INTERNATIONAL ENERGY AGENCY

IEA R&D WIND

TASK 31
Benchmarking of wind farm flow models

Progress Report to ExCo 67
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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.

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

So far more than 60 expressions of interest have been compiled from 17 IEA countries (Table 1). Negotiations for securing participation fees are underway with different levels of success. Commitment letters will be formalized after ExCo67.

Table 1: List of potential participants

Country	Organization		Contact Person
Australia	Commonwealth Scientific and Industrial Research Organisation	CSIRO	John Finnigan / Ian Harman
	Windlab	Windlab	Keith Ayotte
Canada	Montreal University	ETSMTL	Christian Masson
	York University	YORKU	Peter Taylor
China	Chinese Wind Energy Association	CWEA	Wang Yongli
Denmark	Risø DTU National Laboratory for Sustainable Energy	RisøDTU	Hans E. Jørgensen / Pierre-Elouan Rethore
	DTU Mechanical Engineering	DTU-MEK	Jens N. Sørensen / Kurt S. Hansen
	Aarhus University	AU-INF	Martin Greiner
	VESTAS Wind & Site Competence Centre	VESTAS	Line Gulstad
	EMD International A/S	EMD	Morten Thøgersen
Germany	ZMAW Hamburg University	ZMAW	Michael Schatzmann / Bernt Leitl
	Anemos-Jacob GmbH	Anemos-Jacob	Herbert Schwartz
	ForWind - Oldenburg University	ForWind	Stephan Barth / Detlev Heinemann
Greece	Center For Renewable Energy Sources	CRES	John Prospathopoulos / George Sieros
Ireland	Centre for Renewable Energy, Dundalk Institute of Technology	CREDIT	Raymond Byrne
	Wind Site Evaluation Ltd.	WSE	Bryan Hurley
Italy	University of Perugia	UNIPG	Francesco Castellani
	Institute of Atmospheric Sciences and Climate	CNR-ISAC	Anna Maria Sempreviva
Korea	Korea Institute of Energy Research	KIER	Hyun-Goo Kim
	Pohang University of Science and Technology	POSTECH	Chinwha Chung
Norway	Windsim	Windsim	Arne Reidar Gravdahl
Portugal	Porto University	FEUP	Jose Laginha Palma
Spain	National Renewable Energy Centre of Spain	CENER	Javier Sanz Rodrigo
	Politecnic University of Madrid	UPM-ETSII	Antonio Crespo/ Emilio Migoya
	UPM Instituto de Microgravedad Ignacion da Riva	UPM-IDR	Álvaro Cuerva
	Barlovento Recursos Naturales S.L.	Barlovento	Rafael Zubiaur
Sweeden	Gotland University - Wind Energy	HGO	Stefan Ivanel
	Vattenfall R&D	Vattenfall	Jens Madsen
Switzerland	École Polytechnique Fédérale de Lausanne	EFPL	Fernando Porté-Agel
	Swiss Federal Institute of Technology	ETH	Ndaona Chokani
The Netherlands	Energy Research Centre of the Netherlands	ECN	Arno Brand
	ECOFYS	ECOFYS	Anthony Crockford
United Kingdom	ANSYS UK Ltd	ANSYS	Christiane Montavon
	Oldbaum	Oldbaum	Andy Oldroyd / Poushali Maji
	Centre for Renewable Energy Systems Technology	LBORO	Simon Watson
	Renewable Energy Systems Ltd	RES	Gerd Habenicht
	School of Engineering and Physical Sciences Heriot-Watt Universi	HW	Angus Creech
	Natural Power UK	NP	Claude Abiven
	E.ON New Build & Technology Limited	E.ON	Christopher Belcombe / Mike Colechin
	CD-adapco	CD-adapco	Simon Mountfort
	University of Surrey	US	Philip Hancok
	Glasgow University	GU	Richard Brown
United States	National Renewable Energy Laboratory	NREL	Pat Moriarty
	Indiana University	INDIANA	Rebecca Barthelmie
	Iowa State University	UIOWA	Eugene S. Takle
	Los Alamos National Laboratory	LANL	Rodman Linn
	DNV Renewables (USA) Inc.	DNV	Tony Rogers
	Case Western Reserve University	CASE	Iwan Alexander
	Meteodyn US	Meteodyn	Karim Fahssis
	Lawrence Livermore National Laboratory	LLNL	Bill Henshaw
	University of Wyoming	3Tier	Jim McCaa
	AWS Truepower	AWST	Michael Brower
	WindLogics	WL	Mark Ahlstrom
	Vestas Americas	VestasAM	Brad Johnson
	General Electric	GE	Anurag Gupta
	University of Minnesota	UMN	Leo Chamorro
	Johns Hopkins University	JHU	Charles Meneveau
	University of Colorado	CU	Julie Lundquist
	Rensselaer Polytechnic Institute	RPI	Luciano Castillo
	National Center for Atmospheric Research	NCAR	Ned Patton
	Penn State University	PSU	Jim Brasseur
	Portland State University	PSUO	Raul Cal
	AES	AES	Emil Moroz
	RES Americas	RES	Andy Oliver
	Acusim	Acusim	Steve Cosgrove
	University of Washington	UW	Alberto Aliseda

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.

