Integral design approach and standards

WP1A1
WP1A2
WP1A3
WP1B1
WP1B2
WP1B3
WP1B4
WP2
WP3
WP4
WP5
WP6
WP7
WP8
WP9

THE CHALLENGE

The challenge of the work package (WP) 'Standards and Integration' is to efficiently update design standards and the development of an integrated design approach. This will ensure consistency and strengthen the integration of the advanced models within the wind energy technology, improve test methods and design concepts developed in the scientific work packages 2 to 9. In turn the WP provides a consistent scientific background for standards and design tools. The approach rests on three legs:

- Provision of a reference (wind turbine) for communication between and integration of all WP's;
- Development and definition of an integral design method to be applied in the real design of wind turbines, and not the least;
- Development of (pre)standards for the application of the integral design approach, including interfaces, description of data needs, guidelines and proposals for the formal international standardization process.

The technology of wind turbines and the size and impact of wind farms have made so much progress that the design and development has become dependent on the knowledge and interaction of specialists. Consequentially, design teams face increased complexity, both in the individual disciplines and in the design process of the entire system. To deal with the complexity of the individual disciplines, fundamental knowledge and design tools are continuously improved. Although the improvements of the individual technical disciplines are needed to reduce risks and to increase performance, they implicitly work to strengthen the status quo of current concepts and stimulate improvements that are based on the insights of a single discipline.

Further product improvements, which are expected and needed for the wind turbine and wind farm in 2020, can only be achieved when developments are not obstructed by the boundaries between the contributing disciplines.

The keyword for the approach is 'integral design' or 'system engineering' and the challenge for the wind energy community is to find a way of practical implementation.

The UpWind project, which has a mission to provide the prerequisites for taking a quantum leap in the development of the wind energy technology, not only aims at developing these disciplines, but also at finding the practical implementations for integration of disciplines for the design of wind turbines and support structures.

UpWind

UpWind

SIXTH FRAMEWORK PROGRAMME

WP1A1 LEADER:
Dr. techn. Sten Frandsen
Risø National Laboratory
– Technical University of Denmark (DTU)

EMAIL:
sten.frandsen@risoe.dk

www.upwind.eu

WP MEMBERS:

- Risø National Laboratory – Technical University of Denmark (DTU)
- Aalborg University
- Energy Research Centre of the Netherlands (ECN)
- Stichting Kenniscentrum Windturbine Materialen en Constructies (WMC)
- Technical University of Delft (TUDelft)
- Centre for Renewable Energy Sources (CRES)
- Dong Energy
- Garrad Hassan and Partners Ltd
- Germanischer Lloyd
- SAMTECH S.A.
- Det Norske Veritas

Photography: Vestas - Christian Wilmes-EWEA

THE RESEARCH ACTIVITIES

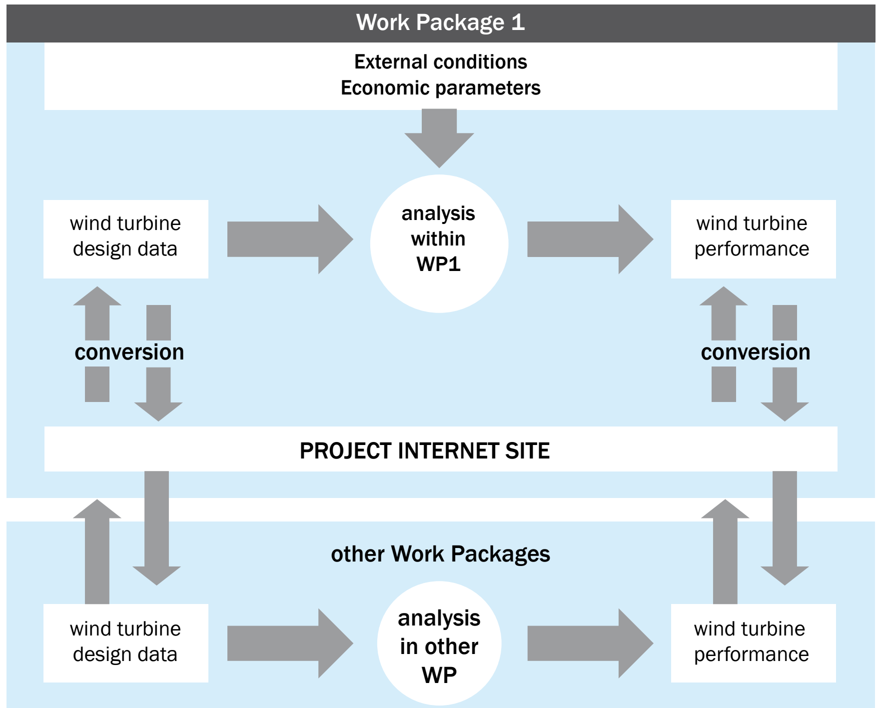
The main research activities for the integral design approach and standards' work package include:

- Defining and updating a reference wind turbine and a reference technical-economic cost model for benchmarking to be used for communication of the design parameters and design developments and the main economic and dynamic performance parameters for all UpWind project activities;
- Development, application and evaluation of an integral design approach methodology in offshore wind turbine design;
- Development of standards in general and for the application of the integral design approach, including definitions of interfaces between models, including data needs, specifications and protocols;
- Definitions and specifications of experimental data to be condensed into input design parameters for the design models or to verify critical design and performance issues.

In practical terms, the above research activities are sub-divided into 4 tasks.

SUBTASK A: REFERENCE WIND TURBINE AND COST MODEL

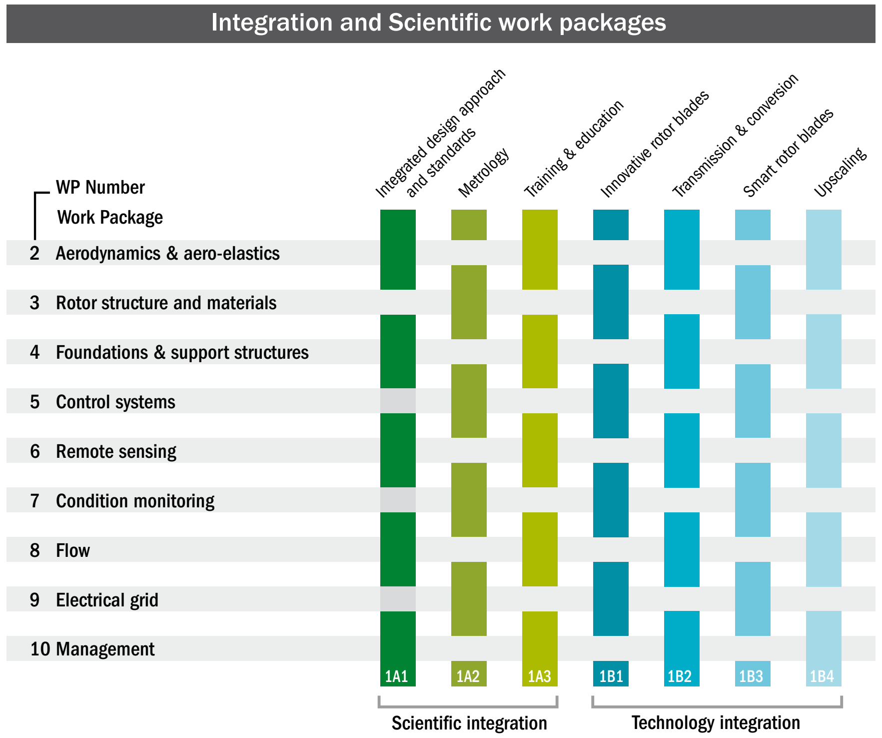
The subtask is dedicated at facilitating the integration of the different activities in all the horizontal (and vertical) work packages throughout the project. For this, a reference wind turbine will be defined to provide a basis for communication and comparisons. The design parameters and the main characteristics, including results of parameter sensitivity studies, will be defined and kept up to date. Input data will be provided from the other work packages. The data will be made easily accessible to all partners in the project.



SUBTASK B: INTEGRAL DESIGN APPROACH METHODOLOGY

Other technology sectors, such as air-transport, have experienced a development similar to wind energy with respect to increasing complexity and focus on specialists. For some of these technologies "Knowledge Based Engineering" (KBE) is investigated as a means to increase productivity of the design teams and to reduce the boundaries between disciplines. KBE tries to model not only properties of a product, but also the knowledge about the product that captures the engineering intent behind the design. KBE can be used in Design and Engineering Engines (DEE), to automate the multi-disciplinary processes. This automation is not intended to replace the design team, but rather to replace routine activities and to improve efficiency and consistency of information exchange. As a result, design teams will have more time for their creative contributions and thus can increase their productivity. Core element of the DEE is a (multi-) model generator in which the parametrical description of the product resides. It gets input from a concept generator and (re)generates the input for the analysis tools: the discipline silos. Typically, the discipline silos are commercial off-the-shelf analysis tools. The Knowledge Based Engineering tools reside in the concept generator.

Thus, the objective of this activity is to assess the feasibility of this approach for wind turbine design and to develop the knowledge needed to generate a DEE for this purpose. It is noted that the analysis tools in the discipline silos are external tools and are not part of the development undertaken in this activity. However, this activity will contribute to and make use of the common formats developed in this task, as these represent the interfaces between the model generator and the analysis tools. The reference turbine will be used as a case study.



Horizontally the scientific work packages are displayed and vertically the integration work packages.

SUBTASK C: DEVELOPMENT OF (PRE) STANDARDS FOR THE APPLICATION OF THE INTEGRAL DESIGN APPROACH

This subtask is dedicated to the development and formulation of standards in a broad sense, and for the application of the integral design approach of subtask B. Hence the subtask C aims at integrating the design models, experimental methods and concepts arising from the horizontal work packages.

SUBTASK D: INTEGRATION, REVIEW AND PLANNING WORKSHOPS

This subtask focuses on coordination and cross-cutting activities.

RESULTS AND EXPECTATIONS

So far cost functions for the components of the wind turbine, for which the input from parallel project activities is needed have been developed.

This WP works in close cooperation with the WP Upscaling (1B4).

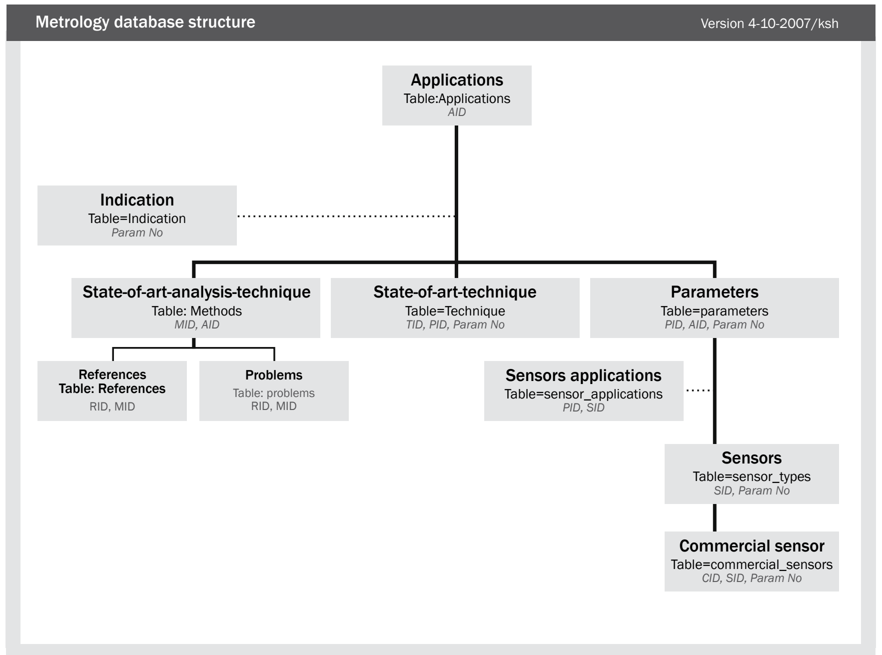
The final results of the work package include:

- Guidelines for the integral design approach, including guidelines for design models, experimental methods and concepts arising from the scientific WP's;
- Recommendations and pre-standards to be submitted for IEC/ISO and CEN/CENELEC for the revision or development of international standards for design and tests of wind energy systems.

RESULTS AND EXPECTATIONS

The objective of the WP Metrology is to develop ways to significantly enhance the quality of measurement and testing techniques for wind energy applications. The specifications of measurement systems become more and more severe as the sizes of the wind turbines increase, the project developers require more security of their investments (warranty of maximum performance during the wind turbine's entire lifetime) and the amount of investment increase.

Results of this WP can be downloaded from the UpWind website.



UpWind

SIXTH FRAMEWORK PROGRAMME

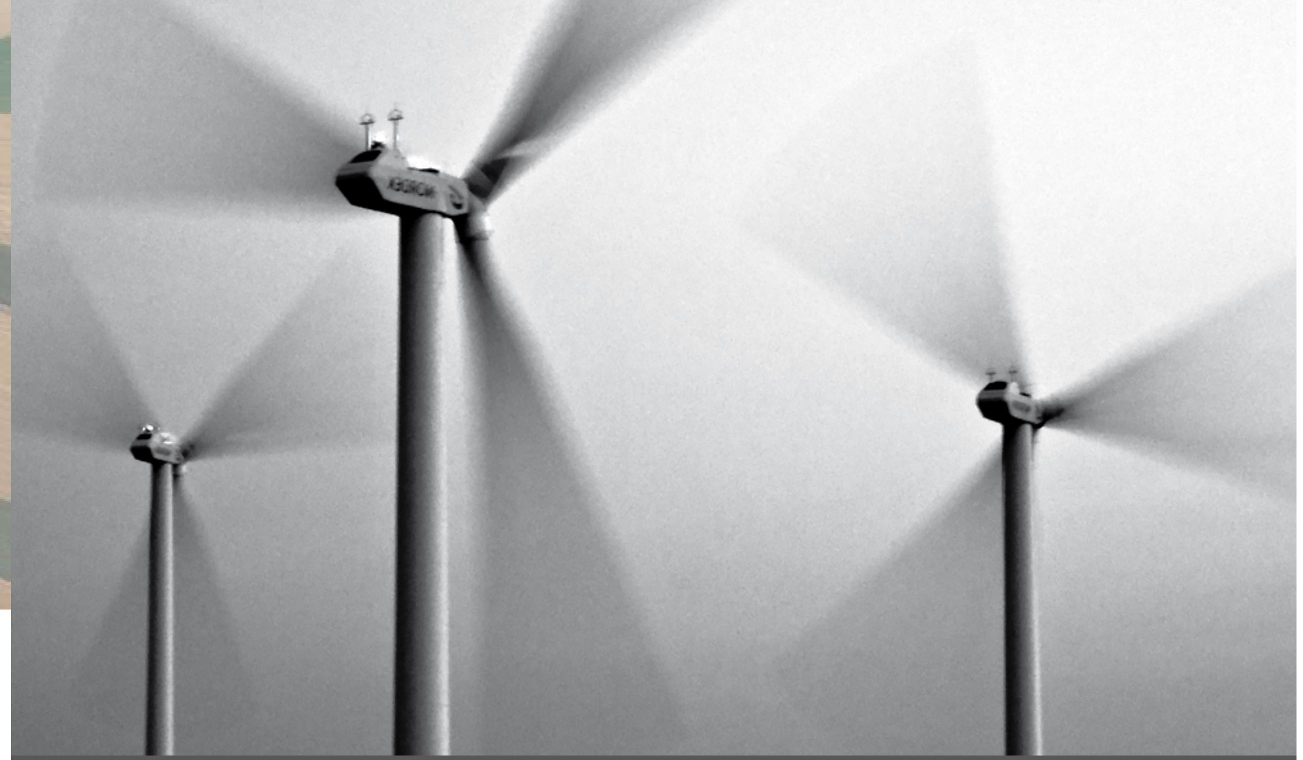
WP1A2 LEADER:
Dr. P.J. Eecen
Energy Research Centre
of the Netherlands (ECN)

EMAIL:
eecen@ecn.nl

WP MEMBERS:
- Energy Research Centre of the Netherlands (ECN)
- Risø National Laboratory – Technical University of Denmark (DTU)
- Centre for Renewable Energy Sources (CRES)

www.upwind.eu

Photography: THEMANS Pascal/DELPLANQUE Charles-EWEA



Metrology

THE CHALLENGE

The development of wind energy is hindered by measurement problems. Therefore, the metrology problems connected to wind turbine technology are the focus of this work package. In particular the fluctuating wind speed introduces large uncertainties as sensors, such as cup anemometers, often do not respond linearly. Wind fluctuations are experienced throughout the entire wind turbine. Loads are proportional to the wind speed squared and power to the wind speed cubed.

An example of a problem through measurement uncertainties is that it is almost impossible to confirm anticipated small performance improvements resulting from design modifications by means of field tests. As long as convincing field tests have not confirmed the actual improvement, the industry will be hesitant in investing in turbine design improvements.

The concept improvements resulting from the research activities of the UpWind project will require validation which is based on reliable and appropriate measurements.

THE RESEARCH ACTIVITIES

The first task towards a development of metrology tools in wind energy in order to significantly enhance the quality of measurement and testing techniques is the establishment of a list of parameters that need to be measured.

This has been done by:
- Identifying all relevant measurements within the wind energy community;
- Describing their definition in detail;
- Identifying all relevant influence parameters;
- Quantifying their systematic influence on measurements;
- Specifying traceability;
- Applying advanced uncertainty analysis methods.

The report that presents a state of the art assessment to identify all relevant measurements can be downloaded from the UpWind website. The required accuracies and required sampling frequencies are stated from the perspective of the users of the data.

The second task is to identify the state of-the-art measurement and analysis techniques together with the available measurement instruments. This analysis also addresses the possible attainable accuracies of the instruments and known operational behaviour.

UpWind

WP1A1
WP1A2
WP1A3
WP1B1
WP1B2
WP1B3
WP1B4
WP2
WP3
WP4
WP5
WP6
WP7
WP8
WP9

UpWind

SIXTH FRAMEWORK PROGRAMME

WP1A3 LEADER:
Dr. Charalampos Malamatenios
Centre for Renewable
Energy Sources (CRES)

EMAIL:
malam@cres.gr

WP MEMBERS:

- Centre for Renewable Energy Sources (CRES)
- Risø National Laboratory – Technical University of Denmark (DTU)
- Aalborg University
- Energy Research Centre of the Netherlands (ECN)
- Stichting Kenniscentrum Windturbine Materialen en Constructies (WMC)
- Technical University of Delft (TUDelft)
- National Technical University of Athens (NTUA)
- University of Patras
- Institut für Solare Energieversorgungstechnik e.V. (ISET)
- SWE University of Stuttgart

www.upwind.eu

Photography: ADELINO Oliveira-EWEA - Inmagine - Winter

Training and education

WP1A1
WP1A2
WP1A3
WP1B1
WP1B2
WP1B3
WP1B4
WP2
WP3
WP4
WP5
WP6
WP7
WP8
WP9

THE CHALLENGE

Further improvement and enlargement of wind turbines implies a deeper understanding of all aspects of the behaviour of the system, including aero-eleastic and structural effects, electrical grid connection and power quality issues, load control and partial load performance, as well as the environmental impact (acoustic noise emission, visual impact, impact on birds, etc.). Significant amount of research and development work has already been performed in this field. However, knowledge dissemination to all relevant users of these new insights is critical. Innovation as a means to make the wind energy technology more competitive will only take place efficiently, if SME's and students - as the future developers - have access to new knowledge through education and training.

The present situation concerning training and educational material is very diffuse. Quite a lot of materials are available but dispersed, they are not standardised for educational levels, not easily accessible, and different courses are overlapping to a great extent.

The specific objective of this work package (WP) is to realise a fully integrated approach, involving academic institutions, industry and research institutes, to provide a unique platform to improve educational materials with respect to content and structure, to avoid overlap and to match the educational contents to the users specifications.

A number of modules for international courses in the Wind Energy (WE) field, including their supporting training materials are being developed in order to provide a suitable vehicle for training of researchers and students on the one hand, and of energy consultants and project developers on the other. Results from the research carried out in the other work packages (WP's) of UpWind will be included in the educational materials, developed in this work package.

The target groups of UpWind training courses do already have basic knowledge in wind energy technology. It is not the aim to create basic training courses, but UpWind courses will rather build up on these level 1 courses (see figure below).

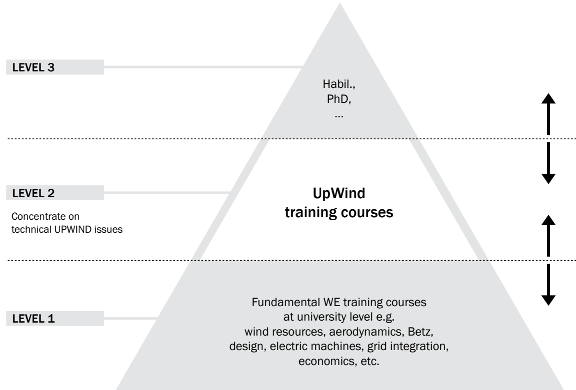


Figure 1: UpWind training is targeted to participants of levels 2 and 3.

UpWind

THE RESEARCH ACTIVITIES

The tasks of this WP include:

1. PRODUCING A SURVEY OF THE EXISTING INFRASTRUCTURE OF WIND POWER TECHNOLOGY-RELATED EDUCATION AND TRAINING IN ALL EU MEMBER STATES.

Information about existing WE education programmes was collected. The information was provided by higher education institutions, vocational training centres and other institutes active in the field. A list of these including the persons responsible for these courses was compiled.

Then, the needs of both the training organisations and the students they provide for (questionnaire survey) were examined. Issues that were discussed with the relevant course administrators included course content and duration, target student characteristics, student assessment methods, and recommendations for minimum skill levels.

2. ESTABLISHMENT OF A CONTINUOUSLY UPDATED DATABASE OF EDUCATIONAL/ TRAINING MATERIAL (THE WIND ENERGY INFORMATION AND EDUCATION NETWORK - WEIEN).

The information which is being gathered is processed by means of the hardware and software offered by the ReKnow.Net, (through ISET), a project sponsored by the German government.

The task further includes the development and continuous operation of the tools set at the disposal of WEIEN. It enables a feedback from the end-users of the modular trainings blocks (forum, database). This will allow a better identification of the needs for training as well as getting feedback on specific course elements (open source knowledge composition).

Further training experts and stakeholders who are interested in the training activities are being invited to join the WEIEN Area.

3. THE DEVELOPMENT OF A MODULAR APPROACH TO WIND POWER COURSE MATERIALS.

The common components of the existing curricula surveyed in the frame of task 1 were identified and the most essential ones have been selected to be used for the development of new curricula and training materials. Key issues were the determination of the specific training material which is required for the different groups of key actors (two levels) and the formulation of the course programmes accordingly as well as the decisions made about the specific modules which need to be developed or updated in order to be integrated into existing and new WE courses

4. PRODUCTION OF THE COURSE MATERIALS IN THE FORM OF INDIVIDUAL MODULES COVERING FOCUSED TECHNOLOGICAL TOPICS, INCLUDING RESULTS FROM UPWIND RESEARCH.

