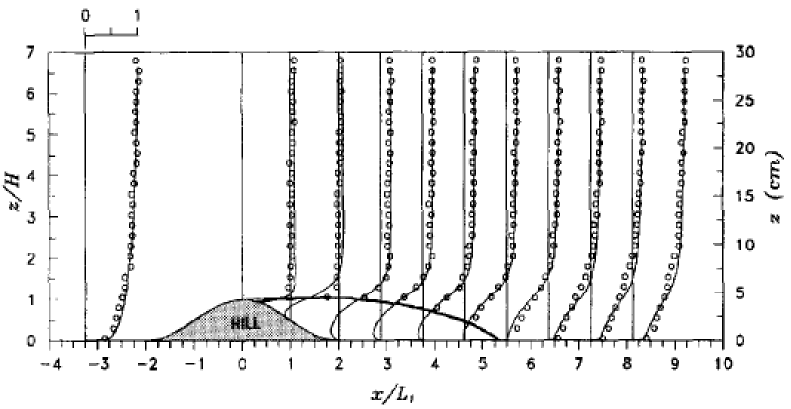

Figure 3: Isolated hill with flow separation (Kim et al., 1997)

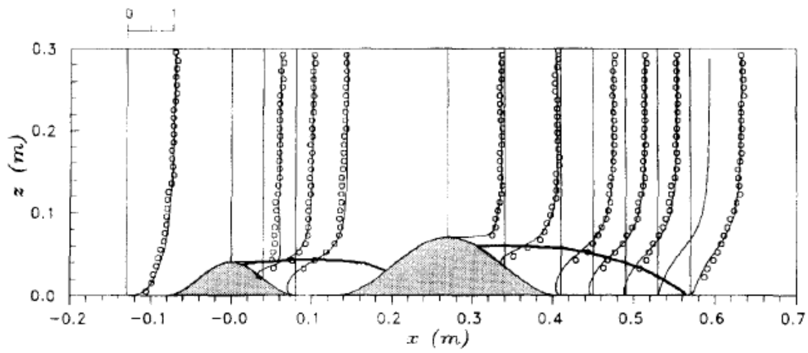

Figure 4: hill-hill interaction with flow separation (Kim et al., 1997)

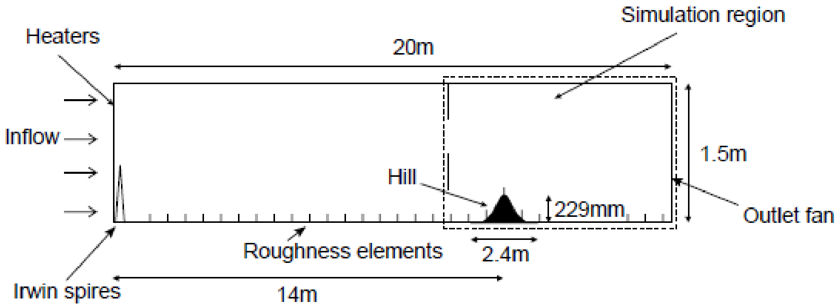

Figure 5: Wind tunnel set up for the EnFlo stratified hill experiments (Ross et al., 2004)

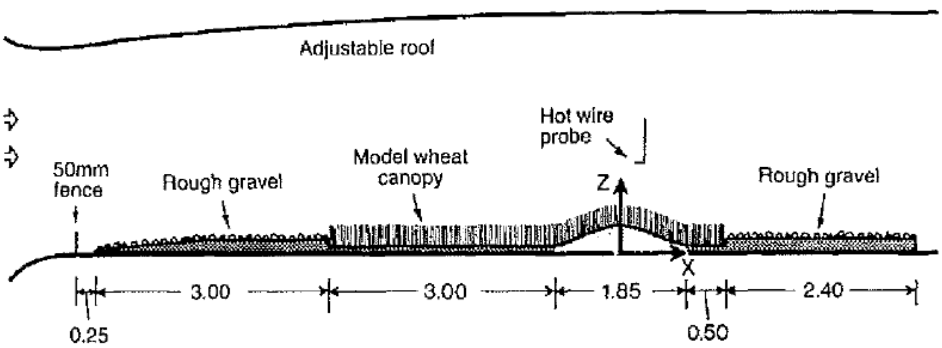

Figure 6: Wind tunnel set up for the Furry Hill experiment (Finnigan and Brunet, 1995)

WG3. Flow over hills in the field

Objective: Reproduce speed-up and added turbulence effects with and without terrain induced flow separation in field conditions

Description: The models will be tested on real hills of different terrain complexities and various stratification conditions.

