UpWind

Design limits and solutions for very large wind turbines

March 2011

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A 20 MW turbine is feasible

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1 UPWIND: SUMMARY A 20 MW TURBINE IS FEASIBLE

“They did not know it was impossible, so they did it.”

Mark Twain, American novelist, 1835 - 1910

The need for the UpWind project: exploring the design limits of upscaling

The key objective of the European wind industry‘s research and development strategy for the next ten years is to become the most competitive energy source by 2020 onshore and offshore by 2030[1], without accounting for external costs.

In October 2009, the European Commission published its Communication “Investing in the Development of Low Carbon Technologies (SET-Plan)”, stating that wind power would be “capable of contributing up to 20% of EU electricity by 2020 and as much as 33% by 2030” were the industry‘s research needs fully met. The wind industry agrees with the Commission‘s assessment. Significant additional research efforts in wind energy are needed to bridge the gap between the 5% of the European electricity demand which is currently covered by wind energy, and one-fifth of electricity demand in 2020, one-third in 2030 and half by 2050.

Meeting the European Commission‘s ambitions for wind energy would require meeting EWEA‘s high scenario of 265 GW of wind power capacity, including 55 GW of offshore wind by 2020. The Commission‘s 2030 target of 33% of EU power from wind energy can be reached by meeting EWEA‘s 2030 installed capacity target of 400 GW wind, 150 GW of which would be offshore. Up to 2050 a total of 600 GW of wind energy capacity would be envisaged, 250 GW would be onshore and 350 GW offshore. Assuming a total electricity demand of 4,000 TWh in 2050 this amount of installed wind power could produce about 2,000 TWh and hence meet 50% of the EU‘s electricity demand.

Thus a significant part of the required future installed wind power will be located offshore. For offshore application new technologies and know how are needed beyond the existing knowledge base, which is mainly focused on onshore applications. Going offshore implies not only new technologies but also upscaling of wind turbine dimensions, wind farm capacities and required – not yet existing – electrical infrastructure. The need for upscaling found its origin in the cost structure of offshore installations and is the “motor” of modern wind energy research. The results will not be applicable to offshore wind energy technology only, but will also lead to more cost effective onshore installations.

Ultimately, all research activities, aside from other implementation measures, are focused on reductions to the cost of energy. The industry is taking two pathways towards cost reductions in parallel:

- Incremental innovation: cost reductions through economies of scale resulting from increased market volumes of mainstream products, with a continuous improvement of the manufacturing and installation methods and products;
- Breakthrough innovation: creation of innovative products, including significantly upscaled dedicated (offshore) turbines, to be considered as new products.

The UpWind project explores both innovation pathways. In formulating the UpWind project the initiators realised that wind energy technology disciplines were rather fragmented (no integrated verified design methods were available), that essential knowledge was still missing in high priority areas (e.g. external loads), measuring equipment was still not accurate or fast enough, and external factors were not taken into consideration in minimising cost of energy (grid connection, foundations, wind farm interaction).

[1] http://www.ewea.org/fileadmin/ewea_documents/documents/publications/EWI/EWI_2010_final.pdf

In order to be able to address all shortcomings in an effective way a comprehensive matrix project structure was designed, where disciplinary, scientific integration and technology integration were included (see page 18). A key issue for integrating various research results was developing an overall engineering cost model.

This unique UpWind approach quantifies the contribution of the different types of innovation resulting from the project. Not only are upscaling parameters incorporated, but also innovation effects are defined as a separate independent parameter. At the time of writing the full results of the integration process through cost modelling was not yet available, but will be published in 2011. However, some early conclusions may already be drawn, such as the benefits of distributed aerodynamic blade control.

The question often arises whether there is one single "optimum" technology. UpWind did not seek to define one unique optimum technology but rather explored various high-potential solutions and integrated them with respect to the potential reduction of cost of energy. An optimised wind turbine is the outcome of a complex function combining requirements in terms of efficiency (electricity production), reliability, access, transport and storage, installation, visibility, support to the electricity network, noise emission, cost, and so on.

UpWind's focus was the wind turbine as the essential component of a wind electricity plant. Thus external conditions were only investigated if the results were needed to optimise the turbine configuration (e.g. grid connection options) and the other way around (control options for wind turbines) in order to optimise wind farms.

UpWind did not seek the optimal wind turbine size, but investigated the limits of upscaling, up to, approximately, 20 MW / 250 m rotor diameter. Looking at very large designs, attention is focused on physical phenomena or model behaviour that are relevant for large-scale structures but have negligible effects at lower scales.

For instance, the development of control methods for very large rotors requires the full wind behaviour, including wind shear and turbulence, to be taken into account.

This in turn means the anemometer values must be corrected based on the rotor effects and therefore advanced wind measurement technologies need to be used. UpWind therefore developed and validated the measurement devices and models able to provide such measurements (LIDAR).

UpWind also developed the tools and specified the methods to enable large designs. These tools and methods are available to optimise today's designs, and are used to improve the reliability and efficiency of current products, such as drive trains.

UpWind demonstrates that a 20 MW design is feasible. No significant problems have been found when upscaling wind turbines to that scale, provided some key innovations are developed and integrated. These innovations come with extra cost, and the cost/benefit ratio depends on a complex set of parameters. The project resulted for instance in the specification of mass/strength ratios for future very large blades securing the same load levels as the present generation wind turbines. Thus in principle, future large rotors and other turbine components could be realised without cost increases, assuming the new materials are within certain set cost limits.

As the UpWind project's scope is very wide and the project has laid the basis for essential future strategies for decreasing cost of energy, UpWind contributed considerably to the recommendations of the European Wind Energy Technology Platform and the foundation for the European Wind Initiative. It is clear from the conclusions of UpWind that the European Wind Initiative's research agenda is both feasible and necessary and should therefore be financed without delay by the European Commission, national governments and the European wind energy sector.

UpWind methodology – a lighthouse approach

For its assessment of the differences between the parameters of the upscaled wind turbine, UpWind adopted a reference 5 MW wind turbine. This reference was based on the IEA reference turbine developed by the National Renewable Energy Laboratory's (NREL). As a first step, this reference design was extrapolated ("upscaled") to 10 MW. The 20 MW goal emerged progressively during the project, while the industry in the meantime worked on larger machines. The largest concepts which are now on the drawing board measure close to 150 m rotor diameter and have an installed power capacity of 10 MW. While a 10 MW concept progressively took shape, UpWind set its mind to a larger wind turbine, a turbine of about 250 m rotor diameter and a rated power of 20 MW. Also the idea of the lighthouse concept was adopted to present the many results of UpWind in one image.

The lighthouse concept is a virtual concept design of a wind turbine in which promising innovations, either mature or embryonic, are incorporated. The lighthouse is not a pre-design of a wind turbine actually to be realised, but a concept from which ideas can be drawn for the industry's own product development. One of the innovations, for example, is a blade made from thermoplastic materials, incorporating distributed blade control, including a control system, the input of which is partly fed by LIDARs.

The 20 MW concept provides values and behaviour used as model entries for optimisation. It is a virtual 20 MW turbine, which could be designed with the existing tools, without including the UpWind innovations. This extrapolated virtual 20 MW design was unanimously assessed as almost impossible to manufacture, and uneconomic. The extrapolated 20 MW design would weigh 880 tonnes on top of a tower making it impossible to store today at a standard dockside, or install offshore with the current installation vessels and cranes.

		Reference wind turbine 5 MW	Extrapolated turbine 10 MW	Extrapolated virtual turbine 20 MW
Rating	MW	5.00	10.00	20.00
Wind regime		IEC class 1B [2]	IEC class 1B	IEC class 1B
No of blades		3	3	3
Rotor orientation		Upwind	Upwind	Upwind
Control		Variable speed, control pitch	Variable speed, control pitch	Variable speed, control pitch
Rotor diameter	M	126	178	252
Hub height	M	90	116	153
Max. rotor speed	Rpm	12	9	6
Rotor mass	Tones	122	305	770
Tower top mass	Tones	320	760	880
Tower mass	Tones	347	983	2,780
Theoretical electricity production	GWh	369	774	1,626

[2] IEC 61400 class IB is an average wind speed at hub height of 10 m/s, V50 extreme gusts 70 m/s, 16% characteristic turbulence, wind shear exponent is 0.2.

The support structures able to carry such mass placed at 153 m height are not possible to mass manufacture today. The blade length would exceed 120 m, making it the world's largest ever manufactured composite element, which cannot be produced as a single piece with today's technologies. The blade wall thickness would exceed 30 cm, which puts constraints on the heating of inner material core during the manufacturing process. The blade length would also require new types of fibres to resist the loads.

However, the UpWind project developed innovations to enable this basic design to be significantly improved, and therefore enable a potentially economically sound design.

UpWind: 20 MW innovative turbine

Key weaknesses of the extrapolated virtual 20 MW design are the weight on top of the tower, the corresponding loads on the entire structure and the aerodynamic rotor blade control. The future large-scale wind turbine system drawn up by the UpWind project, however, is smart, reliable, accessible, efficient and lightweight.

A part of UpWind (WP3)[3] analysed wind turbine materials. This enabled the micro-structure of the blade materials to be studied and optimised in order to **develop stronger and lighter blades**. However, this would not be sufficient unless fatigue loading is also reduced.

Reducing fatigue loading means longer and lighter blades can be built. The aerodynamic and aeroelastic qualities of the models were significantly improved within the UpWind project, for example by integrating the shear effect over large rotors WP2. Significant knowledge was gained on load mitigation and noise modelling.

UpWind demonstrated **that advanced blade designs could alleviate loads by 10%, by using more flexible materials and fore-bending the blades (WP2).**

After reducing fatigue loads and applying materials with a lower mass to strength ratio, a third essential step is needed. **The application of distributed aerodynamic blade control, requiring advanced blade concepts with integrated control features and aerodynamic devices. Fatigue loads could be reduced 20-40%** (WP2). Various devices can be utilised to achieve this, such as trailing edge flaps, (continuous) camber control, synthetic jets, micro tabs, or flexible, controllable blade root coupling. Within UpWind, **prototypes of adapting trailing edges, based on piezo electrically deformable materials and SMA (shape memory alloys) were demonstrated** (WP1B.3). However, the control system only works if both hardware and software are incorporated in the blade design. Thus advanced modelling and control algorithms need to be developed and applied. This was investigated in WP1B3.

Further reducing the loads requires advanced rotor control strategies (WP5) for "smart" turbines. These control strategies should be taken into account in the design of offshore support structures (WP4). **The UpWind project demonstrated that individual pitching of the blades could lower fatigue loads by 20-30%.** Dual pitch as the first step towards a more continuous distributed blade control (pitching the blade in two sections) could lead to load reductions of 15%. In addition, the future smart turbine will use advanced features to perform site adaptation of its controller in order to adapt to local conditions (WP5).

Advanced control strategies are particularly relevant for large offshore arrays, where UpWind demonstrated that 20% of the power output can be lost due to wake effects between turbines.

Optimised wind farm layouts were proposed, and innovative control strategies were developed, for instance lowering the power output of the first row (thus making these wind turbines a bit more transparent for the air flow), facing the undisturbed wind, allowing for higher overall wind farm efficiency (WP8).

[3] The reference WP in brackets refers to the specific 'work package' or sub-programme fiche provided within this report.

Control and maintenance strategies require load sensors, which were adapted and tested within UpWind. To avoid sensor failures causing too much loss of energy output, loss of sensor signals was incorporated into the control strategies (WP5) and a strategy was developed to reduce the number of sensors. The fatigue loading on individual wind turbines can be estimated from one heavily instrumented turbine in a wind farm if the relationship of fatigue loading between wind turbines inside a wind farm is known. The so-called Flight Leader Concept[4] was developed in WP7.

Those load sensors can be Bragg sensors, which were tested and validated within the project (WP7). **UpWind demonstrated the efficiency and reliability of such sensors, and assessed the possibility of including optic fibres within the blade material without damaging the structure** (WP3).

However, using sensors implies the rotor is only reacting to the actual loading phenomenon. As a result of the system inertia, the load will be partly absorbed. **A step further is to develop preventative load alleviation strategies by detecting and evaluating the upcoming gust or vortex before it arrives at the turbine. A nacelle-mounted LIDAR is able to do this** (WP6), and can be used as an input signal for the individual blade pitching, or in distributed blade control strategies (WP5).

In recent years, **UpWind has been a focal point for LIDAR development, and has considerably helped the market penetration of LIDAR technologies**. Although LIDARs are still considerably more expensive than SODARs for instance, their technical performance, and thus potential, is substantial. **UpWind demonstrated that LIDARs are sufficiently accurate for wind energy applications.** (WP1A2). LIDARs can be used for the power curve estimation of large turbines, for control systems, for resource assessment in flat terrain, including offshore and soon in complex terrains (WP1A2 and WP6), and for measuring the wind shear over the entire rotor area.

UpWind demonstrated the need to take the wind shear into account for large rotors (WP6 and WP2). The 20 MW rotor is so large that the wind inflow needs to be treated as an inhomogeneous phenomenon. One point measurement, as recommended by IEC standards, is not representative anymore. A correction method was developed and demonstrated within UpWind.

The smart control strategies and high resolution modelling described above require a highly accurate wind measurement, since a small deviation can have a significant impact on reliability. In the metrology domain, **UpWind considerably improved knowledge on wind measurement accuracy** within the MEASNET[5] community. Cup anemometers, LIDARs, SODARs and sonic anemometers (WP1A.2 and WP6) were tested, demonstrated and improved. UpWind's WP1A.2 had access to almost all existing wind measurement databases.

The advanced control strategies of smart blades using smart sensors enable loads to be lowered considerably, so lighter structures can be developed. The improved modelling capability means the design safety factors can be less conservative, paving the way to lighter structures (WP1A1). UpWind investigated this path, developing accurate integral design tools that took into account transport, installation, and operation and maintenance (O&M). Onshore, the transport of large blades is a particular challenge, **and UpWind developed innovative blade concepts (WP1B1) enabling a component to be transported in two sections without endangering its structural safety or aerodynamic efficiency.**

Integral design tools were also developed to improve the reliability of the entire drive train (WP1B.2), and to investigate the possibility of developing proportionally lighter generators for large wind turbine designs. UpWind investigated ten different generator configurations and found promising potential weight reductions for permanent magnet transversal flux generators.

[4] The "flight leader" is a term used in aircraft technologies. The idea behind the "flight leader turbines" is to equip selected turbines at representative positions in the wind farm with the required load measurement. The flight leader turbines are thus subject to higher, or at least similar, loads to other turbines in a wind farm.

[5] www.measnet.com

The UpWind project worked on ensuring the reliability of large turbines, in particular for far offshore applications. UpWind focused on condition monitoring technologies (WP7) and fault prediction systems. Such advanced systems enable fault detection and preventative maintenance to be carried out, with a large potential for cutting O&M costs. **The reliability of the future large blades can be assessed using probabilistic blade failure simulation tools** (WP3).

Reducing the loads and the nacelle weight enables the offshore substructure design to be optimised (WP4). **UpWind developed integrated wind turbine/substructure design tools and investigated optimal offshore substructure configurations** according to the type of turbine, type of soil and water depth. Future deeper water locations were investigated and innovative cost-effective designs were analysed.

Progress was made on deep water foundation analysis, including the development of advanced modelling techniques and enhancements of current design standards which for example become very important for floating designs.

With the improved intelligence of wind turbines, wind farms are operated more and more as power plants, providing services to the electricity system, such as flexibility and controllability of active and reactive power, frequency and voltage, fault-ride-through or black start capabilities (WP9). Those capabilities will allow for substantially increased penetration of wind power in the grid in the near future. The future large offshore wind farms, far from shore, will be connected to HVDC VSC, forming the backbone of an integrated European offshore grid, and supporting the emergence of a single electricity market.

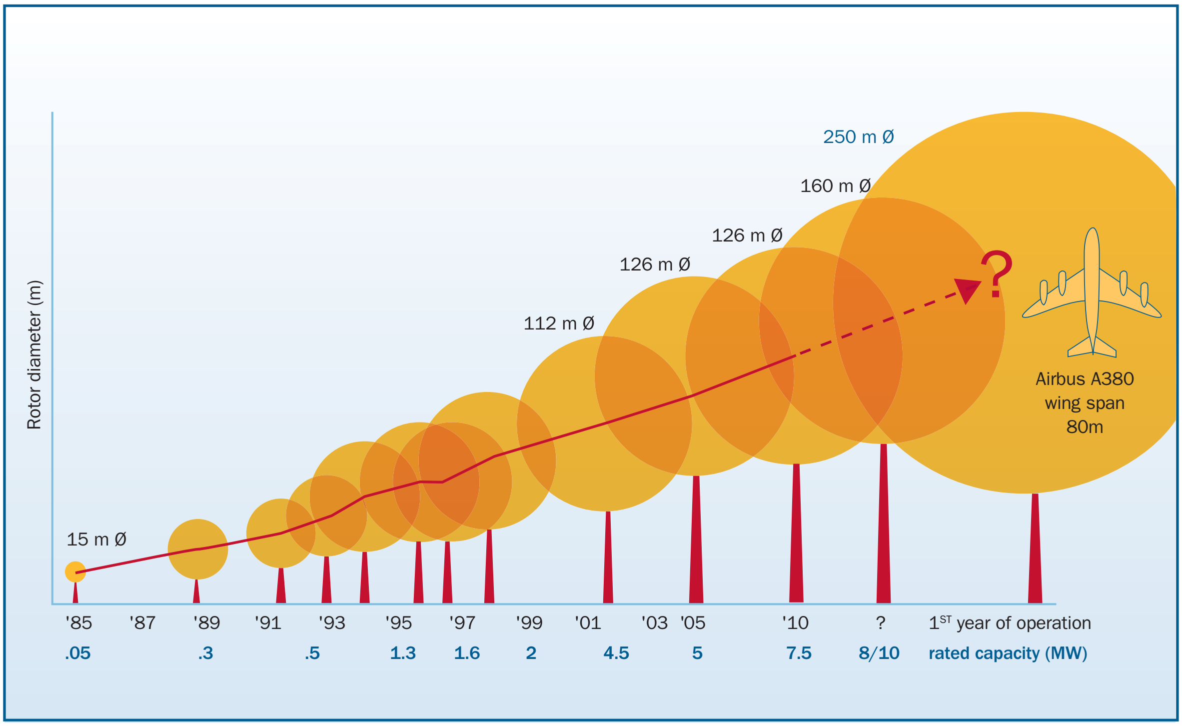
It will be challenging for the wind energy sector to attract and train the required number of engineers, postgraduates and PhD students to fulfil its needs. UpWind focused on training and education (WP1A3), and developed free of charge advanced training modules on wind energy, including the latest innovations in the field. This content is distributed through the REnKnow database[6].

UpWind: rooted in history

UpWind is the largest-ever EU-funded research and development project on wind energy. In terms of scope, content and volume, the project can be compared to typical national R&D programmes carried out in countries like Denmark, Spain, the Netherlands and the USA. The UpWind project was made up of 48 partners, all leaders in their field, half from the private sector, and half from the research and academic sector. This makes UpWind the largest public/private partnership ever designed for the wind energy sector.

The story of the UpWind project starts in 2001. At that time, the 2001 renewable electricity directive (2001/77/EC) was facilitating the rapid growth of wind energy in Europe. By the end of 2000, the installed wind capacity in Europe was 13 GW. Growth was based on 1 to 2 MW wind turbines, the work horses of that time, and demonstrators of 4 to 5 MW were under development, showing the potential for upscaling and innovation. Large cost reductions were envisaged. However, the wind energy sector needed to considerably accelerate its innovation rate if the energy objectives were to be achieved.