UpWind training modules will mainly comprise of scientific findings achieved in the UpWind project, e.g. concepts and solutions which will lead to a new state-of-the-art wind turbine technology. Existing material will be reviewed, revised and updated. In addition, new course materials will be developed for topics that have not already been covered before.

For each of the modules identified in task 3, three sets of coherent supporting material will be produced:

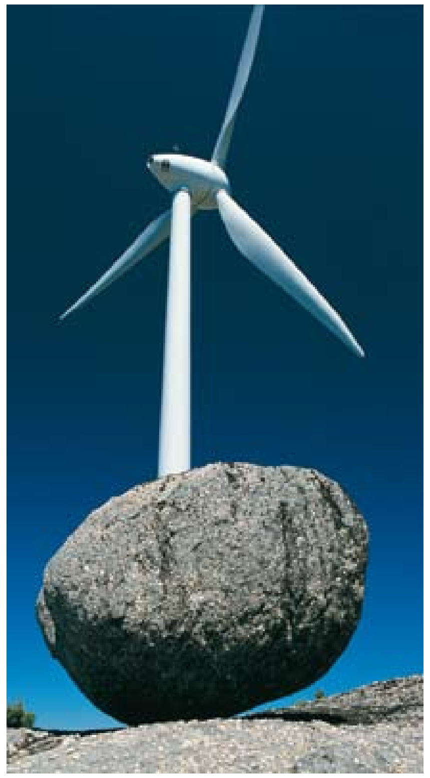
- training modules ready for incorporation into e-learning environments;
- presentations in the form of PowerPoint show files;
- students handouts and lecturers notes, with text for detailed information about each subject.

5. DISSEMINATION OF THE RESULTS OF THIS WP THROUGH PILOT TESTING OF TRAINING MODULES BY THE PROJECT PARTNERS.

The wind power course materials will be made available from the WEIEN e-database. There are a number of ways that will be used to disseminate the results/products of this WP:

- University status partners will use the modules developed in delivering courses to postgraduate students and lecturers from other universities they collaborate with;
- Non-university status partners will use selected modules developed herein to run workshops on the main topics of wind energy technology.

A detailed presentation of the products of this WP will be made available in a workshop that will address PhD candidates with an engineering background.



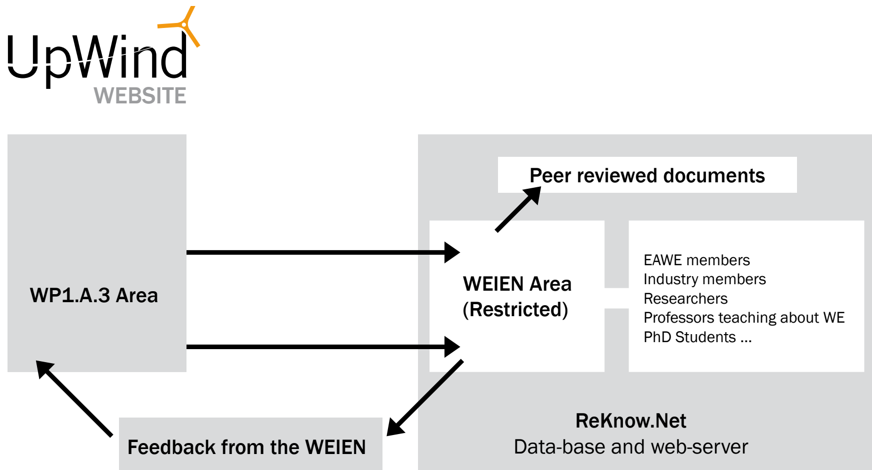


Figure 2: Interaction of the WEIEN (restricted area in ReKnow.Net) with the UpWind website

RESULTS AND EXPECTATIONS

A lot of preliminary material (in the form of guidelines, templates, etc.) was developed in the first stages of this work package. This helped the whole procedure related to the design of the course(s) modules in order to be of real use to this UpWind project WP's target groups.

So, apart from the detailed literature and web-based survey made for Task 1 of WP1A.3, a questionnaire based survey was also carried out, in the frame of which valuable information of WE trainings was collected from 43 respondents that have responded to the enquiry (representing course providers), forming quite an interesting overview.

In order to present in a more systematic way all the raw material on wind courses which has been collected, an on-line database of all relevant courses including all details such as education level, contents, duration, contacts, etc. was created. The title of the data base is: "Database of EU courses in the field of Wind Energy".

As regards the Wind Energy Information and Education Network – WEIEN (e-database), a restricted area within the ReKnow.net website has been created for the WEIEN members with all relevant functionalities of the ReKnow.Net website, specifically:

- A database for up- and downloading of documents;
- A forum for discussion;
- An "Open Source Knowledge Creation" tool (internal "Wikipedia");
- A peer-review process.

The work on WEIEN is a continuous process.

Also the resource guide of course modules to be developed within the WP has been finalised This includes the most essential of the common components of the existing curricula surveyed, as well as the specific modules that need to be developed or updated in order to be integrated into existing and new WE courses. This way, the detailed curriculum of a course that will lead to a PhD decree was formed (with topics, ways of presentation, required learning units, etc.).

Currently work is in progress for developing the comprehensive set of wind power training modules, single-issue presentations, self-assessment tools, handouts and lecturers notes, which could be applied for individual e-learning purposes but also as supporting material for existing or new courses.

Pilot applications of the different training modules in parts of courses for faster dissemination purposes will be carried out and workshops will be organised to present new wind power courses.

RESULTS AND EXPECTATIONS

The following results have been achieved:

- Main characteristics of the blade structure and joint section of the blade, including the associated maximum loads at this section;
- Study of the state of the art in sensor and monitoring techniques. Evaluation of different wireless alternatives;
- Blade functional specification that defines specific sectional blade design requirements, blade design implementation plan;
- Various alternatives for joining blades and trade-off matrix that supports the selection of the joint concept;
- Concept design of a blade root fairing element.

When the WP is finalised it is expected that the following achievements will be realised:

- Definition and assessment of blade requirements to be fulfilled by a sectional blade, evaluation of different concepts and materials for blade joints;
- Study of the dynamic behaviour and aero-elastic considerations for a sectional blade in operational conditions. Improvement of large blade aerodynamics by means of a blade root fairing device;
- Blade sectional design concept, which is fully validated;
- Wireless sensor monitoring system adjusted to a sectional blade. Viability study for monitoring the stress and strains in different areas and specifically at the blade joint. The design criteria will also include the evaluation of a possible integration within the blade in order to provide data over the lifetime of the blade.

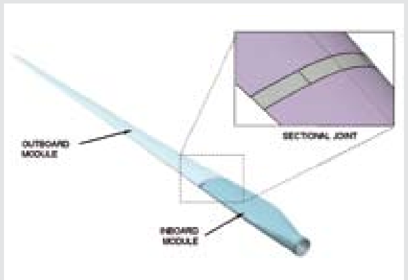


Figure 4: Blade preliminary design.

UpWind

SIXTH FRAMEWORK PROGRAMME

WP1B1 LEADER:
Dr. Maite Basurto
Gamesa Innovation
& Technology

EMAIL:
mbasurto@gamesacorp.com

WP MEMBERS:

- Gamesa Innovation & Technology
- Energy Research Centre of the Netherlands (ECN)
- Stichting Kenniscentrum Windturbine Materialen en Constructies (WMC)
- Technical University of Delft (TUDelft)
- Centre for Renewable Energy Sources (CRES)
- National Technical University of Athens (NTUA)
- University of Patras (UP)
- Fundación Robotiker

www.upwind.eu

Photography : ROEHLE Gabriele-EWEA - Vestas - Winter

Innovative Rotor Blades – Innoblade

WP1A1
WP1A2
WP1A3
WP1B1
WP1B2
WP1B3
WP1B4
WP2
WP3
WP4
WP5
WP6
WP7
WP8
WP9

THE CHALLENGE

During the last few decades the cost of wind energy has decreased, to a significant part due to component and system improvements in aerodynamics, materials and structures, at present reaching an almost constant cost per m^2 rotor swept area. Further cost breakthrough can only be achieved by introducing new innovative improvements.

Sectional blades will be required for multi-megawatt machines as the blade transportation cost over land increases for blades over approximately 46 meters length and even more dramatically for blades over 60 meters length. The transportation costs become prohibitive unless length is limited by splitting the blades. Thus, sectional blade means dividing one blade in sections in order to ease handling and transportation works and consequently will reduce costs.

This work package (WP) focuses on the design and validation of a sectional blade specimen aimed at global cost of energy reduction and larger turbines development. This blade will include all the new technological advances regarding blade design and manufacturing.

WP Innoblade focuses on the following specific objectives:

- Development of a concept for joining the sections of a sectional blade;
- Implementation of new aerodynamic and structural design features;
- Utilisation of innovative materials and processes;
- Advanced blade instrumentation and monitoring;
- Development of a fully modular blade concept.

UpWind

THE RESEARCH ACTIVITIES

The WP comprises of the following tasks:

AERODYNAMIC DESIGN AND LOAD CALCULATION

This task includes aerodynamics design, aero-elastic design and loads consideration, making use of current practice methodologies and innovative methods that are not yet commonly used, such as:

- Profile design for efficient energy production as a design option, in relation to the Sirocco project in which both Gamesa Innovation and Technology and ECN are involved. For an optimum design and performance, materials and structural design improvements will be considered;
- Contribution of aero-elastic analysis, with the results from FP5 projects Dampblade and Stabcon;
- Aerodynamics design taking into account blade deformation;
- The use of the blade joints and their effect on modal shapes;
- Integration of the control system in the aerodynamic design and loads calculation, considering blade monitoring and load mitigation strategies;
- Optimisation criteria and design optimisation procedures.

The application of such methods however entails certain risks and careful consideration are being made in selecting and applying these methods.

MATERIALS SELECTION, STRUCTURAL DESIGN AND STRUCTURAL VERIFICATION

This task includes two elements:

a) Materials Selection. In order to obtain a cost effective design, special effort must be made on appropriate materials selection, lay-out of the blade and laminates lay-up definition analysing the important parameters. Fundamental understanding and behaviour of materials, use of new

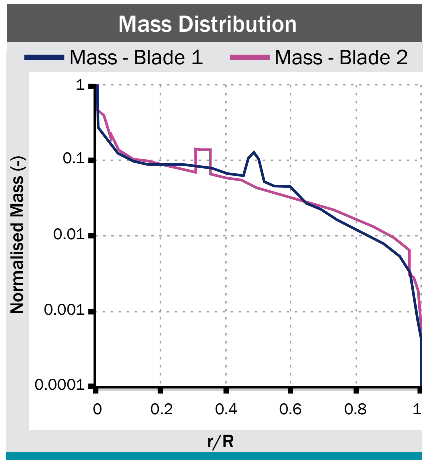


Figure 1: Sectional blade normalised mass distribution.

design tools based on extensive fundamentals knowledge of materials, usage of new databases for materials selection and consideration of tolerant design concepts in the specimen structural design are key activities.

The use of different types of joints, specifically metallic fasteners, adhesive joints between and composites are also considered. The evaluation of the behaviour of different combination of materials is assessed as well.

b) Structural Design and Structural Verification. From the structural point of view, this activity consists of a definition of the complete blade structure and preliminary study of a blade root fairing using the aerodynamic surface defined in the previous task and the type of material proposed. The preliminary assessment of the mechanical structure will show whether there is a need for cost increasing features like internal ribs, webs, stiffeners, bearing in mind the weight and special manufacturing processes.

SENSOR MONITORING WITH RESPONSE ACTIONS

This task is directed towards the achievement of a wireless sensor system specially designed to provide data about the behaviour of joints and modules during on field testing of the sectional blade concept.
The ultimate goal is to determine whether or not to integrate the wireless sensors in the blade, in order to provide data over the lifetime of the blade. Wireless communication and auto-feeding capabilities will be kept as constraints with the purpose of achieving a non-intrusive integration. A basic test campaign of a wireless system will be implemented in a blade to determine a further feasibility.

BLADE JOINT

This task consists of the development of the appropriate intermediate joint between composite laminates. It includes research on bonded or bolted joints, taking into account the complex stress states generated in the proximity to the joint. It also includes a study to evaluate the impact of the sectional joint in the blade mass and stiffness distribution, on blade aerodynamics and on blade dynamic behaviour to identify possible risks and constraints.

Different joint alternatives are considered and compared resulting in a trade-off matrix. The comparison is done, among others in terms of cost, weight, assembly, and modularity. Thus, the most appropriate joint concepts are preliminary sized in order to support a final decision for the optimum concept. As a complementary task the preliminary structural design of the section is to be completed in order to fulfil requirements like stiffness, weight and cost. Other important criteria such as failsafe concept, assembly and disassembly easiness, accessibility, reduced steps and other aerodynamic requirements, reduced maintenance schedule and leadtime, structural integrity, reparability, will be also regarded. A complete study will be performed for the integration of all the systems through the joint (lightning, sensors, draining, etc.).
The task includes a plan for validation of the joint concept.

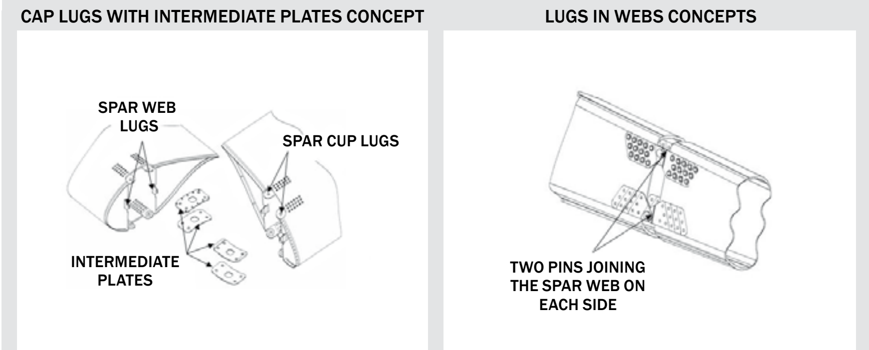


Figure 2: Different concepts used in the blade sectional joint trade-off decision matrix.

JOINTS AND MATERIAL TESTING

Joints and materials testing constitute a fundamental issue. In order to evaluate different joint alternatives and to support the selection of the one that best fits within this application, a campaign of subcomponents testing is to be carried out. This task includes static and fatigue tests for the different joint alternatives. This task will be followed with the blade specimen testing task described later on.

PROCESS / TOOLING

The sectional blade requires a thorough evaluation of innovative production technologies in order to select and implement the most appropriate one. This evaluation will be done by means of a comparison-matrix including different manufacturing process and materials selection. Other criteria such as assembly and disassembly easiness and maintenance will be kept in mind.

BLADE SPECIMEN MANUFACTURING

All the experiences and results obtained in the different tasks are to be integrated through the construction and validation of a blade design demonstration specimen. The aim of the blade specimen construction and testing is validation of the new concept.

BLADE SPECIMEN TESTING

The validation of the sectional blade is to be done not only by means of the subcomponent testing but also by means of a full-scale test. The full-scale test serves as the validation of the structural design.

Figure 3: Blade manufacturing and assembly assessment.

at the grid interface. The improvements on the harmonic performance are achieved on the expense of some additional circulating currents.

A fact common to all three topologies is that the highest conversion efficiency is achieved with the use of low voltage semiconductors. Out of the IGBT blocking voltage classes under investigation (1700V, 3300V and 6500V), the 1700V IGBTs offer highest conversion efficiency and lowest semiconductor losses. 1700V IGBTs can be operated at a higher switching frequency compared to 3300V and 6500V devices. This reduces the filtering requirements in order to comply with the applicable grid standards. However from the point of view of total system cost there is a tendency to aim at voltages as high as possible because transformer cost and conductor cost could be decreased.

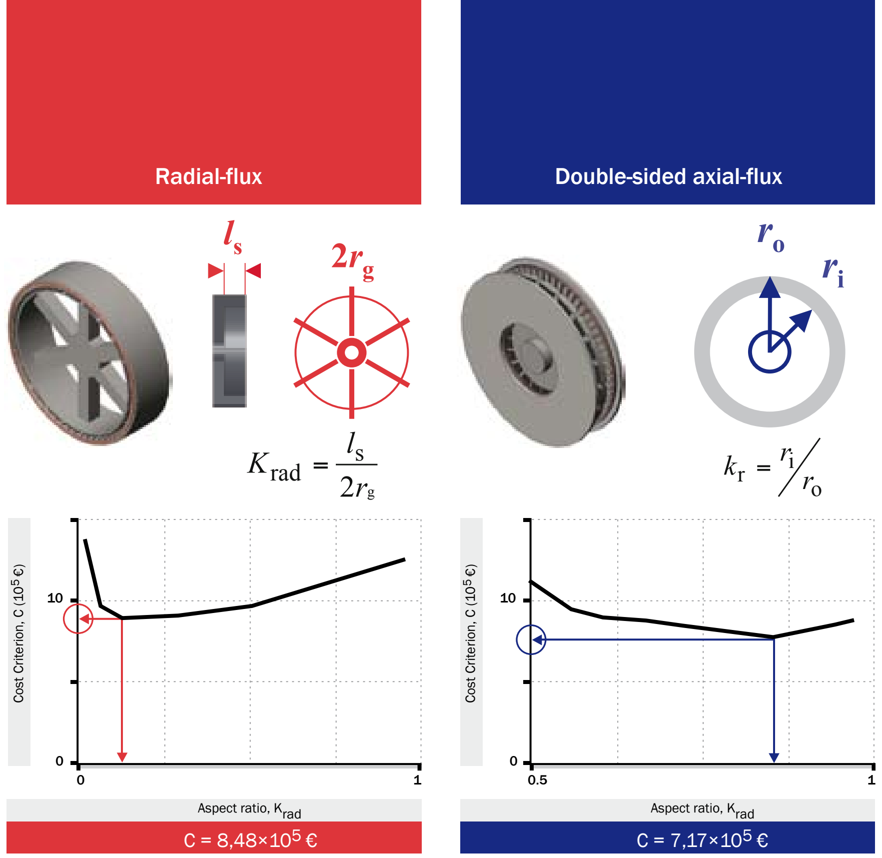


Figure 4: Simulation results for axial and radial flux PM machines.

UpWind

SIXTH FRAMEWORK PROGRAMME

WP1B2 LEADER:
Dr. Jan Hemmelmann
GE Global Research

EMAIL:
jan.hemmelmann@research.ge.com

WP MEMBERS:
- GE Global Research
- Aalborg University
- Technical University of Delft (TUDelft)
- University of Edinburgh
- RWTH Aachen University
- Bosch Rexroth AG
- SAMTECH S.A.
- Fundación Robotiker
- Institut für Solare Energieversorgungstechnik e.V. (ISET)
- Risø National Laboratory - Technical University of Denmark (DTU)

www.upwind.eu

Photography: MALBETE Francis-EWEA

Transmission and Conversion

THE CHALLENGE

This work package (WP) covers the entire drive train including mechanical and electrical components. The overall purpose is to develop the technology necessary to overcome the present limitations in turbine size, power and efficiency and to increase predictability and reliability. The WP is divided into the three sub-tasks: mechanical transmission, generators and power electronics.

THE RESEARCH ACTIVITIES; RESULTS AND EXPECTATIONS

MECHANICAL TRANSMISSION

In terms of reliability the drive train today is the most critical component of modern wind turbines. Nowadays the typical design of the drive train consists of an integrated serial approach where the single components, such as rotor shaft, main bearing, gearbox and generator are as close together as possible with the aim of compactness and mass reduction. Field experiences throughout the entire wind industry show that this construction approach results in many types of failures (especially gearbox failures) of drive train components, although the components are well designed according to contemporary design methods and all known loads. It is assumed that the basic problem of all these unexpected failures is based on a basic misunderstanding of the dynamic behaviour of the complete wind turbine system due to the lack of a ready-to-use integral design approach. This approach should simultaneously integrate the structural nonlinear elastic behaviour with the coupled dynamic behaviour of multi body systems together with the properties of electrical components. The following different system parts need to be addressed within one coupled "integral" model:

- Wind field simulation;
- Aero-elastic interaction at blades;
- Nonlinear flexibilities of fibre blades;
- Linear flexibilities of metal components of e.g. drive train;
- Nonlinear behaviour of drive train components e.g. gears, bearings, bushings;
- Electro-mechanic behaviour of generator;
- Electrical behaviour of power electronic converter and grid.

Within this WP three main issues for the construction of future large-scale wind turbines are addressed:

- In-depth and realistic simulation of the complete system behaviour for the design of reliable and cost effective components;
- Systematic analysis and test of gearboxes to ensure and verify a desired lifetime and at the same time reduce noise emission;
- Verification of common load assumptions for drive train design through long-term measurement technique and development of low-cost down counting technique of remaining drive train life-time due to actual measured stresses.

UpWind

To overcome the actual limitations in design and reliability, it is necessary to develop and verify new and enhanced simulation tools. A Multi Flexible Body Dynamics (MFBD) simulation tool based on the pre-existing non-linear Finite Element Analysis (FEA) code SAMCEF Mecano is used, adapted and verified for detailed analyses of drive train behaviour.

A customized Open Computer Aided Engineering software platform based on plug-in techniques for wind turbine application is also being developed. It contains the pre-defined or user defined models developed and validated during the project, with focus on drive train. Figure 1 shows the Graphical User Interface of this professional software environment that can also be used for various kinds of analyses and post-processing. It is open to be extended towards specialised computation software to cover the whole design process from concept level to detailed component analysis.

The tool and the model have to be validated by comparison with experimental results. Measurements have been taken on a 1.5 MW class turbine and compared to simulation results, with emphasis on drive train behaviour. It could be shown that specific behaviour of drive train components can be simulated, matching the observations. Figure 2 shows exemplarily the movement of the gearbox torque arms during an e-stop event.

Further enhancements to the multi-body simulation tools are studied with regard to gear mesh behaviour. Normally the gear stiffness (for MFBD) is defined as a constant value or an analytic function in dependency of time, but for detailed gearbox analysis these assumptions are too simplistic. It is proposed to use realistic time varying stiffness gained via FE-simulation. Using a 3D model of the gear also considering modifications of the teeth like e.g. crownings constitutes a challenge as well. Also it has to be expected that for different torques different stiffnesses do result. To take account of these boundary conditions the mesh stiffness shall be computed using tooth contact analysis software. Thus the mesh stiffness can be won in accordance to the applied torque, the rolling position of the gears and the gear deflection in a static mode. The challenge of this task is the coupling with the MBS model of the wind turbine. Figure 3 shows the proposed methodology for integrated tooth contact analysis.