Benchmarks:

- ☐ Askervein 210º: Neutral ABL perpendicular to the long axis of the hill. Well known reference for the flow-over-hills community
- ☐ Askervein different wind directions: Complement previous benchmark with other wind directions like: 180 (oblique flow), 130 (flow along the long axis) or 90 (hill upstream producing high variability, not so well defined inflow conditions though)
- ☐ Bolund: complex terrain due to escarpment. Revisit the simulations made for the 2009 blind test (four wind direction runs). This time, the validation data is known in advance
- ☐ CSIRO Cooper's Ridge: quasy-2D hill under different incoming atmospheric stratification conditions
- ☐ Other. Please specify...

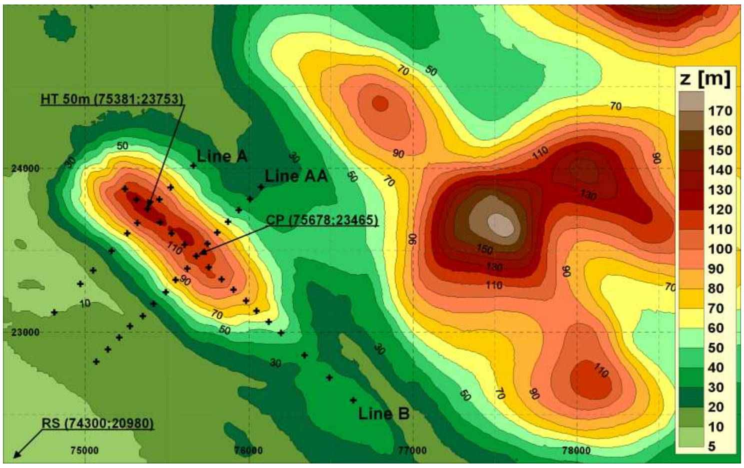

Figure 7: Askervein hill, mast layout

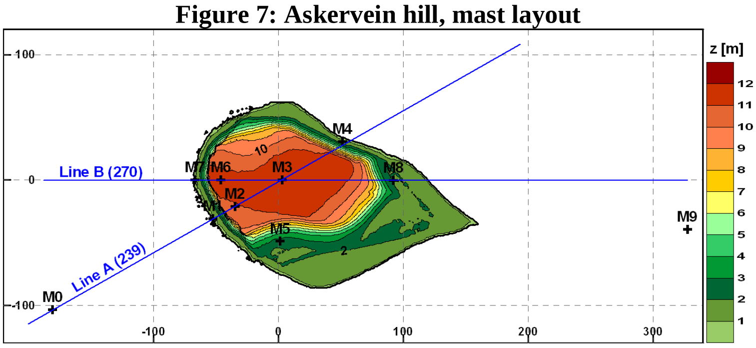

Figure 8: Bolund hill, mast layout

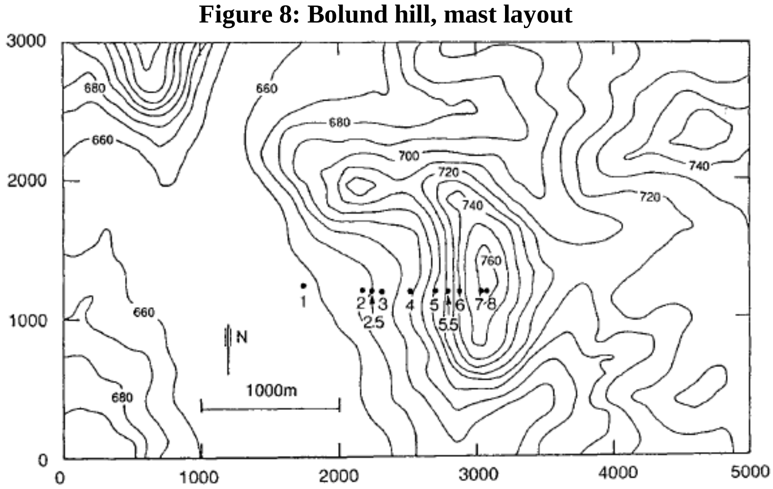

Figure 9: Cooper's Ridge, mast layout (Coppin et al., 1994)

WG4. Flow in and above forest canopies

Objective: Evaluate forest canopy models in simple terrain geometries

Description: The models will be tested using wind tunnel and field experiments in neutral and stratified atmospheric conditions.

Benchmarks:

Wind tunnel:

- ☐ CSIRO Homogeneous Forest: fully developed profile over homogeneous model of waving wheat crop (same canopy used in the Furry Hill experiment)
- ☐ VKI 2D Forest Clearing: 5h clearing inside homogeneous foam of two porosities and upstream forest fetch of 2h, 5h and 10h
- ☐ CSIRO 2D Furry Hill: Isolated 2D hill covered by a modelled forest canopy

Field:

- ☐ Bradley's Roughness Change: smooth (0.002m) <--> rough (0.25m) transition
- ☐ Falster 2D Forest Edge: vertical profiles before and after a 2D forest edge under different atmospheric stratification and leaf area density conditions
- ☐ Other. Please specify...