[6] http://www.renknow.net/



An innovation accelerator was required that could set clear pathways for future development and rapidly transfer technological advances to the market. In order to shape such a vehicle, the wind industry created what was known as a 'Wind Energy Thematic Network' (WEN), an initiative supported as a project by the European Commission. Through an extended consultation process, WEN identified the key innovation areas and put forward recommendations to address the declining public R&D funding in the wind energy sector. The WEN placed wind energy innovation in the context of the newly adopted Lisbon strategy for the first time[7]: wind energy was identified as being able to improve European competitiveness.

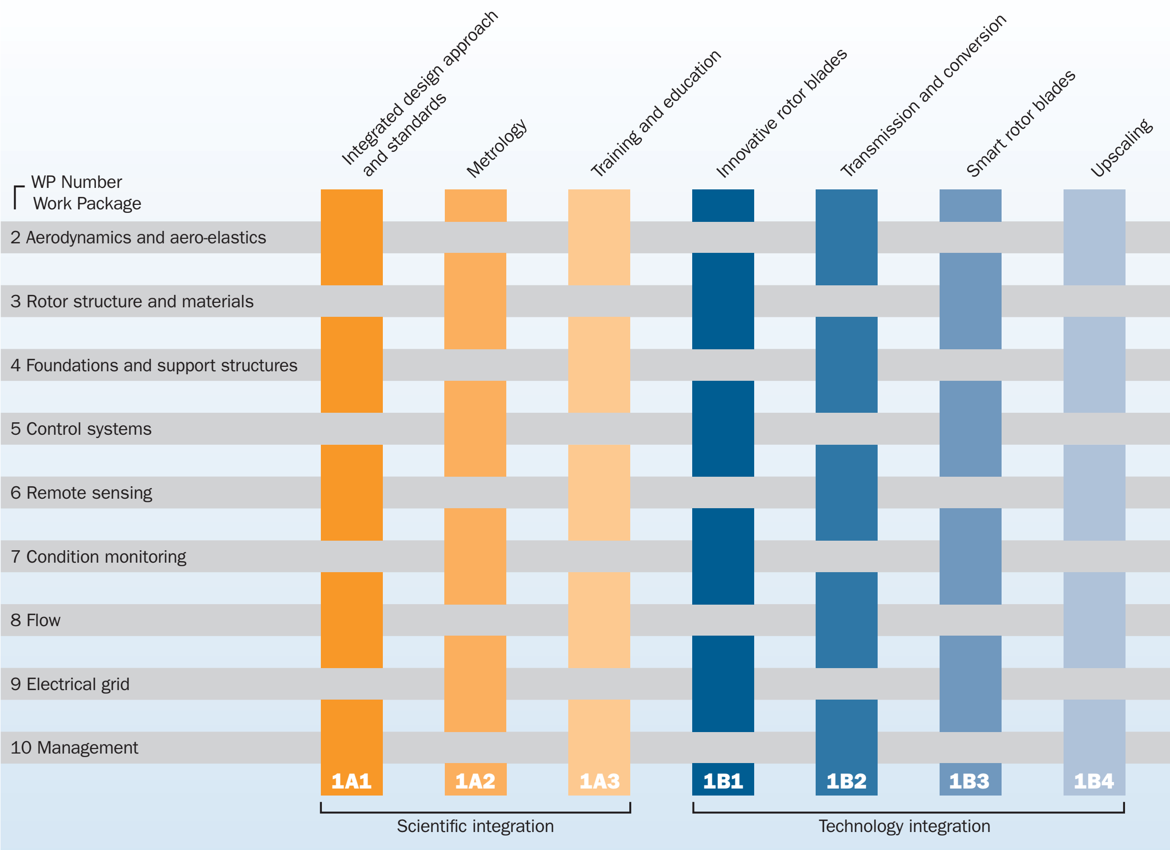
In 2005 WEN published a roadmap for innovation, which was the first Strategic Research Agenda for the wind energy sector. This document was used as a basis for the European Wind Energy Technology Platform. TPWind updated the Strategic Research Agenda and developed an industry-led master plan with a total R&D budget of €6 billion up to 2020: the European Wind Industrial Initiative (EWI). The recently created European Energy Research Alliance (EERA) reinforces this trend by putting more emphasis on long-term research. The UpWind proposal and consortium, financed by the European Commission under the sixth Framework Programme (FP6), was developed in parallel with the creation of the Technology Platform by the sector involving individual key institutions and companies with the European Academy of Wind Energy (EAWE) and the European Wind Energy Association (EWEA) as essential catalysers. Building on UpWind's achievements, EERA and EWI together cover the main road of designing the European wind energy technology of the future and helping to meet the EU's 2020 renewable energy targets, and beyond.

[7] One objective was a level of spending of 3% of the EU GDP in R&D in 2010. The Lisbon objective was not achieved, and the strategy was relaunched through the recent Europe 2020 strategy.

UpWind: continuous innovation

UpWind is one of the few integrated projects launched under FP6. Integrated projects were designed to cover the whole research spectrum. Due to the broad range of innovation challenges to be covered in a single field, such projects required a high level of coordination and consistency. Due to their size and complexity, high demands were put on the management. An innovative management concept was designed, enabling research to be carried out on specific issues, both scientific and technological ones, while at the same time integration of the results was guaranteed.

These considerations led to a matrix structure shown below. In this structure, scientific and technical disciplines are dealt with within horizontal work packages (WP's), and integration through vertical activities. The vertical activities are themselves grouped into scientific and technology integration work WP's respectively. The earlier mentioned *lighthouse approach*[8] forms the focus of the WP1A.1 Integrated Design Approach and Standards and WP1B.4 Upscaling. All other WPs provide inputs.



[8] UpWind investigated a *lighthouse vision*, which means a vision that defines the options and necessities for future very large wind turbines.

In addition to defining a clear way forward for wind energy technology, UpWind had the responsibility of accelerating innovation within the sector. This required strong involvement from the private sector. The involvement in UpWind of leading wind turbine and component manufacturers, as well as software providers, technical consultants and energy companies, demonstrated the sector's high level of maturity. Handling Intellectual Property within large EU-funded projects was secured by IP agreements and was dealt with inside the WP concerned. This proved to be a very effective model.

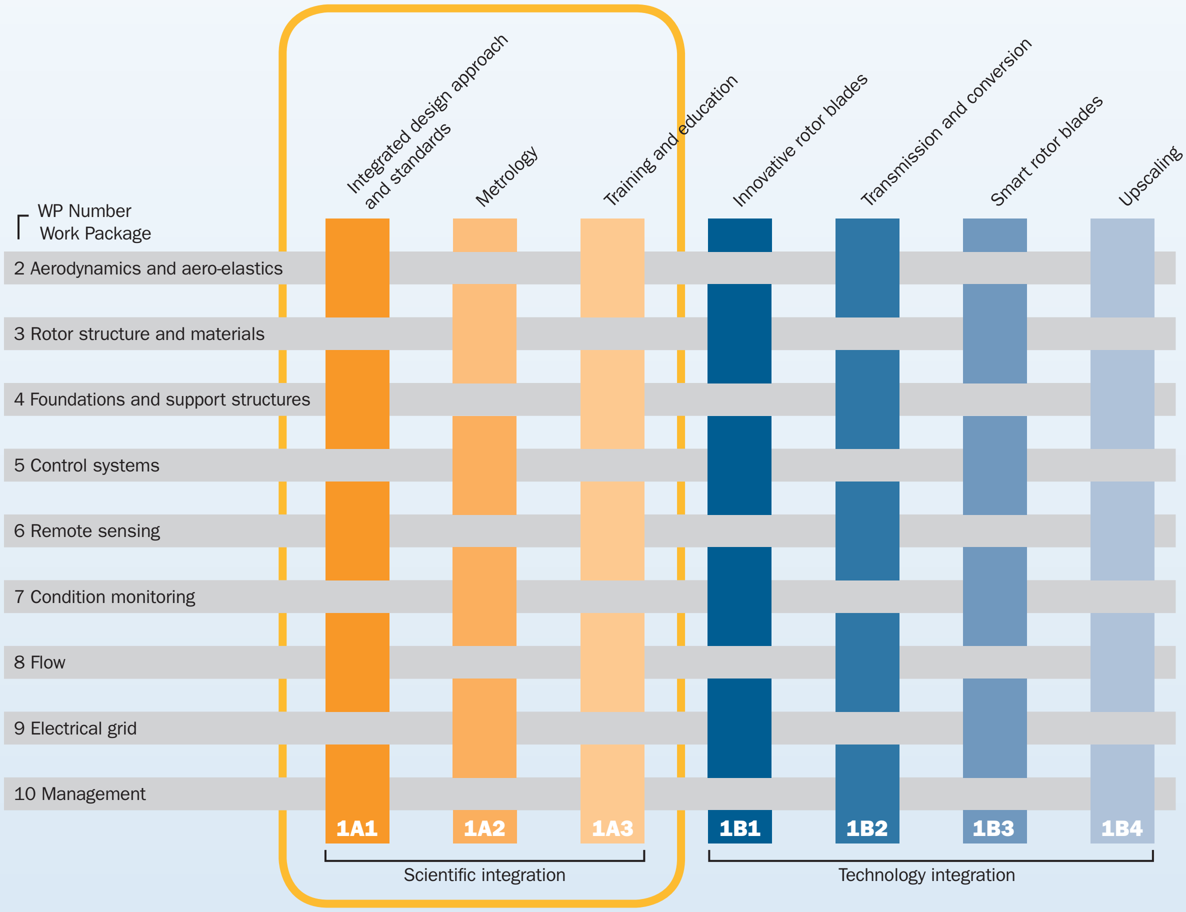
The strategy followed by UpWind was to focus on innovation with a long-term aim: exploring the design limits of very large-scale wind turbines, in the 10-20 MW range. UpWind used upscaling as a driver for innovation, and moved away from the competitive arena. Along the way, the challenges dealt with in UpWind became a reality, with the demonstration of 5 MW turbines, the current testing of 7 MW machines, and the development of 10 MW designs. The innovation developed within the project helped solve day-to-day challenges, such as was the case in the field of WP1B.2 Transmission and Conversion. UpWind had an international impact, through the IEA Wind Implementing agreement, where the UpWind results are included in several international task activities. Partnerships, especially in the field of material research (WP3), were developed with India, Ukraine and China.

In terms of project financing, UpWind shows the way forward for public-private partnership instruments. The scale of today's challenges, and the scarcity of resources require developing innovative funding instruments able to create a leverage effect. Those should combine funding from the Framework Programmes, other Community programmes and Member States, private capital, and European Investment Bank instruments. The future FP8 instruments are likely to be flexible, with less red tape, and their structure is likely to be shaped by the time-to-market of innovation, and able to combine those various sources of funding in a coordinated manner. Although UpWind was financed under the FP6, some specific WP activities were co-financed by Member State programmes beyond the financial scope of UpWind. One outstanding example is the development of LIDAR remote sensing techniques (WP6). This made UpWind the first project within the European Wind Initiative priorities that complemented support from the Framework Programmes with coordinated calls for proposals from committed countries. Within EWI, UpWind is used as a reference case for such instruments.

2 UPWIND: SCIENTIFIC INTEGRATION

UpWind: Scientific integration

- 1A1 Standards and integration
- 1A2 Metrology
- 1A3 Training and education



2.1 Work Package 1A1: Standards and integration

Mr. Sten Frandsen from RisøNational Laboratory - DTU died during the month of October 2010. He was the Work Package leader of WP 1A1.

The entire UpWind consortium would like to acknowledge the human and scientific abilities he demonstrated along his career. Mr. Frandsen was known as a man expressing and standing for his ideas and his contribution to the UpWind project was invaluable.

UpWind demonstrates that an integral design approach can significantly cut costs for current and upscaled products. UpWind was trying to find an optimal wind turbine design: cost-effective and with appropriate design safety levels, influenced by operation and maintenance and installation strategies.

Challenges and main innovations

The UpWind project needed a baseline case study to benchmark innovation. UpWind defined a reference 5 MW turbine, adapted from NREL's 5 MW design. During the project, these reference design parameters were extrapolated to a virtual 20 MW machine. This enables a comparison to be made between a virtual extrapolated 20 MW machine and the UpWind innovative 20 MW machine. A cost model was developed in order to isolate and study the dimensioning cost parameters of this upscaled wind turbine. However, as an optimal design should account for the external design constraints, an innovative design approach was developed that includes both technical and non-technical disciplines within the same framework. In this framework, manufacturing, transport, installation and O&M procedures become design parameters rather than constraints. It enables the system as a whole to be optimised at a design stage. Finally, a large potential for cost optimisation lies in the design safety levels. A probabilistic design of structural wind turbine components can be used to design components directly, thereby ensuring the design is more uniform and economic than that obtained by traditional design using standards such as the IEC 61400 series.

The challenge is to efficiently update the design standards and to promote the use of an integrated design approach. This will ensure consistency between the advanced models and strengthen their integration into wind energy technology, improve the test methods and design concepts developed in UpWind and in turn provide a consistent scientific background for standards and design tools. The approach has four parts:

- Providing a reference wind turbine for ease of communication between the work packages and integration and benchmarking of their findings;
- Development of cost models for upscaling to very large wind turbines (20 MW) – in cooperation with the upscaling work package;
- Development and definition of an integral design method; and
- Development of (pre)standards for the application of the integral design approach, including interfaces, data needs guidelines and proposals for a formal international standardisation process.

Results

Subtask A: Reference wind turbine and cost model

As reference wind turbine an NREL 5 MW model - was used (see [1]) and improved. An overall framework for an optimal design of wind turbines was formulated, taking up-scaling and cost modelling into account [2] and [3]. The approach is based on a life-cycle analysis including all the expected costs and benefits throughout the lifetime of the wind turbine (wind farm).

The cost model was developed for wind turbine up-scaling up to 20 MW. These wind turbines are expected to have a rotor diameter of approximately 250m and a hub height of 153m. A theoretical framework for a risk-based optimal design of large wind turbines was formulated. Three types of formulation were made: 1) a risk / reliability-based formulation, 2) a deterministic, code-based formulation and 3) a crude deterministic formulation. These formulations are described in [2] and [3].

In the third formulation (crude, deterministic), generic cost models are given as a function of the design parameters using basic up-scaling laws adjusted for technology improvement effects. There, the optimal design is the one which minimises the levelised production costs. The main design parameters are: the rotor diameter, the hub height, the tip speed and where the wind turbines are placed in relation to one another in wind farms. In a more detailed approach, the cross-sectional dimensions (such as the geometry of the blade or the tower), the O&M strategy, or more refined input parameters can be included. External design parameters are fixed regarding the size of the wind farm (in terms of MW capacity and / or the geographical area covered by the wind farm), the wind climate including the terrain (mean wind speed and turbulence), wave and current climate (offshore), water depth, soil conditions and distance from land (or nearest harbour).

The cost model is based on a life-cycle approach including all capitalised costs. The main up-scaling parameter is typically the rotor diameter. The cost model is basically formulated as function of this design parameter using an up-scaling factor with an up-scaling exponent (typically 3) and a time-dependent technology improvement factor.

Subtask B: Integral design approach methodology

UpWind addresses the full life-cycle of the large-scale wind turbines of the future, including the technical and commercial aspects. However, non-technical disciplines do not use any kind of model that is compatible with the technical disciplines. There is a strong need for new design paradigms that are able to account for both technical and non-technical disciplines within the same framework so that manufacturing, transport, installation and O&M procedures become design parameters rather than constraints. A new design approach was proposed in UpWind. This approach is based on the principles of systems engineering and features elements of Multi-disciplinary Design Optimisation (MDO), Knowledge Based Engineering (KBE) and Mono-disciplinary Computational Analysis Methods (MCAM).

The approach requires knowledge on the design processes of the wind turbine and their subsystems to be captured and written down. The wind turbine technologies currently applied are in this approach, as well as those being studied and developed within the UpWind project. The captured knowledge is analysed and translated into knowledge applications through KBE. These applications address the following areas of the design:

- The development of a parametric Multi Model Generator (MMG) for existing and new wind turbine concepts.
- Automation of the prepared models and aerodynamic and structural analysis of the wind turbine components.
- Automation of the prepared models and aero-elastic analysis of wind turbine components.
- Automation of the prepared models and cost analysis of wind turbine components including material, manufacturing, transport and installation.
- Standardisation of a communication framework between the different disciplines.

This set of automated tools allows new wind turbine concepts to be designed. Furthermore, the tools are interconnected within what is known as a "Design and Engineering Engine" (DEE) [4, 5, 6]. This framework enables the software tools to communicate through agents or functions and provides a loosely coupled demand-driven structure for the DEE. Within the framework, each tool is considered an engineering service providing functionality to the framework.

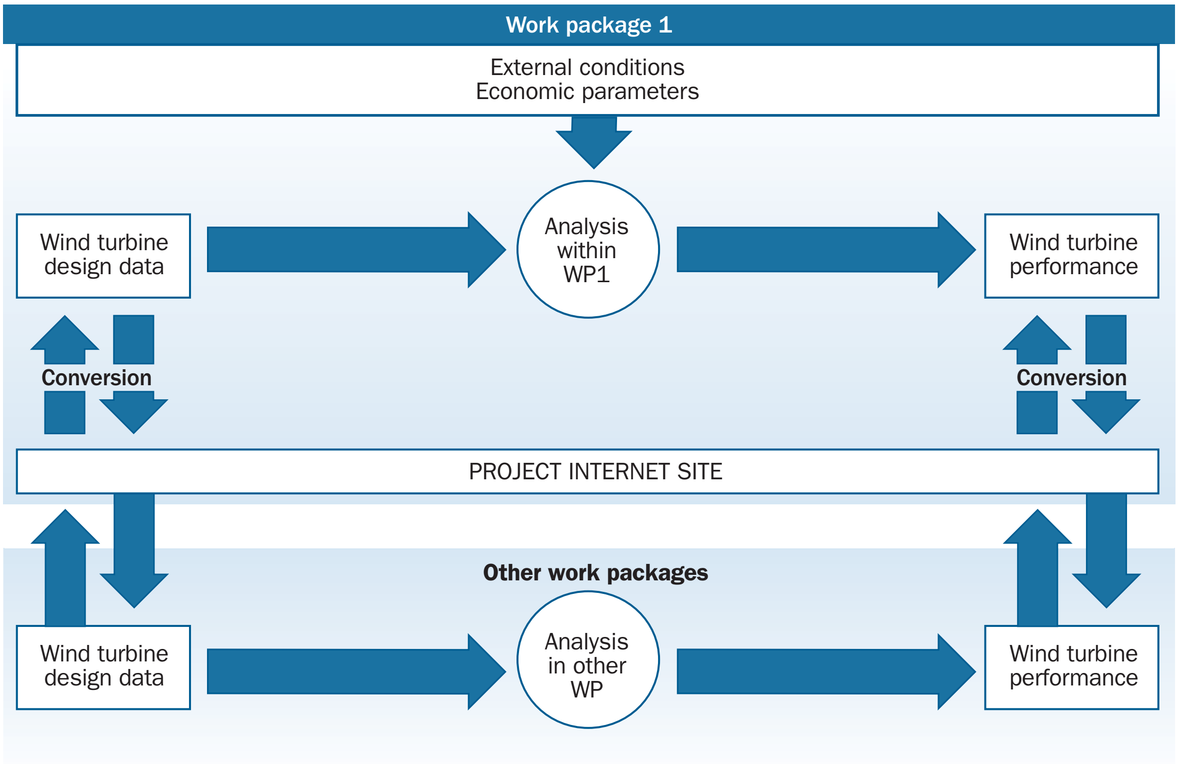


Figure 1: The design and engineering engine

Subtask C: Development of (pre)standards for the application of the integral design approach

Broad standards were developed and formulated to clarify the design requirements of multi megawatt turbines. Special emphasis has been put on probabilistic design of wind turbines, and recommendations of how to implement research results in international design standards [7].