Work Plan

The project structure is composed of four work packages:

- WP0: Management and coordination
- WP1: Setting-up of the benchmark platform and schedule
- WP2: Benchmark of research and industrial test cases
- WP3: Best practice procedures

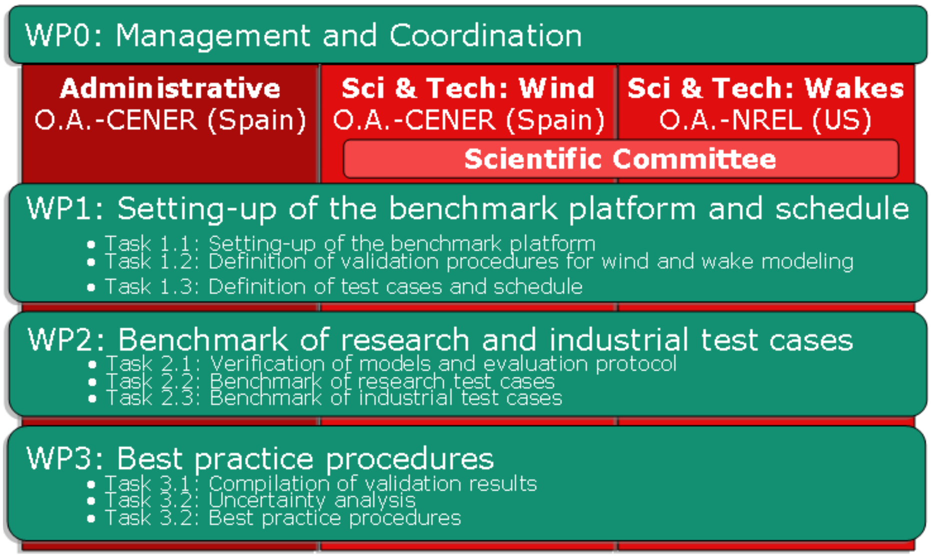

Figure 1: Structure of Wakebench IEA Task

WP0: Management and Coordination

Period: T0-M36

Deliverables:

- D0.1: Web site (M6)
- D0.2: First annual progress report (M12)
- D0.3: Second annual progress report (M24)
- D0.4: Final report (M36)

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.

Task 0.1: Administrative management

The kick-off meeting will be hosted by CENER in October 2011 (**T0**). Exact dates are being discussed among the interested participants. Until then, the O.A. will be busy reaching formal commitments from IEA members and drafting the work plan.

The most convenient dates and venues for the annual workshops will be discussed during the kick-off meeting.

The O.A.-CENER will take care of the preparation of the progress reports and the attendance of the IEA Wind ExCo meetings.

Task 0.2: Science and Technical management

The work plan will be discussed and approved by the active participants in the kick-off meeting.

A **Scientific Committee (SC)** will be appointed in the kick-off meeting for monitoring the scientific and technical progress of the Task related to the objectives foreseen. The SC plays an essential role in the model evaluation protocol as being responsible for the supervision of the whole evaluation process, determining by consensus the appropriateness of the models, the test cases and the validation process.

A **Test Case Manager (TCM)** will be appointed for each of the test cases scheduled in the work plan, in order to administrate the participants, organize the workspace information and monitor the progress of work. The TCM can be the owner of the data to take full control on accessibility rights or a delegate (typically one of the O.A.).

WP1: Setting-up of the benchmark platform and schedule (T0-M12)

Period: M1-M12

Deliverables:

- D1.1: Inventory of models and test cases (M6)
- D1.2: Report on model evaluation protocol for wind farm modeling (M12)

Task 1.1: Setting-up of the benchmark platform

The *Windbench* model evaluation web platform is under construction at CENER. 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 and test cases will be compiled with standardized questionnaires approved by the SC.

A prototype of *Windbench* will be presented in the kick-off meeting. It will contain the basic functionalities in order to start operating the Task. During the duration of WP1 the contents and functionalities of the platform will be iterated based on the feedback of the users.

A user manual will be developed by the O.A. to guide ongoing and future benchmarks.

Task 1.2: Definition of validation procedures for wind and wake modeling

The principles behind the evaluation protocol developed in the European COST Action 732 (2009), partly based on the AIAA guidelines (1998), will be explored in order to benefit from previous experiences. The **evaluation protocol** consists on the following items:

- A scientific evaluation process, that considers the formulation of the models in terms of physics included and the degree of suitability for the intended use
- A verification process that addresses both the code (consistency with the conceptual model) and the solution procedure (to estimate the numerical error)
- The provision of appropriate and quality assured validation datasets
- A model validation process in which model results are compared with experimental datasets
- An operational evaluation process that reflects the needs and responsibilities of the model user

The SC is responsible for the definition and implementation of the evaluation protocol.