Depending on the specific location of a wind turbine, the actual loads on the components can be quite different from the design loads. Therefore the availability of a long-term measurement technique is the necessary tool to provide load cycle analysis for all turbine conditions and for different turbine locations. The same technology can be used for development of a low-cost drive train load monitoring system, which enables to down-count the proposed and designed lifetime according to the actual measured load cycles. The measured load cycles for specific conditions will be compared to simulation results. Thus the commonly used assumptions for component design can be verified and enhanced towards future large-scale wind turbines. Preliminary simulations and measurements have indicated that there is a significant dynamic coupling between the generator and the wind turbine structure beyond the drive train, and that this coupling can cause oscillations in the drive train and tower. The interaction between the mechanical system and the generator will be studied further. The proposed drive train measurement system for long-time measurements will particularly use generator power and angular rotor speed with high accuracy both in time resolution and with appropriate dynamical performance. The aim is to demonstrate that the drive train conditions can be measured in a simple and robust way. In order to ensure sufficient bandwidth, the generator power is derived by measured 3-phase generator AC current and voltage.

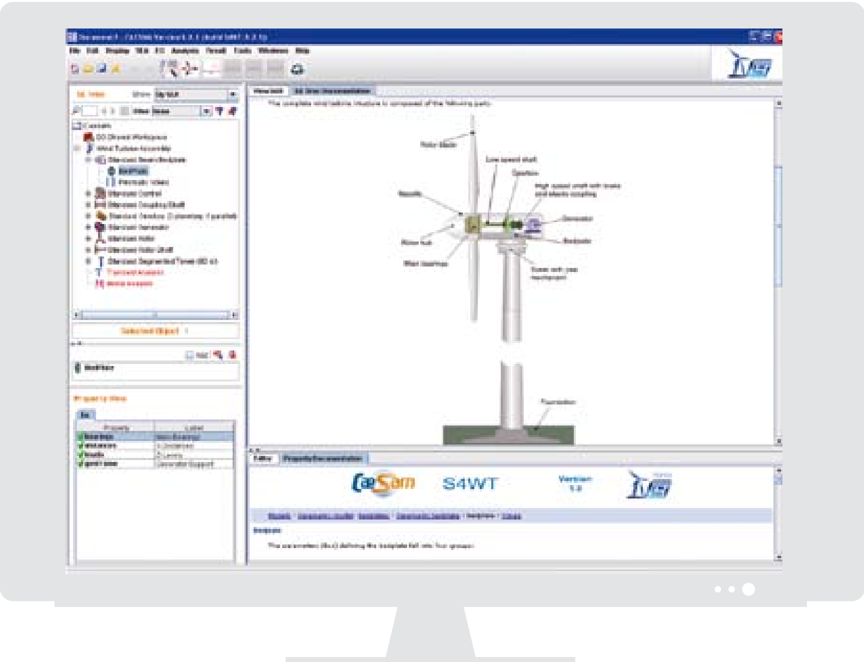


Figure 1: Graphical User Interface.

GENERATORS

The main objective of this task is to find the most suitable generator system for the wind turbine for the year 2020. Currently, there are three main generator systems used in wind turbines: constant speed with gearbox and squirrel cage induction generator, variable speed with gearbox and doubly-fed induction generators, and variable speed direct-drive generators without gearbox. Each concept has its typical weaknesses. A thorough comparison of these and other possible generator concepts based on cost models and energy yield models is the focus of this task.

During the last two decades, various wind turbine concepts with different generator systems have been developed and built to maximize the energy capture, to minimize costs, to improve power quality, and others. An overview of wind turbine technologies and a comparison of different generator topologies based on literature and market supply review has been performed. Secondly, promising direct-drive permanent magnet (PM) machines, which include the axial flux (AF), radial flux (RF) and transverse flux (TF) machines, have been surveyed in literature to find the most suitable generator type for direct-drive large scale wind turbines. The advantages and disadvantages of each type are investigated and discussed, and comparison of different generator topologies based on the technical data and market aspects have been mapped using appropriate comparison criteria.

Promising PM machines, such as AFPM, RFPM and TFPM, have been surveyed more in depth, as PM machines are more attractive because they possess higher efficiency and power-to-weight ratio compared to electrically excited machines. In case of RFPM machines, the electromagnetic design and optimisation with general topology have been discussed in a number of publications. It can be concluded that the machines are almost optimised electromagnetically, so that it is hard to reduce the active material weight and cost of the machines significantly. The disadvantages of the AFPM machine must be solved, because it causes the machine cost to increase and manufacturing to be difficult. TFPM machines also have disadvantages such as low force density in large air-gaps, complicated construction and manufacturing, and low power factor although the machines have advantages such as high force density and simple winding with low copper losses. However, in a number of publications, various topologies of TFPM machine have been proposed to solve or improve the existing drawbacks, since the machine is more flexible and attractive to design.

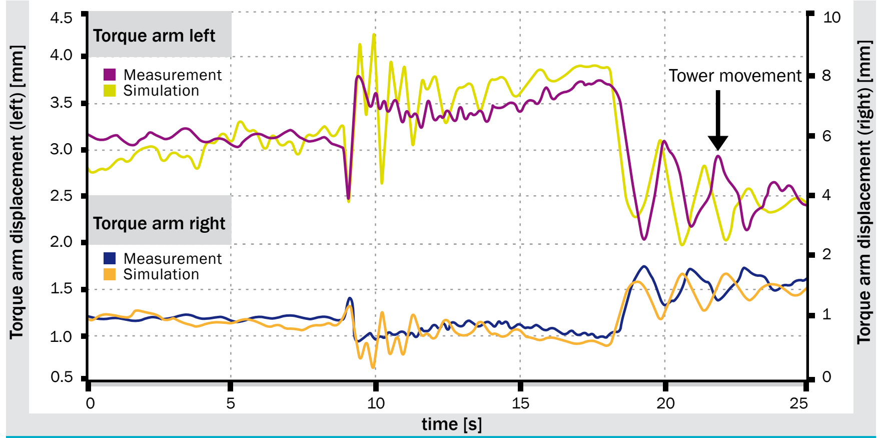


Figure 2: Torque arm displacement - longitudinal.

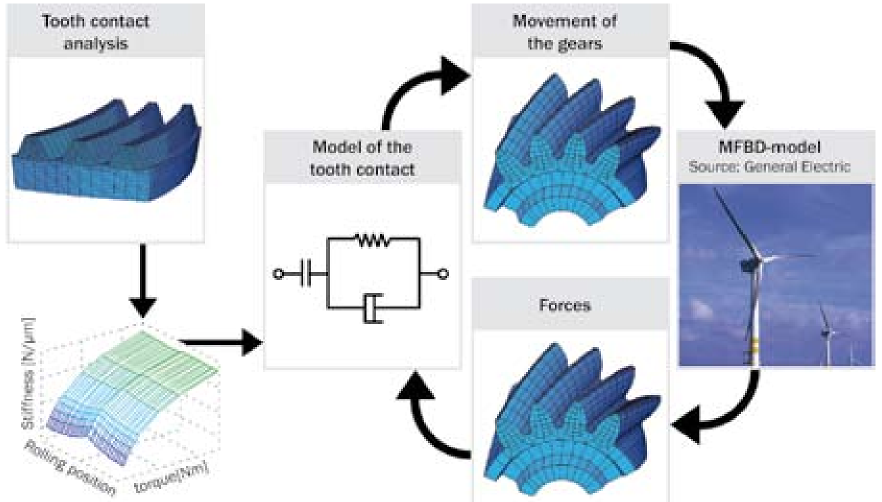


Figure 3. Methodology for integrated tooth contact analysis.

One aim of this task is to evaluate the most cost-effective wind turbine generator systems by applying design optimisation and numerical comparison. The following generator topologies were investigated: the squirrel cage induction generator, the doubly-fed induction generator, the electrically excited synchronous generator and permanent magnet synchronous generator. The fourth picture shows simulation results for axial and radial flux PM machines, with optimum choice of diameter to length ratio for lowest cost.

POWER ELECTRONICS

While acknowledging that doubly-fed induction generators are a sort of standard today, the UpWind research focuses on full converter solutions for synchronous generators. This project task anticipates the market pull for the second next level of offshore wind turbine power of around 5-7 MW. Three different approaches to increase the power rating to the required level will be analysed in detail. An example design per approach including power device selection, selection of switching frequency, filter design, efficiency curve, volume estimates and control scheme will be provided with the final report. These concepts comprise the matrix converter, the 3-level neutral point clamped (NPC) converter and the parallel interleaved converter. The concepts are benchmarked in terms of conversion efficiency, number of semiconductor devices and filtering effort.

As a result of the benchmarks it can be noted that all topologies are potential candidates for next generation wind turbines and can serve the desired power conversion rating. The matrix converter is the topology offering the most potential for future developments. Currently the lack of tailor made power semiconductors is a substantial drawback. The 3-level NPC is a well established converter topology for the desired output power range, and it supports different output voltage levels. The parallel interleaved converter topology provides very good harmonic performance

INSTITUTE OF PHYSICS, ACADEMY OF SCIENCES OF THE CZECH REPUBLIC (CZ)

At ASCR modeling and characterizing of shape memory alloys. Measurements which were performed include:

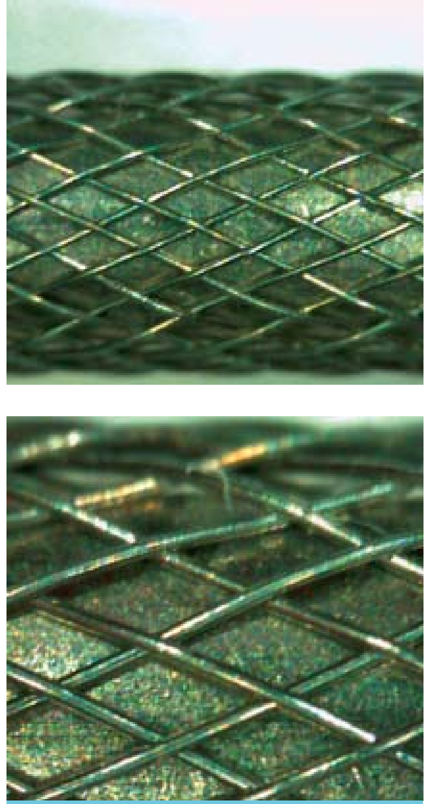
- Mechanical properties;
- In-situ electrical resistivity;
- Recovery stress tests;
- Fatigue properties.

Furthermore, a new SMA-based actuator has been developed.

Such a wire architecture was designed in order to meet the requirements on fast cooling of the actuator allowing to increase response time and actuation frequency. The use of this actuator design leads to an increase of actuator surface and hence it improves the cooling by convection. The thermo-mechanical properties of the actuator will be tested at IT ACSR.

RESULTS AND EXPECTATIONS

The project will provide at least one working concept for dynamic load alleviation and increased aero-elastic damping of a turbine blade. The concept must be able to significantly control the loads and be a low maintenance solution. This will be demonstrated in at least two experiments: one with a rotating rotor model of about two meter diameter. The primary goal of this demonstrator is to show that the dynamic loads can actually be mitigated. A second, non-rotating, experiment will be conducted on a blade section that is of the same order of magnitude of a full sized blade section (in cord and thickness) and several meters wide. The goal of this demonstrator is to show that the integrated actuators can sufficiently change the aerodynamics around the section to achieve the performance on a full scale blade demonstrated in the rotating experiment. Beside this, several experiments will be conducted on noise and the smart blade-hub coupling and aero-elastic models of blades and turbines with load control will be developed. For now, the partners have chosen to focus on trailing edge flaps and camber control as aerodynamic devices, as well as bend-twist coupling and the active blade-hub interface as other load alleviation devices.



Picture (top) and close-up (bottom) of a novel SMA-wire actuator.

UpWind

SIXTH FRAMEWORK PROGRAMME

WP1B3 LEADER:
Dr. Harald Bersee
Technical University Delft,
The Netherlands (TUDelft)

EMAIL:
H.E.N.Bersee@lr-tudelft.nl

www.upwind.eu

WP MEMBERS:

- Technical University Delft, The Netherlands (TUDelft)
- Risø National Laboratory – Technical University of Denmark (DTU)
- Energy Research Centre of the Netherlands (ECN)
- SWE University of Stuttgart
- LM Glasfiber A.S.
- Fundación Robotiker
- Technical Research Centre of Finland (VTT)
- Instytut Podstawowych Problemow Techniki (IPPT)
- Institute of Physics, Academy of Sciences of the Czech Republic

Photography: EWEA - Vestas

Smart rotor blades and rotor control

THE CHALLENGE

Almost all loads on the components of the wind turbine are derived from the loads at the rotor blades. Therefore it is very important to keep these loads as low as possible and to control them as much as possible.

Modern rotor control technology has its limitations: only the rotor speed, and the pitch angle of the blades can be varied. With the increasing size, the local angle of attack of the blade may vary considerably because of the effect of varying wind speeds along the blade due to turbulence, wind shear and other effects. So, for large blades it does not make sense to pitch the blade as one single rigid piece as has been the case until now. A much more detailed control is necessary to alleviate blade loads, to control them at any moment and any position in the rotor plan, and to add aerodynamic damping when necessary. To achieve this, the blades will be equipped with aerodynamic control devices distributed along the span of the blade. Airplanes have similar devices: the flaps at the wings.

The specific objectives are to obtain lower loads and to improve stability. The stepping stones towards a full concept are to:

- establish the potential of embedded control by aerodynamic/aero elastic analysis;
- specify the requirements of the sensors, actuators and control equipment, to select the most promising options and verify them by means of component-prototypes;
- develop and verify design codes (models) for the aerodynamic & control aspects of composite structures including smart materials;
- verify the load alleviation and increased stability by wind tunnel experiments;
- verify the robustness of the construction, by the design and the construction of a representative part of a blade;
- verify the aerodynamic performance of this blade section by non-rotating tests in a wind tunnel.

This R&D programme builds on many disciplines. These include aerodynamics and aero-acoustics, adaptive materials and dynamics and control. As such, this programme constitutes an integrating, multi-disciplinary approach.

An additional challenge is to develop the technology which needs to be maintenance-free, extremely reliable during a very long time, and low cost.

UpWind

THE RESEARCH ACTIVITIES

The research activities are being carried out by eight different institutions, each with a specific task based on their specific scientific skills.

DELFT UNIVERSITY OF TECHNOLOGY (NL). AERODYNAMIC LOAD CONTROL EXPERIMENTS, AERO-ELASTIC MODELLING AND ACTUATOR DESIGN.

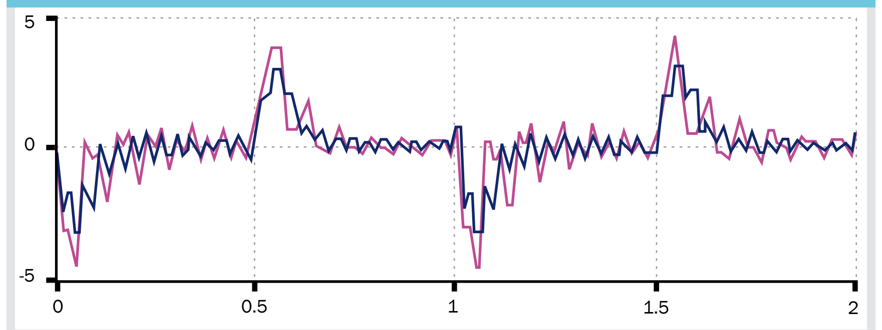
In order to realistically evaluate the potential for load reduction and benchmark design concepts, first order wind tunnel experiments have been performed. The design of the blade was performed within several strict design constraints: high strength, low eigen-frequency and limited geometric possibilities (thin aerodynamic profile). The blade was constructed out of glass fiber reinforced epoxy (GFRP) because this would allow for precise tuning of the mechanical properties. The blade was equipped with piezo electric activated continuously deforming trailing edge flaps in the outboard section and active feedback control was applied for the alleviation of fluctuating loads. It has been shown that strains on the blade root induced by dynamically scaled excitations can been considerably reduced by applying feedback control on the flaps motion. This comprises a novel result in feedback control, which provided necessary knowledge for future experiments on actually rotating model rotors.

Test set-up of the load mitigation experiment at TUDelft.

Models able to evaluate the potential for load reduction in smart rotor control have been developed. The aero-servo-elastic model, which was developed, serves as a prediction tool, but also as a controller design platform.

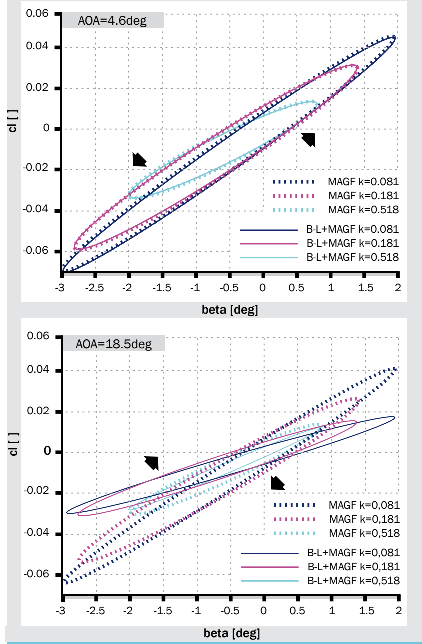
In establishing a knowledge base, an evaluation of the available adaptive materials was performed. Adaptive materials in this case are described as materials which show a mechanical response under a non-mechanical stimulus, and can thus act as embedded actuators. Shape memory alloys (SMA) and piezo electric materials are identified as the adaptive materials with most potential.

Strain at the root of the blade as a result of a step on the angle of attack.
When comparing the response with feedback control (blue line) to the one without control (red line), a lower peak and faster decay of the vibrations can be observed with control.



RISØ NATIONAL LABORATORY (DK). AERODYNAMIC MODELS FOR AEROFOILS WITH DEFORMABLE CAMBER

At Risø, modelling as well as experiments into the unsteady aerodynamics for aerofoils with adaptive camber lines, has been performed. The most recent work performed has been on the performance of airfoils with deformable trailing edges with trailing edge separation. The results were compared with previous experiments.



ΔCL loops as function of β for AOA at 4.6º (left) and 18.5º (right). The trailing edge deflection β ranges from -3º to 1.97º for reduced frequency k=ωc/(2Uo)=0.081, for β= -2.8º to 1.3º the k=ωc/(2Uo)=0.181 and finally for β = -2º to 0.76º the k=ωc/(2Uo)=0.518.
Arrows indicate the orientation of the loops in time.

ENERGY RESEARCH CENTRE OF THE NETHERLANDS -ECN (NL). SYNTHETIC JETS

ECN focuses on the aerodynamic performance of synthetic jets and assists in the aero-elastic modelling of turbines. With synthetic jets, air is sucked in, and blown out at the blade's surface at a very high rate. This creates an obstruction for the flow in the boundary layer which is jetted away from the surface, thus changing the circulation and thus the lift, for a low drag penalty.

UNIVERSITY OF STUTTGART (D)

At the University of Stuttgart two separate branches of research are conducted. At the Endowed Chair of Wind Energy (SWE), the feasibility of a bend-twist coupled blade is researched and at the Institute of Aerodynamics and Gas Dynamics (IAG) the noise generated by aerofoils with both rigid flaps and deformable camber line are being researched, as well as the quality of the boundary layer. The first results on noise indicate that there is little difference between the two.

FUNDACIÓN ROBOTIKER (E)

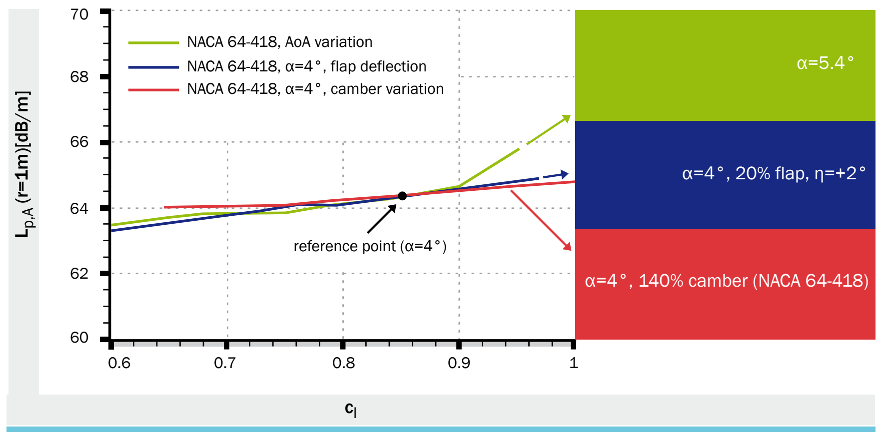
Fundación Robotiker develops and analyses control concepts and sensors. In the first phase of the activities an overview of the different available sensor systems and considerations has been made.

VTT TECHNICAL RESEARCH CENTRE OF FINLAND (SF)

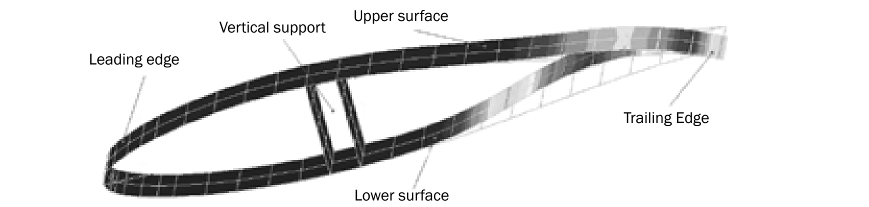
At VTT the continuous deformable camber line concept is being implemented in an aerofoil that is actuated by embedded shape memory alloy wires.
An adaptive wing profile was designed, manufactured and tested. New tools for designing and manufacturing of SMA actuated FRP composite structures were developed and demonstrated. The performance of the system was measured in laboratory conditions and also in wind tunnel. The developed control system works accurately enough for the shape control purpose of the airfoil in laboratory conditions. The changes in lift obtained are very large.

INSTYTUT PODSTAWOWYCH PROBLEMOW TECHNIKI -PAN (PL)

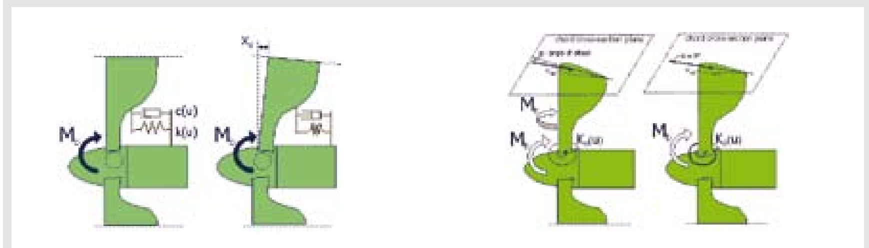
At IPPT a smart blade-hub interface is being researched. The first aim was to obtain a concept whereby the blade would alleviate peaks in the root bending moment by allowing itself to tilt backwards when a gust hits. Later, a concept where the blade were allowed to pitch, thus changing the angle of attack and the aerodynamic loading, was added.