A high reliability level and significant cost reductions are required so that offshore and land-based wind energy generation becomes competitive with other energy technologies. In traditional deterministic, code-based design, the structural costs are determined in part by the safety factors, which reflect the uncertainty related to the design parameters. Improved design with a consistent reliability level for all components can be obtained through probabilistic design methods, where uncertainties connected to loads, strengths and calculation methods are part of the calculation. In probabilistic design, single components are designed to a level of safety, which accounts for an optimal balance between failure consequences, material consumption, O&M costs and the probability of failure. Furthermore, by using a probabilistic design basis, it is possible to design wind turbines so that site-specific information on climatic parameters can be used. Probabilistic design of structural wind turbine components can be used for direct design of components, thereby ensuring a more uniform and economic design than that obtained by traditional design using standards such as the IEC 61400 series.

The IEC 61400-1 and -3 standards were reviewed within the UpWind project, and an assessment was made of design load computations and in particular the needs related to very large wind turbines. The methods, topics and results identified by UpWind create the need for the revision or development of international standards for the design of wind energy plants and associated tests. Proposals will be submitted to the International Organisation for Standards for all electrical, electronic and related technologies known as “electrotechnologies” (IEC) /ISO (International Organisation for Standardisation) and to the European Committee for Standardisation (CEN)/European Committee for Electrotechnical Standardisation (CENELEC).

Special emphasis was put on the synthesis and extrapolation of design load computations as required in IEC 61400-1, in order to arrive at efficient schemes for the derivation of design fatigue and extreme loads (extrapolation of load effects).

The IEC 61400-1 and -3 recommend identifying the 50 year extreme component load on the basis of limited load simulations through the use of statistical extrapolation methods. Such methods are often the cause of large variations in the extreme design load level. The possibility of determining a robust 50 year extreme turbine component load level when using statistical extrapolation methods was investigated, so that the 50 year load shows limited variations due to different turbulent wind seeds or inflow conditions. Case studies of isolated high extreme out of plane loads were also dealt with, so as to demonstrate the underlying physical reasons for them. The extreme load extrapolation methodology was made robust through the use of Principal Component Analysis (PCA) and simulation data from two widely used aeroelastic codes was applied. The results for the blade root out of plane loads and the tower base fore-aft moments were investigated as those extrapolated loads have shown wide variability in the past and are essential for turbine design. The effects of varying wind directions and linear ocean waves on the extreme loads were also included. Parametric fitting techniques that consider all extreme loads including “outliers” were proposed and the physical reasons that result in isolated high extreme loads were highlighted [8]. The isolation of the exact physical reasons that result in the peak extreme component loads also led to the creation of simplified fast solvers to determine the 50 year out of plane load level, as opposed to the numerous aeroelastic simulations that are usually carried out. This was demonstrated for the offshore turbine mudline out of plane loads because simplified, fast and reasonably accurate procedures enable the turbine designer to quickly understand the ultimate design limits [9]. The comparison of wave loading and wind loading on offshore turbine mudline extreme loads showed that the significant influence on the mudline load was due to the wind inflow, but the effect of the waves and soil conditions cannot be neglected. The wave loading was seen to be mildly beneficial for the load extrapolation procedure as the spread in the extreme out of plane loads at each mean wind speed is repeatable, unlike those that occur due to wind inflow variations. The effect of soil flexibility further increases the mudline extreme load level as lower frequencies have higher out of plane load power spectral density. Therefore the soil flexibility must be modelled while the offshore foundation mudline ultimate design loads are determined [10].

Subtask D: Integration, review and planning workshops
In order to bring together the findings of the project's work packages, workshops were regularly arranged with a special focus on the upscaling of turbines and the formulation of cost models.

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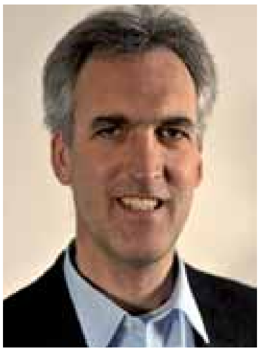


"The more your system is optimised, the more your wind measurement must be reliable and accurate. Wind measurement techniques for wind energy are progressing quickly. New sensors are being validated, with high potential to cut down the costs and lower the risks. The UpWind project acted as a node to narrow down wind measurement uncertainties. It helped translate innovation into IEC standards, with support of the whole measurement community"

Peter Eecen, Work Package Leader, Energy Research Centre of the Netherlands (ECN)

2.2 Work Package 1A2: Metrology

Challenges and main innovations

Small improvements in the wind turbine's performance can generate significant additional revenues over its lifetime. However, if there is too much measurement uncertainty, it becomes impossible to anticipate the improvement to the performance during field tests, and therefore difficult to convince the industry to include those innovations.

The design improvements resulting from the research activities of the UpWind project will require validation based on reliable and appropriate measurements. UpWind therefore studied OR is studying metrology problems related to wind turbine technology. In particular the fluctuations in wind speed lead to large measurement uncertainties, and sensors such as cup anemometers often do not respond in a linear manner. The objective of UpWind's metrology activities was to develop ways to significantly enhance the quality of measurement and testing techniques for wind energy applications. The first part of the metrology task was to identify the current measurement methods through the metrology database, then to identify metrology problems that need further work, and finally to consider problems to advance wind energy metrology.

This task addressed both the fundamental activities for supporting the sector growth (online measurement database, revision of IEC standards), and validated innovative measurement instruments, which could potentially lead to large cost reductions. UpWind acknowledged the following elements:

- LIDARs are potentially reliable measurement instruments for resource assessment, control strategies, or wake monitoring.
- The use and calibration method of sonic anemometers for wind measurements were established, and significant improvements are currently being implemented in available products.
- Onsite work is valuable for wind sensor comparison.

Results

The metrology database

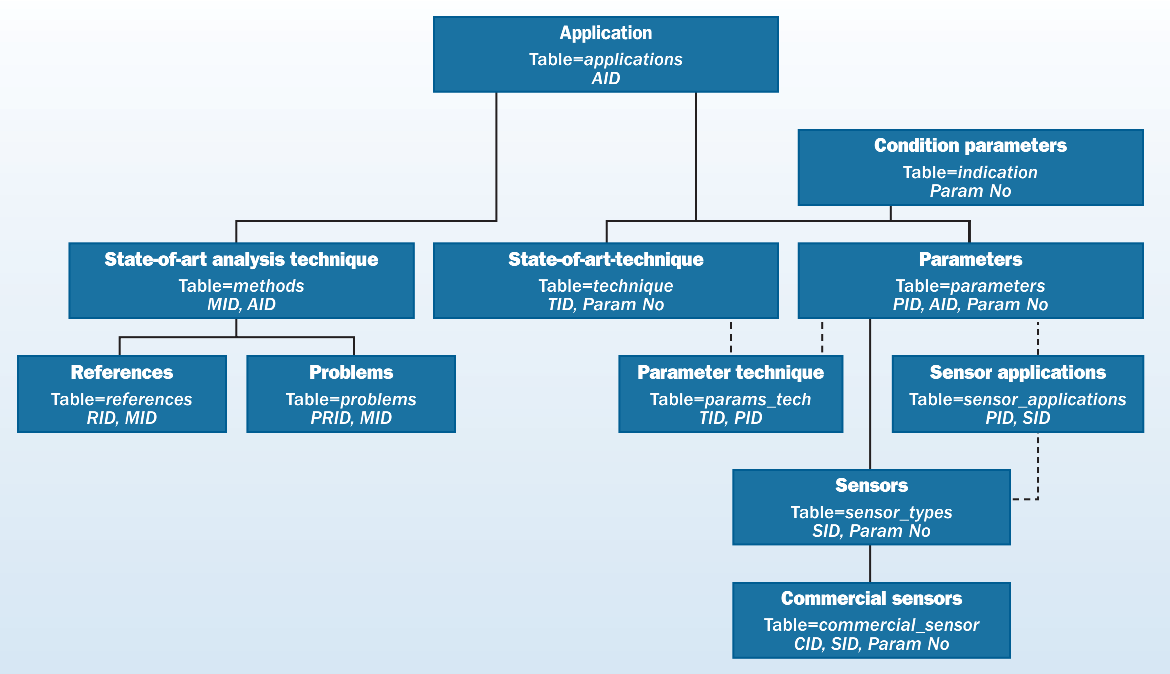
The objective is to develop metrology tools to significantly enhance the quality of measurement and testing techniques. The first outcome is an assessment of current measurement methods and problems. The required accuracies and sampling frequencies were identified from the perspective of the data users, and with regards to the UpWind objectives. The information was categorised in groups according to current analysis techniques, current measurement techniques, a sensor list, derived problems and commercially available sensors. In order to process these large amounts of data a database structure was designed and implemented. The database includes eleven primary tables as shown on Figure 2. The database is available on www.winddata.com as part of a "database on wind characteristics" and for UpWind partners in a portable MS-Access version. Preliminary results are listed in [1] and a detailed description of each table is listed in [2].

Advances in metrology

Metrology for wind energy is in rapid development. Some earlier EU projects considered measurement methods in wind energy [3, 4], making progress on current cup and sonic anemometry, and some development needs were identified for sonic anemometry. Requirements for detailed turbulence measurements call for better procedures in international standards on sonic anemometer calibration and classification. This task is currently considered in the revision work on the IEC standard on performance measurements [3], where cup anemometer calibrations and classifications have already been implemented.

A significant contribution has been made on power performance measurements with the influence of shear. A method has been developed which has a good chance of being implemented in the ongoing revision of the IEC performance standard [5]. A turbulence normalisation method has been tested [7] but not found efficient enough for inclusion in the IEC standard [5]. These methods have been tested on several existing datasets, such as the Riso/DTU and ECN test sites.

Figure 2: Metrology database structure. The database is accessible through www.winddata.com.



In relation to the coming IEC standard on performance verification with the use of nacelle anemometry [8], nacelle anemometry has been studied, both the theory and its practical application [9]. An alternative to nacelle anemometry has also been developed, the so-called spinner anemometer [10, 11]. This type of sensor seems to avoid the draw-backs of nacelle anemometry because the sensors are positioned in front of the rotor on the spinner. Finally, mast correction measurement has also been developed to improve current measurements [12].

With respect to new wind measurement technologies such as remote sensing (LIDAR & SODAR), a substantial number of projects have been undertaken over the last five years. Ground based LIDARS have been developed significantly, and in the past few years calibration and traceability issues have also been tackled and are now being included in the IEC standard revision [5]. An overview is provided by [6], where significant metrology contributions are described.

Focus on LIDAR technology

LIDAR technology is relatively recent and requires testing. Testing against a traditional meteorological mast has been shown to be efficient for gaining confidence and trust in measurement accuracy. In principle, LIDAR measurements could be made traceable through the fundamental measurement principles, but at this stage of development it is not feasible. Instead, traceability is secured through comparison with meteorological masts that are themselves traceable through wind tunnel calibrations of cup anemometers. LIDARs can fulfil different objectives:

- For resource assessment, and replacing the traditional measurement masts, UpWind demonstrated that the ground-based LIDAR measurement principle is efficient in flat terrain. In complex terrain and close to woods, the measurement volume is disturbed by a vertical turbulence component. Due to a large measurement volume, ground-based LIDARs perform a spatial averaging which has the effect of a low pass filter on turbulence measurements. This effect requires special attention and correction methods, which were analysed within the UpWind project by the use of the WAsP engineering tool, which is a computer based program for the estimation of extreme wind speeds, wind shears, wind profiles and turbulences in complex (and simple) terrain.
- LIDAR measurements were made from a rotating spinner. The analysis show good perspectives for scanning the incoming wind, which may lead to better controlled wind turbines.
- LIDARs have also been used to scan the wake of wind turbines. These measurements show the curvy wake pattern. Progress has been made with large-scale site wind scanning with three coordinated LIDARs.

Verification of anemometer calibrations

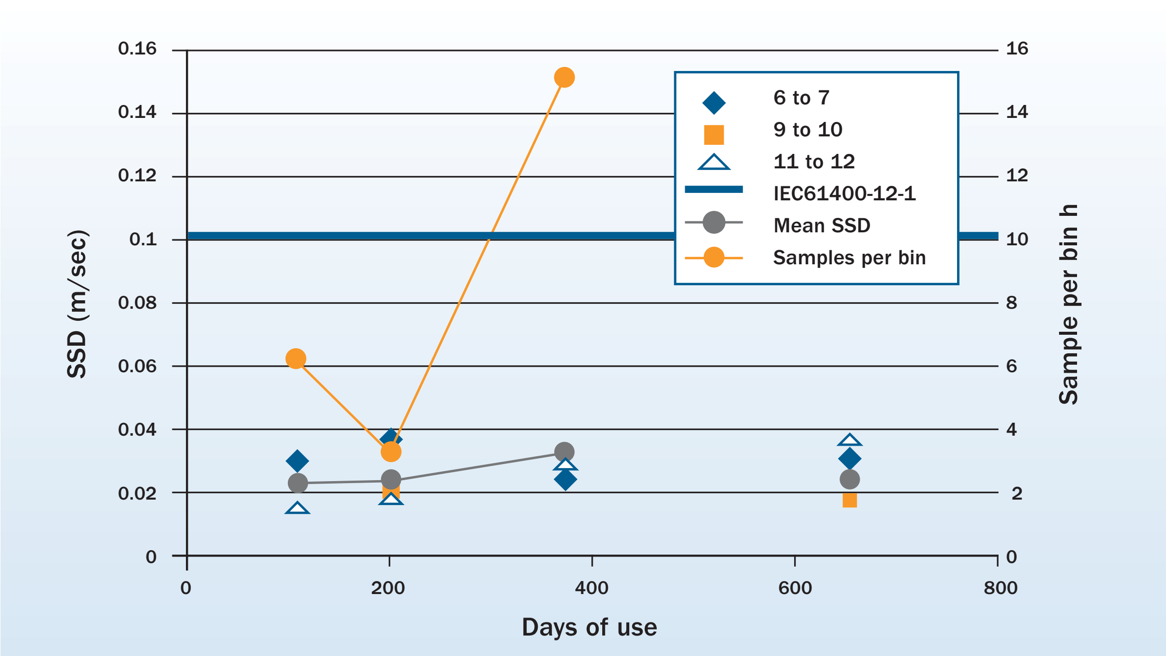
In the context of MEASNET[9] a cup anemometer calibration round robin and acoustic noise measurement round robin were performed [13] with good results for the associated MEASNET institutes. Together with the MEASNET experts, UpWind worked to try and find a procedure for calibrating sonic anemometers. The operational characteristics of 26 sonic anemometers have been investigated over a long period of time by [17]. Improvements were required in order to use the sensors for wind energy applications. These improvements are being implemented by the manufacturer.

[9] Measnet: International network for harmonised and recognised measurements in wind energy. http://www.measnet.com, MEASNET Round Robin (RR) on anemometer calibration is one method of measurement.

Standardisation organisations require additional verification measures for anemometers. The preferred method is to recalibrate the anemometers to verify that any possible degradation of the operational characteristics of anemometers during their operational period is kept within known limits. As an alternative to recalibration, on site comparison was investigated. Data was analysed from various in situ comparisons of anemometer calibrations. As a measure of "anemometer degradation" the square sum of the Systematic Deviation and the Statistical Deviation (SSD) between the two operating periods is used. For the in situ comparison to be considered successful, the SSD must be lower than 0.1 m/s for each wind speed bin (a tool used to make samples of wind speed) in the range of 6 to 12 m/s. In situ comparisons were successful for 90% of the examined cases. Acceptable results were found even for anemometers operating for more than 18 months on site. Recalibrations of anemometers in the wind tunnel after the end of the measurement campaign were in full accordance with the in situ results.

A sensitivity analysis was carried out on the results. The operation time on site, the annual mean wind speed, the mean turbulence intensity and the annual mean temperature were examined. In order to reduce the statistical scatter, and identify possible interactions, the cases studied were separated per anemometer type and binned (categorised) per parameter type. It was seen that binned values for mean SSD with usage time have low dependence, since a longer operation time would cause greater degradation to anemometer bearings. However, for the anemometer type examined here, (Vector A100 series) the SSD values remain below the 0.1 m/s limit even for usage time exceeding 365 days [14, 15]. No obvious effect on deviation from site annual mean wind speed, mean turbulence intensity, or mean air temperature were detected for the covered parameter range. Therefore, "in situ comparison" as described in [16] is a reliable tool for the verification of anemometer calibration integrity.

Figure 3: SSD values as a function of operation time on site (only cases with Vector A100 series anemometers)



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"Wind energy is growing fast, and the technology improves every day. Training and education is fundamental to support the wind sector's development. UpWind collected and developed a unique amount of training materials, and defined the required training modules to be used for the professional development of those that wish to work in this industry"

Charalampos Malamatenios, Work Package Leader, Centre for Renewable Energy Sources and Savings (CRES)

2.3 Work Package 1A3: Training and education

Challenges and main innovations

Over the last ten years, installed wind power capacity has gone up by more than 20% per year. Forecasts from the industry demonstrate the high potential of this technology, which will face a critical shortage of manpower in the coming years. Training and education is fundamental element to sustainable industrial growth.

Working with wind energy technology requires a high level of education, since improving and enlarging wind turbines means dealing with specific aeromechanical and structural effects, electrical grid connection and power quality issues, load regulation and part-load performance, as well as their potential environmental impact (noise, visual obstruction, bird migration, and so on). In the meantime, a significant amount of research and development work has been and is being done in the field of wind energy technology, and on-the-job training is required to update knowledge and skills. The present situation concerning training and educational materials is however not ideal. Quite a lot of material is available, but it is not standardised, it is difficult to access, different courses overlap considerably and so on.

Knowledge dissemination is critical for supporting the technological innovation of SMEs, which should not lag behind as wind power technologies develop. A fully integrated approach, involving academic institutions, industry and research institutes, is thus necessary to provide a unique platform to improve educational materials with respect to content and structure, avoiding overlaps, and being in accordance to the users specifications.

The specific objective of the UpWind training and education section is to propose a number of modules for international courses in the wind energy field and specific supporting training materials. These training modules could then be used (upon request) for researchers and students (PhD level courses), as well as for energy consultants and project developers (for continuous professional development).

Results and conclusions

First, preliminary material (in the form of guidelines, templates and so on) was developed, which helped to design the UpWind course module for the identified target groups. Apart from the detailed literature analysis and web-based survey, a questionnaire based survey was also carried out. Information on wind energy related training courses was collected from 43 course providers.

An online database of all courses relevant to wind energy found all over Europe was developed. This is the *"Database of EU courses in the field of wind energy"*, and it includes all available details (level, contents, duration, contacts, etc.) for the courses. The database can be found on UpWind's website[10].

Another major achievement is the *"Wind Energy Information and Education Network – WEIEN (e-database)"*. This database is a restricted area within the *RenKnow.net*[11] website which has been created for the WEIEN members with all relevant functionalities of the REnKnow.net website.

The WEIEN is:

- A database for up- and downloading documents;
- A forum for discussion;
- An "open source knowledge creation" tool (like an internal "Wikipedia");
- A facilitator of the peer-review process for training materials.

Work on WEIEN is continuous, as the database has to be constantly updated. Also, the "resource guide to course modules" was another important part of this work, which includes the most essential of the common components of the courses surveyed, as well as the key characteristics of the modules that need to be developed or updated in order to be integrated into existing and new wind energy courses.