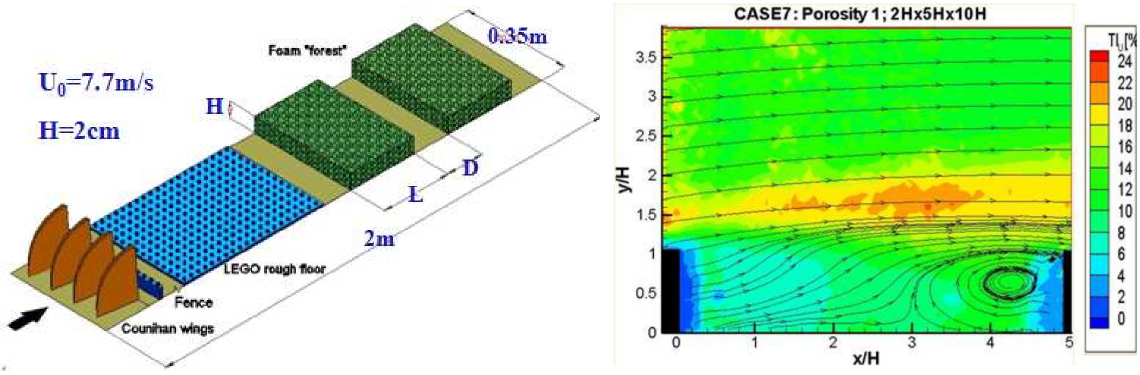

Figure 10: Forest clearing at various upstream forest porosity and fetch (Sanz Rodrigo et al., 2007)

Figure 11: Falster forest edge experiment (Bingöl et al., 2010)

WG5. Flow over mountains

Objective: Evaluate flow models over large domains, typical of wind farms sites in complex topography

Description: Evaluate different modelling criteria when approaching the simulation of a realistic site for wind farms in complex terrain. Several sensitivity tests are performed before the validation exercise (blind tests). Then, a final simulation is performed making use of the validation data to calibrate the models and optimize the performance as much as possible.

Benchmarks:

- ☐ Alaiz 345º: sensitivity tests on incoming boundary layer stratification
- ☐ Alaiz 345º: neutral, uniform roughness, sensitivity to domain dimensions
- ☐ Alaiz 345º: neutral, uniform roughness, grid dependency
- ☐ Alaiz 345º: neutral, sensitivity tests on surface roughness and forest modelling
- ☐ Alaiz 345º: neutral, sensitivity tests on wind direction variability (±15º)
- ☐ Alaiz 345º: blind test neutral and stable conditions
- ☐ Alaiz 345º: model calibration. Redo previous benchmark with a priori knowledge of validation data
- ☐ Other. Please specify...

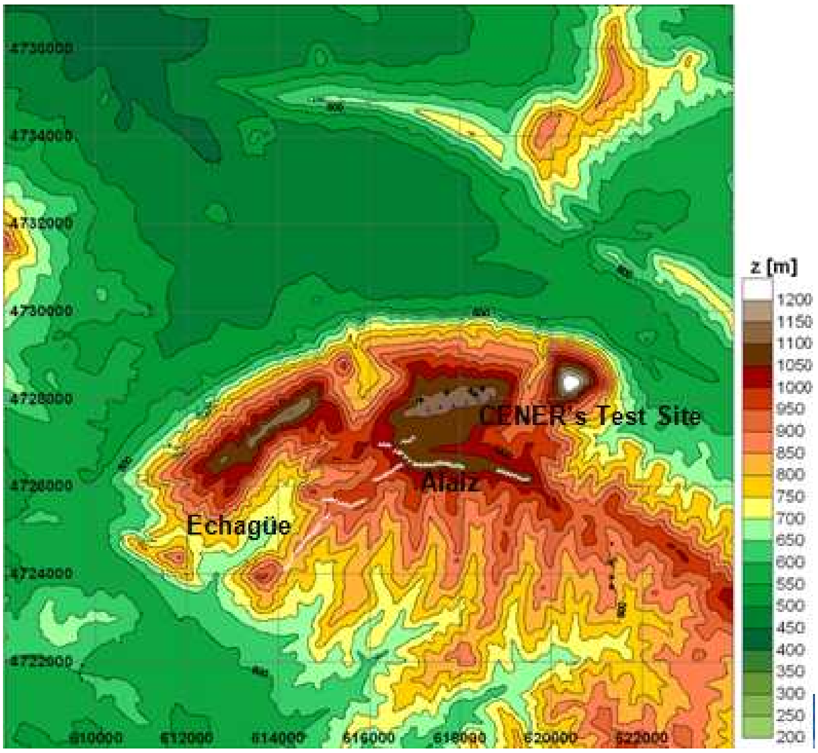

Figure 12: CENER's Test Site in Alaiz ridge, mast layout

WG6. Wind Turbine Wakes. Theoretical verification

Objective: Evaluate wake models relative to self similar and asymptotic behavior

Description: The models will be compared against fundamental self-similarity and asymptotic relationship that generally don't occur in full scale wind plants, but are useful for comparison of model physics.