Noise generated by a baseline, a discretely rotated flap and a continuously deformable trailing edge flap (camber variation).



FE model and test set-up of a aerofoil with embedded SMA wire actuated camber control.



Active blade-hub interaction though tilting (left) or rotating the blade (right).
With the second, rotating is done around the longitudinal axis of the blade, changing the angle of attack. In both cases the stiffness of the interface is controlled.

UpWind

SIXTH FRAMEWORK PROGRAMME

WP1B4 LEADER:
Mr. Ben Hendriks
Energy Research Centre
of the Netherlands (ECN)

EMAIL:
hendriks@ecn.nl

WP MEMBERS:

- Energy Research Centre of the Netherlands (ECN)
- Risø National Laboratory – Technical University of Denmark (DTU)
- Centre for Renewable Energy Sources (CRES)
- Gamesa Innovation & Technology
- Garrad Hassan and Partners Ltd
- Stichting Kenniscentrum Windturbine Materialen en Constructies (WMC)
- LM Glasfiber A.S.

www.upwind.eu

Photography: ROEHLE Gabriele/BENOIST Laure/LECŒUR Pacal-EWEA

Upscaling

THE CHALLENGE

The wind turbine market has grown rapidly and so has the capacity of the wind farms and the size of the wind turbines. During the last 2 decades wind turbines have grown in capacity from 250 kW to 5000 kW and in size from a 25 m rotor diameter to over 125 m respectively.

This work package (WP) targets at research and technology needs for successful upscaling of wind turbines, while securing reliability. For this the optimum technology and economics of future wind turbines, varying in size and concept and for various applications, need to be analysed.

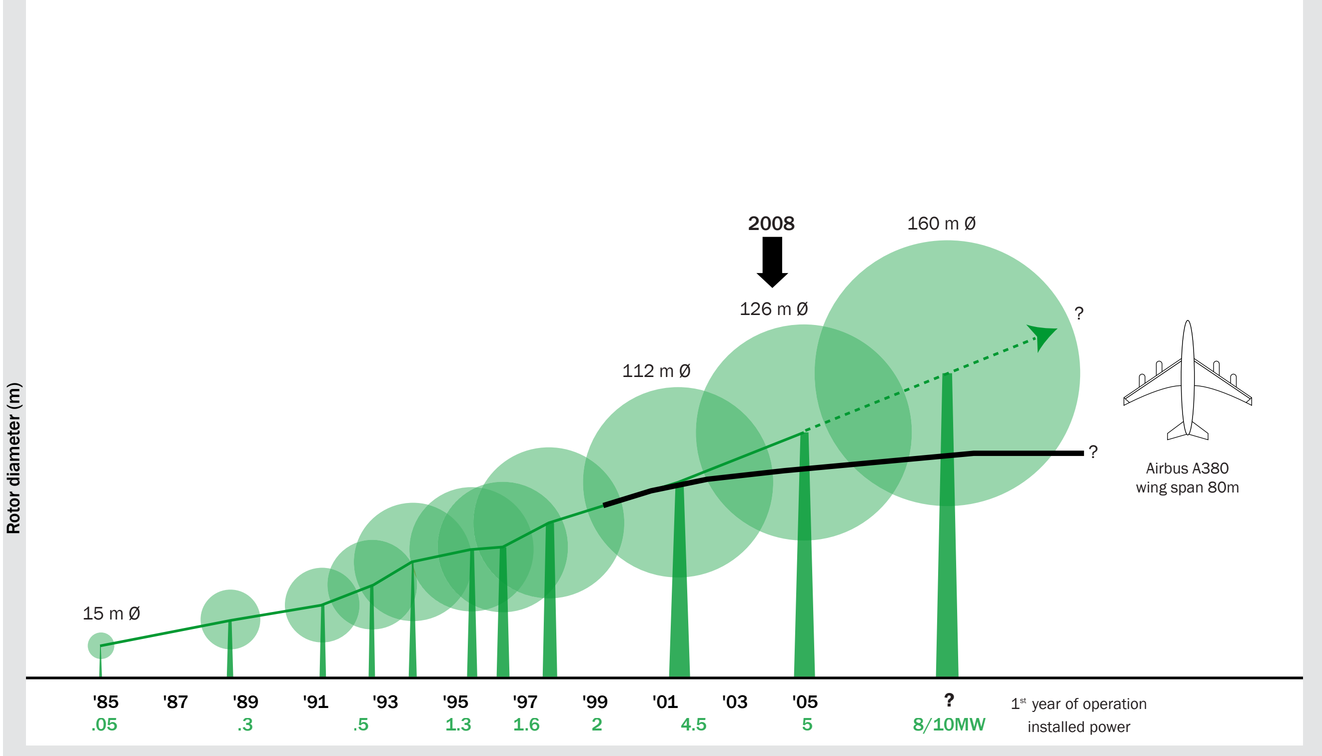
For land application transport, installation and siting limitations might limit the maximum size of wind turbines to a lower value than wind turbines for offshore applications. For offshore the cost structure of wind farms, dominated by the cost of support structures and foundations, requires wind turbines to be as large as possible.

With the growing size of the turbines the technology has developed equally rapid. Constant speed, stall controlled machines with fixed blade pitch equipped with induction generators directly connected to the grid have dominated the market in the early days. Nowadays these are no longer produced. Variable speed turbines with individual blade pitch systems which are connected to the grid via power electronics are main stream.

For further growth of the wind turbine market, in particular for offshore applications, the development of larger machines than those which are now being used is a necessity.

The largest prototypes of wind turbines have a diameter of slightly over 125 metres and a rated power of over 5 MW. The uncertainty about the maximum physical dimensions achievable and installable depend on load mitigation, controllability, and innovative materials.

UpWind



OBJECTIVE

The objective of the WP Upscaling is to identify R&D needs for the expanding future market of large scale machines.

Three parameters will be analysed in this respect: ex-factory cost, transportation, installation and operating and maintenance cost, design limitations. Based on scaling trends and cost models, component and total system "ex-factory" cost will be estimated.

Evaluation of transportation, installation, operating and maintenance costs will indicate the economics of wind energy for very large turbines of present day technology.

The outline design, based on scaling trends and experienced engineering judgement and cost analysis of a 20MW wind turbine will reveal major problem areas in up scaling present day design concepts.

Fundamental technological barriers will be identified. It will probably show that new, disruptive technology must be developed to design very large machines of around 20 MW installed power.

THE RESEARCH ACTIVITIES

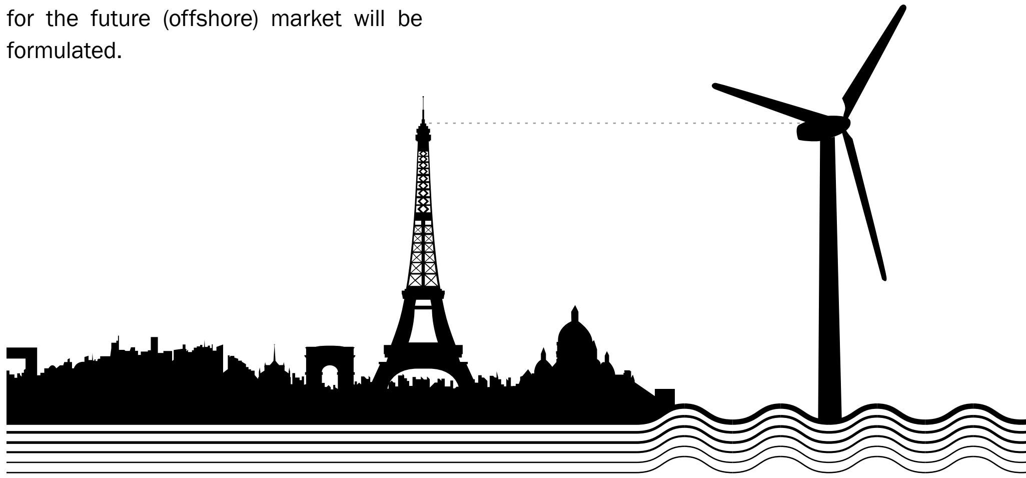
Based on a systematic analysis of the growth in the scale of wind turbines over the last two decades, this task will involve the development of scaling trends to characterize key design parameters as a function of turbine size. Such parameters will include the mass, capacity and cost of major components as well as the complete turbine system, cost per rated kW, and cost per unit rotor swept area. The scaling trends will be used to outline a 20 MW design. For this the scaling trends will be applied to a reference wind turbine. The reference wind turbine is an artificial wind turbine representative for the present largest machines on the market i.e. 5 MW rated power, 125 m rotor diameter, 3-blades, variable speed and power control by pitch to vane. A critical assessment of the upscaled design will be undertaken

in order to determine the engineering feasibility, cost implications, investment risks and overall fundamental barriers, as concerns technology, design tools and concept, which might prevent such large scale wind turbines. The identified barriers may be related to the cost of energy, the manufacturing process, the installation process, the structural integrity, etc. The identified barriers can be used to give direction to the future long term research activities. The results from economic analyses and the conceptual evaluations can be used to inspire the development activities of industry. An iterative procedure is foreseen in which new designs will be proposed to cope with the barriers.

In parallel with the upscaling of a reference wind turbine with a state-of-the-art concept, other promising concepts for the future market are being investigated. For the offshore market the ease of installation and maintenance and the robustness of the design are far more important than for onshore. The typical offshore design drivers are likely to result in quite a different optimum concept from present common technology.

RESULTS AND EXPECTATIONS

The final result of this WP will include a description of the upscaling process and the identification of major barriers, including an outline design and a cost analysis of a 20 MW wind turbine. The technical and fundamental barriers affecting the development of very large wind turbines are being identified and the developments needed to overcome these barriers will be formulated. Additionally, a vision on promising concepts for the future (offshore) market will be formulated.



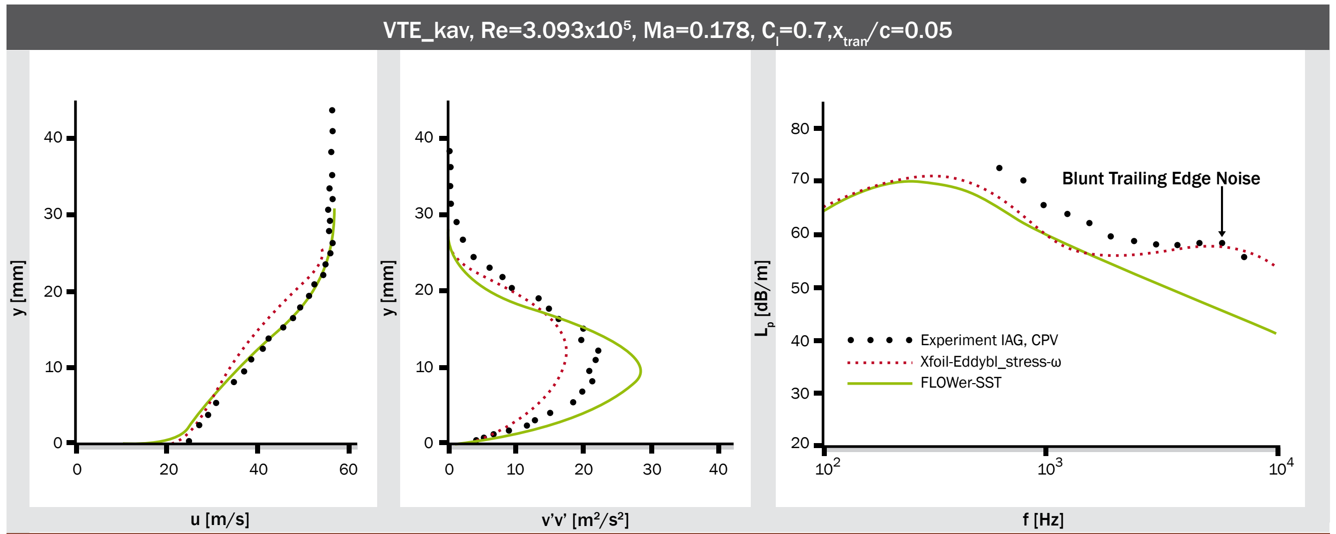


Figure 5: Boundary layer measurements and trailing edge noise on an airfoil compared to predictions.

Results achieved so far:
A RANS based CFD flow solver together with an appropriate turbulence model is coupled with the noise prediction scheme and first validation results are depicted in Figure 5. The detailed boundary-layer experiments have been conducted in the LWT at IAG, and comparison studies are carried out on the calculated noise source parameters and total noise spectra. The CFD computations are performed with isotropic Shear-Stress Transport (SST) two equation turbulence models. Encouraging results are obtained. New detailed BL measurements are ongoing.

RESULTS AND EXPECTATIONS

The final outcome is a design-basis consisting of tools and methods for aerodynamic and aeroelastic design of future large multi-MW turbines covering possible new and innovative concepts.

A summary of the results achieved so far includes:

- Bending-torsion coupling is important;
- Inflow shear is non-trivial and creates phase shifts;
- Dynamic stall models for the variable trailing edge concept has been developed and applied for aeroelastic predictions;
- Stability analysis including nonlinear effects (and structural modal damping prediction) has been performed;
- Noise prediction: Boundary layer predictions and measurements.

SIXTH FRAMEWORK PROGRAMME

WP2 LEADER:
Flemming Rasmussen
Risø National Laboratory
for Sustainable Energy
– Technical University
of Denmark (DTU)

EMAIL:
flemming.rasmussen@risoe.dk

WP MEMBERS:

- Risø National Laboratory for Sustainable Energy – Technical University of Denmark (DTU)
- Energy Research Centre of the Netherlands (ECN)
- Technical University of Delft
- Center for Renewable Energy Sources (CRES)
- National Technical University of Athens (NTUA)
- University of Patras
- SWE University of Stuttgart
- Garrad Hassan and Partners Ltd

www.upwind.eu

Photography : Feindate

Aerodynamics and aeroelastics

THE CHALLENGE

The overall objective of this work package is to develop an aerodynamic and aeroelastic design basis for large multi-MW turbines to facilitate the further development of multi-MW turbines, including new concepts.

The specific objectives of this work package (WP) are:

- The development of structural dynamic models for the complete wind turbine or components that can handle highly nonlinear effects e.g. from flexible blades with complex laminated composite and composite sandwich skins and webs;
- The development of advanced models on rotor and blade aerodynamics, covering full 3D CFD rotor models, free wake models and improved BEM type models;
- The aerodynamic and aeroelastic modelling of aerodynamic control devices;
- The development of models for analysis of aeroelastic stability and total damping;
- The development of models for computation of aerodynamic noise in order to design new airfoils and rotors with reduced noise emission.

The continuous upscaling of wind turbines towards multi-MW turbines has several fundamental implications on the aeroelastic modelling of the wind turbines. In general, the flexibility of the wind turbine structure increases so that more eigen frequencies coincide with peaks in the aerodynamic load input. Also, self induced loads from the eigen motion and flexibility of the wind turbine structure increases. The influence from elastic torsion of the blades of present MW turbines already amounts to 2-3 deg.

An increasing contribution of self-induced loads is one of the results of the upscaling of flexible constructions. Also an increasing part of the natural turbulence structures are comparable with the rotor diameter so that considerable difference in inflow velocity over the rotor disc is observed. This again leads to bigger variations in dynamic induction over the rotor disc.

Active control of aerodynamic loads becomes more important in order to reduce loads and increase stability. This is due to the increasing variations in loads over the rotor disc and the increased dynamic loading from eigen motion of the turbine. It is possible to apply "smart material devices" that can change the local shape or the structural characteristics of a blade segment.

The prediction of total damping for a wind turbine under varying operational- and external conditions, is crucial for the development and optimization of large stable wind turbines. The total damping consists of the aerodynamic- and structural damping in combination with the control actions and for an offshore turbine, the hydro-elastic damping of the foundation. The challenge is to further develop damping predictions in order to reflect on the needs arising from the upscaling of wind turbines.

Aerodynamic noise is an important design parameter in the development of new wind turbine rotors and the constraints on maximum allowable noise often increase the cost of the rotor due to limitations of the tip speed.

THE RESEARCH ACTIVITIES

The work has been divided into five tasks. The research of the first part of the project is focused on:

- Quantifying the importance of nonlinear structural effects on loads and stability;
- Improving modeling and including effects of shear-coupling and large deformation into beam models and finite elements;
- Verifying and developing engineering aerodynamic models by application of full 3D unsteady CFD models in complex inflow such as strong wind shear;
- Overviewing requirements to aerodynamic and aeroelastic design tools in order to analyse the potential of different advanced control features and aerodynamic devices;
- Developing concepts to improve the link between CFD and aeroacoustics predictions.

WP 2.1 STRUCTURAL DYNAMICS-LARGE DEFLECTIONS AND NONLINEAR EFFECTS

Status:

- The flexibility increases by upscaling to multi-MW;
- Eigen frequencies coincide with peaks in the aerodynamic load input;
- Self induced loads increases (influence from elastic torsion can be 2-3 deg).

Results achieved so far:

Assessment of the important nonlinear couplings is performed by means of nonlinear aeroelastic simulations on the 5 MW reference wind turbine (a reference machine defined within IEA WE programme) which are compared to those of a conventional 1st order beam model. Through these comparisons, the effect of various nonlinear higher order structural couplings is quantified. Certain nonlinearities - especially those related to the coupling of the blade torsion with the blade bending - are of great importance and should be taken into account in the modeling of large flexible blades. This is illustrated in Figure 1, which shows, that the tip pitch is up to about one degree different due to nonlinear effects.

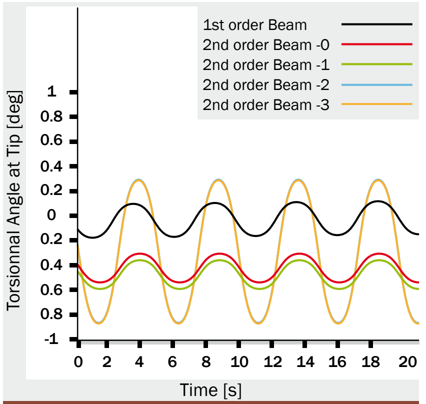


Figure 1: Predicted torsional deformation of blade (5 MW) by beam model taking different nonlinear effects into account.

WP 2.2 ADVANCED AERODYNAMIC MODELS

Status (upscaling):

- Unsteady loading now depends on the actual modal forms of vibration;
- Unsteady aerodynamics is essential for load prediction as well as stability;
- Considerable difference in inflow velocity and variations in dynamic induction over the rotor disc;
- Shear effects become important.

Results achieved so far:

Computations with different models have been performed for the case of a strong wind shear in the rotor inflow for a MW wind turbine. The results from advanced CFD models are illustrated in Figure 2a. These computations show that there is an unexpected phase shift which causes the blade loads to be different in the horizontal position depending upon whether the blade is on its way up or down. This means that the wake is skew in the horizontal plane – a phenomenon that is not taken into account in the usual BEM codes. This is further illustrated in Figure 2b, where the blade's normal forces for the two positions (90 and 270 degrees azimuth) are given for different calculation methods.

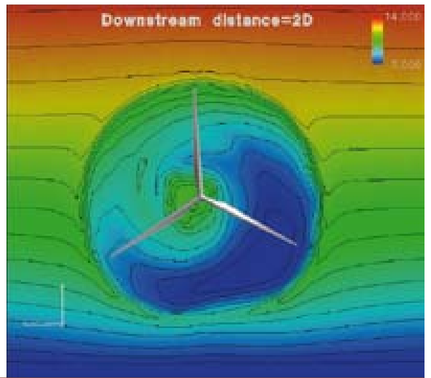
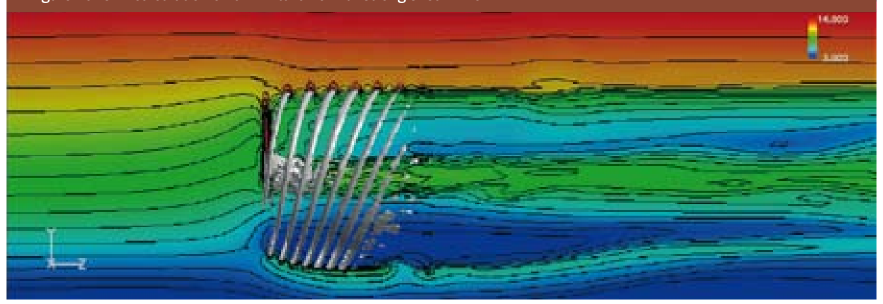


Figure 2a: CFD-calculation on a MW turbine with strong shear inflow.



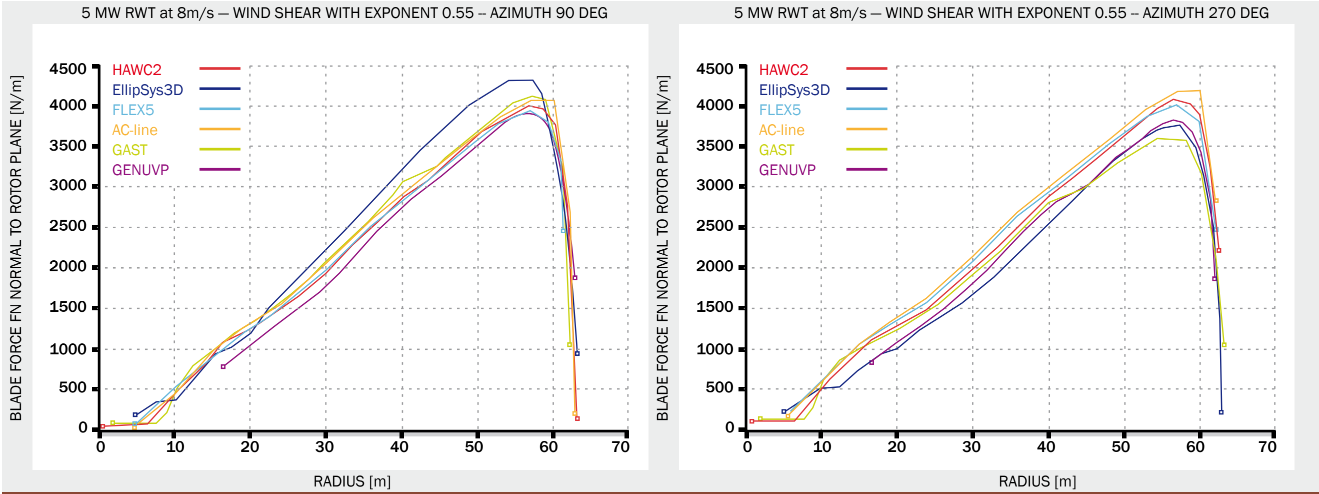


Figure 2b: Predicted blade axial force at 90 and 270 degrees azimuth by different models

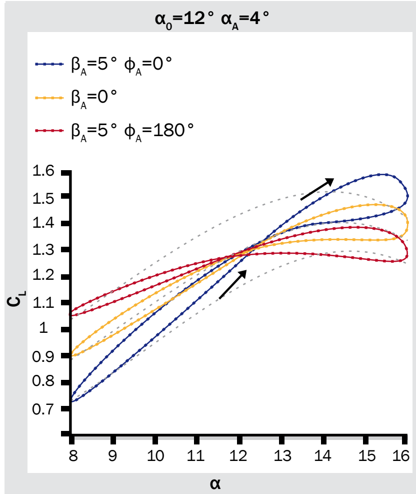


Figure 3: Dynamic stall loops for a pitching airfoil with a cyclic trailing edge deflection.