This way, the topics covered by a course that will lead to a PhD decree were developed. It was decided that the target groups of the UpWind training course(s) should already have some basic knowledge of wind energy technology. Therefore, the aim was not to create training courses for basic studies, but to build on the students' previously acquired knowledge (as shown in Figure 4).

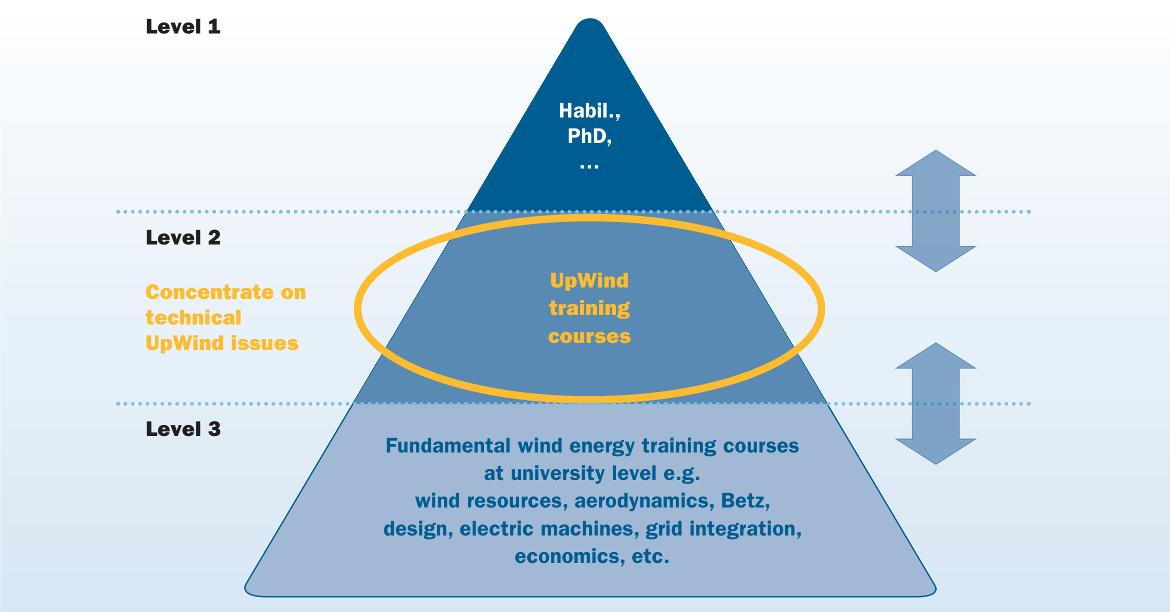


Figure 4: **UpWind training targets students of educational levels 2 (i.e. between the basic Levels of 1 and 3)**

[10] http://www.upwind.eu/Paginas/Publications/1A3%20Training%20and%20Education.aspx
[11] http://renknownet.iset.uni-kassel.de

The "modules" listed by UpWind are neither full courses nor simply lectures. Instead, they are **building blocks** for university lectures/courses, short courses for professionals (CPD units), as well as for any other types of training course. To this end, the content of the UpWind course modules is not a ready-to-go lecture package, but rather the material necessary to set new courses up.

Eleven topics were identified as the key themes of the UpWind course modules, broken down into sub-components (according to what is presented in Table 1). This is a unique attempt to develop up-to-date courses and relevant training materials for wind energy:

1. Aerodynamics and aeroelastics
1.1 Damped structural dynamics for composite rotor blades – tools and exercises
1.2 Advanced aerodynamics and boundary integral element methodology (BEM) corrections
1.3 Aeroelastic stability
2. Rotors Structures and materials
2.1 Innovative materials and processes
2.2 Fundamental and global material models – calculation techniques to evaluate the material damage
2.3 Test/measurement techniques for material and component testing, including procedures
2.4 Elastic stability and static strength of rotor blades – tools and exercises
2.5 Strength and stiffness degradation of rotor blade composites due to fatigue - life prediction
2.6 Structural reliability analysis of composite rotor blades
3. Foundations and support structures
3.1 Introduction to offshore wind technology
3.2 Environmental conditions
3.3 Soil and foundation models
3.4 Support structures I
3.5 Support structures II
3.6 Offshore standardisation
3.7 Integrated design process of explain
3.8 Results of Work Package 4
4. Control systems
4.1 Wind turbine control concepts
4.2 Controller tuning and adjustment
5.3 Control for grid compatibility
5. Condition monitoring
5.1 Optimised Condition Monitoring Systems (CMS) for next generation wind turbines
5.2 "Flight leader turbine" for wind farms
5.3 Fault statistics
5.4 International standards
6. Flow
6.1 Theoretical analysis of wakes
6.2 Analysis of wakes in complex terrain
6.3 Introduction to wake modelling in flow simulation

7. Electrical grid
7.1 Introduction to wind power grid connection and integration
7.2 Introduction to power system reliability
7.3 Wind turbines and wind farm design and reliability
7.4 Power system security and wind turbine stability
7.5 Power system control with wind power
7.6 Results from UpWind Work Package 9
8. Measurements and experiments in wind energy
8.1 Principles of experiments
8.2 Wind turbine test site
8.4 Wind resource measurements
8.5 Special experiments
9. Transmission and conversion
9.1 Mechanical transmission
9.2 Generators
9.3 Power electronics
10. Integral design approach & standards
10.1 Introduction
10.2 Integral design approach
10.3 Cost models
10.4 Uncertainty modelling
10.5 Reliability methods
10.6 Standards
11. Upscaling and integrated design:
11.1 Classical upscaling
11.2 Upscaling through design
11.3 Cost models I
11.4 Cost models II
11.5 Upscaling issues
11.6 Future concepts

Table 1: UpWind training modules.

In the last stages of the project, the various UpWind training modules were run as pilots:

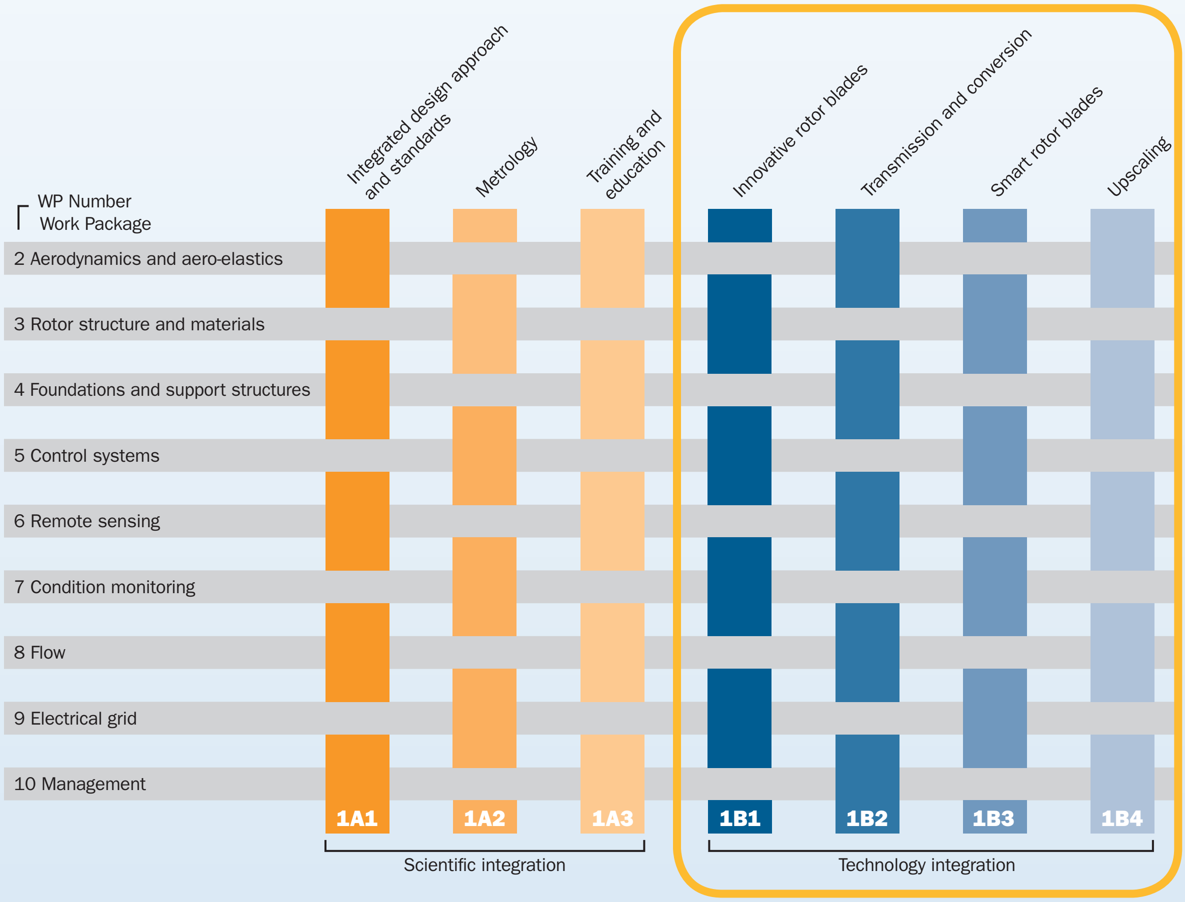
- University status partners used the modules for postgraduate students and lecturers from other universities;
- Non-university status partners used selected modules developed in WP1A.3 to run workshops on the main topics of wind energy technology;
- A detailed presentation of the modules created by this WP was given in a workshop that addressed PhD candidates with a background in engineering.


Photo: Vestas

3 UPWIND: TECHNOLOGY INTEGRATION

UpWind: Technology integration

- **1B1: Innovative rotor blades (Innoblade)**
- **1B2 Transmission and conversion**
- **1B3 Smart rotor blades and rotor control**
- **1B4 Upscaling**



"One key point when thinking about increasing the size of wind turbine blades is transport costs. In order to keep these costs under acceptable limits the best choice is sectional blades, capable of being transported with the same means as smaller blades. The use of new tools for the better understanding of such huge blades as well as a reliable monitoring system of the blade are key factors to this new generation of blades"

Joaquin Arteaga Gomez, Work Package Leader, Gamesa

3.1 Work Package 1B1: Innovative rotor blade (Innoblade)

Challenges and main innovations

In the last years the cost of wind energy has decreased due to technical improvements in aerodynamics, materials and structures, reaching an almost constant cost per KW recently. In order to move towards more efficient wind turbine designs (bigger rotor diameters with lower energy costs), new innovative improvements are needed.

Future multi-megawatt machines will require large blades whose transport costs would become unaffordable for blades longer than 50m. Sectional blades, meaning blades divided into sections, are the best way to reduce transport costs while increasing the length of the blades. These blades will be manufactured in separated modules that will be assembled on site.

UpWind has focused on the design and validation of a *sectional blade* concept which aims to reduce the global cost of energy and to help develop larger turbines. This blade concept includes several new technological advances regarding blade design and manufacturing, such as advanced aerodynamic profiles, advanced design solutions, analysis of new materials, and advanced sensor and monitoring technologies, among others.

Results

Blade aerodynamic design and load calculation

This analysis included aerodynamics design, aeroelastic design and loads consideration, making use of all current methodologies, but also employing innovative methods that are beyond current practice, 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 optimal design and performance, materials and structural design improvements were 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.

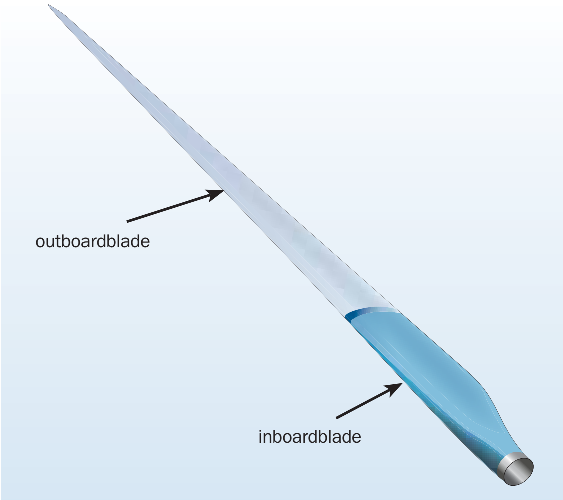


Figure 5: **Sectional blade**

These methods were applied to the design of a 42.5 m blade (this size was chosen to test these new technologies, using a Gamesa design as starting point) leading to a functional design of a sectional blade with the following characteristics and conclusions:

- Brand new "flat–back" profiles were developed for the sections close to the base of the blade (of special relevance for larger blades)
- The use of a root fairing was analysed, with the conclusion that it would lead to a small increase in the power produced
- The effects on the modal shapes and natural frequencies of the sectional joint position were studied, with the conclusion that no relevant differences appear when it is placed between R 10 to R20 (measure of resistance).

A study of blade damping checked the stability of the blade at different configurations (for example, the effect of wind with an angle of attack of around 90° on inactive wind turbines). These results were presented at the EWEA Annual Event (formerly EWEC) 2009.

Material selection, structural design and structural verification

The current state of composite materials was analysed as well as any new potential materials or innovations that could contribute to better blade designs, and specifically to the design of sectional blades. This analysis found that even though there were promising research areas in the field, no breakthroughs were about to be achieved, so today a large blade (sectional or otherwise) is built using the standard materials and processes (glass fibre and carbon fibre, as prepregs or dry plies for infusion).

After this, the structural design of the proposed blade was examined, first considering the blade as a single component and secondly as a sectional blade using the one piece configuration as a starting point. This also included the selection of the position of the sectional joint, choosing the R15 after considering all the factors (effects on modal shapes and frequencies, weight and length of the two modules and so on).

Sensor monitoring with response actions

The possibility to monitor the behaviour of the sectional joint of the innovative blade at any given time (for analysis, validation and maintenance) is important. A series of sensors is required, and the measured data needs to be transferred to a processing unit. The use of cable for this transferring is complicated and risky. As an alternative, a wireless sensor system was considered by UpWind. After the current technology had been reviewed and the different solutions analysed, a system was designed based on the Zigbee certification standard. From the test carried out using this system it was found that:

- Signal reception was good up to 30-40 m with a sensor-emitter placed inside the blade and a receiver at the nacelle, showing no differences between carbon or glass fibre blades.
- Wireless sensors shouldn't be placed too close to metallic components of the blade.
- The results were satisfactory (good signal reception) even with the machine rotating.
- Power consumption was acceptable, and will depend on the amount of data to be transmitted.

Blade joint

Since the main aim of work package is to study the design of a sectional blade, one of the most important tasks is designing the sectional joint that will allow the blade to be put together on site. The first obvious action was a trade-off study considering different alternatives for the joint:

- ***Spar lugs***: this option consist of lugs embedded into the laminates of the spar (both webs and caps). The lugs form the inboard and outboard module are bolted transferring the load by shear.
- ***Channel fittings:*** this option bolts two metallic fittings that will transfer the load between modules axially. To bond the fitting to the spar some kind of embedding must be carried out.
- ***T-bolts:*** this solution also uses bolts transferring the spar loads axially, but in this case the bolts are anchored in holes in the laminate.

After considering several factors such as weight, cost, assembly and reliability, the project team concluded that channel fittings were the better choice. This option was applied to the blade being studied:

- Each of the modules of the blade (inboard and outboard) will have channel fittings at the joint section, and the two modules will be joined by bolting the fittings of both sides.
- These fittings are bonded to a carbon fibre pultruded profile that is embedded within the laminates of the caps.
- In order to reduce the load transmitted by each fitting, the spar widens near the joint section, in order to allocate a bigger number of fittings.

With this solution, the joint of the two modules is built from two bonded joints (between the fittings and the profiles, and between the profiles and the laminates) and a bolted joint between the two channel fittings. The behaviour of these kind of joints (bolted and bonded) is well known, but due to the complex geometry of some of the components, finer and deeper analysis is considered necessary. Only after several calculations and designs were made the main parameters of the components were fixed (such as the geometry of the fitting, length of the bonded joints, and so on).

The validation of the joint's final configuration has been established through detailed 3D FEM simulations and a series of tests. These tests were specifically designed to test the strength and fatigue resistance of the bolted and bonded joints.

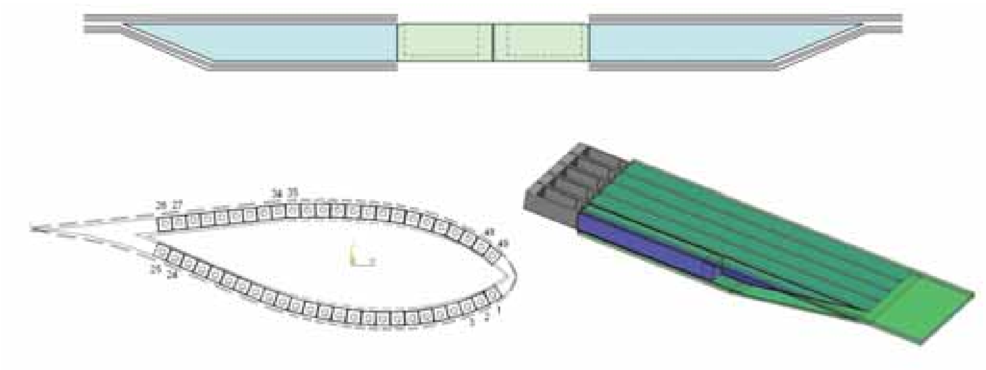


Figure 6: **Scheme showing: (a) how inboard and outboard modules are connected (b) detail on how the spar in widen to include more fitting (c) 3D transparent view showing how the fitting is bonded to the profile and the latter inside the laminate**

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> "Size and weight do matter. We had to investigate the limits of current designs. UpWind provided the necessary tools for upscaling. Integral design tools will significantly increase the reliability of future drive trains, and avoid costly drive train failures. UpWind specified the future generator type, which is proportionally lighter than today's designs."

Jan Hemmelmann, Work Package Leader, GE Global Research

3.2 Work Package 1B2: Transmission and conversion

Challenges and main innovations

The aim for both current wind turbine sizes and for future larger-scale designs is to increase reliability, predictability and efficiency. In terms of reliability, the drive train today is still among the most critical components. It is assumed that the underlying problem of unexpected failures is based on a misunderstanding of the dynamic behaviour of the complete wind turbine system due to the lack of a ready-to-use integral design approach. UpWind developed and validated the necessary simulation tools to overcome this problem.

Concentrating on upscaled designs, the weight on top of the mast is critical for transport, installation and design loading. The perfect generator would be reliable, efficient and light. UpWind investigated the pathways towards efficient large-scale generators, comparing the existing generator types on energy yields and through cost models. Particular attention was paid to permanent magnet generators, currently entering the market with competitive designs, and potentially opening the door to increased reliability and efficiency.

Little room is available for the optimisation of radial flux permanent magnet generators, although their shape is a compromise between diameter and weight. On the contrary, transversal flux permanent magnet generators could be promising. An analysis was performed to compare the mass of ten different generator configurations. It seems the transversal flux generators could be significantly lighter, thus avoiding a linear increase of the top of mast weight ratio for increasingly large turbines, and opening new possibilities for upscaling. Different voltage levels were studied and assessed, potentially further decreasing the costs.

Results

Mechanical transmission

In terms of reliability, the drive train is still among the most critical components of modern wind turbines. Nowadays the typical design of the drive train consists of an integrated serial approach where the single components, such as the rotor shaft, main bearing, gearbox and generator are as close together as possible to ensure compactness and as low a mass as possible. Experience from across the wind industry shows that this construction approach results in many types of failures (especially gearbox failures) of drive train components, although the components are designed according to contemporary design methods and known loads. It is assumed that the underlying 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. The construction 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;
- Non-linear flexibilities of fibre blades;
- Linear flexibilities of metal components e.g. of drive train;
- Non-linear behaviour of drive train components e.g. gears, bearings, bushings;
- Electro-mechanic behaviour of generator;
- Electrical behaviour of power electronic converter and grid.