Benchmarks:

☐ Self-similar Turbulent Circular Wake: Wake width and velocity deficit as a function of downstream distance for both mean velocity and turbulence quantities
☐ Infinite wind farm: determine how many rows of turbines until the power loss asymptotes to an asymptotic level for a given turbine spacing and thrust coefficient.
☐ Other. Please specify...

WG7. Wind Turbine Wakes. Wind Tunnel Experiments

Objective: Evaluate models based on wind tunnel measurements of single and multiple turbine experiments.

Description: Simulation models will be compared to highly detailed measurements of scale wind turbine model wakes that may be higher fidelity in time and space than is possible at full scale.

Benchmarks:

☐ Chalmers University: Axisymmetric wake of a behind a solid disk
☐ University of Minnesota: single or multiple turbines with different stability
☐ Johns Hopkins University: multiple turbines
☐ University of Orléans and Surrey: multiple turbines and mesh disks
☐ Other. Please specify...

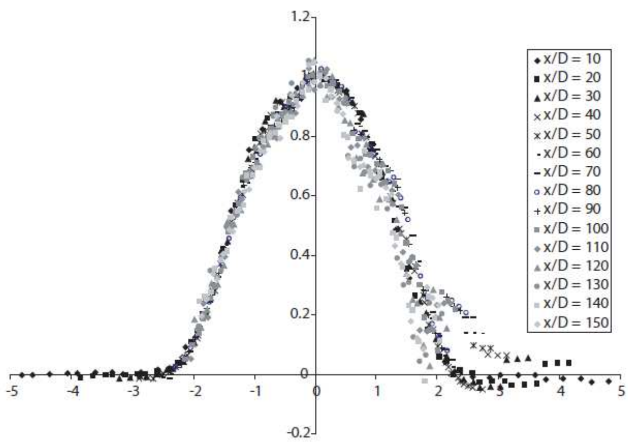

Figure 13 Normalized mean velocity profiles behind an axisymmetric wake (Johansson, 2002)

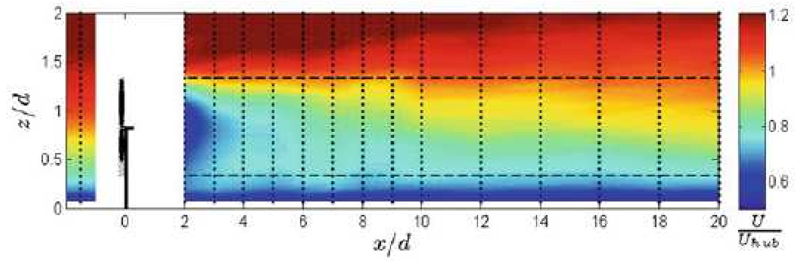

Figure 14 Mean velocity contours behind a single turbine in stable boundary layer (Chamorro and Porté-Agel, 2010)

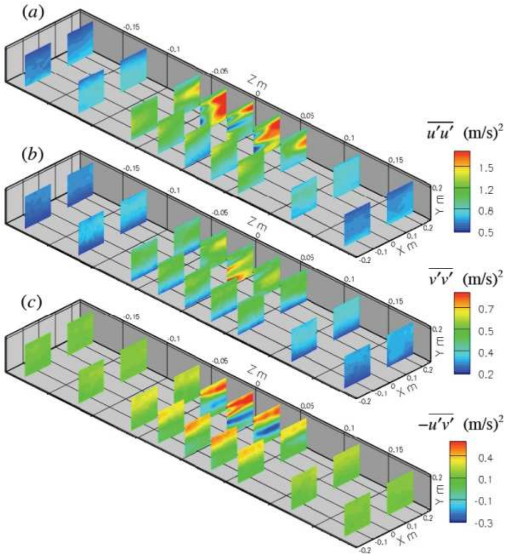

Figure 15 Reynolds stresses in multiple wind turbine wakes (Cal et al. 2010)