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.

To illustrate the validation phases, a case study of the Alaiz mountain is sketched out in Figure 2. The site is characterized by rather uniform slopes of 20-30% to the North, where the prevailing winds are coming from. Secondary winds are coming from the South where the terrain is more complex. The site is partly covered by a 10-20m high forest. Three wind farm sites are displayed: CENER's Test Site in the frontline ridge and Echagüe and Alaiz wind farms to the South.

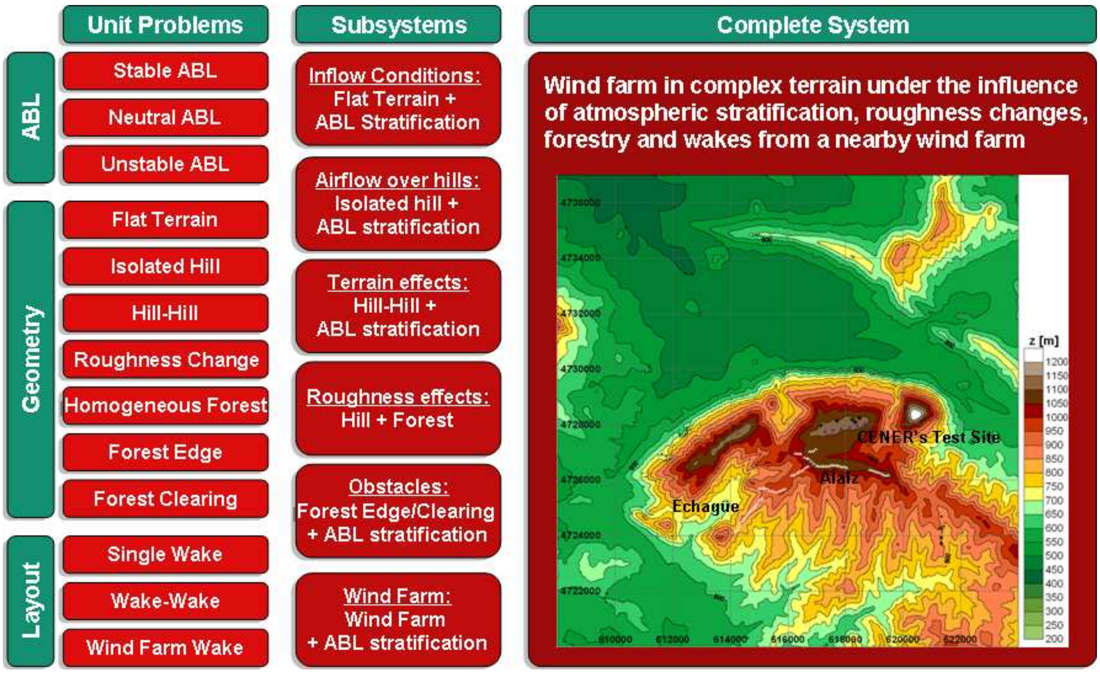

Figure 2: Sketch of the building-block approach for the Alaiz case study

For example, let us consider the objective of validating wind farm models for the Echagüe wind farm conditions. The system is characterized by complex terrain under the influence of atmospheric stratification, roughness changes, forestry and wind turbine wakes within the wind farm and from the nearby Alaiz wind farm. It is indeed a very complex system that includes many coupled physical modeling issues. The system can be divided in a number of simplified subsystem cases, each one targeting key elements of the model chain. For instance:

- Atmospheric boundary layer (ABL) in flat terrain under different thermal stratifications: This is the subsystem that includes the background physics of the flow and therefore a basic requirement for any wind related validation process. Horizontally homogeneous profiles are typically needed to define the inflow conditions in CFD models.

- Flow over hills under different ABL stratifications: The ABL model is perturbed with a hill obstacle and depending on the background stability and the size of the hill (Froude number) the flow will show different preferential patterns, around and above the hill, and flow separation characteristics in the lee of the hill.
- Terrain induced wakes: At site level the flow is largely modified by the topography in a series of superimposed terrain induced wakes. This problem is simplified by looking at the interaction of two hills of simplified geometry and studying the ability of the turbulence model to simulate flow separation areas. Background stability will modify the wake development enhancing or suppressing turbulent mixing.
- Roughness effects on hills: The presence of high roughness areas like forests on the topography also has an impact on the development of the surface boundary layer, adding turbulence and wind shear and eventually triggering flow separation.
- Obstacles like forests: Some wind turbines could be placed in the vicinity of a forest edge or inside a forest clearing. In this case the nearby forest is not only a roughness element but also an obstacle that will substantially modify the flow field as seen by the wind turbine. Shear layers and wakes behind trees are also affected by background stability.
- Wind turbine wakes: The wind turbine is a complete system in itself but, in this modeling context, it is considered as another obstacle to the flow that extracts axial momentum and induces swirl downstream. The wind turbine wake interacts with neighboring wakes differently depending on the layout of the wind farm and the background stability.