To overcome the limitations identified in design and reliability, it was 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 was used, adapted and verified for detailed analyses of drive train behaviour. A customised Open Computer Aided Engineering software platform based on plug-in techniques for a wind turbine application has been developed. It contains the pre-defined or user defined models developed and validated during the project, with a focus on the drive train. **Figure 7** shows the graphical user interface of this professional software environment that can also be used for various kinds of analyses and post-processing. It can also be extended towards specialised computation software to cover the whole design process from the concept to a detailed analysis of the components.

The tool and the model had to be validated through a comparison with the results of the experiments. Measurements have been taken on a 1.5 MW turbine and compared to the 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.

Further enhancements to the multi-body simulation tools were studied with regard to gear mesh behaviour. Usually the gear stiffness (for MFBD) is defined as a constant value or an analytic function changing with time, but for a detailed gearbox analysis these assumptions are too simplistic. It was proposed that realistic time varying stiffness gained via FE-simulation could be used. The mesh stiffness can be computed using gear tooth contact analysis software, considering modifications of the teeth like e.g. crownings, and also considering different torque levels. Thus the mesh stiffness can be varied depending on the torque, the rolling position of the gears and the gear deflection in a static mode, and used for the dynamic simulation.

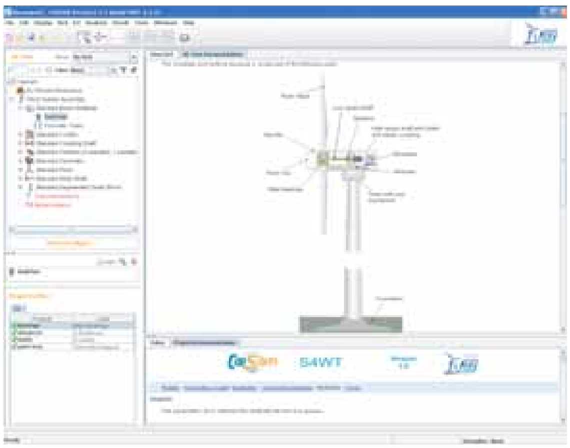


Figure 7: The challenge of this task was the coupling with the MBS model of the wind turbine.

Generators

The main objective was to find the most suitable generator system for the large wind turbines expected by 2020. Currently, there are three main generator systems used in wind turbines: constant speed with a gearbox and a squirrel cage induction generator, variable speed with a gearbox and doubly-fed induction generators, and variable speed direct-drive generators without a gearbox. Each concept has its disadvantages.

A first task was a thorough comparison of these and other possible generator concepts based on cost models and energy yield models. An overview of wind turbine technologies and a comparison of different generator topologies based on literature and market supply review was carried out. 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 and compared based on the technical data and market aspects. In case of RFPM machines, 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 have disadvantages such as 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.

The second task was to evaluate the most cost-effective wind turbine generator systems by applying design optimisation and numerical comparison. An integrated electromagnetic-structural optimisation strategy was developed to provide the best structural design for direct drive RFPM generators. The preliminary results of a structural optimisation highlighted the danger of not optimising the active and inactive material together – that is, the fact that a generator design that minimises active mass leads to a design that maximises inactive or structural mass. Traditionally in the design of the active mass, the air gap is kept as small as possible to optimise the electromagnetic performance. However, the integrated electromagnetic–structural optimisation strategy indicated that machines with a larger air gap will result in lower mass. The aspect ratio of the generator (ratio of length to air gap radius), depends upon the optimisation criteria. For minimum mass, large aspect ratios with a larger air gap is desirable, leading to a sausage shaped machine. If cost is key, then small aspect ratios or pancake machines are more desirable, because active mass decreases with radius, and this is the most expensive part of the generator. The optimisation strategies were also been applied to TFPM machine topologies.

A third task was to identify the most suitable generator type for large direct-drive wind turbines based on electromagnetic analysis models for various configurations of PM machines. The surface mounted RFPM machine and four different flux-concentrating TFPM machines with single-winding were chosen for the comparative design, where a single-sided single-winding flux-concentrating TFPM generator was found to be most promising. The analysis models were verified by experiments and finite element analyses of a down-scaled, linearised generator.

In order to further reduce the active mass of TFPM machines, a configuration with multiple-slots is proposed in order to shorten the length of the flux path, which yields more potential to reduce the active mass than RFPM generators. **Figure 8** illustrates the active mass comparison of different 10 MW PM generators, where the RFPM generator serves as baseline and nine different TFPM generators are compared to it. The active mass of a claw pole design with limited pole area and up to four slots per phase seems to have potential against the baseline machine. To validate these analytical design results, three-dimensional finite element analyses are needed.

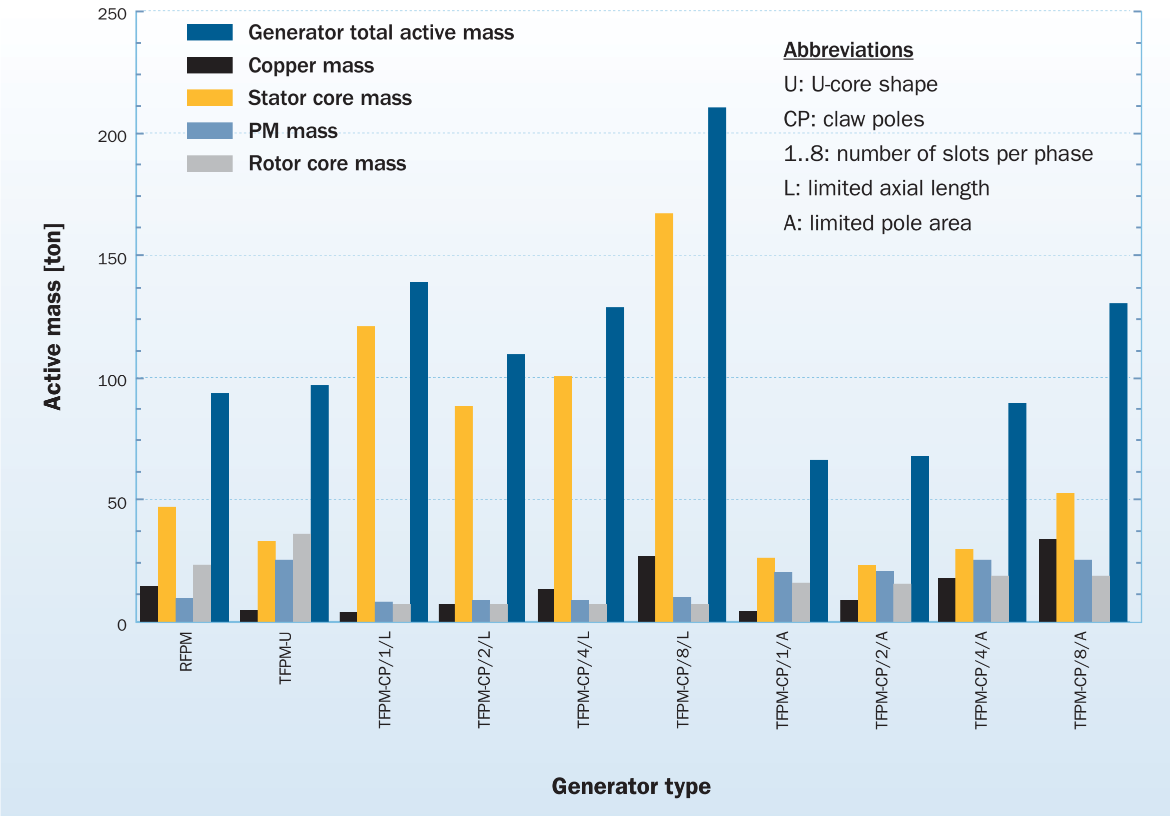
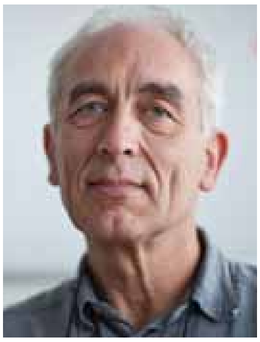


Figure 8: Active mass comparison of different 10 MW PM generators.

Power electronics

While acknowledging that doubly-fed induction generators are almost standard today, the UpWind research focused on full converter solutions for synchronous generators. Three different approaches to increase the power rating to the required level were analysed in detail. An example of a design approach including power device selection, selection of switching frequency, filter design, efficiency curve, volume estimates and control scheme was drawn up. These concepts include the matrix converter, the three-level neutral point clamped (NPC) converter and the parallel interleaved converter.

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 three-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 at the grid interface. The improvements on the harmonic performance are achieved at 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 (1700V IGBTs). However from the point of view of total system cost there is a tendency to aim for voltages that are as high as possible to decrease transformer and conductor costs.



"Longer blades mean more energy harnessed, but higher loads which could hamper an efficient design. UpWind successfully simulated and tested several techniques to control the loads along the blade span. This is the first step towards a new rotor technology"

Gijs van Kuik, Work Package Leader, Energy Research Centre of the Netherlands (ECN)

3.3 Work Package 1B3: Smart rotor blades and rotor control

Challenges and main innovations

Increasing the rotor diameters of current turbines enables more energy to be generated, but without innovation in load control, this would also increase the fatigue loading on the entire structure, and require costly structure reinforcements. Load control is also crucial to reduce the structural requirements of the large turbines of the future, with their large rotor diameters. Load control can lead to lighter blades or longer blades with the same weight, increased component lifetime, and so it can help with upscaling.

Reducing the fatigue loads leads to lower cost energy, if it can be implemented in a way that does not add too much complexity to the turbine. Today, the current control features of wind turbines do provide the control authority over the loading that is required for fatigue load reduction. Therefore, UpWind researched the potential of the alleviation of unwanted loading of wind turbines, not only of fatigue loads, but also of peak loads as a result of gusts, with new tools. The challenges that are encountered in this work are related to:

- Sensors and control issues, related to the servo-aero-elastic behaviour of the turbine;
- Actuator technology;
- The (unsteady) aerodynamics of aerofoils with control devices;

The way the control devices are implemented is important. Control devices influence the aerodynamics, while seeking a reduction in a structural response. Numerous devices can be implemented in this regard, such as trailing edge flaps, (continuous) camber control, synthetic jets, micro tabs, or flexible, controllable blade root coupling.

Little is known about the aerodynamic performance of those devices on wind turbines or how they should be integrated in the blade's structure. UpWind investigated different options. First by simulating a rotor for a 5 MW turbine, and demonstrating 15 to 25% load reduction, then by investigating adaptive trailing edges using shape memory alloys, or increasing flexibility by allowing a degree of freedom between the hub and the blade to be temporarily uncoupled. The necessary simulation and control tools were developed, and wind tunnel experiments of smart rotor blades were implemented. The final result consists of a set of tools for further development and for the industry, ranging from aero-elastic codes to predict the behaviour of wind turbines with smart features to dedicated aerofoils and smart actuators.

Research activities and working methods

Task 1: Aerodynamic controls and aero-elastic modeling

An aerofoil with flap design was tested and an aerodynamic analysis carried out on it. Current aerofoils are not developed for trailing edge flap operation. UpWind investigated the lift and drag characteristics of a typical, existing tip-aerofoil with trailing edge flap and a new aerofoil has been specially designed. Numerical investigations have been made into the unsteady performance of micro-tabs. Benchmarking against a trailing edge flap is planned.

Furthermore, an aeroservoelastic model DU_SWAMP[12] was developed and is used to evaluate global control concepts for smart rotors. A preliminary investigation has already been performed, comparing centralised and decentralised control concepts on the 5 MW reference turbine. The work includes the design of multivariable controllers for distributed flaps, investigation of the influence of actuator dynamics, and focus on extreme load cases. For a 5 MW turbine with a blade length of 63m, this model can generate 15 to 25% of the equivalent load of fatigue damage. In parallel, the model is used to evaluate the performance of the experimental rotor at the TUDelft OJF wind tunnel, as described by Task 4.

Task 2: Smart structures

The initial focus was the selection of adaptive material concepts on which to base the actuator, but this was later shifted towards addressing specific issues encountered with Shape Memory Alloys (SMA), such as fatigue properties and actuation speed. In addition, the potential of SMAs to apply damping to the structure of the blade was evaluated. The SMA morphing surfaces are applied in different demonstrators of blade sections. One is based on so called R-phase SMA material and the other tackles the bandwidth and controllability issues of the material. The combined results lead to a SMA driven trailing edge morphing surface that meets the speed, deflection and durability requirements for load control on wind turbines. In addition, piezoelectric actuators and sensors are also tested.

Figure 9: **Demonstrator of a blade section with a R-phase SMA activated trailing edge**

[12] DU SWAMP aeroservoelastic simulation environment is employed to capture the complexity of the control design scenario.

Task 3: Control systems

A system for the control of spanwise distributed devices was developed. Moreover, several control tasks, mainly regarding the placement of sensors and the development of algorithms, were carried out in Task 4.

Task 4: Smart wind turbine wind tunnel model

A scaled turbine was built for wind tunnel research. This was used to research the feasibility of different load control concepts in the project (notably camber control and the 'smart' blade-hub interface) and to validate turbine models.

In wind tunnel experiments, a large load reduction potential was observed – up to 60% in the standard deviation of the strain root sensor.

Figure 10: **The scale model of a smart rotor in the wind tunnel. The flaps are the silver area's in the outboard section of the blade.**

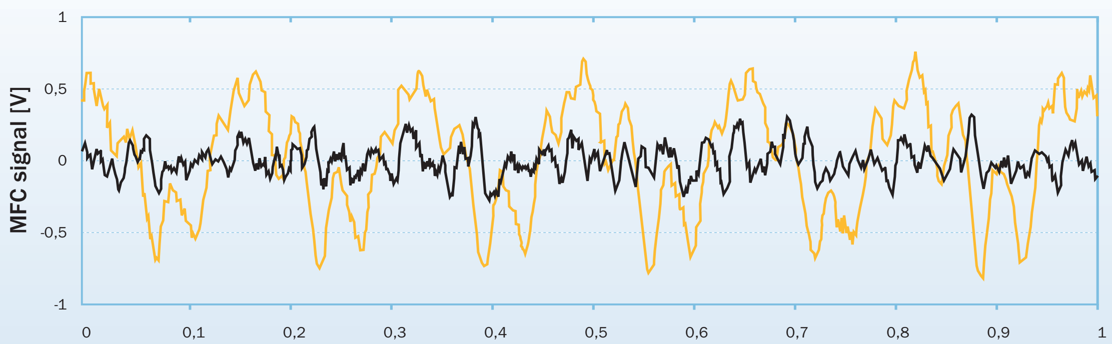


Figure 11: **Wind tunnel tests on a scaled smart rotor – flapwise root bending moment with (black) and without flap activation (yellow).**

Task 5: Interfaces

Researching the feasibility of 'smart interfaces'. These interfaces would allow a degree of freedom between the hub and the blade (the torsional blade, in this case), which could be temporarily uncoupled. This could alleviate gust loads since during uncoupling the aerodynamic moment will pitch the blade to feather as the DoF is released. The load alleviation potential of the concept was researched in this task. The results show that the system can be very effective in alleviating gust loads as can be seen below.

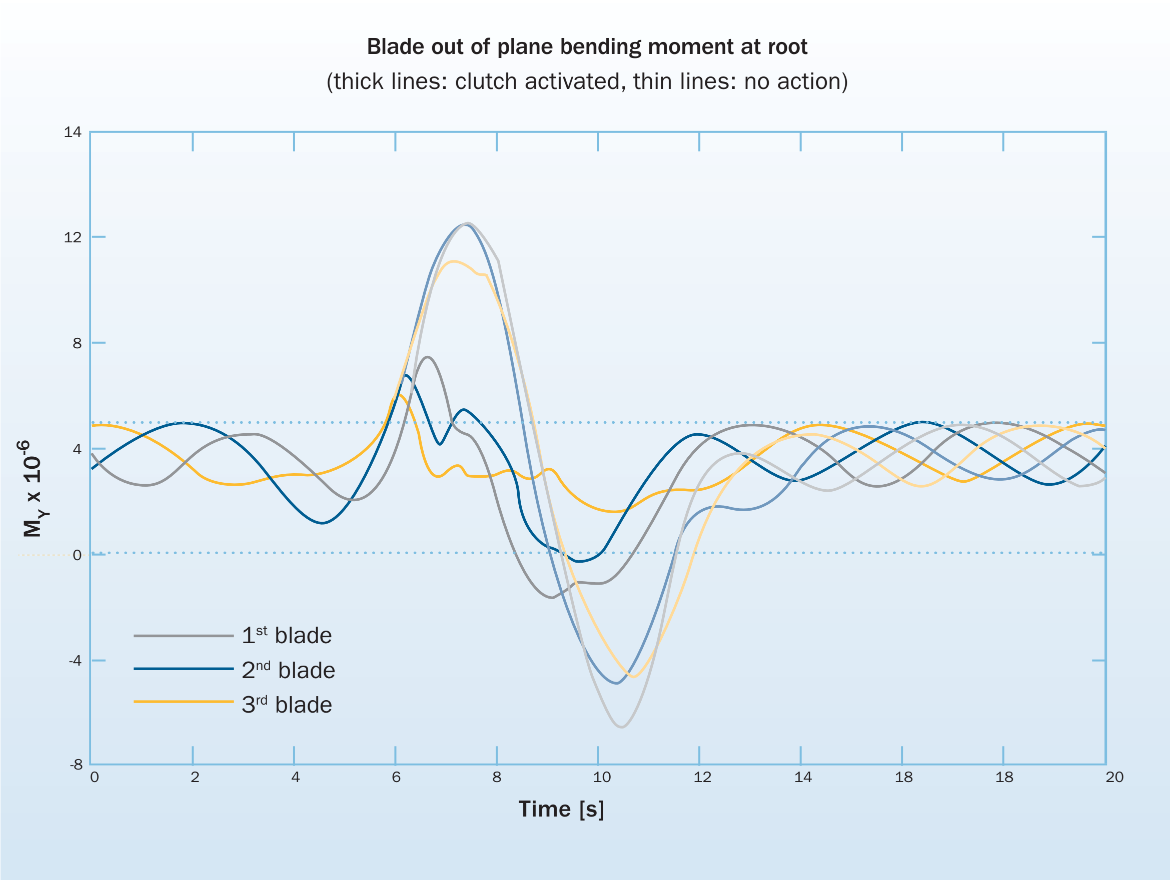


Figure 12: Gust load reduction potential with a torsional "clutch" in the blade-hub-interface.

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"Is bigger cheaper? How far can we go in upscaling? Yes, we have the technology but the economics will decide. UpWind compared 20 MW designs, with and without including the UpWind innovations and compared them with present technology. Costs models will tell us the way forward."

Bernard Bulder, Work Package Leader, Energy Research Centre of the Netherlands (ECN)

3.4 Work Package 1B4: Upscaling

Challenges and main innovations

The wind turbine market has grown rapidly together with the capacity of wind farms and the size of wind turbines. The upscaling trend reflects the market reality, where the average wind turbine size is constantly increasing. Upscaling is performed to harness a larger resource, and benefit from economies of scale. As a result, during the last two decades wind turbines have grown in capacity from 250 kW to 6-7 MW in size from a 25 m rotor diameter to over 125 m. Recent announcements were made regarding 10 MW turbines, which should be tested in the coming years. No agreement has been reached yet on the optimal capacity of a wind turbine or how far upscaling can be performed. The uncertainty about the maximum achievable dimensions depends on load mitigation, controllability, and innovative materials and structures.