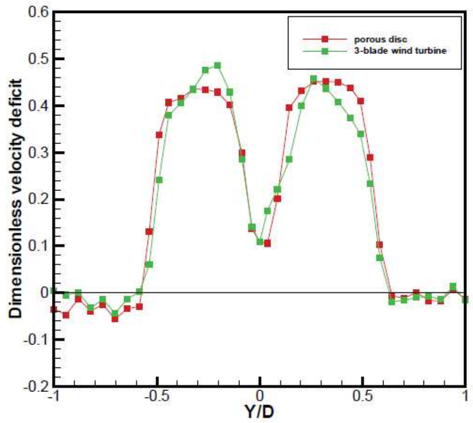

Figure 16 Comparison of wakes between a three bladed turbine and a porous disk (Aubrun et al., 2011)

WG8. Small Wind Farms / Individual Turbines

Objective: Evaluate models based on measurements of full scale standalone turbines or those in arrays of 10 turbines or less.

Description: Models will be compared to measurements of velocity profiles and turbulence quantities behind individual turbines. Temperature information may also be available. Some comparisons could be blind as full datasets are not yet released.

Benchmarks:

☐ Nibe: two 20m diameter turbines, 4 met towers, single and double wake, flat terrain.
☐ MOD-2 Medicine Bow: Vertical profiles of wind speed, temperature and turbulence measurements
☐ Sexbierum: Onshore flat, wakes of one or two 300kW tubrines, 30m diameter, 35 hub height, masts at -2.8D, 2.5D, 5D and 8D, neutral
☐ ECN Scale Wind Farm (ESWF): Onshore flat, 10x10kW turbines, 14 met-mast; in between two large wind turbines of Wieringermeer Test Wind Farm
☐ Wieringermeer Test Wind Farm (EWTW): Onshore flat, 5x2.5MW Nordex N80 turbines, 2x100m + 1x108m meteo masts, sonics, cups and temperature.
☐ TWICS project: Single 2.3 MW turbine multiple upstream lidars and sodar, NOAA HRDL lidar for wake, data available Jan. 2012
☐ Other. Please specify...

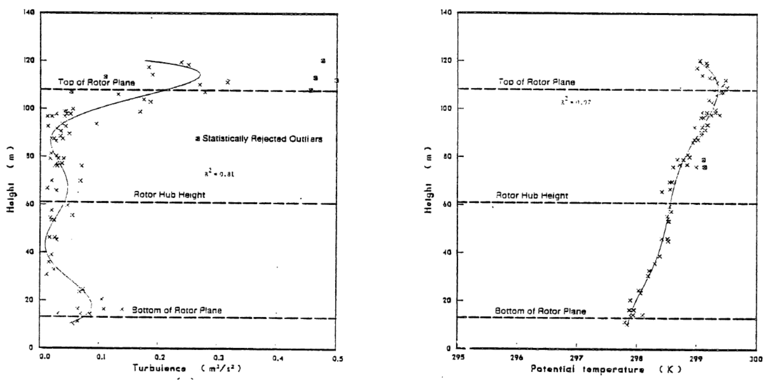

Figure 17 Turbulence and temperature profiles behind MOD2 turbine (Jacobs et al. 1984)

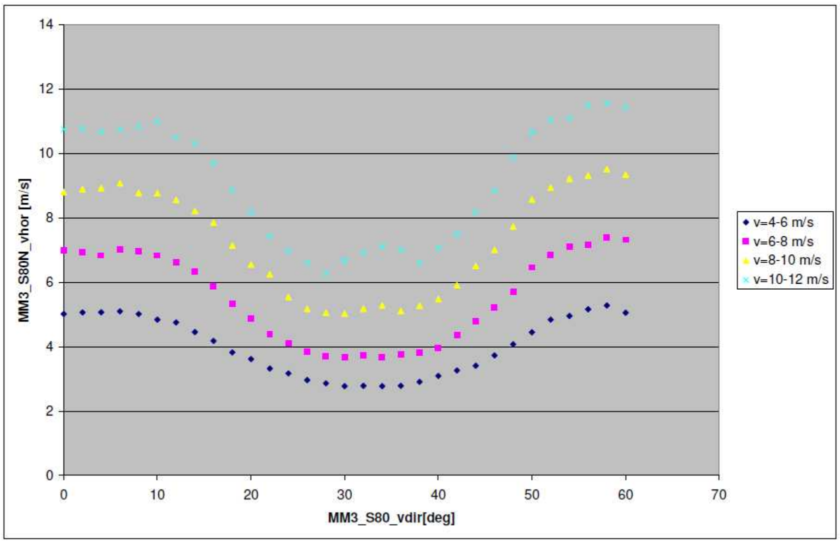

Figure 18 Velocity profiles 2.5D behind EWTW turbine (Schepers 2009)