WP 2.3 AERODYNAMIC AND AEROELASTIC MODELING OF ADVANCED CONTROL FEATURES AND AERODYNAMIC DEVICES

Status:

- Potentials in active control of local aerodynamic loads;
- Potentials in active control of local structural characteristics.

Results achieved so far:

Focus has been on the development of unsteady aerodynamic models for the simulation of a variable trailing edge flap that can be incorporated in aeroelastic simulation tools to identify the potentials with respect to load reduction or power enhancement by application of this concept for large MW turbines. How one model works is illustrated in Figure 3, which reflects the effect of a combined pitching motion of an airfoil with a trailing edge flapping movement at different phases corresponding to a changing camber line. The trailing edge flap movement can either increase or decrease the lift curve slope depending on the phase, and is thus an efficient way to control the loading on a blade.

WP 2.4: AEROELASTIC STABILITY AND TOTAL DAMPING PREDICTION INCLUDING HYDROELASTIC INTERACTION

Status:

- Development of aero-servo-elastic stability tools was performed in STABCON project;
- Need for aero-servo-hydro-elastic stability tools and design guidelines.

Results achieved so far:

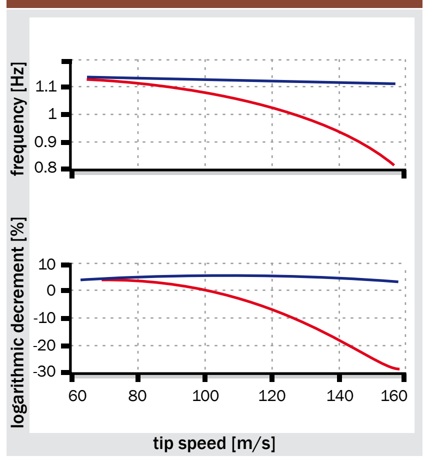
Stability tools have been further developed e.g. to account for large deflections. Deflection of the long slender blades results in coupling between the different deflections and thus changing stability characteristics. An example of this is illustrated in Fig. 4, where the frequency and damping of the lowest damped mode (the edgewise/torsional mode) is shown as function of tip speed for a non-deflected and a deflected blade (red), respectively. The mode corresponds to a kind of "flutter mode" which is stable for all tip-speeds considering the blade is non-deflected, however, for the deflected blade, which is closer to reality; this mode gets unstable beyond 100 m/s tip speed.

WP 2.5 COMPUTATION OF AERODYNAMIC NOISE – RANS BASED ACOUSTICS MODELS

Status:

- Aerodynamic noise is a design parameter influencing cost;
- Design codes for prediction of broad band noise give reasonable overall results;
- Improvements needed for detailed airfoil and blade design;
- Considerable improvements of 2D and 3D RANS CFD computations;
- Challenge is to compute the generation of noise with local turbulence parameters up through the boundary layer height at the airfoil trailing edge.

Figure 4: Frequency and damping for a non-deflected and a deflected blade (red), respectively (5 MW turbine).



COHERENCE OF THE ACTIVITIES IN THE WORK PACKAGE

In Figure 5 the relation between the different analytical and experimental activities in the WP is schematically shown.

RESULTS AND EXPECTATIONS

After 18 months the project generated the following results:

- Adaptation of the material database OptiDat. The database is now suited for more material data aspects and LCA data. The interactive capabilities have been extended; the LCA data can be directly coupled to the design tools;
- Selection of the test specimen geometry for the material characterization;
- A selection process for the blade detail test specimen has started and a preliminary design has been selected for detailed analyses en pre-testing;
- Numerical investigations of the damage evolution in glass fibre reinforced polymer matrix composites are used to analyse the interplay of damage mechanisms (fibre, matrix, interface cracking) and the effect of local properties on the microscopic damage mechanisms;

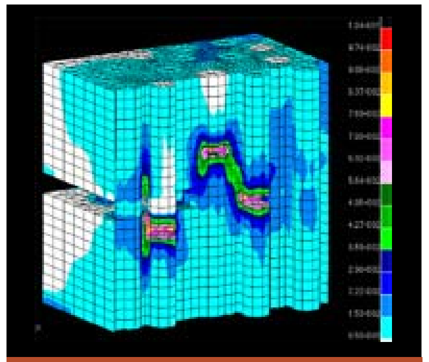


Figure 6: Interaction between fibres and matrix. Maximum shear strain after fibre failure with a cracked matrix.

- An anisotropic non-linear material constitutive model is developed along with a thick shell element implementing progressive damage concepts to predict the load bearing capacity and life of composite structures;
- An analytical approximation, namely the Edgeworth Expansion Technique, was presented for the estimation of the failure probability of a laminated composite plate under general in-plane loading, considering the material mechanical properties as being stochastic. Results were compared with the advanced first order second moment method and Monte Carlo simulation data and were found in good agreement for most of the cases.

It is expected that after five years the results set as targets for this work package will be achieved.

More specifically:

- The OptiDat database will include the material data for the UpWind reference material and one or two alternative materials, including the LCA data for these materials;
- The database can be linked to design tools;
- Material testing procedures will be established and design recommendations will be drafted;
- Empirical and fundamental material models will be available which are based on the material data collected within the WP. The models will be partly embedded in FEM tools;
- Methods to perform probabilistic strength analyses will be available;
- Several measurement techniques will be developed or evaluated. Amongst them non destructive and fibre-optic techniques;
- Blade substructure models will be developed including test methods and design recommendations.

UpWind

SIXTH FRAMEWORK PROGRAMME

WP3 LEADER:
Mr. Bert Janssen
Energy Research Centre
of the Netherlands (ECN)

EMAIL:
l.janssen@ecn.nl

WP MEMBERS:

- Energy Research Centre of the Netherlands (ECN)
- National Laboratory for Sustainable Energy
- Risø National Laboratory - Technical University of Denmark (DTU)
- Stichting Kenniscentrum Windturbine Materialen en Constructies-WMC, The Netherlands
- Centre for Renewable Energy Sources (CRES), Greece
- University of Patras, Greece
- Technical Research Centre of Finland (VTT), Finland
- Lulea University of Technology, Sweden
- Council for the Central Laboratory of the Research Councils, UK
- Vrije Universiteit Brussels, Belgium
- Gamesa Innovation & Technology, Spain
- GE Global Research, Germany
- CENER, Spain
- Institute for Super hard Materials of the National Academy of Science of Ukraine, Ukraine
- Department of Civil Engineering, Thapar Institute of Engineering & Technology, India
- China University of Mining and Technology (Beijing), China

www.upwind.eu

Photography: DIAMANTAKIS George-EWEA - Vestas

Rotor structures and Materials

THE CHALLENGE

For larger wind turbines, the potential power yields scales with the square of the rotor diameter, but the blade mass scales to the third power of rotor diameter (square-cube law). With the gravity load induced by the dead weight of the blades, this increase of blade mass can even prevent successful and economical employment of larger wind turbines. In order to meet this challenge and allow for the next generation of larger wind turbines, higher demands are placed on materials and structures. This requires more thorough knowledge of materials and safety factors, as well as further investigation into new materials.

Furthermore, a change in the whole concept of structural safety of the blade might be required.

The specific objectives of this work package (WP) include:

- Improvement of both empirical and fundamental understanding of materials and extension of material database;
- Study on effective blade details;
- Establishment of tolerant design concepts and probabilistic strength analysis;
- Establishment of a material testing procedure and design recommendations.

UpWind

THE RESEARCH ACTIVITIES

The activities in the work package are divided into three major tasks.

1. APPLIED (PHENOMENOLOGICAL) MATERIAL MODEL

In order to serve as a basis for advanced material models, the existing OPTIDAT database is extended with new materials. The results of this task will enable checking the models derived in task 2 as well as input data for a number of integration work packages. Together with the work carried out in 2, this will result in an integrated material model, based on both tests and micro-mechanics, for which design recommendations and material test recommendations will be established.

The data and test methods for static compression, fatigue and residual strength will be refined where needed. Following the main route in implementation of carbon fibre- and/or glass-carbon fibre hybrid thermoplastic composites, a number of material combinations and reinforcement architectures can be investigated. Due to the increase in both number and size of wind turbines, life cycle analysis of the turbines, particularly of the fibre-reinforced blades will become more prominent. Life cycle analysis data of materials will be collected and a methodology will be introduced to enable instant LCA of the rotor structures, to facilitate direct evaluation of various concepts.

In collaboration with WP 7 research will be carried out on the applicability of fibre optical strain measurement techniques. Especially the possibilities of embedded strain gauges will be subject of strength and fatigue experiments.

A structure, representing a structural blade detail, e.g. shear web/spar cap construction will be selected, analysed and tested, assisted with NDT methods, to come up with improved understanding of the structural behaviour of this detail.

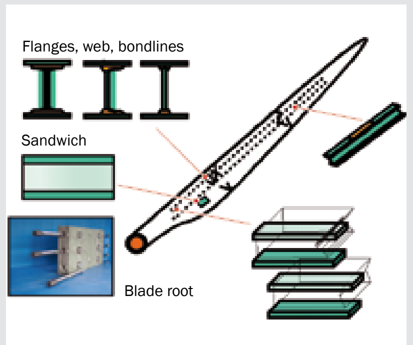


Figure 2: Blade details under consideration.

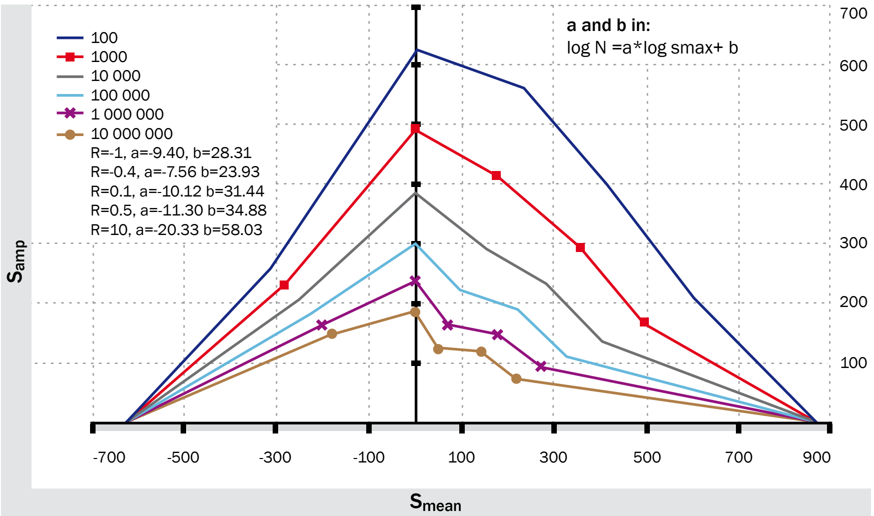


Figure 1: Constant Life Diagram for MD material.

2. MICRO-MECHANICS-BASED MATERIAL MODEL

In addition to empirical tests, a more fundamental understanding of materials will be necessary in the long run. The success of this task depends on several factors:

- The gained knowledge and understanding regarding the basic mechanisms governing the composite material performance in compression and in fatigue;
- The efficient implementation of the knowledge in easy-to-use predictive/ design tools;
- The ability to produce on the laboratory and/or industrial scale the material combinations, surface treatments etc. required to utilize the whole potential of the optimised composites;
- The identification and optimisation of the most important processing/manufacturing parameters affecting the composite quality/performance (initial defect state related to voids, bad impregnation etc.).

The existing models available in literature will be examined with respect to damage mechanisms and micromechanics that are identified and characterized within Task 1. The Interface/matrix materials influence and Fibre fracture/kink-band formation are considered as most significant mechanisms, and will be systematically investigated to greater details. They will be looked upon as part of Micromechanics/Damage mechanics models, and results will be incorporated as particular damage mechanisms described in model. Strength predictions can be compared with the results of Task 2.1 or used as input to macroscopic/phenomenological models. Both, macroscopic phenomenological analysis and model composites will be used in this study.

The work will be concentrated around the following items:

- Non-linear constitutive modelling;
- Interface/matrix materials influence on compression strength;
- Fibre fracture/kink-band formation in compression.

The work of this task is supported by the UpWind.TTC project. In this project three partners will carry out research on:

- Experimental analysis of micro-mechanisms of fatigue damage;
- Micro-mechanical analysis of damage under cyclic loading;
- Computational modelling of damage evolution and interaction under fatigue loading.

3. DAMAGE TOLERANT DESIGN CONCEPT

The effect of fatigue on static strength and stiffness, as well as the effect of post first ply failure strength are studied and included in the material models, composed of the following aspects:

- Nonlinear stress analysis, especially for the highly nonlinear in-plane shear response and the usually weak non-linearity observed under transverse compression of a FRP UD layer;
- Failure prediction under static loads. Several failure criteria sets, e.g. Puck, will be implemented in a commercial finite element code, to provide designers with more effective design options;
- Failure prediction under cyclic loads and rules for strength and stiffness degradation. Implementation of appropriate residual strength and stiffness theories into a commercial FEM code so as to formulate life prediction procedures for the blade under cyclic loading;
- Macroscopic blade failure. The synthesis of modules already discussed above, once implemented in FE codes, will provide at any desired load configuration, static or cyclic, the residual strength, stiffness and remaining life of the blade.

Numerical procedures will be developed for determining strength of a composite laminate, using various failure criteria, by taking into account the stochastic nature of anisotropic material properties. This will lead to the quantification of blade design reliability.

Development of appropriate software in the form of pre- and post-processors that can be used along with current aero-elastic codes is foreseen.

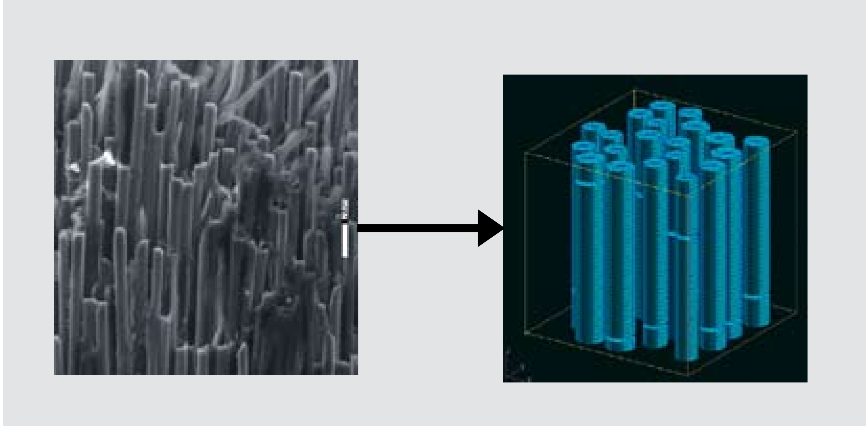


Figure 3: Modelling fibre matrix interaction.

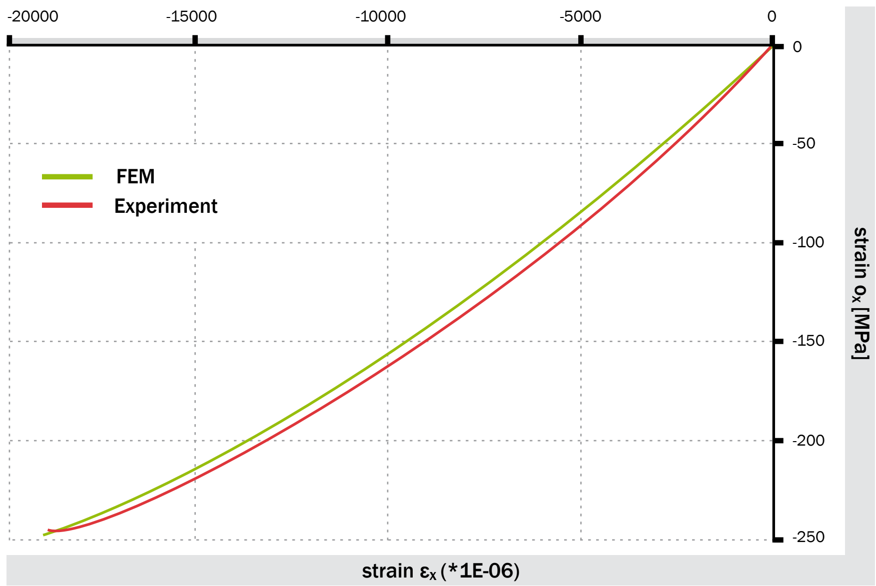


Figure 4: Failure load for a 60°off-axis compressed OB MD coupon.
Comparison of test results and FEM simulation predictions.

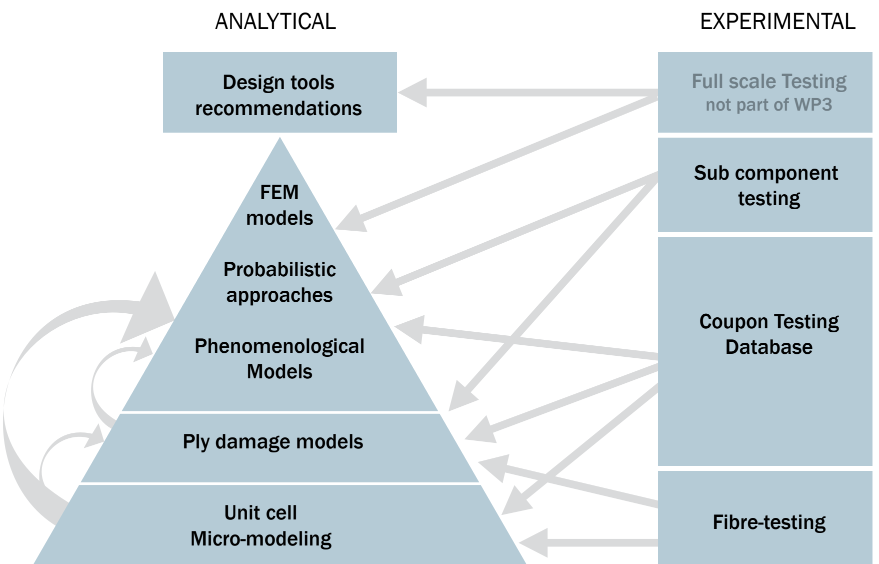
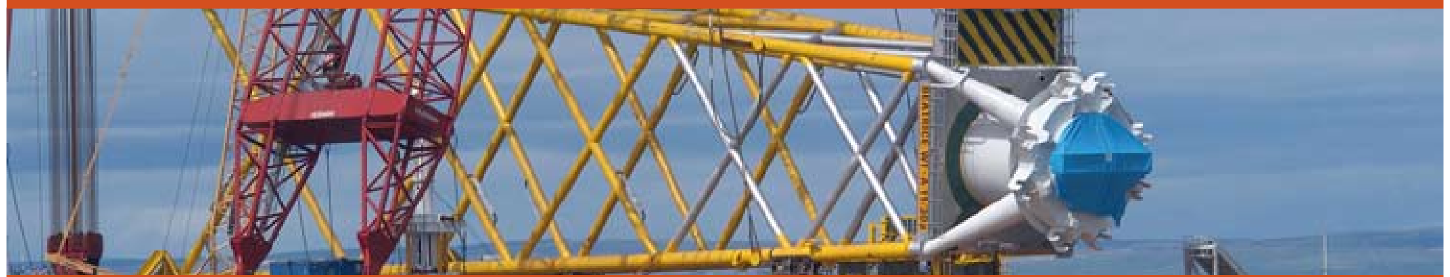


Figure 5: Coherence of Analytical and experimental research in WP 3.

UpWind

SIXTH FRAMEWORK PROGRAMME



WP4 LEADER:
Prof. Martin Kühn
Endowed Chair of Wind Energy,
University of Stuttgart

EMAIL:
kuehn@ifb.uni-stuttgart.de

WP MEMBERS:

- University of Stuttgart
- Technical University of Delft (TUDelft)
- Dong Energy
- Rambøll
- Garrad Hassan and Partners Ltd
- Risø National Laboratory – Technical University of Denmark (DTU)
- GE Global Research
- Shell Wind Energy
- Germanischer Lloyd

www.upwind.eu

Photography: Talisman - DONG Energy

Foundations and Support Structures

WP1A1
WP1A2
WP1A3
WP1B1
WP1B2
WP1B3
WP1B4
WP2
WP3
WP4
WP5
WP6
WP7
WP8
WP9

THE CHALLENGE

In Europe the total capacity of installed offshore wind power is expected to increase from today's approximately 1 GW up to 20 – 40 GW in 2020 (see Figure 1). Today, only a small number of offshore wind farms with very few of them as large as the 160 MW plant with 80 turbines at Horns Rev have been installed or are currently under construction. The proposed exploitation of the enormous offshore wind potential will be technically and economically feasible only with much larger wind farms at more exposed sites.

Valuable experience regarding different aspects of offshore wind farm design such as installation, marine environment and component design is available from previous projects. Most of the offshore projects currently under way use mono-pile or gravity-based support structures designed for shallow water locations up to 20 m water depth only. Future sites in European waters will require deep-water foundation concepts though. Beside the challenges these site conditions pose, offshore wind farms of the future will have a typical installed capacity of 400 MW and will be equipped with turbines in the 5MW class and possibly larger, involving new installation and maintenance strategies.

Therefore, the primary objective of work package (WP) 4 Offshore Foundations and Support Structures is to develop innovative, cost-efficient wind turbine support structures to enable the large-scale implementation of offshore wind farms across the EU, from sheltered Baltic sites to deep-water Atlantic and Mediterranean locations, as well as in other emerging markets worldwide. The WP will achieve this by seeking solutions which integrate the designs of the foundation, support structure and turbine machinery in order to optimise the structure as a whole. Particular emphasis will be placed on large wind turbines, deep-water solutions and designs insensitive to site conditions, allowing cost-reduction through series production.