With the growing size of turbines, the technology has developed rapidly. Constant speed, stall-controlled machines with fixed blade pitch equipped with induction directly connected to the grid 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 becoming a mainstream.

For land application, transportation, installation and sitting limitations might limit the maximum size of wind turbines, contrary to offshore applications. To enable the future targets for implementation of wind energy to be met, offshore wind energy will need to become more competitive. Due to the capital cost structure of wind farms offshore, dominated by the cost of support structures and foundations, offshore applications could require wind turbines to be as large as possible.

The UpWind project focused on investigating the feasibility and limits of reliable and efficient large concepts. The objective of the within the upscaling work package activities is to identify R&D needs for the expanding future market of large scale machines. The optimum technology and economics of future wind turbines, varying in size and concept and for various applications, needed to be analysed. This required a value for the innovations and developments for all developments that are being investigated in UpWind. The UpWind investigated a lighthouse vision defining the options and necessities for future very large wind turbines.

This required a cost analysis of wind turbines, and the relation between cost, size and power rating, and some other major cost components are taken into consideration. Three major cost components were analysed in this respect: ex-factory costs like transportation, installation and operating and maintenance. Based on engineering cost models and models based on scaling laws, component and total system "ex-factory" costs are estimated. Evaluation of transportation, installation, operating and maintenance costs indicate the economics of wind energy for very large turbines of present day technology.

The outline design, based on scaling trends and experienced engineering judgment and cost analysis of a 20 MW wind turbine, reveals major problem areas in upscaling current design concepts. Fundamental techno-economical barriers are identified and new, disruptive technology must be developed to design very large machines of a rated power between 10 to 20 MW, with a rotor diameter between 175 to 250 m.

The final results include a description of the upscaling process and the identification of major barriers and options to break through these barriers. An outline design and a cost analysis of a 20 MW wind turbine based on the upscaling of current technology is compared to integrating the innovative developments of the UpWind project.

A vision on promising concepts for the future (offshore) market is formulated and a road map towards identifying the requirements making the development of larger wind turbines technically and possibly economically viable.

Activities

Based on a systematic analysis of the growth in the scale of wind turbines over the last decades, a scaling model was developed, based on classical scaling relations compared with actual trends to characterise key design parameters as a function of turbine size. This model characterises technological developments in over four rotor blades and wind turbine towers. The key scaling parameters includes the mass, rated 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 are used to outline a reference 20 MW design, based on the upscaling of the 5 MW reference UpWind turbine. The reference wind turbine is an artificial wind turbine representative for the current largest machines on the market: 5 MW rated power, 126 m rotor diameter, three-blades, variable speed and power control by pitch to vane. Virtual upscaled designs are created based on scaling models and optimised with present technology. 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 will 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.

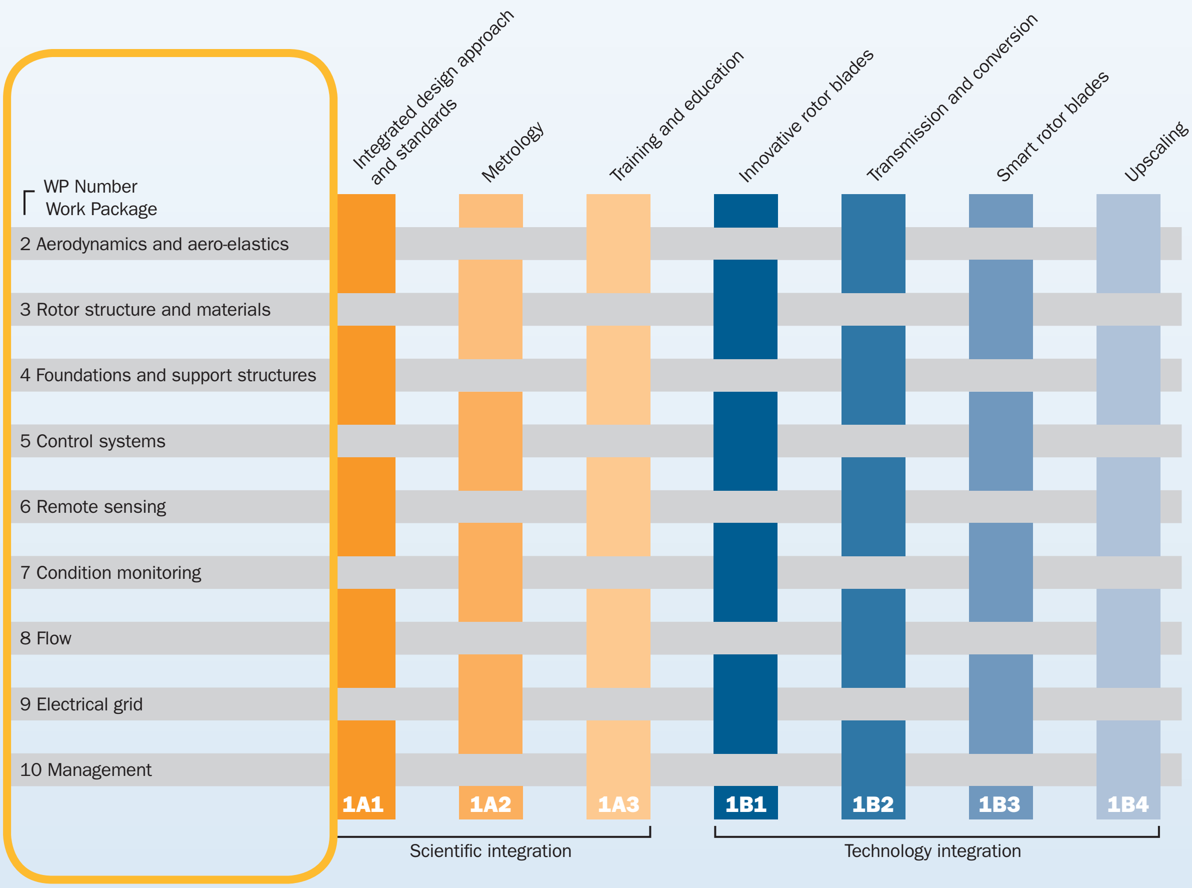
In parallel with the upscaling of the reference wind turbine, the innovative developments in UpWind are evaluated regarding their impact on the cost of energy. Promising concepts for future very large offshore wind turbines are being investigated. For the offshore market the ease of installation and 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.

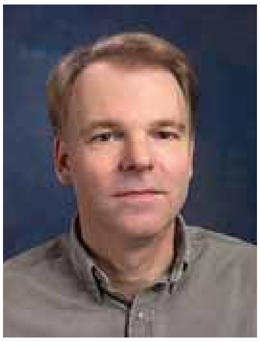

Photo: RES Group

4 UPWIND: RESEARCH ACTIVITIES

UpWind: Research activities

- 2 Aerodynamics and aeroelastics
- 3 Rotor structures and materials
- 4 Foundations and support structures
- 5 Control systems
- 6 Remote sensing
- 7 Condition monitoring
- 8 Flow
- 9 Electrical grid





"Upscaling changes the wind turbine dynamic behaviour. UpWind investigated fundamental aspects related to coupling aerodynamic and aeroelastic modeling. The new reliable models enabled the proposition of innovative development paths. They demonstrated the perspectives of intelligent blade concepts, and advanced blade designs."

Flemming Rasmussen, Work Package Leader, Risø DTU

4.1 Work Package 2: Aerodynamics and aeroelastics

Challenges and main innovations

Upscaling of wind turbines has several fundamental implications on the aeroelastic modelling. UpWind investigated an aerodynamic and aeroelastic design basis for large multi-MW turbines. With upscaling, the flexibility of the wind turbine structure increases so that more eigen-frequencies coincide with peaks in the aerodynamic load input, and the self induced loads, e.g. from elastic torsion of the blades, become more important.

Another effect of upscaling is that an increasing part of the scales in the natural turbulence are comparable with the rotor diameter and become concentrated at multiples of the rotational frequency (1p). This leads to bigger variations in dynamic induction over the rotor disc, which also originates from atmospheric shear and wake effects, as well as from the increased eigen-motion of the blades and possibly from distributed control.

The final outcome of this work 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 consensus was created regarding intelligent blade concepts, supported by the tools developed in UpWind. Different aspects were investigated:

- The importance of non-linear structural effects on loads and stability was quantified, and tools were developed to account for it. UpWind demonstrated that bending-torsion coupling is important and can be tailored to reduce fatigue loads. We could reduce the loads by 10% in flapwise direction by using more flexible materials or bending the blades. Fore-bended blades today appearing on the market are therefore highly beneficial, as fore pre-bending is beneficial with respect to stability;
- Shear-coupling and large deformation into beam and finite elements models were included. UpWind showed inflow shear causes dynamic induction and creates phase shifts, which should be included in models. Phase shifts accounts for 10% of the fatigue loads in current BEM codes and this effect becomes more important for larger turbines. As well, ground effect is significant in shear and should be included in models to increase efficiency;

- Engineering aerodynamic models by application of full 3D unsteady CFD models in complex inflow such as strong wind shear were analysed and developed. There, stability analysis including non-linear effects (and structural modal damping prediction) show that coupling effects are important;
- Overview of requirements to aerodynamic and aeroelastic design tools in order to predict the potential of different advanced control features and aerodynamic devices. Here, dynamic stall models for the variable trailing edge concept were developed and applied for aeroelastic predictions. Fatigue load reductions of 20 – 40% have been identified;
- Development of concepts to improve the link between CFD and aeroacoustic predictions. Results show boundary layer predictions and measurements are in reasonable agreement with advanced UpWind methods.

Research activities and results

Structural dynamics — large deflections and non-linear effects

Aeroelastic tools that account for important non-linear structural and geometric effects were developed and applied to estimate the importance for loads and stability of the blades. The structural modelling capabilities were advanced by developing new beam models that account for the detailed inner structure (complex laminates and sandwich skins). It was identified that the torsional deformation was affected by the coupling of the blade torsion with the blade bending and should be taken into account in the modeling of large flexible blades.

This is illustrated in **Figure 13**, which shows that the tip pitch is up to about one degree different due to non-linear effects. With respect to the geometrical non-linearities, it was found that the bending-torsion coupling drives differences in the response of pre-curved blades as compared to straight ones. So-fore blade pre-bend reduces torsion loads and increases the blade stability. On the contrary, aft pre-bend reduces the damping of the low damped edge-wise modes. Pre-sweeping the blades also drives a bending/torsion coupling which leads to nose down torsion deformation and reduced fatigue loads in aft pre-sweep configurations. The opposite effect is obtained for forward sweep.

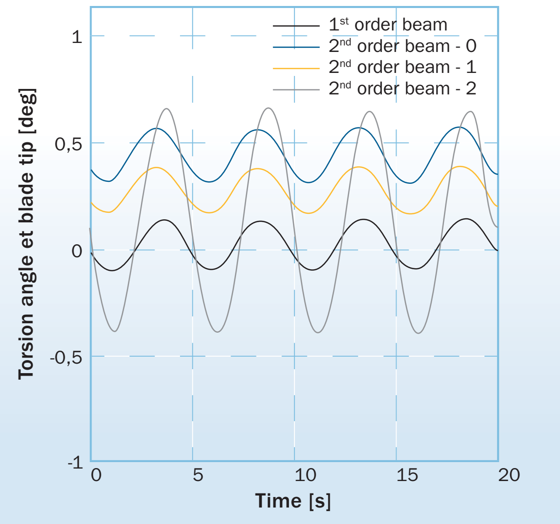


Figure 13: **Predicted torsional deformation of blade (5 MW) by beam model taking different nonlinear effects into account.**

Advanced aerodynamic models

Results from different levels of aerodynamic models have been compared. The advanced models show that the induction varies for the blade in different azimuthal positions when there is shear in the in-flow, due to the skew vortex sheets. BEM models should be implemented such that they model the local inflow and load distribution on the rotor. Another flow mechanism observed in the simulations of inflow with strong shear is a considerable interaction with the ground. There is a speed-up of the flow below the rotor due to the constraint from the ground on the flow expansion. This means that the ground influences the aerodynamics of the rotor.

Shear due to the wake from an upstream turbine is another example of a complex inflow case with considerable variations of loading and induction across the rotor disc, as shown in Figure 14. For the BEM type codes this requires a computation of induction that is a function of both radial and azimuthal position.

Figure 14: **Half wake flow case at 3D downstream simulated with a full 3D CFD code. Contour of axial velocity is shown together with a contour of vorticity (the vortices).**

Aerodynamic and aeroelastic modeling of advanced control features and aerodynamic devices

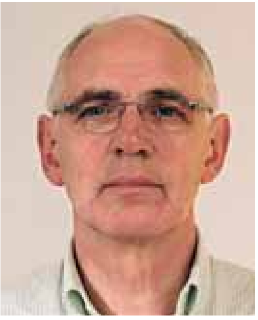
Unsteady aerodynamic models for the simulation of a variable trailing edge flap have been developed and incorporated in aeroelastic simulation tools to identify the potentials with respect to load reduction or power enhancement. The variable trailing edge flap has proved to be an efficient way to control the loading on a blade. There is a good agreement between the simple engineering model and the computationally more demanding methods, indicating that the engineering type of modeling is adequate for modeling the 2D behaviour of airfoil sections with trailing edge flaps. The aeroelastic simulations indicate that loads could be reduced between 20 and 40% by application of this concept to large MW turbines.

Aeroelastic stability and total damping prediction including hydroelastic interaction

Stability tools have been developed to account for large blade deflections. Deflection of the long slender blades results in coupling between the different deflections and thus changes stability characteristics. As an example, the damping of the first edgewise is decreased due to the flap wise blade deformation, and it becomes negative damped at a much lower rotor speed than the flutter speed. It is the geometrical coupling with blade torsion that explains the decreased and even negative aerodynamic damping of the first edgewise bending mode. For deformed blade the edgewise bending-torsion coupling changes as the rotor speed increases leading to a change in looping direction and thus a change in aerodynamic damping.

Computation of aerodynamic noise

An extensive assessment and step-by-step validation of different prediction schemes as developed by various partners have been conducted by comparison to detailed measurements of turbulent boundary-layer properties, wall pressure fluctuations and far-field trailing-edge noise. New schemes have been developed that allows direct derivation of the turbulence properties by means of different turbulence models and consider anisotropy features of the flow. It was found that the isotropic version of the Rnoise and RISOE-CFD code produce almost the same results if RANS predicted turbulence data are identical. The improved anisotropic prediction scheme provides the best results on the condition that the turbulence noise source parameters are estimated properly including turbulence anisotropy effects. The accuracy and consistency of the prediction schemes, therefore, completely depends on the accurate RANS simulation results. LES-CAA computations show good agreement with measurements in the frequency region higher than 1~kHz whereas it over-predicts the sound pressure level in the low frequency region.



"Upscaling the current designs with the existing technology has its limits. New designs and/or materials are needed. But UpWind found a way forward, as better knowledge of material behaviour, advanced methods for the structural design and improved manufacturing processes could help in releasing the material safety factors."

Bert Janssen, Work Package Leader, Energy Research Centre of the Netherlands (ECN), Wind Energy Department

4.2 Work Package 3: Rotor structures and materials

Challenges and main innovations

For larger wind turbines, the potential power yield 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. Previous projects have emphasised the necessity for improved and detailed fatigue life modeling for reliable and optimal blade design. In addition, it has become clear that knowledge on the behaviour of larger scale subcomponents might be indispensable in the blade design process. Furthermore, a change in the whole concept of structural safety of the blade might be required. UpWind investigated several aspects:

- Improvement of both empirical and fundamental understanding of materials and extension of the OPTIDAT material database, including a simplified life-cycle analysis. The extended database was used to develop an integrated material model based on both tests and micro-mechanics. Design and test recommendations are established. Micro scale analysis and microstructure optimization represent an important source of the future optimization of the blade materials.
- Study on effective blade details. A structure, representing a structural blade detail, e.g. shear web/spar cap construction was manufactured, tested, analysed numerically and with the assistance of NDT methods, to improve understanding of the structural behaviour of such a detail. This type of blade details can be tested before performing full scale testing.
- Establishment of damage tolerant design concepts and probabilistic strength analysis. A shell-based finite element numerical methodology for life prediction as well as residual strength was developed. The numerical simulations were compared to experiments. Two numerical methodologies were developed to analyse the probability of failure on layer level. Simulations were performed to compute the probability failure along the profile of a 26 m blade.
- Analysis of scaling limits for large blades show the future need for new structural designs, improved material models, manufacturing processes and/or breakthroughs in material development can lead to more accurate determination of the partial material safety factors.

Results

Task 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 enable validation of the models derived in task 2 and serve as input data for UpWind activities. Together with the work carried out in 2, the result is an integrated material model, based on both tests and micro-mechanics, for which design recommendations and material test recommendations are established, Figure 15.

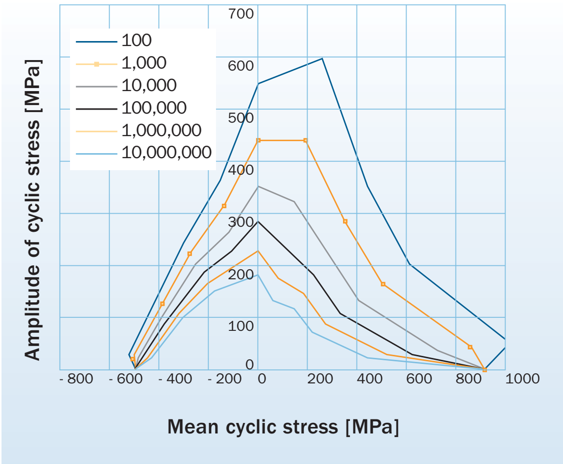


Figure 15: **Constant life diagram**

Test methods for static compression, fatigue and static shear were reviewed and compared qualitatively and quantitatively. These results provide valuable input for refinement of test procedures and design recommendations.

Extensive experimental work was done at off-reference conditions, performing tests on reference specimens in an attempt to decouple the temperature and frequency effects, for use in the integral material model.

In collaboration with the Condition Monitoring activities, research was carried out on the applicability of fibre optical strain measurement techniques. The possibility of embedded strain gauges was the subject of strength and fatigue experiments.

A structure, representing a structural blade detail, e.g. shear web/spar cap construction, was manufactured, tested, analysed numerically and with the assistance of NDT methods, to improve understanding of the structural behaviour of this detail, Figure 16.

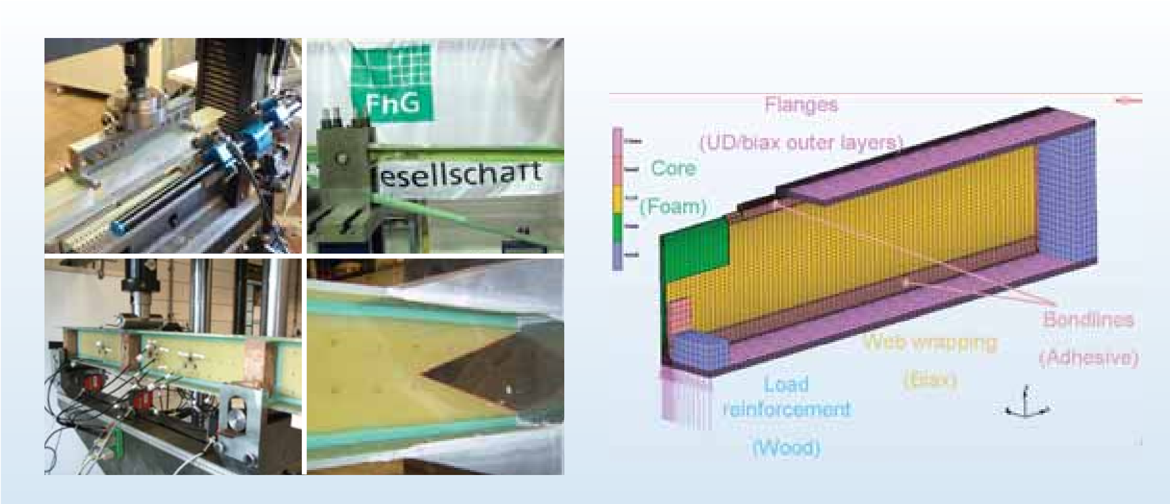


Figure 16: **Subcomponent testing and modelling**

Following the main route in implementation of a carbon fibre — and/or glass-carbon fibre — hybrid, and thermoplastic composites, a number of material combinations and reinforcement architectures were also investigated. Life Cycle Assessment (LCA) data of materials were collected and a methodology was introduced to enable instant LCA of the rotor structures, to facilitate direct evaluation of various concepts.