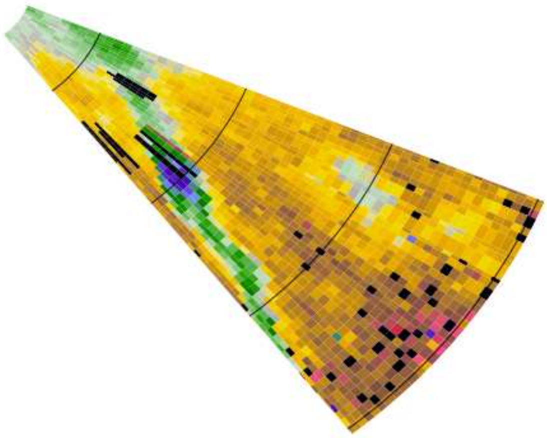

Figure 19 Lidar wake profile behind 2.3 MW TWICS turbine (Lundquist, publication pending 2012)

WG9. Large Wind Farms

Objective: Evaluate models relative to measurements within large operational wind farms

Description: Simulation models will be compared to measurements of large wind farms with more than 4 rows. Here the importance of deep array effects, multiple wake merging, and potential mesoscale variation will be examined.

Benchmarks:

- ☐ San Gorgonio: 2500 - 65 kW machines - turbulence statistics at row 37 and downwind of entire wind farm
- ☐ Horns Rev: Offshore 80x2MW Vestas V80 turbines, 70m hub height, 7Dx7D matrix, 1 upwind and 2 downwind masts, various stabilities
- ☐ Nysted: Offshore 72x2.3MW Bonus B82 turbines, 69 hub height, 10.5Dx5.8D matrix, 1 upwind and 2 downwind masts, various stabilities

☐ Spanish Complex Terrain Wind Farm: 43 turbines, 48.4m diameter, 45&55m hub height, 5 lines 13Dx1.5D, 1 mast
☐ Middlegrunden: Offshore Copenhagen harbor - 40 MW - 20x2MW Siemens turbines
☐ Lillgrund: Offshore power measurements - 48 2.3 MW Siemens machines - near wake model performance - spacing is 3.3D and 4.3D along dominant rows , also a gap in the middle
☐ Vindeby: Offshore - power and SODAR measurements - vertical and horizontal profiles - 11 450 kW in two rows
☐ Egmond aan Zee: Offshore 36x2MW Vestas V90 turbiens
☐ CWEX11/12: Large US onshore wind farm 1.5 MW turbines, vertical lidar upstream and downstream, surface flux stations, radiometer. Data available early 2012.
☐ Other. Please specify...

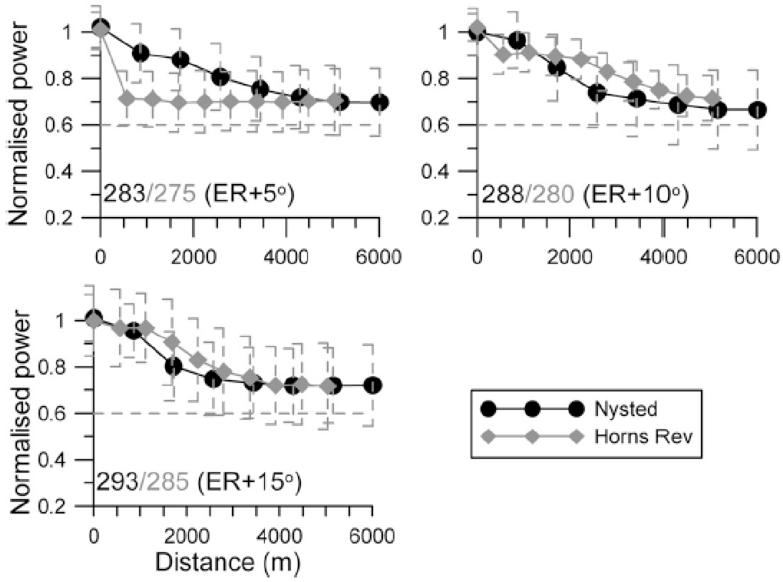

Figure 20 Wake losses for Nysted and Horns Rev (Barthelmie et al. 2010)

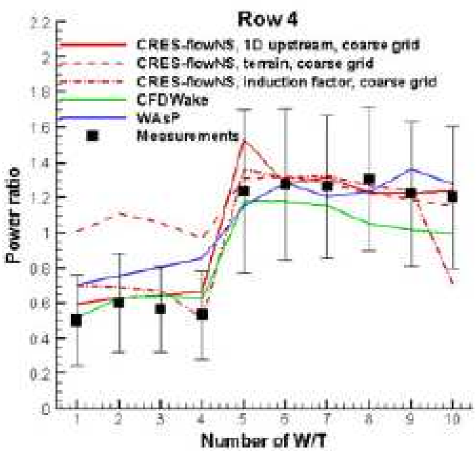

Figure 21 Wake losses in Spanish complex terrain wind farm (Politis et al. 2011)