All these subsystems are combinations of typically two or three unit problems. Through parametric testing in a wind tunnel or with dedicated field tests, one can assess the impact of the most relevant geometrical and atmospheric variables of the complete system. This hierarchical process allows a more comprehensive approach to the prediction of the model uncertainties and the identification of the model gaps.

The building-block approach is more effective if the system is divided in more hierarchical levels. Of course in our context this is a very costly process specially when moving from wind tunnel to field testing, where the much higher level of physical complexity requires very significant efforts in the instrumentation if meaningful flow characterization and model validation are pursued. In practice, it is often necessary to go beyond the validated range of the model using engineering approaches in order to build a bridge between the closest validation case and the real conditions. This process can be called extrapolation and, if onsite measurements are available, it is customary to include calibration in order to decrease the uncertainties. While hierarchical model validation is essential to understand the physics of the system and introduce improvements in the model chain, model calibration is also very important in order to reduce uncertainties in the applied world. Both aspects will be the object of study in Wakebench.

Task 1.3: Definition of test cases and schedule

For each test case, it is necessary to define clear objectives with associated metrics (i.e. methods of comparison) that constitute objective performance indicators. In many cases, the test case will prescribe a certain number of settings in order to focus on specific aspects of the models. Some test cases will be blind, i.e. without a priori access to the experimental data, in order to test the model without calibration possibilities. Based on the results of the different models and test cases, it is possible to determine in a systematic way the quality of each model and its range of validated applicability.

As preparatory work before the kick-off meeting, the O.A. will interact with the interested participants to compile a list of test cases for model validation. Besides, the participants will be asked to set priorities in the list in order to identify the most relevant benchmarks that will be scheduled in the kick-off meeting. It is anticipated that model developers will focus more on test cases related to unit problems and subsystems and end-users will focus more on test cases with more realistic conditions of real wind farms. It is also likely that some participants will be more interested in looking at specific topics like forest or stability effects in order to limit the work load. Therefore, some flexibility should be allowed when configuring the benchmarks schedule. Three levels of actuation are foreseen in connection to WP2:

1. Basic unit and subsystem test cases that **every model** should do before approaching a complex system. This is a condition in order to clearly monitor the range of applicability of each model and compare with others. At least one participant per model should contribute (Task 2.1).
2. Specialized unit and subsystem test cases, typically considered by **model developers** to look in more detail to specific topics of the model chain. Dedicated groups of a few participants contribute to each topic (Task 2.2).
3. Reference test cases that **every user** should do in order to study user dependency. This type of intercomparison studies is performed in order to assess the robustness of each model, especially concerning commercial software. This category shall include both research and industrial test cases in order to determine the dependency of the model on the experimental data. All participants should contribute (Task 2.2 and Task 2.3).

A first list of test cases is provided in the Annex I. At the end of WP1 an inventory of models and test cases will be produced, as a dynamic catalogue of the state-of-the-art on wind farm models and the validation possibilities. In connection to this catalogue, a second deliverable will consist on the model evaluation protocol, which will guide developers and end users on the best way of using the database.

WP2: Benchmark of research and industrial test cases

<u>Period</u>: M3-M30

<u>Deliverables</u>:

- D2.1: Test cases reports (M6-M30)

The kick-off meeting will be oriented to the scheduling of benchmarks and the configuration of the working groups. Three phases are foreseen:

- Phase 1: During the first year, the focus will be on verification of basic model features and validation of simple and well known test cases. The objective of this phase is to get acquainted with the models and the evaluation protocol.
- Phase 2: With a well established evaluation protocol, the focus during the second year will be on the validation of test cases from research projects and/or field laboratories. Higher levels of complexity will be pursued. Sensitivity tests will be run in order to assess the numerical uncertainty of the models.
- Phase 3: The modelling methodologies developed in the first two years will be now applied to test cases from industry.

Task 2.1: Verification of models and evaluation protocol

This task will target those verification and validation exercises that allow an objective evaluation of the model performance and range of applicability. Therefore it will consist on the essential unit and subsystem test cases, required for each model to be categorized and documented properly.

This task is particularly addressed to developers of research and commercial models. The SC will supervise carefully this task since it will form the basis of the model evaluation protocol.

Task 2.2: Benchmark of research test cases

'Research' test cases are test cases with well defined boundary conditions and high level of instrumentation. Working groups will be formed around specific topics of the model chain, for instance:

- Forests: roughness changes, homogeneous forests, forest edges and clearings, forested hills
- Atmospheric stability: horizontally homogeneous stable ABL, coastal thermal/roughness changes, stratification and hills
- Wake-wake interaction: single wake neutral, single wake in stratified ABL, wake-wake interaction in full, partial and yawed conditions, wake in sloping terrain
- Mesh generation: structured vs unstructured, rectangular vs polar grid, immerse boundary

Besides some reference research test cases will be identified in order to gather as many participants as possible and evaluate user dependency. If possible this type of experiments will be done in blind conditions first, i.e. without a priori knowledge of the validation data.