Task 3.2 Micro-mechanics-based material model

In this task, the micro-mechanisms of strength, degradation and failure of the rotor blade materials are studied experimentally, theoretically and numerically. The answers on the following questions were sought: which physical mechanisms control the strength and failure of the wind turbine blade materials? Which parameters of microstructures of the materials influence the strength of wind turbine blade materials? How can the service properties of the materials be improved by modifying the micro-scale structures? The sensitivity of the strength of the composites toward different microstructure parameters and loading conditions has been studied with respect to static and cyclic strengths, and the most significant ones are identified.

In order to study the effect of micro-scale parameters of wind turbine blade composites on their strength, special software for the automatic generation of 3D computational micromechanical models of the composites was developed, and used in the numerical experiments. Figure 3 shows the micrograph of a composite, and the 3D finite element model as well as the crack growth scheme. The effects of the statistical variability of fibre strengths, viscosity of the polymer matrix as well as the interaction between the damage processes in matrix, fibres and interface are investigated numerically, by testing different multi-fibre unit cell models of the composites. It was demonstrated in the simulations that fibres with constant strengths ensure the higher strength of a composite at the pre-critical load, while the fibres with randomly distributed strengths lead to the higher strength of the composite at post-critical loads. In the case of randomly distributed fibre strengths, the damage growth in fibres seems to be almost independent from the crack length in matrix, while the influence of matrix cracks on the beginning of fibre cracking is clearly seen for the case of the constant fibre strength. Competition between the matrix cracking and interface debonding was observed in the simulations: in the areas with intensive interface cracking, both fibre fracture and the matrix cracking are delayed. Reversely, in the area where a long matrix crack is formed, the fibre cracking does not lead to the interface damage.

In compression, the dominating failure mode of carbon-fibre reinforced polymer composites is a so-called kink band formation. In order to study the compressive strength of composites, a statistical computational

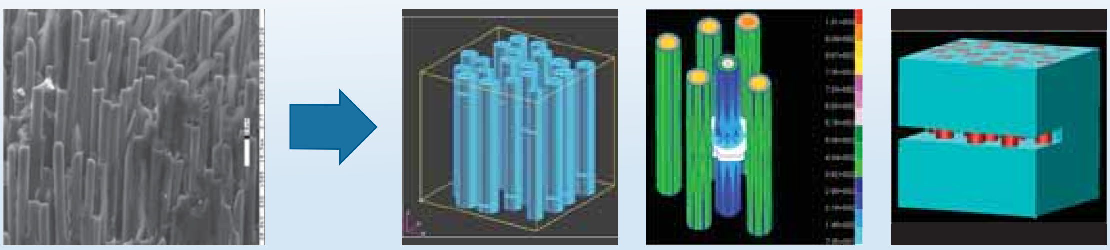


Figure 17: **Micrograph of the composite, 3D FE micromechanical model, crack growth between the fibres, and fibre bridging over the matrix crack**

model was developed on the basis of the Monte-Carlo method and the Budiansky-Fleck fibre kinking condition. The effects of fibre misalignment variability, fibre clustering and load sharing rules on the damage in composite are studied numerically. It was demonstrated that the clustering of fibres has a negative effect of the damage resistance of a composite. Further, the static compressive loading model is generalised for the case of cyclic compressive loading, with and without micro-degradation of the matrix, and with and without random variations of loading. It was observed that the random variations of loading shorten the lifetime of the composite: the larger the variability of applied load, the shorter the lifetime. The model was further generalised to include the irregular fibre waviness and the interface defects. Considering the cases of small and large interface defects with different density, we observed that the small interface micro-cracks do not lead to the sufficient reduction of compressive strength even at unrealistically high micro-crack density. In contrast, large interface defects have a strong effect on the compressive strength of the composite.

In the computational studies of the effects of micro-structures of rotor blade materials on their strength and damage resistance, it was observed that a weaker fibre/matrix interface prevents the development of matrix cracks in the composites. Further, replacement of fibre reinforcements by clusters or bundles of thinner fibres can ensure higher strength of the composite. The effect of the loading frequency on the lifetime of materials depends strongly on the damage mechanisms: whether it is rate-dependent or creep-related damage. Generally, the micro scale analysis and micro-structure optimization represent an important source of the optimization of the wind blade materials. And potential review of the safety factors for large blades should include an analysis of the material properties.

Task 3.3: Damage-tolerant design concept

Nowadays, fibre reinforced plastics (FRP) rotor blades are designed according to regulations based on very first principles of composite mechanics, in which ply failure of a multilayer element in a finite element (FE) model is not followed by property degradation and thus, investigation of post-FPF (first ply failure) load bearing capability is not implemented. Furthermore, material constitutive equations are considered linear, although it is common knowledge that in-plane shear and transverse compressive response of a uniform direction layer is from moderately to highly non-linear.

The objective of the work performed was to formulate and develop a shell-based finite element numerical methodology for life prediction, as well as residual strength and stiffness of wind turbine rotor blades made of FRP, subjected to irregular cyclic loads. In this task therefore, a continuum damage mechanics method was implemented in a ply-to-laminate life prediction scheme for composite laminates under cyclic constant amplitude (CA) or variable amplitude (VA) loading. Instead of considering the geometric description of a type of defect induced by local failure, a set of appropriate stiffness degradation rules was applied, resulting in a modified stiffness tensor, i.e. an equivalent, homogeneous, continuum description, such that either the resulting strain field or strain energy density under the same load is similar to that of the damaged medium.

An extensive comparison of life prediction numerical results with experimental data from CA or VA tensile cyclic testing of a [±45]S plate and loading at various R-ratios of a multidirectional (MD) Glass/Epoxy laminate [(±45/0)4/±45]T has been performed.

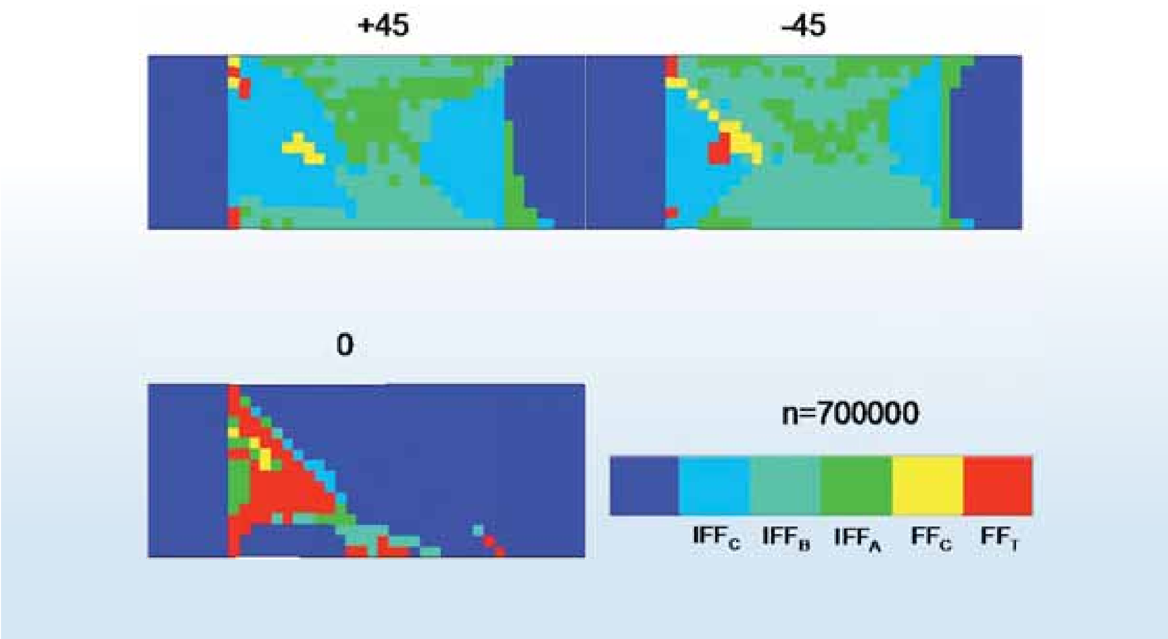


Figure 18: **Damage modes according to Puck failure criteria of a [(±45/0)4/±45] Gl/Ep MD coupon, at a stress level of σ_{max}=193 [MPa], R=0.1**

As an example, in Figure 18 damage patterns in the outer three layers of an MD coupon after 700,000 cycles were shown.

Additionally, quantification of the structural reliability level of the wind turbine blade with respect to its strength, stiffness and elastic stability should be performed in probabilistic terms by relying both on load uncertainty quantification as well as on material, due to the use of composite materials, exhibiting great inherent variability of mechanical properties. To this end, two methodologies were developed within task 3.3, where the probability of failure is estimated on the layer level, taking into consideration the variability of applied loads, material strength and elasticity properties. One, based on the Edgeworth Expansion method, allows for direct connection with currently employed aero-elastic wind turbine design codes, while the other, employing the Response Surface Method in combination with a finite element shell model, allows a more accurate representation of the blade structure.

Task 3.4: Upscaling - cost factors

Input with respect to blades and blade materials for the identification of the technological and economic barriers associated with the dimensioning of very large wind turbine design up to 20 MW, through upscaling of a reference wind turbine of 5 MW were the major core of investigation within this task. The most important aspects addressed in these studies were:

- The feasibility of increasing the number of layers or the layer thickness, when considering that until now the upscaling of a wind turbine, as well as the wall thickness of the blades is linear with rotor radius, R.
- The possibility of mitigating blade loads by using other materials or other lay-ups.
- The perspectives of using enhanced materials with respect to possible blade weight reduction.
- Quantified possibilities and perspectives of reducing safety factors.
- The validity of a cost factor of 2.4 in the upscaling of blades, since weight itself is not the design driver but the costs are.
- The formulation of a cost model for the wind turbine blade, serving as an input to the overall wind turbine cost model produced within UpWind.

Results on the discussed issues of scaling limits, of the possibilities of new blade materials, of safety factors and of costs of several alternative materials and blade concepts have been included in a comprehensive report to be directly used as input for other UpWind activities. The following results have been achieved and are included in the report:

- Thickness limitations: today's root section thickness is in the 10-15 cm range. For 20 MW blades, with current design parameters, this thickness could increase to 30 cm. This poses challenges for production, as well as connection to the hub.
- Possibilities for weight reductions for load mitigation, including the possibilities of other materials and stiffness issues were indicated under current design constraints.
- Discussion on failure modes necessary for safety factors review. A comparison was performed for the current design standards available at the moment. Today, different levels of partial safety factors exist, for DNV or GL, which differ from IEC. GL uses more stringent partial safety factors, but DNV asks for more experimental proof.
- Cost issues under currently available technological solutions. For the cost function, as has been developed in UpWind, reference values are provided depending on the type of blade materials and manufacturing processes.

“ UpWind demonstrated the importance of an integrated wind turbine and substructure design together with advanced control concepts to lower the support structure loading and thus enable cost effective designs. Significant progress was made on deep water foundation designs, including the development of advanced modeling techniques and enhancements of current design standards which for example become very important for coming floating designs. Thanks to UpWind, the industry is better equipped for the challenges it will face in the coming years. ”

Tim Fischer, Endowed Chair of Wind Energy (SWE), Universität Stuttgart

4.3 Work Package 4: Foundations and support structures

Challenges and main innovations

In Europe the total capacity of installed offshore wind power is expected to increase from today’s approximately 3 GW up to 40 GW in 2020. The future exploitation of the enormous offshore wind potential will be technically and economically feasible only with much larger wind farms further offshore.

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 monopile foundations or gravity-based support structures designed for shallow water locations up to 20 m water depth. Future sites in European waters will require deeper water foundation concepts though. Beside the challenges these site conditions will pose, offshore wind farms of the future will have a typical total capacity of 400-500 MW and will be equipped with turbines in the 5 MW class or more, impacting installation and maintenance strategies.

Therefore, the primary objective of UpWind activities on 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 UpWind project looked for solutions integrating the foundation design, support structure and turbine machinery, in order to optimise the structure as a whole. A particular emphasis was placed on large wind turbines, deep-water solutions and designs insensitive to site conditions, allowing cost-reduction through series production. Open source design and costs models were developed for monopile and jacket structure designs. Costs models are able to take into consideration different sites (depth and soil) and turbines (mass and size).

Task 1 Integration of support structure and wind turbine design	Task 2 Support structure concepts for deep water sites	Task 3 Enhancement of design methods and standards
Develop and enhance the integrated design process for offshore wind turbines	*Design innovative bottom-mounted support structures*	*Design tools and methods for bottom-mounted support structures*
Control concepts for mitigating aerodynamic and hydrodynamic loading	*Analysis of very soft structures*	*Design tools and methods for floating support structures*
Compensation of site and structural variability	*Integration of support structure and wind turbine design*	*Integration of support structure and wind turbine design*

While innovative solutions for the rotor nacelle assembly will be made available by close cooperation with other UpWind activities, emphasis is put on the support structure and the interaction of the design of the support structure and the rotor nacelle assembly. The research activities were divided into three Tasks, as shown in the table below.

The objectives of Task 1 are mitigation of dynamic support structure loading and compensation of the inherent variability of site conditions within a large wind farm. Integration of the support structure design and the turbine design and use of smart turbine control are expected to achieve this. The task mainly focuses on the development of control algorithms, where different methods ranging from operational control to dynamic control are 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) is attempted by employing the control system, structural tuning and the selection of particular structural concepts.

In Task 2, the goal is to develop support structure concepts for water depths beyond 30m through innovative bottom-mounted concepts. In this task, current design practice and experience are merged with the new techniques from Task 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.

Finally, Task 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 1 and 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.

Results

Task 1: Integration of support structure and wind turbine design

The work focused on the mitigation of aerodynamic and hydrodynamic loads on the total offshore wind turbine system, as through this an optimised and cost-effective design can be ensured. Load mitigation can be tackled at three different levels, i.e. at the design, operational control and dynamic control level (see Figure 19).

On the design level, an objective could be to design the support structure with smaller water piercing members in order to reduce inertia-dominated fatigue waves. Beside changes in the design characteristics, new approaches for operating offshore wind turbines might result in lower total loading. A solution can imply an extension of the power production range to wind speed of 30 m/s or higher in order to enlarge the effects of aerodynamic damping on the hydrodynamic loading and also to support grid stability. Finally, different advanced dynamic control systems are available to damp the loads on an offshore wind turbine actively. An example is the usage of tower-feedback controller for mitigation of the bending moments in the fore-aft support structure motion or an active generator torque controller for the equivalent sideways support structure mode.

The task has evaluated different load mitigation options for a 5 MW turbine model on a monopile in 25 m deep water. It demonstrated that a case-dependent choice of load mitigation systems and a fine-tuned controller can provide sufficient damping to the system in order to reduce hydrodynamic-induced vibrations without significantly increasing the loading on other components. In this study, the load reduction was used to optimise the structure in terms of cost. The achieved load reducations for the studied monopile were almost 15% lower fatigue loaqds, which led finally to mass savings of 85 tonnes in steel. However, the application of such control concepts could also extend the application range for monopiles to deeper sites, as this concept will probably still be competitive against other more complex structures, such as jackets or tripods.

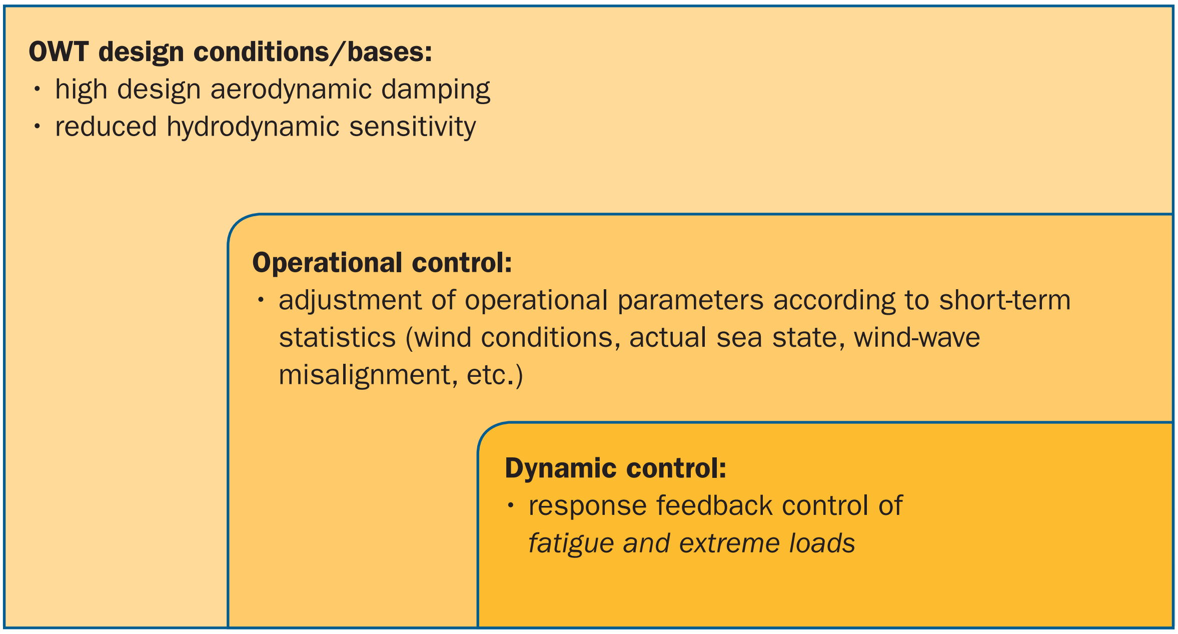


Figure 19: **Levels of load reduction concepts**

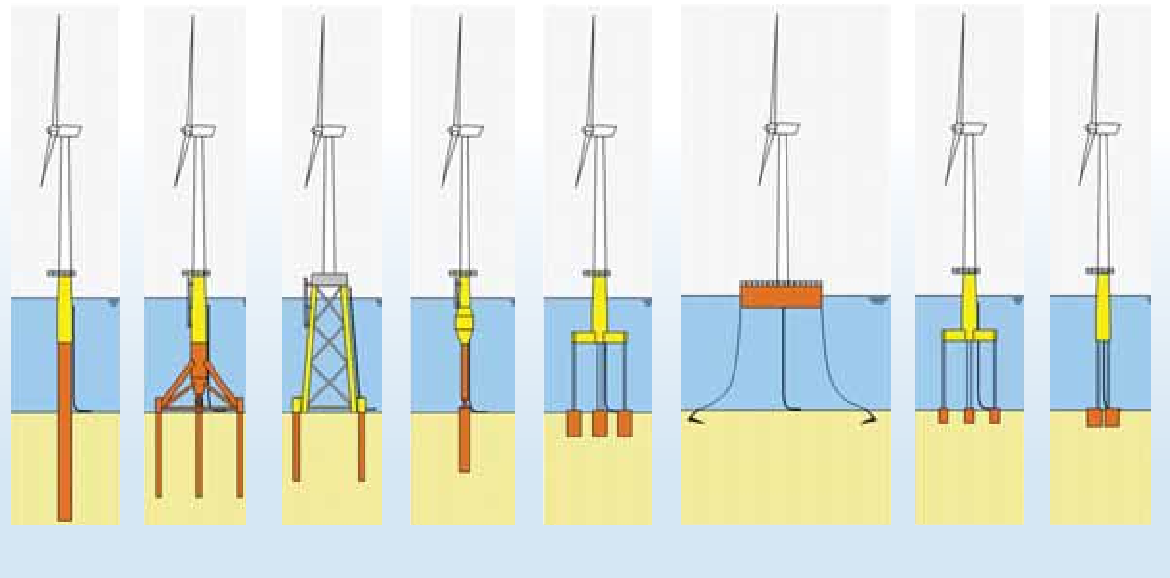


Figure 20: **Different support structure concepts. From left to right: monopile, tripod, jacket, compliant, barge floater, tension leg platform and spar floater structure.**

Task 2: Support structure concepts for deep water sites
The first step was a review of support structure concepts and fabrication and installation methods. A preliminary design approach was presented and an evaluation of the proposed support structure concepts was made on the basis of expert opinions, showing that gravity based foundations and monopiles were the preferred concepts for depths up to 25 m, tripods and jackets were most suitable for the intermediate water depths up to 60 m and compliant and floating structures were most applicable in waters beyond those depths.