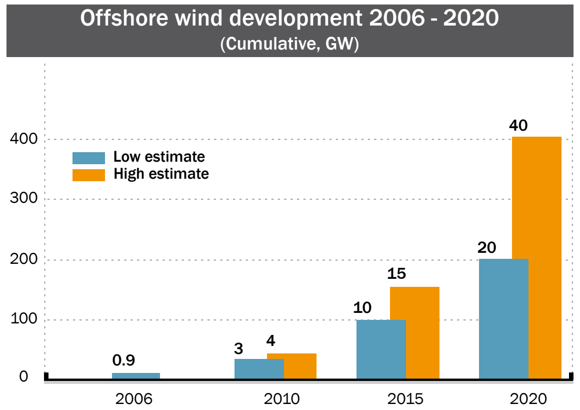


Figure 1: Offshore development up to 2020 [EWEA].

UpWind

THE RESEARCH ACTIVITIES

While innovative solutions for the rotor nacelle assembly will result from the other WP's, the emphasis of this WP lies on the support structure and the interaction of the design of the support structure and the rotor nacelle assembly. The research activities are divided into three areas, as shown in the table below.

The objectives of Task 4.1 are mitigation of dynamic support structure loading and compensation of the inherent variability of site conditions within a large wind farm. The integration of support structure and turbine designs and the use of smart turbine control are expected to achieve this. The task will mainly focus on the development of control algorithms, where different methods ranging from operational control to dynamic control will be further evaluated in order to select the most promising approaches for development. Simultaneously, a reduction of the site sensitivity of structures (e.g. different conditions with respect to water depth, soil, wind and waves) will be attempted by employing the control system, structural tuning and the selection of particular structural concepts.

In Task 4.2, the goal is to develop support structure concepts for water depths beyond 30m through innovative bottom-mounted, very soft or floating concepts. In this task, current design practice and experience will be merged with the new techniques from Task 4.1 and applied to concept development for deeper water. The planned method is based on a preliminary review of design and installation methods, and a study of the range and applicability of different foundation and support structure types, e.g. monopile (soft-stiff or soft-soft), tripod or lattice type with soft-stiff characteristics, and very soft compliant structures as well as floating structures.

Finally, Task 4.3 aims to enhance integrated design tools for the design of large numbers of structures at deep-water sites, and to actively support the development of dedicated international standards which specify best practice for the design of offshore wind farms (e.g. site-specific design, aerodynamic and hydrodynamic impact, low-risk structures, floating concepts). The development of innovative concepts in Tasks 4.1 and 4.2 requires enhancement of the capabilities of existing design tools and methods with respect to the description of turbine, support structures and site characteristics as well as the rapid processing of many similar designs.

WP 4 "Offshore Foundations and Support Structures"		
TASK 4.1 Integration of support structure and wind turbine design	**TASK 4.2** Support structure concepts for deep water sites	**TASK 4.3** Enhancement of design methods and standards
Develop and enhance the integrated design process for offshore wind turbines	Design innovative bottom-mounted support structures (e.g. truss-type)	Design tools and methods for bottom-mounted support structures
Control concepts for mitigating aerodynamic and hydrodynamic loading	Analysis of very soft structures (monopile- or braced-type)	Design tools and methods for floating support structures
Compensation of site and structural variability	Design floating structures	Support of the IEC-61400-3 offshore standard

Table 1: Contents of WP4 "Offshore Foundations and Support Structures".

RESULTS AND EXPECTATIONS

The major goal of this WP is to enable large-scale implementation of offshore wind farms. This aim can be reached mainly through cost-effective design solutions – both on the turbine and the support structure side. In Task 4.1, the first studies focused on the mitigation of aerodynamic and hydrodynamic loads on the total offshore wind turbine system. Load mitigation can be tackled at four different levels, i.e. at the design base, operational control, dynamic control of fatigue loads and event-triggered dynamic loads (see Figure 2).

On the design level / base, an objective is to design the support structure with smaller water piercing members in order to reduce inertia-dominated fatigue waves. A further reduction of hydrodynamic sensitivity can be achieved by combining relatively stiff foundations and substructures with relatively soft tower designs. This will result in small deflections in the submerged part and associated low overall excitations.

Beside changes in the design characteristics, new approaches for operating offshore wind turbines might result in lower total loading. Certain loading situations such as varying site conditions or failure/emergency cases might be solved with the aid of advanced operational control strategies. These strategies could imply new control devices like tower feedback or a tower mass damper, but also changing the operational definitions of the turbine model.

As already addressed while discussing operational control, new dynamic control systems are expected to be the main solution for mitigation loads on the offshore turbine. Indeed, different studies have shown that relatively small pitching actions can generate quite effective damping of the fore-aft tower top loading.

Therefore, a further preliminary study of a tower feedback control device was performed and showed promising results. This device will be further developed for offshore purposes, since especially wave excitation dominates the vibrations of the system in deep-water locations.

The first step in Task 4.2 was to evaluate different support structure types with the aid of an evaluation matrix. The matrix was used to identify critical aspects for the choice of support structure concepts for various conditions – e.g. varying water depths or soil conditions. A further objective of the analysis was to gain insight in the problems involved in designing support structures for offshore wind turbines in deeper waters. After this step a review of different installation methods for various existing bottom-founded support structure types was performed. Following these pre-studies, a cost model for support structures was developed, which will be a main decision driver for later design solutions and developments, especially in Task 4.1.

A first preliminary design is being made for a support structure solution, whereas different solutions will be compared in the end of the project. An UpWind reference support structure design for a given deep-water offshore site will be presented by the end of the project.

In the third Task 4.3, a review of various models for irregular, non-linear waves suitable for design purposes was performed in order to assess their relevance for future offshore wind farms. In addition, support was given to the finalisation of the draft of a new international standard for offshore wind turbines IEC 61400-3 ed.1. In parallel a new design tool for integrated simulations of offshore wind turbines with advanced deep-water support structures was developed. In the support structure part, a finite element based code with hydrodynamic loading capabilities is employed for the dynamic modelling of arbitrary space frame structures. As common for finite element codes, structures are defined on the basis of many discrete elements by definitions of their node connectivity, properties and types. The rotor nacelle assembly with all required aeroelastic, electro-mechanical and control features is modelled with relatively few model degrees of freedom with the FLEX5 simulation code, a tool used throughout the wind industry. A well-defined interface between both codes allows fully-integrated aero-elastic simulations without major invasive changes in the source code and algorithms of the subsystems codes. The new software capabilities are demonstrated by the analysis of a typical tripod support structure (see Figure 4).

The verification of the design tool for bottom-mounted support structures is ongoing, but first results in comparison to the industry standard wind turbine simulation code Bladed are promising. After a successful verification of the present tool, the next step will be the analysis of other arbitrary structures such as jackets.

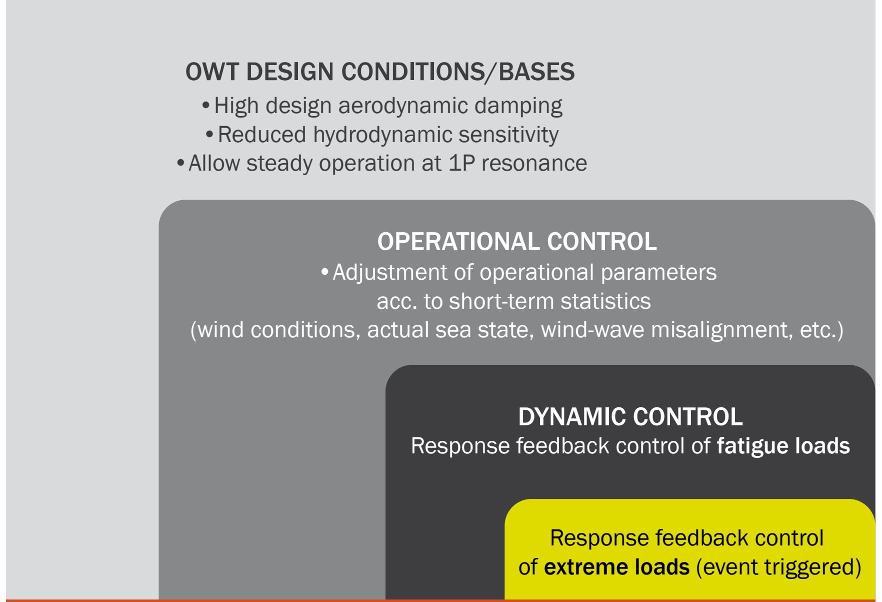


Figure 2: Levels of load reduction concepts.

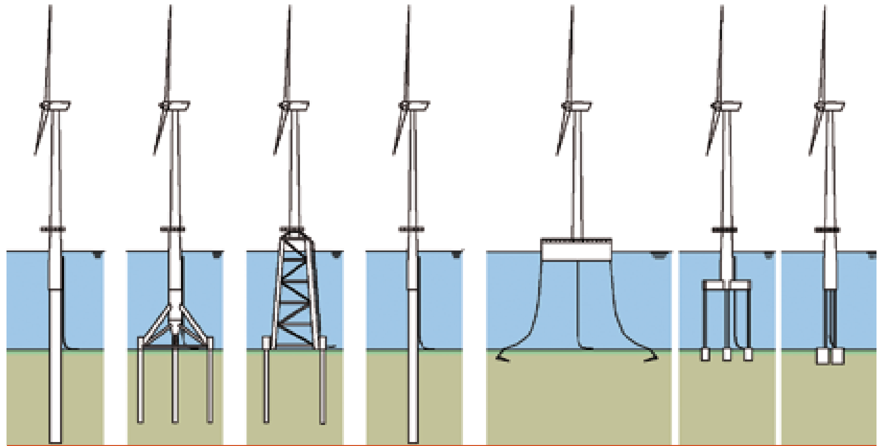


Figure 3: Different support structure concepts. From left to right: monopile, tripod, jacket, compliant, barge floater, tension leg platform and spar floater structure.

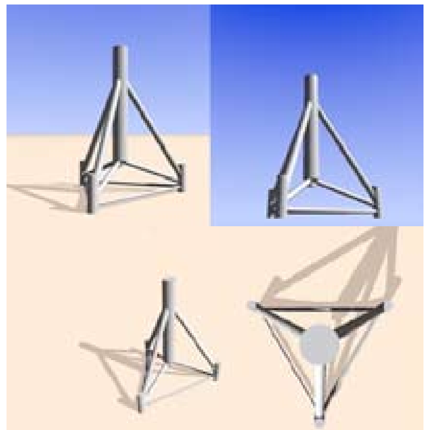


Figure 4: Tripod structural model for test simulations.

UpWind

SIXTH FRAMEWORK PROGRAMME

WP5 LEADER:
Dr Ervin Bossanyi,
Garrad Hassan and Partners Ltd.

EMAIL:
ervin.bossanyi@garradhassan.com

WP MEMBERS:
- Garrad Hassan and Partners Ltd
- Institut für Solare Energieversorgungstechnik e.V. (ISET)
- Energy Research Centre of the Netherlands (ECN)
- Ecotècnia
- Fundación CENER - CIEMAT
- LM Glasfiber A.S.
- GE Global Research
- REpower Systems AG
- Risø National Laboratory – Technical University of Denmark (DTU)
- Gamesa Innovation & Technology

www.upwind.eu

Photography: EWEA - Repower - Vestas

Control Systems

THE CHALLENGE

To achieve further improvements in the cost-effectiveness of wind turbines, designers are aiming towards larger, lighter, more flexible structures, in which more 'intelligent' control systems play an important part in actively reducing the applied structural loads. This strategy of "brain over brawn" will therefore avoid the need for wind turbines to simply withstand the full force of the applied loads through the use of stronger, heavier and therefore more expensive structures. To reach this point it is now necessary to demonstrate these load reductions in full-scale field tests on a well-instrumented turbine. These control techniques can then be used with more confidence in the design of new, larger and innovative turbines, which are to be studied in this project.

As the penetration of wind energy increases, real issues are already arising relating to the control of the electrical network and its interaction with wind farms. These issues must be resolved before the penetration of wind power can increase further.

There are three main areas/objectives of work within the work package (WP):

1. Further development of control systems for achieving reductions in wind turbine loads. This includes the sensors and actuators which are required and development of algorithms for estimation of unmeasured loads, as well as further development of the control algorithms themselves. For the algorithms to be effective, efficient methods of adjusting and testing controllers are also being developed. The application of these techniques to new larger and innovative turbines is also an important aspect of the work.

2. Field tests on a commercial turbine to demonstrate that the expected load reductions can be achieved reliably in practice. This is important so that future designs can confidently be optimised to take advantage of these techniques in arriving at improved overall cost-effectiveness.

3. Development of wind turbine and wind farm control techniques aimed at increasing the acceptable penetration of wind energy, by allowing wind turbines to ride through network disturbances, and to contribute to voltage and frequency stability and overall reliability of the network.

UpWind

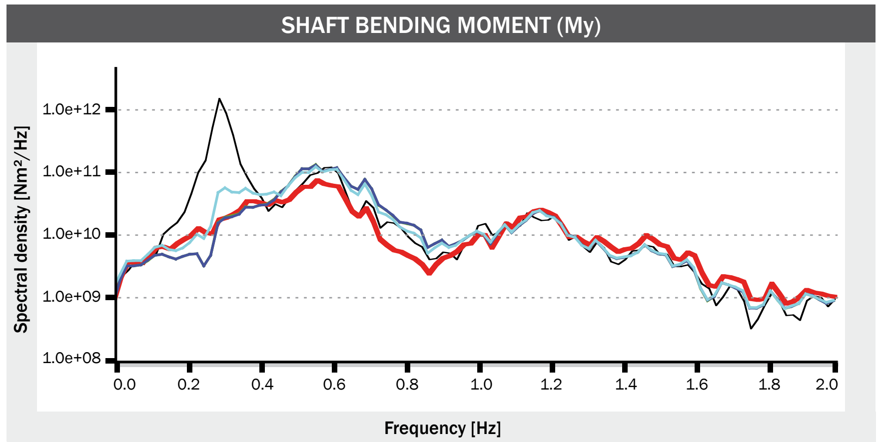
THE RESEARCH ACTIVITIES

There are three main types of research in the WP.

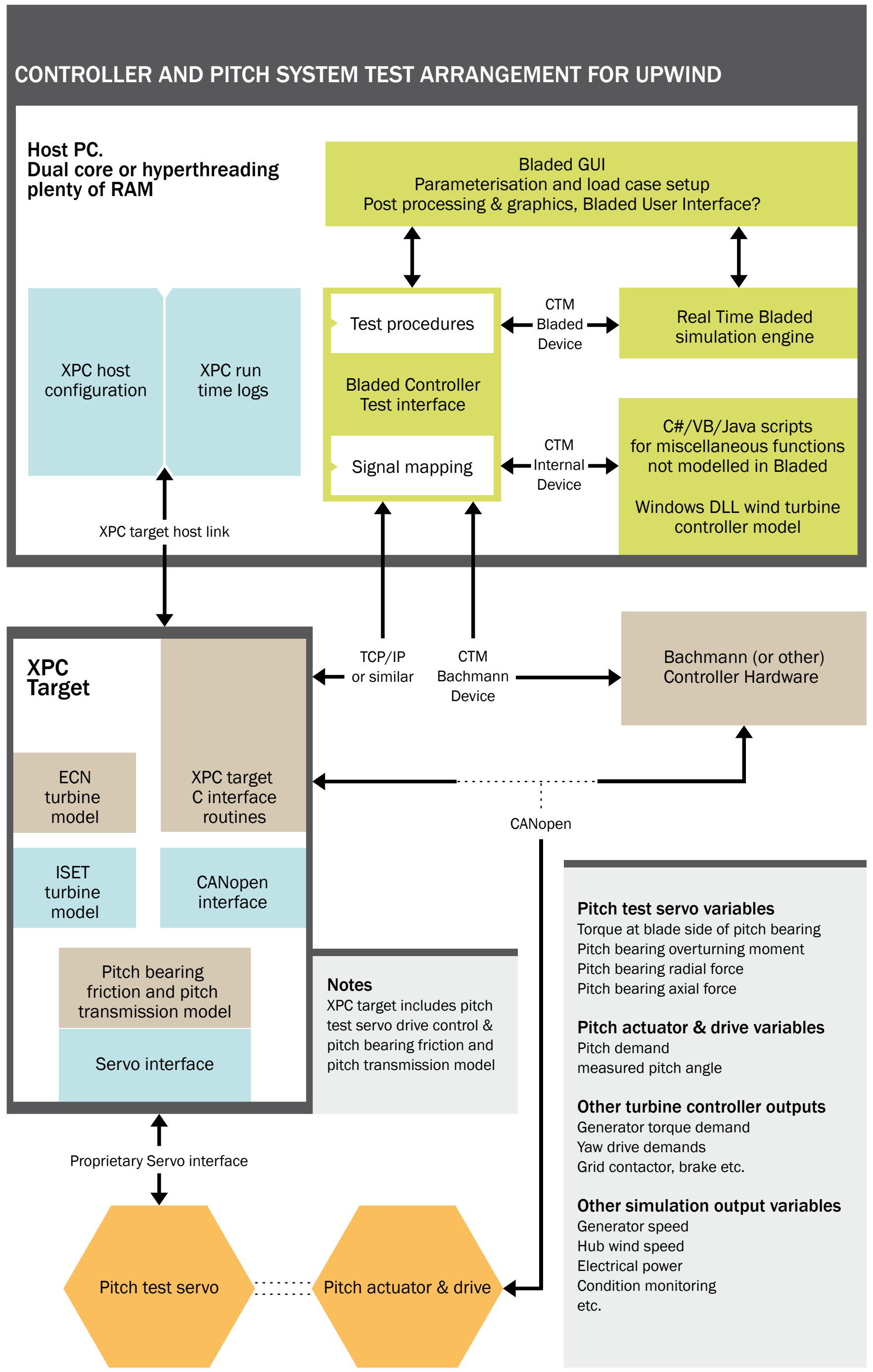
1. Theoretical research making use of existing analytical models. This research covers a number of different areas, and includes the development of new algorithms as well as the testing of these algorithms using simulation models representing the reference wind turbine designs being used as part of the UpWind project. Topics include:

(a) Further possibilities for load reduction;
(b) Load estimation algorithms;
(c) System identification methods to determine the true dynamic response of a turbine, thereby allowing the controller tuning to be adjusted if necessary;
(d) Possibilities for automated fine-tuning of particular control loops;
(e) Feasibility of dual-control blades with an additional pitch actuator at partial span;
(f) Distributed control of advanced blades whose aerodynamic properties can be varied along the span;
(g) Control for offshore turbines on very soft support structures;
(h) Control for very large turbines (up to 20MW rating);
(i) Adjustments of high wind shutdown strategies to improve wind farm output predictability.

2. Development of testing tools, in particular using hardware-in-the-loop methods to allow subsystems of the controller to be tested in conjunction with a simulated wind turbine. In particular a test setup is being developed in which real turbine controller and/or pitch actuator hardware is interfaced to a real-time simulation of the remainder of the turbine. This allows the detailed functioning of the hardware to be tested easily and repeatedly in the



This figure illustrates the dramatic reduction in the 1P (once-per-revolution) loading peak seen in conventional machines (black line) when individual pitch control is used (coloured lines). The fatigue load reduction can be as much as 40% in some cases.



laboratory in any simulated environmental conditions, including conditions such as extreme gusts which one would be very unlikely to experience during field tests. This setup is then easily extended to allow other hardware components to be tested, such as generators, yaw drives, etc.

3. Experimental field testing to validate theoretical models. This includes:

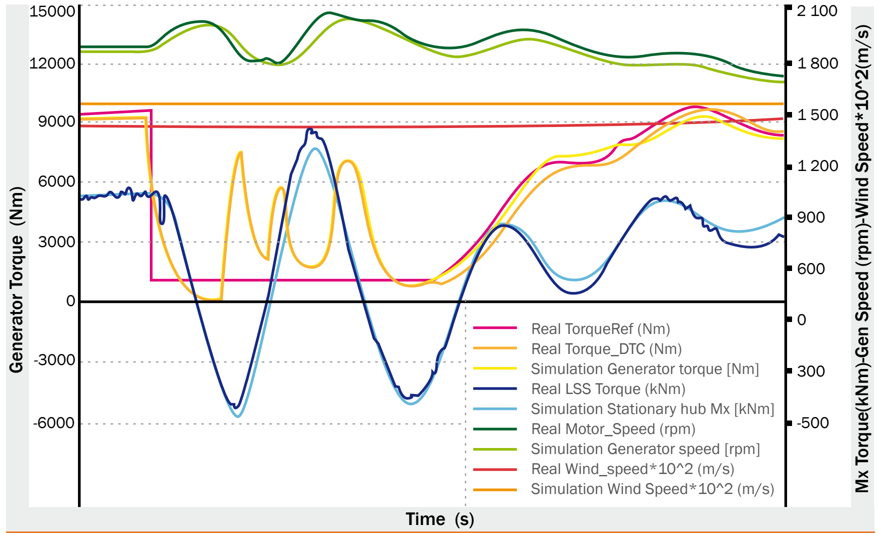
(a) Validation of the significant load reduction potential of individual pitch control which has already been demonstrated in simulations, by implementing and testing the control algorithms on a full-scale commercial turbine;

(b) Validation of electrical transient models of the turbine generator and power converter coupled to a full wind turbine simulation, by comparison against existing field test results which include network voltage dips.

RESULTS AND EXPECTATIONS

This work package is still in progress, and although it is too early to report significant conclusions there are a few findings which can already be mentioned:

- The work on load estimation algorithms has so far focused on the case of tower bending estimation from measured accelerations and is beginning to show some promising results;
- There are also some promising early results on closed loop system identification using measurements from a turbine in closed loop operation to estimate a plant model suitable for tuning of a drive train damper algorithm. Initial work has used data from Bladed simulations, but if successful the method should also be applicable to real turbines;



Comparison of measured and simulated response to a large dip in network voltage.

- A controllability matrix has been derived from a model of a turbine with dual-control blades. Analysis of this has demonstrated that torque and thrust are closely coupled, irrespective of the spanwise position of the second actuator. This means that to decouple the control of torque and thrust is barely feasible, and this concept therefore appears not to be worth pursuing further;
- Many elements of the hardware test facility are already available in the form of the pitch actuator test rig at ISET, the GH Bladed hardware test interface, and simulation software at ECN which has now been extended with thermal models of components to provide realistic temperature input signals for the controller. These elements will be brought together in 2008, and a series of test cases developed to demonstrate the capabilities and the usefulness of the system;
- A fibre-optic sensor system to be used as input for an individual pitch control algorithm is being mounted on a test turbine for detailed evaluation, prior to using such a system for the experimental field testing of the individual pitch controller.