Task 2.3: Benchmark of industrial test cases

A call for test cases will be released at the beginning of the project. The wind industry will be offered the possibility to contribute to the project by delivering test cases from their wind farm portfolio. The SC will guide interested industrial partners with the selection and the configuration of the test cases. Careful evaluation of gaps in the building-block validation chain at the beginning of the Task will guide a more effective search of suitable sites. Preferably, industrial test cases will contain data from the resource assessment phase (wakes-free) and from the operational phase (wakes). Each test case shall run in blind conditions first and then with site-specific calibration. This way the added value of the experimental data will be put in evidence.

This task will take place during the second half of the Task, as soon as the evaluation protocol is assimilated by the participants. The objective of this Task is to train participants in how to make best use of the limited measurements in operational conditions for model calibration.

WP3: Best practice procedures

<u>Period</u>: M24-M36

<u>Deliverables</u>:

- D3.1: Best practice procedures for wind and wake modeling (M36)

The results of the benchmark exercises will be compiled and analyzed thoroughly. The aim of WP3 will be to reach consensus about best practice procedures for the modeling of wind farms. The performance of each model will be analyzed in order to identify its range of applicability. An uncertainty analysis will determine the critical aspects of the modeling chain.

Task 3.1: Compilation of validation results

The results of the different benchmarks will be compiled and summary tables will be produced in order to compare models systematically. To this end it is important that evaluation metrics have been carefully defined in the evaluation protocol in order to match the intended use of the model. For instance, in wind assessment studies, the main focus shall be on mean velocity and turbulent kinetic energy as they are directly related to the wind energy yield and turbulence intensity, target parameters for developers and wind turbine manufacturers.

Task 3.2: Uncertainty analysis

The characterization of the error propagation throughout the model chain goes beyond the scope of this Task as it would take a very substantial effort in terms of measurement campaign evaluations and sensitivity tests of numerical models. In this task uncertainties from the benchmarks will be evaluated in order to identify the critical aspects of the model chain. It is expected that the model evaluation protocol will also guide developers in considering more carefully where to place measurements and how to reduce uncertainties by adding instrumentation in complex sites. Besides, model calibration will be explored as the best way to lower uncertainties once best practice modeling procedures have been adopted.

Task 3.2: Best practice procedures

The experience gathered throughout this Task will be merged in a document of best practices for the use of wind farm models. It is hoped that this first edition will be updated regularly in the future as the state-of-the-art evolves with the addition of new model features supported with more validation results.