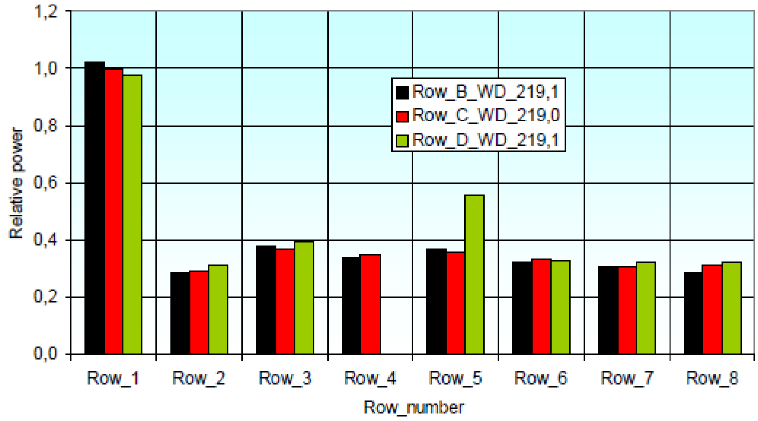

Figure 22 Power losses down rows in Lillgrund (Dahlberg, 2009)

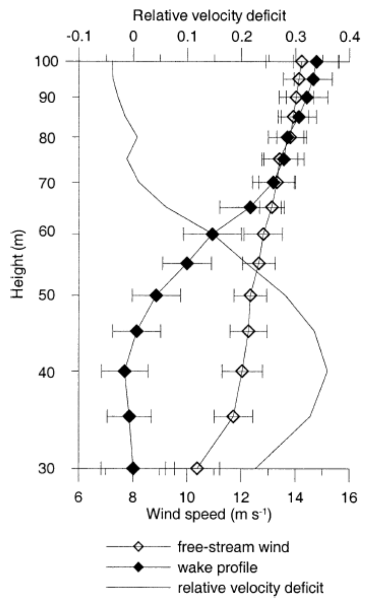

Figure 23Sodar wake profile from Vindeby (Barthelmie, 2002)

12. Would you like to propose a working group?

    Please specify...

Continuous call for test cases...

Even though the survey of test cases considered so far is extensive, it is always possible to submit proposals for new benchmarks throughout the Task duration. If you have a test case that would complement the current list please inform at an early stage. The SC will consider the appropriateness of the test case considering the complementarities with the work programme.

Besides, it is important to identify at an early stage test cases needs, i.e. validation data that is not well covered in the building-block approach defined with current test case list.

13. What test cases are missing?

    Please specify...

14. Would you like to propose a test case? Please describe it and/or send a description in a separate document.

    Site description: Please specify...

    Measurement campaign: Please specify...

    Input data: Please specify...

    Validation data: Please specify...

    Data accessibility: Please specify...

    Objectives: why is the test case particularly interesting compared to the others? Please specify...

Suggestions welcome...

15. Your comments are appreciated.

Please specify...

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Annex 3: List of Test Cases / Benchmarks