UpWind

SIXTH FRAMEWORK PROGRAMME

WP6 LEADER:
Hans E. Jørgensen
Risø National Laboratory
– Technical University
of Denmark (DTU)

EMAIL:
hans.e.joergensen@risoe.dk

WP MEMBERS:
- Risø National Laboratory – Technical University of Denmark (DTU)
- Fundación CENER
- Centre for Renewable Energy Sources (CRES)
- University of Salford
- Vestas Asia Pacific A/S
- Qinetiq

www.upwind.eu

Photography: LEEMING Ted/BOULLEY Barbarav/KONSTANDINIDIS Mihalis-EWEA

Remote Sensing

THE CHALLENGE

Measuring wind speeds for the evaluation of modern large wind turbines requires measuring masts comparable in height to the wind turbines. These instrumented masts are very expensive. The challenge of this work package (WP) is to research into remote sensing methods as a more cost effective alternative to measuring masts. Two such alternatives are SODAR (an acoustical version of RADAR) and LIDAR (an optical version of RADAR). The SODAR receives reflections of an emitted sound pulse from atmospheric fluctuations of temperature and speed and measures the mean wind speed based on the principle of the Doppler shift. The LIDAR receives reflections of an emitted laser beam from atmospheric particles and measures the wind speed also based on the Doppler shift. Recently new LIDAR technologies have emerged which are targeted towards wind measurements over height ranges relevant to wind turbine applications, and which do not require the expense and logistics of liquid nitrogen cooling systems or stabilised optical platforms, usually needed for optical measurements.

More specifically, the objectives of this WP are to answer the questions – can remote sensing techniques substitute conventional towers with the precision required by the IEC standards, and secondly - how do we best exploit the freedom to measure detailed profiles offered by remote sensing techniques.

UpWind

THE RESEARCH ACTIVITIES

PROBLEMS TO SOLVE, BACKGROUND

The work of this WP concentrates on LIDARs, monostatic and bistatic SODARs. Existing work already resulted in examples of both instruments showing their capabilities (determination of power curves using SODARs and LIDARs, site assessment and comparisons with cup anemometer measurements). The intention of this WP is to mature the work, which has already taken place, on the LIDAR and the monostatic SODAR techniques, through a coordinated effort. By the end of the project, the remote sensing methods will be introduced into the existing standards (the relevant IEC and MEASNET documents) as valid alternatives to the existing methods for measuring wind speed and direction. For the bistatic SODAR, the intention is to investigate further into this technique, since the theory shows that it possesses a large potential.

The main research activities of the WP can be summarised as follows:

- A description of Remote sensing of the wind flow in all stages;
- Perform traceable calibrations for the monostatic SODAR and LIDAR's;
- Define improvements on the Monostatic SODAR and the LIDAR;
- Improvement work on Bistatic SODARs
- Measurements including comparisons in flat terrain (monostatic SODAR, LIDAR, met tower, w/t);
- Measurements and inter-comparisons in complex terrain (monostatic SODAR, LIDAR, met tower, w/t);
- Measurements with a LIDAR system mounted on the turbine nacelle in order to measure the near flow field in front of the rotor and measurements in flat terrain.

The work has been divided into 5 different subtasks.

IMPROVEMENTS ON THE MONO-STATIC SODAR AND THE LIDAR

The use of the mono-static SODAR and the LIDAR depends on a number of external factors, which have a direct impact on the availability and the quality of data from each instrument. For the SODAR, rain, echoes from the surroundings, the songs of birds and cicadas are some examples of disturbing phenomena. Improvements are possible by changing the instrument's software. Taking advantage of the differences in the spectra of various incidents in combination with the use of more advanced filtering methods could result in increased availability. Incidents like precipitation, snow and low clouds are known to influence the LIDAR response.

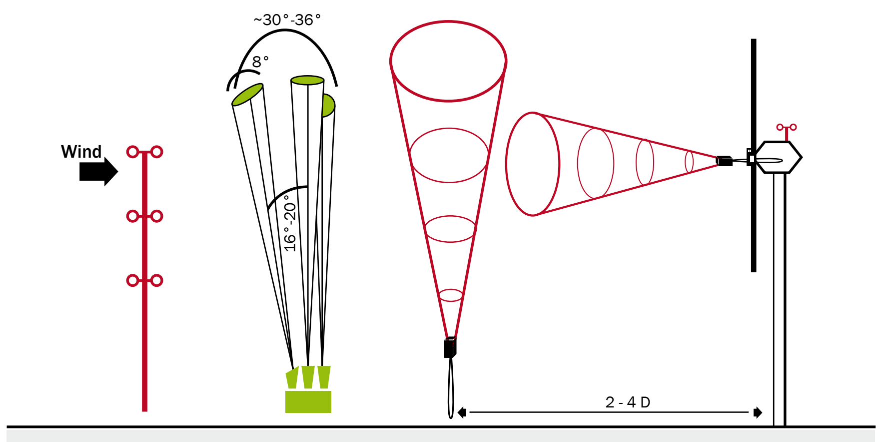
Thus, there is a need to develop corrective algorithms in order to enhance the data availability and reduce the number of erroneous data during such atmospheric conditions. The geometric lay out of the measurement system also needs to be improved or modified. Other possible issues include the scan rate, the FFT size and the number of averaging operations needed to achieve the required accuracy of the results. The measurement results will be tested and verified as part of the following task.

COMPARATIVE MEASUREMENTS IN FLAT TERRAIN (MONOSTATIC SODAR, LIDAR, MET TOWER, WIND TURBINE)

Long-term measurements in flat terrain will be carried out using one SODAR, one LIDAR and a met tower, which is fully equipped with instruments, and preferably located adjacent to a wind turbine. Two LIDAR's will be situated close to each other in order to check the repeatability of the measurements. The power curve of a multi MW wind turbine will be measured simultaneously. The data set will support the flow analysis, which has taken place in other WP's and together with the traceable calibration methods, will be used for the introduction of the remote sensing methods in the IEC Standards for power curve measurements.

INTER COMPARISON MEASUREMENTS IN COMPLEX TERRAIN (MONOSTATIC SODAR, LIDAR, MET TOWER, WIND TURBINE)

Simultaneous measurements will be performed by both a monostatic SODAR, a LIDAR and a heavily instrumented met tower preferably located near a MW size wind turbine in complex terrain. In a second case, comparative measurements will take place between a LIDAR, a met mast and a wind turbine. The goal of the measurements is to enhance our knowledge of problems and pitfalls of using remote sensing measurements in complex terrain. The goal is to present a power curve and a siting measurement technique using the instruments in complex terrain. At a later stage, measurements will take place using either two SODARs or two LIDARs placed close to each other for inter-comparison purposes. During this campaign care will be taken that the same type instruments (SODAR-SODAR or LIDAR-LIDAR) are used while sampling overlapping atmospheric volumes.



WORK ON THE BISTATIC SODAR

In the bistatic SODAR, the two major elements, the transmitter and the receiver, are spatially separated. This makes its deployment more complex since the position of the different parts must be known to high precision. However, advances in satellite positioning systems have largely removed these obstacles. Bistatic SODARs have a number of theoretical advantages over a monostatic system. They receive backscatter not only from temperature inhomogeneities as a bistatic SODAR, but also from velocity fluctuations. Not only does this improve the signal to noise ratio but it also enables the bistatic sodar to measure in neutral conditions where a monostatic system would normally fail. This makes the instrument a potentially attractive alternative to other remote sensing systems. A bistatic SODAR will be designed, built and tested against the SODAR and LIDAR remote sensing instruments and an instrumented met mast. The bistatic SODAR to be built will be combined with a conventional monostatic, phased array option which will allow scanning at different heights and thus produce the wind profile at a certain location.

TURBINE MOUNTED LIDAR

The option to use the LIDAR on the turbine nacelle is investigated. The idea is to take advantage of the information about the upstream wind velocity, which the turbine rotor will experience a short time later. The rotor control system could use this supplementary information for optimising the power production and minimising the loads. The LIDAR output needs to be incorporated in the control system of the turbine. Basic load/power measurement will take place in order to demonstrate the advantages and difficulties of the setup relative to the normal configuration mode.

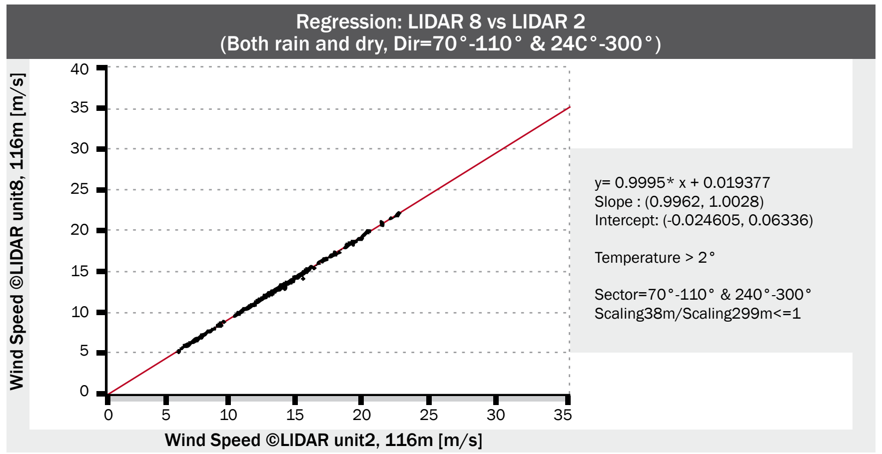
RESULTS AND EXPECTATIONS

Research carried out so far (two years) has produced the following results:

- The inter comparison between two LIDARS have shown very similar results;
- A new cloud algorithm has been implemented and has improved the quality of the LIDAR measurements in comparison with cup anemometer measurements;
- Power curves, established on the basis of SODAR measurements have been measured with a scatter that is slightly larger than cup anemometers;
- At higher heights, influence from wind shear on the ratio between LIDAR and cup anemometer measurements was observed, which now can be theoretically explained.

Further expectations of the research include:

- An analysis of the inaccuracies and uncertainties of LIDAR and SODAR measurements.;
- A report containing considerations with respect to the acceptance of remote sensing in IEC power performance measurements;
- A description of the principles of the LIDAR calibration method;
- An analysis of the impact of volume integration and sampling frequency on the measurement of the wind speed by both LIDARs and SODARs as compared to the measurements carried out by cup anemometers;
- Measurement of turbulence parameters through remote sensing in both flat and complex terrain. The analysis of the procedure for making turbulence measurements using LIDARs and SODARs will be supplemented with measurements and comparisons with met mast data;
- A comprehensive literature review, field testing work with a new compact bi-static design, design work on reducing horizontally-propagating sound;
- Measurements in flat terrain using a SODAR, a LIDAR and an instrumented met mast in front of a wind turbine Inter-comparison of two LIDARs closely situated next to each other to test traceability;
- Measurements in complex terrain using a SODAR, a LIDAR and an instrumented met mast in front of a wind turbine.
- Measurements in complex terrain using a LIDAR and an instrumented met mast in front of a wind turbine;
- The QinetiQ prototype LIDAR will be placed on a turbine nacelle in order to measure the wind speed in front of the turbine and thereby investigate the possibility of using turbine mounted LIDARs for measuring power curves.



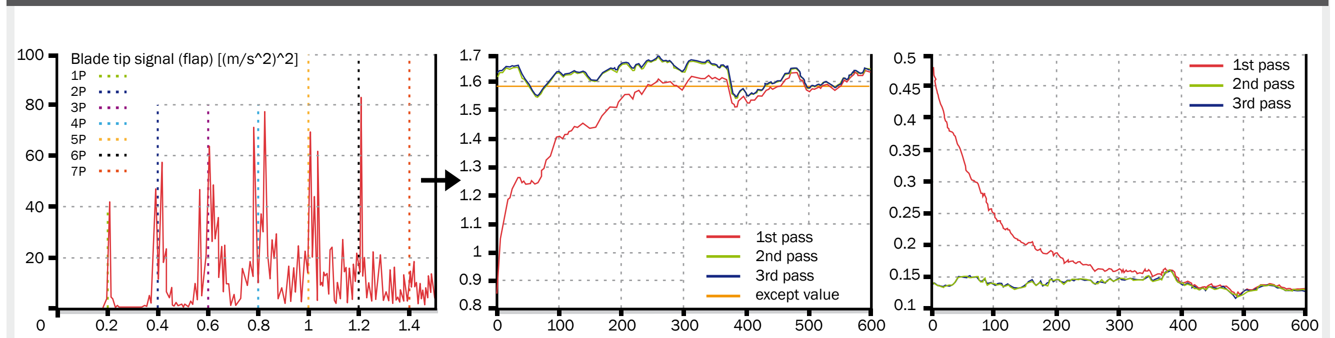


Figure 7: Performance of a Kalman Filter for identification of wind turbine blade structural oscillation parameters stiffness and damping.

reliability and remaining life time curves of wind turbines and their major components. With a growing number of fault statistic data sets, the results of the PLP can be used to estimate the remaining life time of a component. This will allow the improvement of offshore wind turbine O&M strategies, e. g. the performance of the condition based maintenance approach.

RESULTS AND EXPECTATIONS

Some practical results of the work done so far include:

- A state of the art report about condition monitoring for wind turbines. This report describes the required measurements and the related sensor technology to perform condition monitoring and fault prediction tasks. The basic data evaluation and fault prediction algorithms are presented. A description of the basic condition monitoring functionalities and the integration of these items into international standards complete the report. The report is available on the UpWind project web site;
- In close co-operation with the WP3, first laboratory tests have been started. Within these tests, the stress and fatigue behaviour of the GRP material itself and of the applied FBG sensors is being determined simultaneously. Another laboratory test has been carried out to demonstrate the principle functionality of the FBG sensors to be installed in the N-80 test turbine;
- First investigations of the "Flight Leader Turbine" concept have been applied to a simulated 5 x 5 wind turbines offshore wind farm. The fatigue damage has been estimated for the individual turbines;
- With the fault statistic data bases identified so far, first evaluations have been performed. These evaluations should deliver a ranking for wind turbine components according to their fault and reliability relevance. Furthermore, the interdependence of the wind turbine concept and its reliability has been analysed;

All in all the R&D activities of WP Condition Monitoring will lead to an O&M cost optimisation concept for the next generation of offshore wind turbines with power outputs of up to 20 MW. The results will be fed into the integration work of other WP's. Basic scientific and technical results will be made available in international publications and conference presentations as well as education material for WP Education and Training. Technical knowledge will be communicated to relevant international standardisation working groups.

UpWind

SIXTH FRAMEWORK PROGRAMME

WP7 LEADER:
Jochen Giebhardt
Institut für Solare Energieversorgungstechnik (ISET)

EMAIL:
jgiebhardt@iset.uni-kassel.de

WP MEMBERS:

- Institut für Solare Energieversorgungstechnik (ISET)
- Energy Research Centre of the Netherlands (ECN)
- Risoe National Laboratory - Technical University of Denmark (DTU)
- Smart Fibres Limited (SmartFibres)

www.upwind.eu

Photography: Vestas

Condition Monitoring

THE CHALLENGE

The main challenge of the work package (WP) Condition Monitoring is supporting the incorporation of new condition monitoring, fault prediction and operation & maintenance approaches into the next generation of wind turbines for offshore wind farms, leading to improving the cost effectiveness and availability of offshore wind farms.

THE RESEARCH ACTIVITIES

The WP is divided into four subtasks:

OPTIMISED CONDITION MONITORING SYSTEMS FOR USE IN WIND TURBINES OF THE NEXT GENERATION

With increasing size and innovative features of the next wind turbine generation, new approaches for measurement equipment as well as for signal acquisition and evaluation is required to perform condition monitoring and fault prediction. This subtask investigates the required improvements and new developments of the condition monitoring systems (hardware and software) for wind turbines.

'FLIGHT LEADER' TURBINES FOR WIND FARMS

The planning of operation and maintenance (O&M) measures and the estimation of its cost requires extensive knowledge about the load applied to an individual turbine in a wind farm during its life time. Instrumentation of all the turbines in a wind farm is too costly. Therefore, the idea is to equip selected turbines, the so called "flight leader turbines", at representative positions in the wind farm with the required load measurement sensors. Flight leader (a term used in aircraft technology) turbines are subject to higher, or at least similar, loads as other turbines in a wind farm. The probability that failures occur first to the flight leader turbines is higher than the other way around. This provides an opportunity to take measures to avoid similar damage to the whole population of wind turbines. Other applications of the Flight leader concept include rational O&M planning. From the measurements at the flight leader turbines, the load for all turbines in the wind farm will be estimated. With these data, a comprehensive O&M scheduling and cost estimation at reasonable cost for sensor and data acquisition is possible.

FAULT STATISTICS

Fault statistics will be used as a starting point for investigations in new diagnostic methods, materials and wind turbine models. They are essential to identify weak points in the design of wind turbines and their components and to establish new O&M strategies, for instance condition based maintenance. Within this subtask, available fault statistic data bases will be analysed. Based on this, improvements and extensions of the data bases will be discussed and possibilities for combination and consolidation of the different data sets will be assessed.

UpWind

STANDARDISATION

During the last years, several national, European and international standards have been established or are currently under development. Within this task, the implementation of the standards will be observed and the results of the WP will be included as far as possible into the standards by participation of WP7 members in the respective standardisation working groups.

RESEARCH STRATEGIES

The major route for research in WP7 is to combine theoretical investigations, like physical modelling, combined with laboratory and field measurements for verification and testing. The details will be described below.

MODELLING

Mathematical models of sensor behaviour due to bending forces at the roots of the blades will be implemented. The models will be used to estimate the sensor's dynamic response and the expected range of the output signals. Furthermore, approaches for the system identification using the blade's oscillations in the flap wise plane will be investigated by use of numerical models. The derived parameters will be used to retrieve information about the structural health of the blade. In an iterative process, the models will be verified and optimised with the measurements from both laboratory and field tests.

A different modeling approach is used for the flight leader concept. In a first step, the concept will be evaluated by wind farm model calculations, including wake effects and loads to translate measured data of a reference unit into data representing the degree of degradation of other turbines in the wind farm. Based on the simulation results, a model for the estimation of O&M costs in offshore wind turbines will be designed.

LABORATORY AND FIELD TESTS

As mentioned above, the laboratory and field test results will be used to refine the physical and mathematical models. The following hardware installation and testing is planned:

1. Material testing of fibre optic strain sensor: In co-operation with WP3 on Rotor Structures and Materials, Fibre Bragg Grating (FBG) fibre optic sensors, which use the "Bragg Grating Principle" to generate strain measurement signals, are tested. For this, samples (coupons) of GRP blade material will be stressed over longer periods with high numbers of load cycles. The test stress will represent a real blade's load exposure over the designed life time. Two types of sensors are tested: FGB patches, which will have a carrier material for the fibres. The carrier will be glued to the surface of the coupon. Second type under test is the inline sensor, where the optical fibre is directly incorporated in the matrix of the GRP coupon during manufacturing.

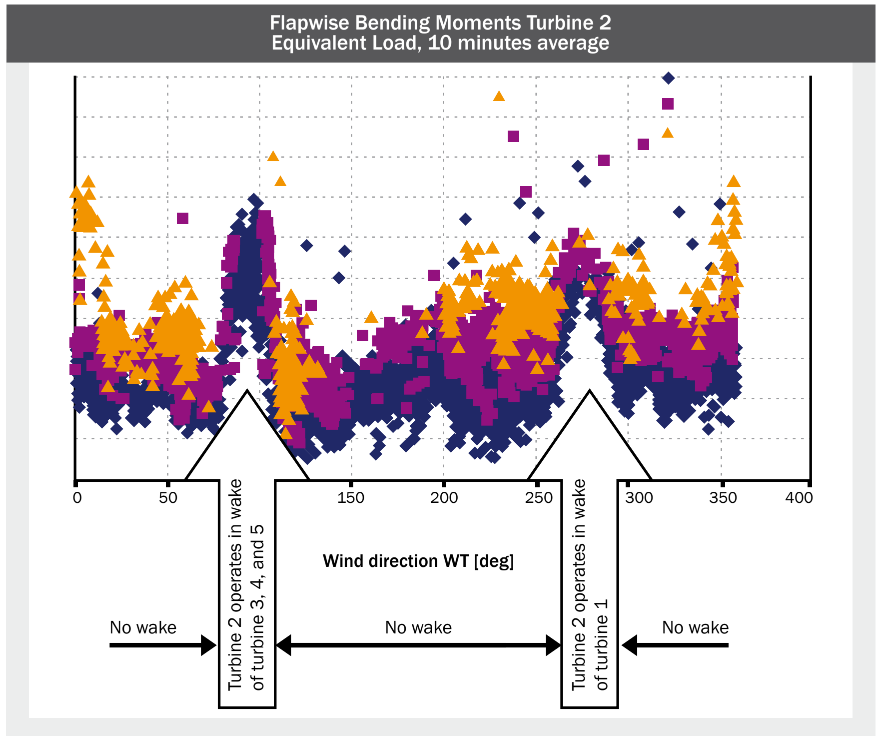


Figure 1: Wake analysis by measured data of the flapwise bending moments for the wind turbine 2 in ECN's test field in Wieringermeer, NL.

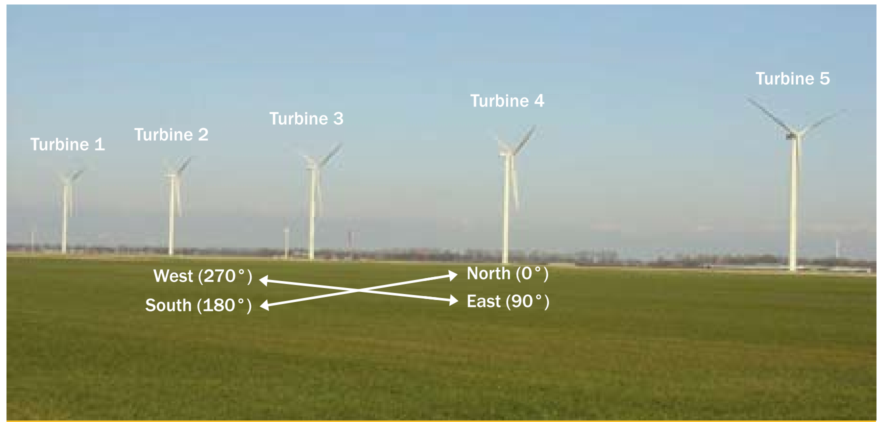


Figure 2: Configuration of ECN's wind turbine test field in Wieringermeer, NL.

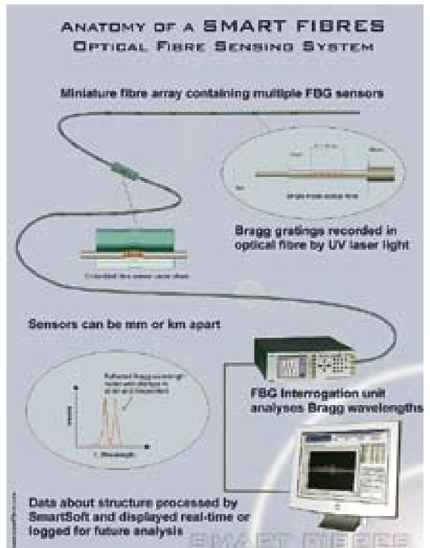


Figure 3: Fibre Brag Grating (FBG) optical strain measurement system.