Chronogram

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

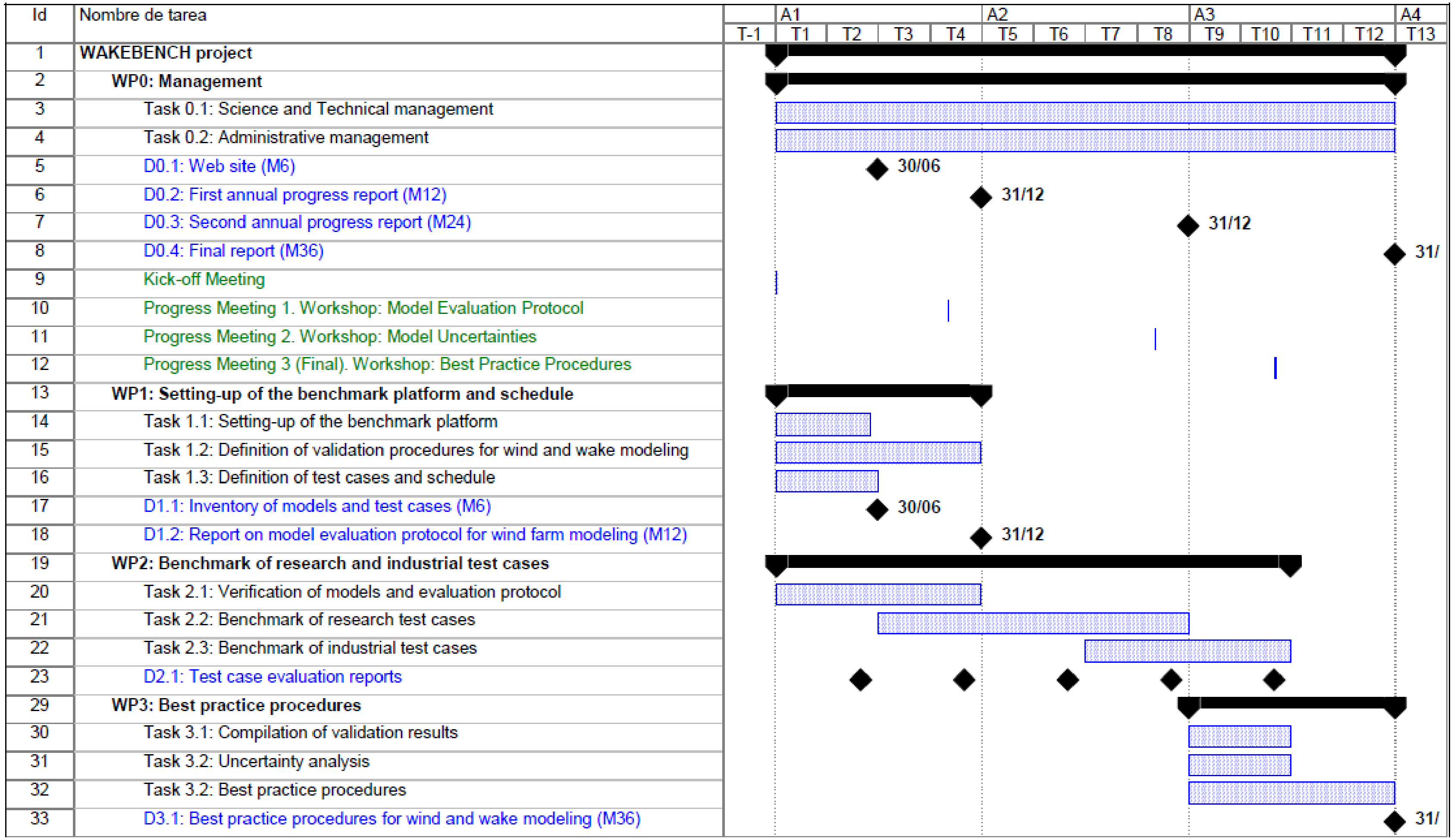

Figure 3: Gantt chart for WAKEBENCH project

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 2.

Table 2: 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

Deliverable D2.1 "Test cases reports", will be a continuous reporting activity throughout most of the project. As new test cases are completed, a report with the evaluation of the models will be delivered.

All the intermediate deliverables will be used to prepare the final deliverable D3.1 "Best practice procedure for wind and wake modeling", which is the most important product of this IEA Task.

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 3: 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

Economic Status

United States (NREL) and Spain (CENER) are providing support for the O.A. during these preliminary stages of the project.

The total costs of the Operating Agents for coordination, management, reporting, and data base maintenance and operation is 100 kEuro/yr during a projected three year period, and may not exceed this level except by unanimous agreement of the Participants, acting in the ExCo.

Projected expense items of the operating agent are as follows (per year):

▪ Management	5 person-months	Euro 87000
▪ Travel	3 meetings (plenary + ExCo)	Euro 12,000
▪ Administrative	Misc expenses	Euro 1,000

The budget will be shared in the following way: 2/3 for CENER and 1/3 for NREL. Spain will manage the payments from the individual member countries and reimburse NREL for its O.A. expenses according to a separate arrangement to avoid member countries from making separate payments to different O.A.

A target of 10-12 participating countries has been initially set. A participation fee of 8.5 kEuro/yr has been established as a baseline for the first year and shall be lowered in subsequent years if more countries join.

Within each participating country, there is no limit on the number of experts who can contribute, but each contributor should be approved by the country's IEA Wind ExCo representative. Meetings are hosted by participants that donate the costs of holding the meeting.

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ANNEX I: Test Cases Matrix

V	Virtual/ Theory	**U**	Unstable	**E**	Flat (Empty)	**T0**	No wind turbines
F	Field	**N**	Neutral	**H**	Hilly	**T1**	Monorotor
L	Laboratory	**S**	Stable	**C**	Complex Terrain	**T2**	Wind Farm Array
				O	Offshore	**T3**	Wind Farm Matrix
				R	Roughness/Forest		