WG	WG	Test Case	Benchmark
1	Flat Terrain ABL	Monin-Obukhov	Quasy-steady surface layer profiles at different stabilities
1	Flat Terrain ABL	Leipzig	Quasy-steady ABL in neutral conditions
1	Flat Terrain ABL	Hovshore	Quasy-steady ABL profiles at different stabilities
1	Flat Terrain ABL	Fino1	Quasy-steady ABL profiles at different stabilities
1	Flat Terrain ABL	GABLS	Stable ABL 9hr run (GABLS1)
1	Flat Terrain ABL	GABLS	Daily cycle (GABLS2)
2	Flow over hills in wind tunnel	POSTECH 2D hills	Isolated 2D hills with and without flow separation
2	Flow over hills in wind tunnel	POSTECH 2D hills	Hill-hill interaction using the same hill geometries of previous
2	Flow over hills in wind tunnel	EnFlo 2D stratified hills	Isolated 2D hills, with and without flow separation, in neutral and stable cc
2	Flow over hills in wind tunnel	CSIRO 2D Furry hill	Isolated 2D hill covered by modelled forest canopy
2	Flow over hills in wind tunnel	UMN 2D and 3D hills	2D and 3D hills in wind tunnel
2	Flow over hills in wind tunnel	PSU flow over hills	New test cases
3	Flow over hills in the field	Askervein	Askervein 210. Isolated hill, historical reference
3	Flow over hills in the field	Askervein	Askervein different wind directions
3	Flow over hills in the field	Bolund	Revisit blind test simulations, now calibration is allowed
3	Flow over hills in the field	CSIRO Cooper's Ridge	Quasy-2D hill under different stratification conditions
3	Flow over hills in the field	Benakanahalli	Hill under different stratification conditions
4	Flow in and above forest canopies	CSIRO homogeneous forest	1D profile in and above canopy (Furry hill)
4	Flow in and above forest canopies	VKI 2D forest clearings	PIV fields in different layouts of forest clearing
4	Flow in and above forest canopies	UMN 2D forest clearings	2D forest clearings under different stability and LAI
4	Flow in and above forest canopies	OrleansU forest canopy test case	Complex forest area in a wind tunnel
4	Flow in and above forest canopies	OrleansU Turbine and forest canopy	Single turbine located in a homogeneous wind tunnel forest
4	Flow in and above forest canopies	CSIRO 2D Furry hill	Isolated 2D hill covered by modelled forest canopy
4	Flow in and above forest canopies	Bradley's roughness change	Smooth <--> Rough transition in the field
4	Flow in and above forest canopies	Falster 2D forest edge	Different stratification and LAD (seasonal) conditions
5	Flow over mountains	Alaiz Test Site	Sensitivity tests on different modelling issues
6	WT Wakes. Theoretical verification	Theory	Self-similar turbulent circular wake
6	WT Wakes. Theoretical verification	Theory	Infinite wind farm
6	WT Wakes. Theoretical verification	Theory	Self-similar turbulent swirling wake
7	WT Wakes. Wind Tunnel Experiments	Chalmers University	Axisymmetric wake behind a solid disk
7	WT Wakes. Wind Tunnel Experiments	University of Minnesota	Single or multiple turbines with different stability
7	WT Wakes. Wind Tunnel Experiments	Johns Hopkins University	Multiple turbines
7	WT Wakes. Wind Tunnel Experiments	University of Orleans and Surrey	Multiple turbines on mesh disks
7	WT Wakes. Wind Tunnel Experiments	Swirling wake	Axisymmetric swirling wake, LDA/PIV measurements
7	WT Wakes. Wind Tunnel Experiments	NREL Phase IV	Single wind turbine in wind tunnel
7	WT Wakes. Wind Tunnel Experiments	MEXICO	Single wind turbine in wind tunnel
7	WT Wakes. Wind Tunnel Experiments	PSU wind turbines in wind tunnel	Multiple wind turbines in stratified/neutral flow
7	WT Wakes. Wind Tunnel Experiments	WAUDIT wind turbine wake experiments	Single wind turbine in wind tunnel
8	Small Wind Farms / Individual Turbines	Nibe	Two 20m diameter turbines, single and double wake
8	Small Wind Farms / Individual Turbines	MOD-2 Medicine Bow	Vertical profiles of wind speed, temperature and turbulence
8	Small Wind Farms / Individual Turbines	Sexbierum	Single and double wake on 30m diameter turbines
8	Small Wind Farms / Individual Turbines	ECN Scale Wind Farm (ESWF)	10x10kW turbines, 14 met-masts
8	Small Wind Farms / Individual Turbines	Wieringermeer Test Wind Farm (EWTW)	5x2.5MW array, 3 tall masts
8	Small Wind Farms / Individual Turbines	TWICS	Single 2.3MW turbine and remote sensors
8	Small Wind Farms / Individual Turbines	Nordtank	41m/500kW Single wake mast measurements at 1D and 2.5D
8	Small Wind Farms / Individual Turbines	NM80	80m/2.5MW single wake with nacelle-based lidar 1-2.5D
9	Large Wind Farms	San Gorgonio	2500x65kW, turbulence at row 37 and downwind of wf
9	Large Wind Farms	Horns Rev	Offshore, 80x2MW, 7Dx7D spacing, various stabilities
9	Large Wind Farms	Nysted	Offshore, 72x2.3MW, 10.5Dx5.8D, various stabilities
9	Large Wind Farms	UpWind Complex Terrain	Complex terrain, 43 turbines, 13Dx1.5D
9	Large Wind Farms	Middlegrunden	Offshore, 20x2MW, arch array
9	Large Wind Farms	Lillgrund	Offshore, 48x2.3MW, 3.3Dx4.3D, gap in the middle
9	Large Wind Farms	Vindevy	Offshore, 11x450kW, two rows, power and sodar measurments
9	Large Wind Farms	Egmond aan Zee	Offshore, 36x2MW
9	Large Wind Farms	CWEX 11/12	Large onshore in the US, 1.5MW machines, remote sensors
9	Large Wind Farms	UpWind Complex Terrain 2	Complex terrain, 13xV90
10	Requirements for validation experiments and generation of new test cases (UniHH)		