2. Installation of FBG strain sensors in the blades of an N-80 wind turbine: To test the performance of the sensors in the real world, a set of 12 FBG patches will be retrofitted into the blades of a Nordex N-80 machine in the wind turbine test field of partner ECN in Wieringermeer, NL. The patches will be glued to the surface of the inner blade walls to measure the flap wise and edge wise blade bending. Two sensors on opposite positions will be installed for one measurement direction. A so called interrogation unit will be installed in the hub of the N-80. This unit acquires sequentially the strain measurement signal from the FBG sensors. It has four channels, whereas each channel will be attached to the sensors in one blade.

3. Installation of accelerometers in one blade: The remaining input channel of the interrogation unit will be connected to FBG accelerometers, which will be installed in one blade. These sensors measure the oscillation of the blade in the flap wise plane at four positions. Each two pair of sensors will be attached to the inner web structure of the blade near to leading and trailing edge in a distance of about 8 m and 16 m respectively from the rotor axis. The acceleration signals will be used as input for the parameter identification algorithms mentioned above.

4. Installation of accelerometers in the nacelle and strain sensors in the tower base: To analyse the structural oscillation behaviour of the tower of the N-80, two additional accelerometers will be installed to detect the nacelle's oscillation in axial and transverse direction (related to the rotor axis). Additionally, FBG strain measurement sensors will be installed in the tower base. These sensors will measure tower torsion and the tower bending in two axes. To acquire the data, a second interrogation unit will be installed in the tower base.

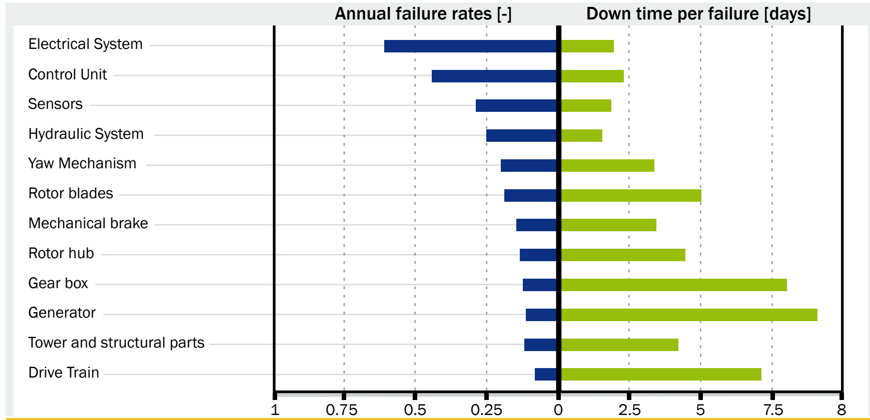


Figure 4: Comparison of wind turbine components according to thier annual failure rates and resulting downtimes.

Figure 5: Comparison of different O&M strategies for wind turbines in offshore wind farms.

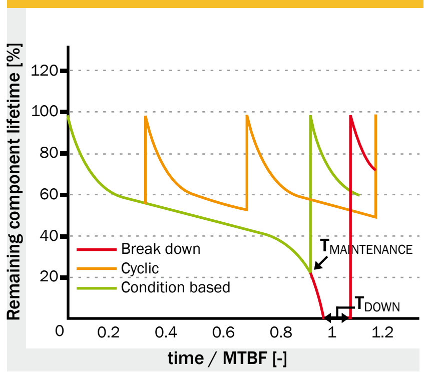


Figure 6: FBG sensor patches and 4channel interrogation unit to be installed in the test wind turbine.

NUMERICAL DATA EVALUATIONS

The measured structural oscillation data resulting from the fibre optic strain and acceleration sensors will be evaluated by extended numerical spectral analysis algorithms. These algorithms are further developed on the basis of the common numerical Fast Fourier Transform (FFT). Required extensions to the FFT will be the adaptation of the algorithm to the very low rotational and structural oscillation Eigen frequencies of the next generation of wind turbines. Another point is the variable speed of the turbines, which requires an RPM tracking of the FFT algorithm, the so called order analysis.

For extracting basic information from the fault statistic data bases, the standard statistical algorithms (averaging, correlation, etc.) will be used. To refine the results, new statistical algorithms will be developed. A promising approach seems to be the Power Law Process (PLP) model. This allows modeling the typical shape of

UpWind

SIXTH FRAMEWORK PROGRAMME

WP8 LEADER:
Prof. Rebecca Barthelmie
University of Edinburgh

EMAIL:
R.Barthelmie@ed.ac.uk

WP MEMBERS:
- Risø National Laboratory – Technical University of Denmark (DTU)
- Energy Research Centre of the Netherlands (ECN)
- Centre for Renewable Energy Sources (CRES)
- National Technical University of Athens (NTUA)
- Renewable Energy National Centre of Spain (CENER)
- Garrad Hassan and Partners Limited

www.upwind.eu

Photography: Vestas

Flow

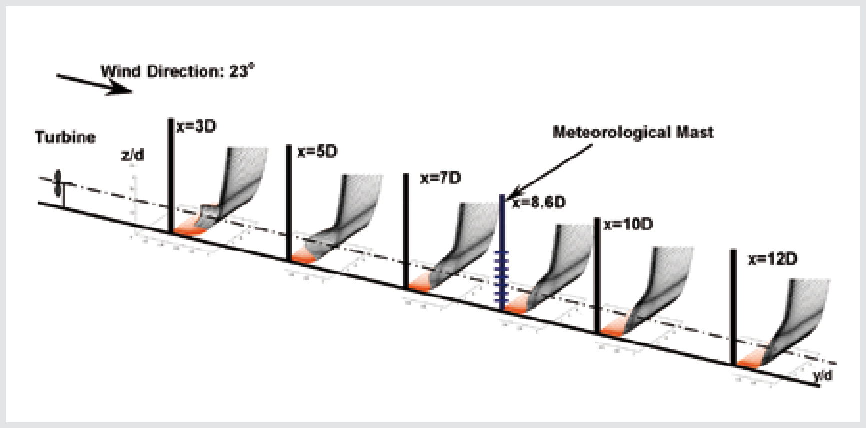
THE CHALLENGE

The challenge is to develop wind farm models that can be used to accurately predict power losses and loads in wind farms and used to optimise wind turbine spacing whether in flat or complex terrain, onshore or offshore.

When wind turbines are placed together in a wind farm, the flow from one turbine impacts the flow of the next turbine downwind. Because the first turbine has extracted energy from the wind, the second (downwind) and subsequent turbines experience lower wind speeds and hence have lower power output. Each turbine also creates turbulence as it rotor rotates so the downwind turbine experiences higher turbulence levels causing increased loads.

The volume of higher turbulence level and lower wind speed behind a wind turbine is called the wind turbine wake. Wakes are a serious problem in wind energy technology because the deficit of energy production can be as high as 20% of the energy produced by a singe turbine at the same site, depending on the size of the wind farm, its location and the type of wind turbine. This work package aims to improve wake models used in wind farm design so that power losses can be accurately predicted.

UpWind



THE RESEARCH ACTIVITIES

R&D is focused on understanding how wind turbine wakes behave in complex terrain and offshore. Many wind farms are now being developed in complex terrain. We know that wakes behave differently in non-flat terrain and it is necessary to understand how wakes change as they move over hills. The strategy is to use more complex Computational Fluid Dynamics (CFD) codes because these are expected to gain a better description of the general flow in complex terrain. These models are computationally intensive and we need new strategies for depicting large numbers of turbines within these codes.

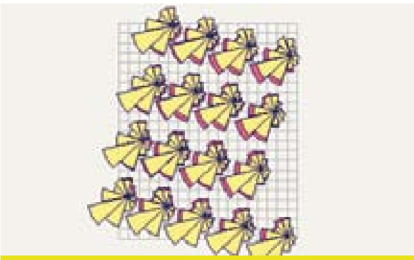
Three model simulation types are being carried out to compare the performance of the CFD models with wind farm models where appropriate:

- Simple terrain (Gaussian Hill);
- Five turbines in flat terrain;
- The complex terrain wind farm.

Very large wind farms are being developed offshore and the first indication from wind farm measurements are that standard wind farm models under-predict power losses due to wakes. We have been able to develop 'engineering solutions' to bring model predictions in line with observations but now R&D activities are focusing on understanding why wind farm models which work well over land or for small wind farms offshore do not work well for large offshore wind farms. There are a number of processes which need to be evaluated including changes in the structure of the boundary layer over the wind farm due to wind turbines wakes, how multiple wakes are combined in wind farm models and the behaviour of wakes at the edges of the wind farm.

Due to the time and expense of taking long-term measurements, research relies on the wind farm developer's willingness to share data with the WP team so that the data can be used (confidentially, if required) to evaluate the performance of the different model formulations. The work is a mix of analysis, building physical models, analysing data sets for specific situations and evaluating and verifying whether the accuracy of the prediction of power losses from wakes has become more accurate.

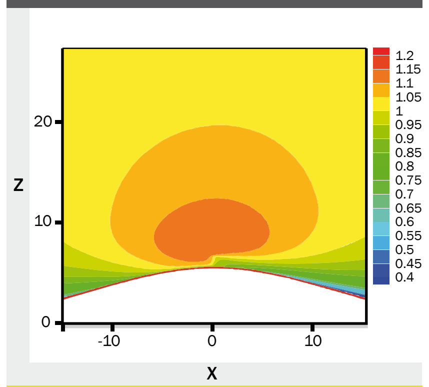
The comparison between wake models and measurements is based on the full spectrum of models from wind farm codes which use moderately simple wake models to full CFD models. The most straightforward models are those using



Wakes losses predicted in a large wind farm.

one equation to determine the wake width/velocity deficit at particular distances from the turbine and then apply a 'top-hat' profile assuming the wake is axis symmetric. One example is the WAsP model. There is a whole group of models which are based on a semi-empirical model, developed by John Ainslie. These include GH WindFarmer. ECN's WAKEFARM model is based on the UPMWAKE code which originally was developed by the Universidad Politécnica de Madrid. By using these models and the simpler models described above, it is not possible to model the near-wake physics explicitly. Hence these models are not valid at less than approximately 3 rotor diameters from the turbine. The remaining models are CFD codes including the CENER model based on the commercial CFD code Fluent. The CRES–flow NS model integrates the governing equations by means of an implicit pressure correction scheme, where wind turbines are modeled as momentum absorbers by means of their thrust coefficient. NTUA CFD model solves the 3D Reynolds averaged incompressible Navier-Stokes equations with second order spatial accuracy.

Symmetry plane - Vx velocity



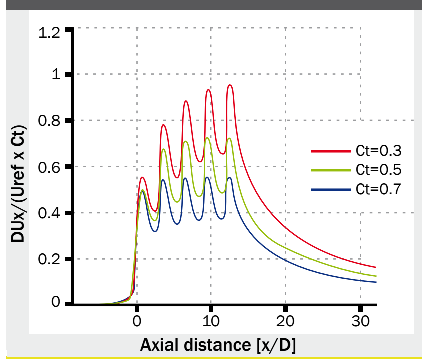
Simulations of the velocity field over an ideal three dimensional hill.

RESULTS AND APPLICATIONS

Evaluation of the CFD codes shows that the axial variation of the velocity deficit at hub height is represented well for the case of five wind turbines with the distance between the machines varying from 3D to 7D. For high values the thrust coefficient, the increase of the velocity deficit at the downwind wind turbines is not significant even when the distance between the machines is small (3D). However, for lower values of the thrust coefficient there is a significant increase in the velocity deficit of the second wind turbine which is larger if the wind turbines are more closely spaced. In general, there is no significant increase in the velocity deficit after the third wind turbine. High values of the turbulence intensity for the five wind turbines case are observed. Compared to the single wind turbine case, the level of maximum turbulence intensity is almost doubled.

In complex terrain, the wind speed deficit remains significant, even 20 rotor diameters downstream from the wind turbine, and the wind speed deficit at hub height does not decrease smoothly with distance. If the turbulence intensity is high this results in a faster flow recovery at long distances and the flow recovery is slower in complex terrain.

TI=13%, Distance=3D

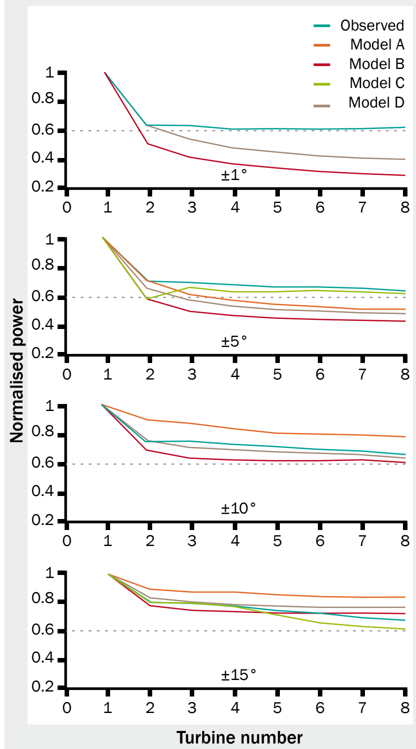


CFD simulations of five wind turbines in flat terrain.

Evaluation of the models in large offshore wind farms indicates that the performance of the models is somewhat variable. For very small wake widths models tend to over-predict wake losses, potentially because they do not account for the directional variability. As the wake widths increase to capture a larger fraction of the wake, the predictions divided into two groups. In general the wind farm models under-predict power losses due to wakes while the CFD models over-predict wake losses. While the wind farm model predictions can be tuned to better fit the observations e.g. using a lower wake decay coefficient or the added roughness approach described below, further investigation is needed to understand the cause of differences between the CFD models and the observations.

The observations show that as the equivalent wake spacing increases, the initial power loss (at the second turbine) decreases but the power loss in the row increases moving down the row. By the fifth turbine all three wake spacing have a similar power output compared to the free stream. The models all predict closer to the observed power output for the larger wake spacing.

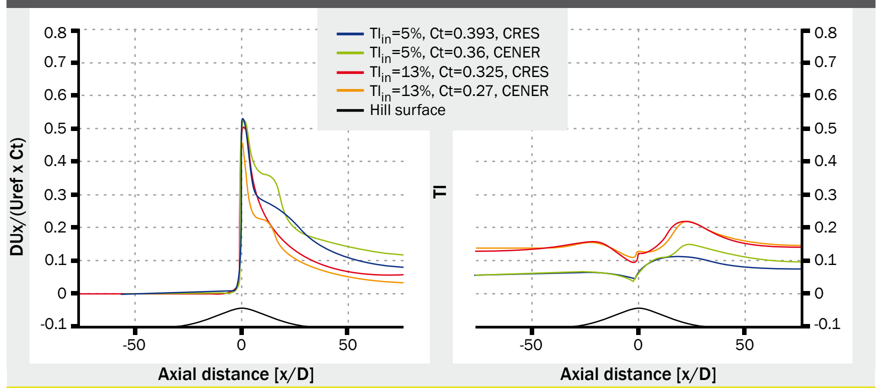
It has become apparent that standard wind farm models are lacking one or more components which account for the modification of the overlying boundary-layer by the reduced wind speed, high turbulence atmosphere generated by large wind farms. This effect is likely to be particularly important offshore due to the low ambient turbulence.



Comparison of models and measurements for Horns Rev (direction 270°) for 8±0.5 m/s for different widths of wake sectors.

Comparisons of wind and turbulence downwind of very large wind farms have tended to focus on a limited range of wind speeds with high thrust coefficient for westerly winds which are well-represented in the database, have flow directly down rows of wind turbines and have downstream masts at distances between

3D axisymmetric hill, L=1750 m



CFD simulations of the velocity deficit and turbulence intensity over an ideal Gaussian hill with a wind turbine placed on the summit.

4 and 11 km for comparison with models. In general, models where some tuning of the turbulence intensity (either directly or through increased roughness) took place, show good agreement with measurements. The wind speed determined from power output within the wind farm can drop to less than 80% of its free stream value (according to the initial wind speed and direction angles considered). Recovery to approximately 90% of the free stream value appears to occur within the first 5 km downwind of the last turbine in the wind farm.

However, further recovery is more gradual and appears to extend for an additional 15-20 km downwind. Considerable work remains to be done in terms of model evaluation and this also relies on additional data from large offshore wind farms becoming available in order that the impact of a range of wind turbine types and wind farm configurations can be determined.

The development of new codes and modifying existing models for more accurate representation of power losses due to wind turbine wakes is foreseen. These new codes can be used by developers to optimise wind farm layouts.

UpWind

SIXTH FRAMEWORK PROGRAMME

WP9 LEADER:

Mr. Ole Holmstroem
DONG Energy Power,
Projects & Technology

EMAIL:
oleho@dongenergy.dk

WP MEMBERS:

- DONG Energy Power
- Risø National Laboratory – Technical University of Denmark (DTU)
- Aalborg University
- Energy Research Centre of the Netherlands (ECN)
- National Technical University of Athens (NTUA)
- Institut für Solare Energieversorgungstechnik e.V. (ISET)
- GE Global Research
- Garrad Hassan and Partners Ltd.
- Vattenfall A/S

www.upwind.eu

Photography: Vestas - DONG Energy

Electrical grid

THE CHALLENGE

As the penetration of wind energy in power systems increases, requirements on power quality and controllability will become more demanding. The rate of wind power development in Spain, Denmark and Northern Germany has been so rapid that it is impacting upon the reliability of the power system. Measures to maintain system security are already being implemented. Improvements incorporated in the wind turbines and wind farms are needed to allow a significant level of penetration.

By planning and improving the controllability of wind power output, satisfactory system reliability can be achieved without excessive investment in transmission or distribution system reinforcement.

The aim of this work package (WP) is to investigate the design requirements of wind turbines which result from the need for reliability of wind farms in power systems, and to study possible solutions that can improve the reliability. Reliability is an important issue as failure of future very large wind farms may have a significant impact on the power balance in the power system. As offshore wind farms are normally more difficult to access than onshore wind farms, failures are likely to cause a significant lower availability than similar failures on land.

The WP investigates operational as well as statistical aspects of wind farm reliability. Operational aspects include grid code requirements, extreme wind conditions and specific wind farm control options. The statistical aspects will be covered by the development of a database and by statistical modelling.

UpWind considers future large wind turbines 5-10-20 MW in very large offshore wind farms of hundreds of MW. Technical and economical barriers in relation to grid connection of these installations are being investigated. Significant up scaling will have an impact on electrical design and may have significant influence on reliability and availability. New methods of risk assessments and standardisation are likely to be needed.

UpWind

THE RESEARCH ACTIVITIES, RESULTS AND EXPECTATIONS

The reliability of wind farms as power producing units may be considered in two respects: the availability of the individual wind farm itself, and its impact on the reliability of the overall electrical power system.

The initial task to be performed is to provide adequate general models and accurate data for the reliability and risk assessments of wind turbines and wind farms. Such models are essential to enable comparison of different electrical design and grid connection options. The reliability model and data has to take into account the intermittent nature of the energy source, the grid events, and the dependability on electrical components.

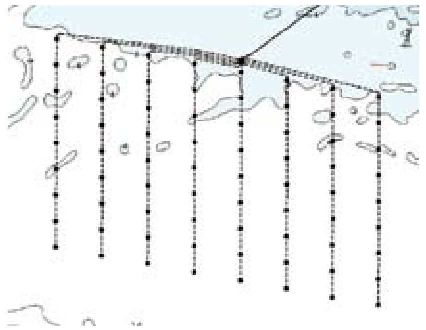
The overall power system requirements are reflected in the grid codes. In this context it is important to predict what the future requirements of the transmission system operators might be in order to integrate increased amounts of wind power in the system. Additionally, future networks with higher levels of wind penetration requires analysis.

Equally important and with reference to electrical transmission systems, is the requirement to establish new design criteria for future wind turbines. In this respect, it may be necessary to predict the power quality performance standards as offered by wind turbine manufacturers and how these standards may address the requirements of grid codes.

Extreme wind conditions influence reliability and are particularly important when several large wind farms are geographically adjacent. A critical issue constitutes an increase of the wind speed exceeding the cut-out wind speed of wind turbines.

Many wind turbines have a cut-out wind speed of 25 m/s or below. It is important to quantify the impact of these events and to develop new solutions.

The impact of various electrical and control concepts of wind farms on the reliability are investigated. The considered electrical designs need to comply with relevant European grid codes and should maximize reliability observing reasonable cost constraints. Different designs of electrical systems for wind farms with respect to their susceptibility to grid deviations. Requirements can then be established and issued in the new design criteria in accordance with grid code requirements. Different designs of electrical systems for wind farms will be evaluated with respect to their ability to participate in power control.



Finally the consequences of up scaling of wind turbines and wind farms for the cost model and reliability are being investigated.

The research activities of WP9 are purely analytical and focus mainly on reliability modelling, on design criteria of future large wind turbines, and on improved grid integration.

Initially, a survey on reliability of existing large offshore wind farms was based on available operational statistics in order to enable comparison of different options and identify factors that influence reliability, taking into account grid events, electrical construction and protection systems.

A database with data on the reliability of electrical components in wind farms will be set up. This database will serve as the basis for a subsequent evaluation of the reliability of different electrical system options.

Subsequently, reliability software tools for wind turbines and wind farms will be developed. One model will be developed and incorporated into a general commercial reliability software package. Another model is developed for ECN simulation programmes Vision and EeFarm. These models will focus on the effect of electrical design on the reliability of large offshore wind farms. The reliability model will be enhanced during the project. Limitations and various detail levels of models will be investigated as well.

The requirements and design criteria with reference to electrical networks (transmission and distribution grids) are established in two steps. First a state-of-the-art survey is made on existing European grid codes and corresponding performance of existing wind turbines. Secondly, the future grid code requirements for higher wind penetration will be analyzed and new design criteria for future wind turbines with respect to electrical networks will be established for single wind turbines or wind farms.

Different designs of electrical systems for wind farms are being evaluated with respect to their impact on system security. Based on representative turbine and electrical system parameters, the different electrical concepts will be ranked with respect to their compliance with new design criteria and grid code requirements. Similarly, different designs of electrical systems for wind farms will be evaluated in relation to their ability to participate in power control, including automatic frequency and voltage control.

Isolated island grids with high penetration of wind results in specific requirements on the reliability. The need for security of operation results into frequent wind power curtailments. Island grids depend more on the reliability of the wind than large interconnected systems like the UCTE. Hence, specific requirements to fully exploit the high wind potential, will be specified for wind turbines operating in such systems.

The investigation of how extreme wind conditions influence the reliabilities will quantify the probability of these events, in connection with the amount of lost generation and also study the influence of control system modifications, aiming at less abrupt cut-out of large-scale wind power generation.

Finally, the research activities will focus on up scaling of the electric system of wind turbines and assess possible technical and economical barriers. Cost functions will be derived for grid connection of wind turbines of 5, 10, 20 MW and offshore wind farms of 500 to 1000 MW.