Test Case	Exp			Stability			Topography					Wakes				Date	Description	Source	Access	Reference	Remarks
Wind	V	F	L	U	N	S	E	H	C	O	R	T0	T1	T2	T3						
Flat Terrain / Offshore																					
Leipzig		x			x		x					x				1950	Neutral ABL in flat terrain	Literature	Public	Letau, 1950	Single profile, benchmark for neutral ABL schemes
Cabauw		x		x	x	x	x					x				1996	ABL in flat terrain, all regimes, 200m mast	Literature	Public	Verkaik and Holstag, 2007	Heterogeneous roughness lengths
GABLS	x					x	x					x				2000	Stable ABL in flat terrain, 9hr uniform cooling	Literature	Public	Beare et al., 2006	9hr cooling evolution; Verification vs LES (http://gabls.metoffice.com/)
Høvsøre Test Wind Farm		x		x	x	x	x					x				2004-Ongoing	ABL in flat terrain, all regimes, 100m mast	RisøDTU	Restricted	Gryning et al., 2007	Coastal site, various stabilities
Horns Rev		x		x	x	x				x		x				2006-Ongoing	ABL offshore, all regimes, 45m mast + LIDAR	RisøDTU	Restricted	Peña et al., 2008	Reference for Horns Rev wind farm simulations
Fino1		x		x	x	x				x		x				2004-Ongoing	ABL offshore, all regimes, 100m mast	BSH	Public		Offshore ABL, various regimes, tower distortion effects
Hilly Terrain																					
POSTECH 2D isolated hills			x		x			x				x				1997	2D sinusoidal hills with slopes 0.3 and 0.5 (separated flow) and heights 5 and 7 cm	Literature	Public	Kim et al., 1997	Wake behind hill, neutral, different heights and slopes
POSTECH 2D double hills			x		x			x				x				1997	2D sinusoidal double hills of different size	Literature	Public	Kim et al., 1997	Hill-hill interaction, neutral, different heighs and slopes
RUSVAD 2D isolated valleys			x		x			x				x				1990	2D symetric isolated valleys of different depths	Literature	Public	Khurshudyan et al., 1990	Flow separation at different slopes
Askervein		x			x			x				x				1982, 1983	Isolated 126m-high gentle hill, neutral, 50x10m mast arrays, 3x50m masts	Literature	Public	Taylor and Teunissen, 1987	Benchmark for hilly terrain, 210º wind direction, neutral. Other interesting runs?
Bolund		x		x	x	x			x			x				2007, 2008	Isolated 12m-high 150m-long complex hill, 10 masts, 23 sonics and 12 cups	RisøDTU/ Vestas	Public	Bechmann et al., 2009	Small hill with escarpment, well defined boundary conditions, various stabilities
Sirhowy Valley		x			x			x				x				1984	Succesion of nearly-2D ridges and valleys. Array of 12x8m in one of the valleys. Max. slopes of 30º	Literature	Public	Mason and King, 1984	Flow separation. Two cross-valley wind directions. Uncertain inlet conditions
Cooper's Ridge		x		x	x	x		x				x				1985	Nearly-2D ridge (witch of Agnesi) with no flow separation. Array of 7x4m masts and 2x30m masts	Literature	Public	Coppin et al., 1994	Neutral and moderate stable and unstable ABL over a hill with no flow separation
Forested Terrain																					
CSIRO Homogeneous Forest			x		x		x				x	x				1994	Model of waving wheat crop	Literature	Public	Brunet et al., 1994	Ensemble-averaged profiles of statistical moments and spectra from X-wire measurements
UBC 2D Forest Edge			x		x		x				x	x				1995	Measurements downwind of a homogeneous forest edge	Literature	Public	Chen et al., 1995	Velocity and turbulence profiles down to a distance of x/h = 21.8
VKI 2D Forest Clearing			x		x		x				x	x				2004	2D forest clearing inside homogeneous 'foam' forest	Literature	Public	Sanz Rodrigo et al. 2007	2D PIV fields of the flow within different configurations of the forest clearing
CSIRO 2D Furry Hill			x		x						x	x				1995	2D polynomial hill with a slope of 0.36 covered by waving wheat crop model	Literature	Public	Finnigan and Brunet, 1995	Same forest model of Brunet et al. (1994). Velocity and turbulence profiles from -5L to 3L
EnFlo 2D Stratified Hill			x		x	x					x	x				2004	2D sinusoidal hill with slopes 0.3 and 0.7, covered with roughness elements	Literature	Public	Ross et al., 2004	2 slopes x (Neutral and 2 stable ABL) = 6 runs
Bradley's Roughness Change		x			x		x				x	x				1968	Smooth (0.002m) <--> Rough (0.25m) over an array of 8x1m masts over 15m, Neutral	Literature	Public	Bradley, 1968	More recent experiment?
Falster 2D Forest Edge		x		x	x	x					x	x				2009	2x45m masts and Lidar before and after a homogeneous forest edge	RisøDTU	Restricted	Bingöl et al, 2009	Different Winter/Summer LAI profiles. Various stabilities
Mountaineous Terrain																					
ALAIZ Test Wind Farm		x		x	x	x			x		x	x				2010-Ongoing	700m-high mountain, 4x120m mast positions at hilltop (cups and few sonics), one met mast inside dense forest	CENER	Restricted	Measurement campaign for validation underway	Flow over mountain at different stability (Fr) regimes, incoming ABL not measured for the moment. Limit of microscale models

V Virtual/ Theory
F Field
L Laboratory

U Unstable
N Neutral
S Stable

E Flat (Empty)
H Hilly
C Complex Terrain
O Offshore
R Roughness/Forest

T0 No wind turbines
T1 Monorotor
T2 Wind Farm Array
T3 Wind Farm Matrix

Test Case	Exp			Stability			Topography					Wakes				Date	Description	Source	Access	Reference	Remarks
Wakes	V	F	L	U	N	S	E	H	C	O	R	T0	T1	T2	T3						
Theoretical Verification																					
Self-Similar Turbulent Circular Wake	x				x		x						x			1986	Classic scaling laws of turbulent wakes	Literature	Public	Wygnanski, 1986	See if models follow classic laws for wake width growth and deficit decay
Infintite Wind Farm	x				x		x							x		2005	Classic scaling laws of turbulent wakes	RisøDTU	Public	Frandsen, 2005	At what point do wind farms become infinite? How many rows until momentum extraction is balanced with atmospheric flux?
Wind Tunnel Tests																					
Chalmers University			x		x		x						x			2002	Axisymmetric turbulent wake measurements in wind tunnel	Chalmers	Public	Johansson, 2002	Idealized case of wake only
University of Minnesota			x	x	x	x	x							x	x	2009	Small operational turbine models in wind tunnel with stratification	UMN	TBD	Chammaro et al., 2009	Lots of highly detailed measurements of small scale wind farm
Johns Hopkins University			x	x	x	x	x							x		2010	Small operational turbine models in wind tunnel with stratification	JHU	TBD	Calaf, 2010	Similar to UMN studies
University of Orléans and Surrey			x		x		x						x			2011	Measurements of small scale turbine and mesh disks	UO and USurr	TBD	Aubrun et al., 2011	Good comparison to notice impact of wake rotation
Small Wind Farm/Individual Turbines																					
Nibe		x					x						x			1985-1987	Onshore flat - 2x 40m diamter turbines in Jutland	ETSU	Public	Taylor ETSU WN 5020, 1990	
MOD2 Medicine Bow		x			x			x					x			1985	Vertical profiles from MOD2 in Medicine Bow, WY	NREL	Public	Jacobs et al, 1984	Wind speed, temperature and turbulence measurements
Sexbierum		x			x		x						x			1992	Onshore flat, 1x300kW, 30m diameter, 35 hub height, masts at -2.8D, 2.5D, 5D and 8D, neutral	TNO	Public	Cleijne, 1992	
NREL TWICS		x		x	x	x		x	x				x			2011	Detailed vertical profile measurements of single 2.3 Siemens turbine	NREL	Public	Forthcoming	Turbine data propietary
ECN Scale Wind Farm (ESWF)		x		x	x	x	x								x	2009-Ongoing	Onshore flat, 10x10kW, 14 met-mast; In between two large wind turbines of Wieringermeer Test Wind Farm	ECN	Restricted	UpWind Project 2010	Benchmark for wind farm matrix with numerous met-masts within and above the wind turbines
Wieringermeer Test Wind Farm (EWTW)		x			x		x							x		2003-Ongoing	Onshore flat, 5x2.5MW Nordex N80, 2x100m + 1x108m meteo masts	ECN	Restricted	Machielse, 2007	Benchmark for wind turbine array in flat terrain
Large Wind Farm																					
San Gorgonio		x		x	x	x				x				x	x	1989	Turbulence statistics at row 37 and downwind of San Gorgonio Wind Farm	NREL	Public	Kelley, 1994	2500 - 65 kW machines
Horns Rev		x		x	x	x				x				x	x	2005-Ongoing	Offshore 80x2MW Vestas V80, 70m hub height, 7Dx7D matrix, 1 upwind and 2 downwind masts	Dong/ Vattenfall	Restricted	Barthelmie, 2010	Benchmark for wind farm matrix offshore, various stabilities
Nysted		x		x	x	x				x				x	x	2003-Ongoing	Offshore 72x2.3MW Bonus B82, 69 hub height, 10.5Dx5.8D matrix, 1 upwind and 2 downwind masts	Dong	Restricted	Barthelmie, 2010	Benchmark for wind farm matrix offshore, various stabilities
UpWind Wind Farm in Complex Terrain		x			x				x						x	TBD	Complex terrain, 43 turbines, 48.4m diameter, 45&55m hub height, 5 lines 13Dx1.5D, 1 mast	Industrial	Restricted	Politis et al., 2010	Benchmark for wind farm matrix in complex terrain, neutral
Middlegrunden		x								x						2001-2004	Offshore Copenhagen harbor - 40 MW - 20x2MW Siemens	MWTCE2	Restricted	Barthelmie, 2007	Middelgrunden Wind Turbine Cooperative and Energi E2 (MWTCE2)
Lillgrund		x								x				x		2007-2009	Power measurements - 48 2.3 MW Siemens machines	Vattenfall	Restricted	Dhalberg and Thor, 2009	Good for validation of near wake model performance - spacing is 3.3D and 4.3D along dominant rows
Vindeby		x								x				x		2001	Power and SODAR measuremetns - vertical and horizontal profiles - 11 450 kW in two rows	Indiana University	Public literature	Barthelmie, 2002	
Egmond aan Zee		x		x	x	x				x					x	2007-Ongoing	Offshore 36x2MW Vestas V90,	ECN	Restricted		Benchmark for wind farm matrix offshore, various stabilities