Beside the above mentioned bottom-mounted designs with the fundamental frequency in the soft-stiff range, a study was performed to evaluate the potentials of compliant structures. These structures are in the soft-soft design region, having a fundamental frequency below wave frequencies of appreciable energy, whereby the structure responds in a 'compliant' way to wave loads. It was found that these concepts could be attractive when hybrid solutions of floating and bottom-mounted structures are applied.

One of the final results in this task was the creation of a reference structure for the reference 5 MW turbine for a site in 50 m water depth. The most suitable concept for the reference structure is the jacket. The structure is intended as a reference which can be used for comparison with other support structure concepts, demonstrating the effectiveness of design improvements and to demonstrate the sensitivity to various design parameters. This reference case is used by the IEA Task 30 OC4 project.

Task 3: Enhancement of design methods and standards
A review of various models for irregular, nonlinear waves suitable for design purposes was performed in order to judge their relevance for future offshore wind farms. In addition, support was given to the international standard for offshore wind turbines IEC 61400-3, also with respect to new requirements for floating support structures.

In parallel a new design tool for integrated simulations of offshore wind turbines with advanced deep-water support structures was developed, both for bottom-mounted and floating structures.

For the bottom-mounted part, a finite element based code with hydrodynamic loading capabilities was employed for the dynamic modeling of arbitrary space frame structures and was coupled to the rotor nacelle assembly with all required aeroelastic, electro-mechanical and control features. The rotor nacelle assembly was modelled with relatively few modal degrees of freedom with the FLEX5 simulation code, a tool used throughout the wind industry. Advanced modeling approaches for bottom-mounted structures were analysed, including effects like the super-element technique or joint-flexibilities for braced support structures were implemented and evaluated in the design tool ADCoS-Offshore, a nonlinear finite element code for the modeling of bottom-mounted offshore wind turbines. The studies showed the importance of these modeling techniques, especially for structures with large joints, such as tripods.

For floating structures, a review of the current state-of-the-art in floating wind turbine design tools was performed, giving an overview of modeling techniques for floating wind turbines and the advantages and disadvantages of the various approaches. The development of the GH Bladed code from simple modal representation of structural dynamics into a multi-body representation was supported, which enables more accurate modeling of the large displacements and increased number of degrees of freedom experienced by floating wind turbines. Advanced modeling approaches for floating wind turbines were analysed, including extensions for modelling mooring line dynamics, rotor-wake aerodynamics for floating wind turbines and development of second order effects and non-linearities in the hydrodynamic modeling.

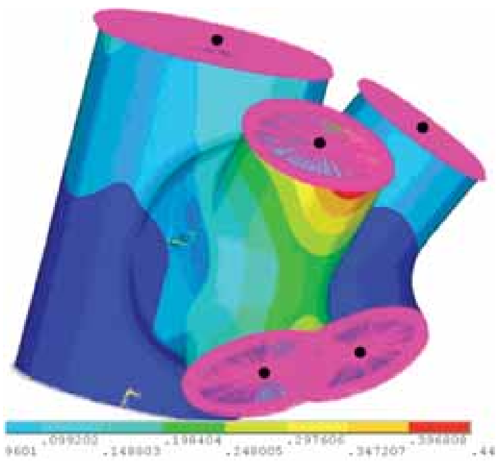


Figure 21: **FE model of double-K-joint in ANSYS**

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"Larger turbines need to reduce their mass, and intelligent control is the key. UpWind demonstrated it is better to control the loads with intelligence rather than building stronger, heavier structures able to withstand those loads. Smart control of blade pitch can achieve large load reductions, and this has been confirmed in field tests on actual turbines. We can now re-optimise the whole design to improve cost effectiveness."

Ervin Bossanyi, Work Package Leader, Garrad Hassan and Partners Ltd. (GL-Garrad Hassan)

4.4 Work Package 5: Control systems

Challenges and main innovations

Further improvements in the cost-effectiveness of wind turbines drives designers towards larger, lighter, more flexible structures, in which more 'intelligent' control systems play an important part in actively reducing the applied structural loads, avoiding the need for wind turbines simply to withstand the full force of the applied loads through the use of stronger, heavier and therefore more expensive structures. UpWind activities were aimed at further developing such control strategies and ensuring that new, often larger and innovative turbines can be designed to use these techniques from the start. For this to be possible, it is important to build up full confidence in the effectiveness and reliability of these strategies in all situations. Different aspects were investigated:

- Individual pitch control can help to significantly reduce fatigue loading by 20-30%. This concept was demonstrated by field testing on a two-bladed turbine. This requires reliable sensors, able to detect their own failures. This technique can be coupled with nacelle-mounted LIDAR sensors, able to visualise incoming gusts, and adapt the pitch in consequence.
- Dual pitch control on a single blade could significantly reduce the loads. Pitching the tip section more than the root section could result in a 15% reduction in the underlying flapwise loading. This innovation can be combined with the 'innoblade' activities.
- Load sensors can be used to measure loads directly, but it is also possible to estimate some loads instead of measuring them directly. This avoids the costs of sensor installation and maintenance, as well as the possibility of sensor malfunction, leading to increased overall reliability.
- On-site adaptation of controllers can be performed in order to adapt to variations in turbine properties. A closed loop system identification algorithm was developed, in which the parameters of a state-space turbine model are automatically adjusted by comparing the predicted and measured responses.
- To ensure fulfilment of the different grid code requirements while simultaneously ensuring that load envelopes are not exceeded in grid fault situations, it is important to be able to model the electrical dynamics accurately in conjunction with the aerodynamics, structural dynamics and controller dynamics of the wind turbine. A model of the electrical and control parts of a doubly fed induction generator (DFIG) turbine has been developed and linked into a *Bladed* model of the turbine, and the combined model validated against field tests.

- Wind farms can be utilised to provide voltage control for the network to which they are connected. A supervisory VAR controller has been developed for a large-scale wind farm to control the voltage at the point of interconnection (POI) with the grid.

Results

Supervisory control implications of advanced control
Individual pitch control (IPC) is a promising technique for reducing wind turbine asymmetric fatigue loads by pitching each blade individually in response to load measurements. However there is also a risk of increasing extreme loads as the blades might be pitched at different angles during shutdowns, or as a result of failures of individual load sensors. This work shows how these extreme load increases can be mitigated by appropriate supervisory control design. For example, Figure 22 shows how the severe increase in yaw moment due to IPC during a grid loss shutdown can be entirely mitigated by phasing out IPC during periods of high acceleration.

Strategies for detecting failures of individual blade load sensors were also investigated. If undetected, these could result in significant fatigue load increases if IPC action continues regardless. Often the sensor itself would detect its own failures, allowing the IPC to be switched off, but an undetected failure case should still be considered. The work has shown that by comparing the mean and peak values of the differences between measured blade loads over each revolution, the controller can detect such a malfunction with a suitable degree of reliability, obviating this risk.

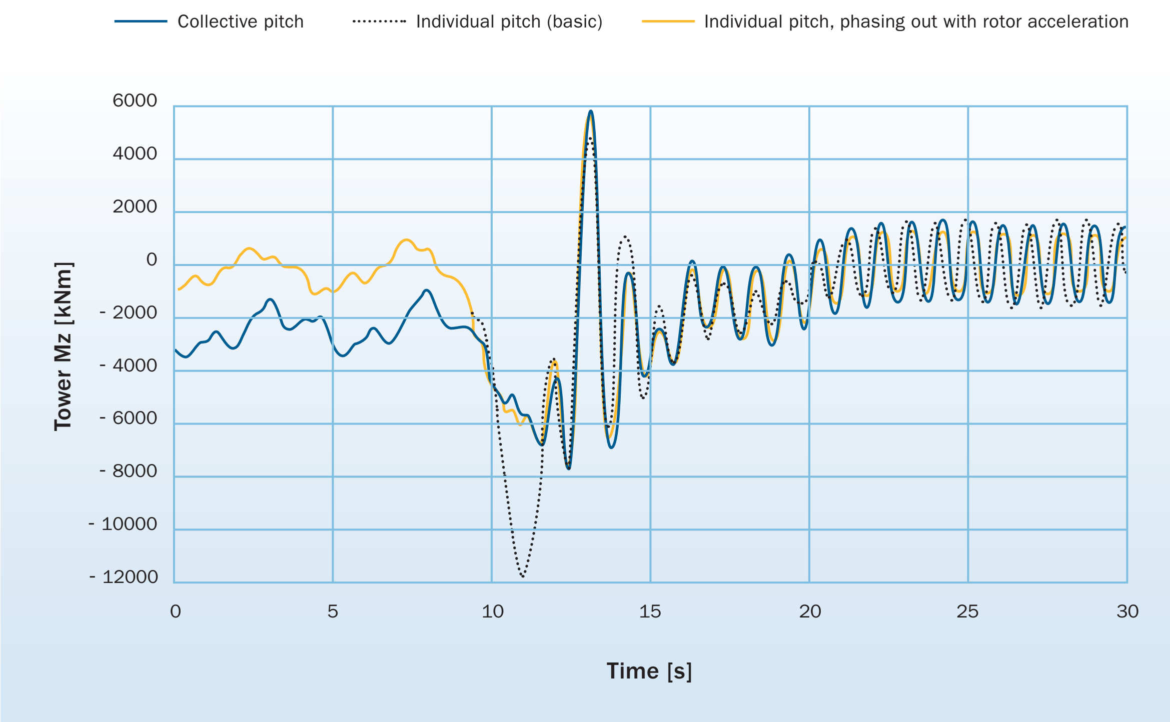

Figure 22: **Effect on loads of phasing out IPC with rotor acceleration**

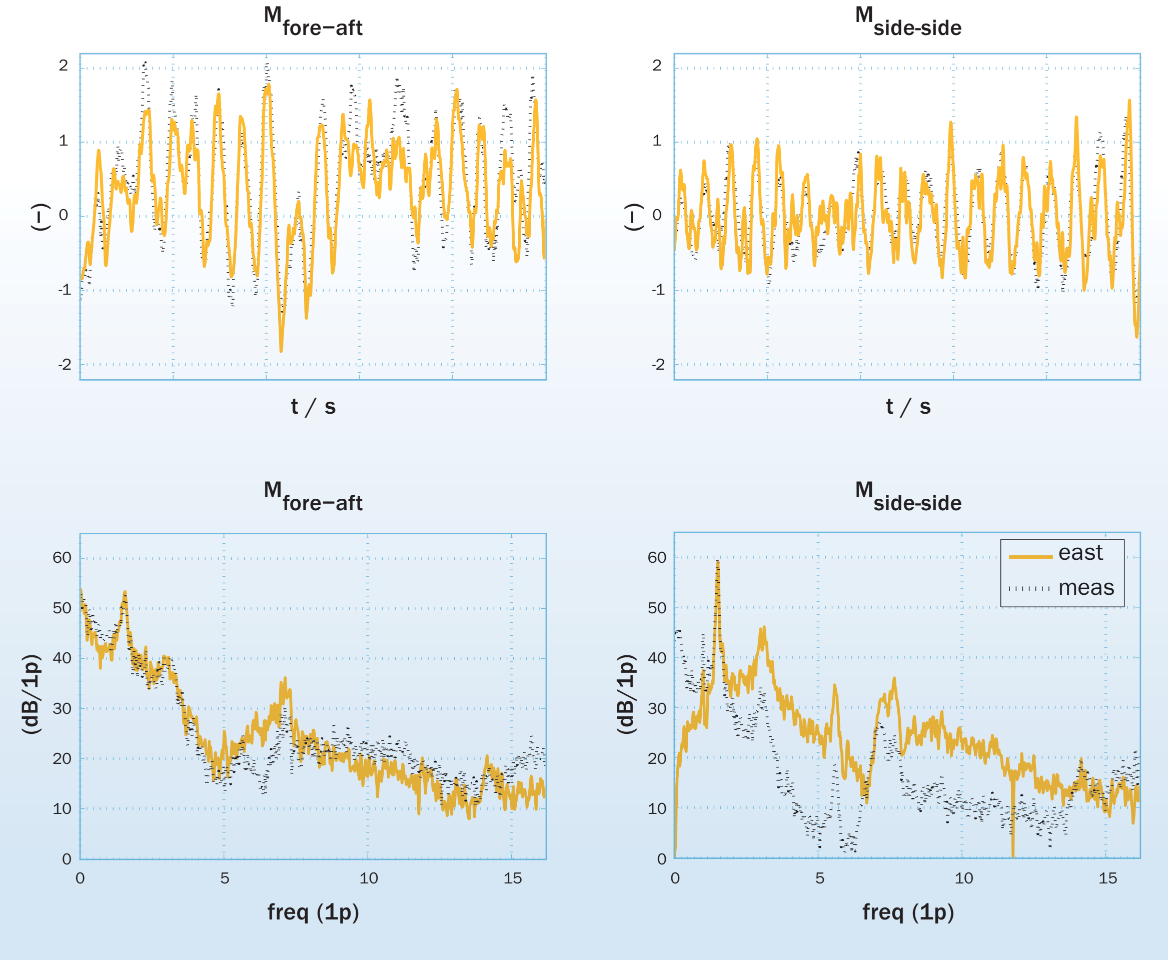

Figure 23: **Tower bending moments during measurement sequence with mean wind speed 18 m/s and turbulence intensity 10%. Thick- estimated, Thin -measured.**

Online estimation of mechanical load for wind turbines
Knowledge of the mechanical loads during wind turbine operation is useful, both for feedback control as in the IPC example above, and also for condition monitoring purposes. Load sensors can be used to measure some of these loads directly, but it is also possible to estimate some loads instead of measuring them directly. This avoids the costs of sensor installation and maintenance, as well as the possibility of sensor malfunction, leading to increased overall reliability.

This work has developed algorithms using existing commonly-used sensors to estimate other loads by means of state-space observers. Following simulation testing, these estimators have also been field tested on a commercial 5 MW Multibrid (Areva Wind) wind turbine.

Figure 23 compares the estimated tower bending moments against actual measurements of the same loads, demonstrating a good level of agreement.

Figure 24: Simulation with single and dual pitch control

Dual pitch control for out of plane blade load reduction
When pitch control is used to regulate rotor torque, the rotor thrust also changes, causing fatigue loading and excitation of tower dynamics. One task was to investigate whether a dual-pitch blade, which has full-span pitch control with an additional pitch actuator allowing the outer part of the blade to pitch relative to the inner part, could be used, adjusting both actuators simultaneously so that as the wind speed changes, both the total torque and the total thrust can be adjusted independently. This was demonstrated in a simulation using an additional actuator at 66% span. As shown in Figure 24, by pitching the tip section more than the root section a 15% reduction in the underlying flapwise loading (excluding the component due to rotational sampling) is achieved without any effect on the speed regulation.

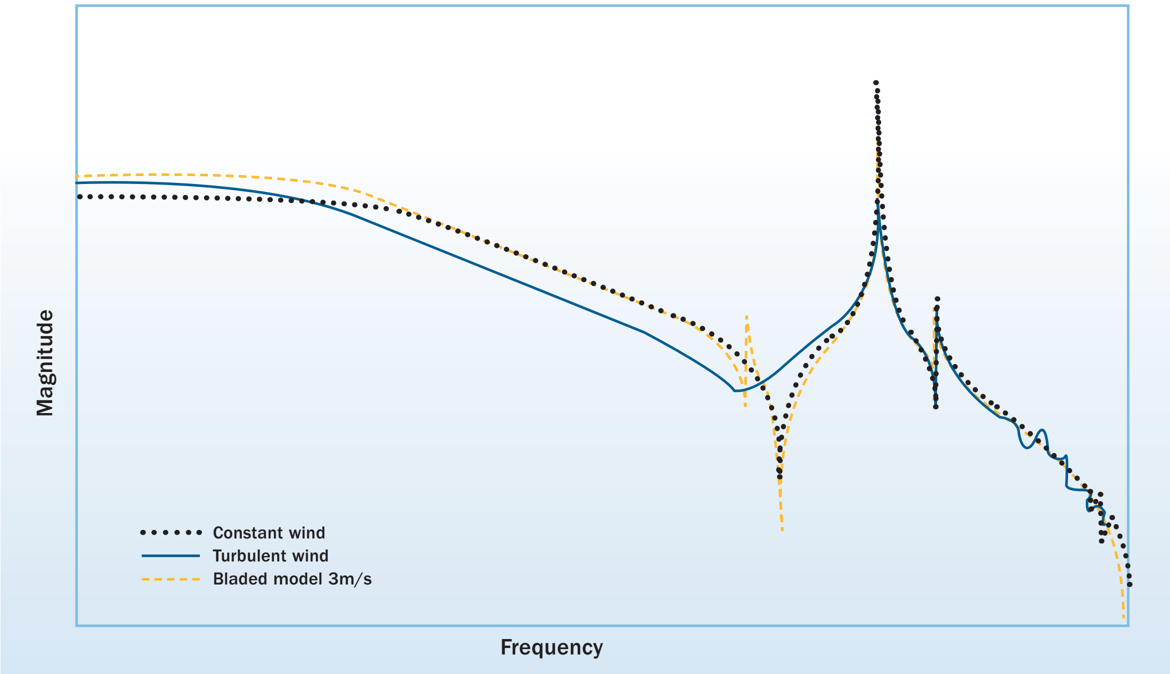

Figure 25: **Comparison of identified models against the theoretical linearised model**

Identification of wind turbines operating in closed loop
At the design stage, controller design starts from linearised models of the turbine dynamics obtained from theoretical models. However, differences in the as-built turbine may mean some controller re-tuning is required at the commissioning stage. System identification techniques are used to estimate linear models starting from measurements of dynamic response, and these linear models can then be used for the controller re-tuning. This work has developed a type of closed loop system identification algorithm in which the parameters of a state-space turbine model are automatically adjusted by comparing the predicted and measured responses.

The algorithms and procedures were originally developed using simulations with standard IEC61400 turbulent winds. Some experimental data were later obtained on NREL's CART2 wind turbine. Figure 25 shows linear models for torque loop design as identified from *Bladed* simulations using either constant or turbulent wind compared to the theoretical model, demonstrating good agreement.

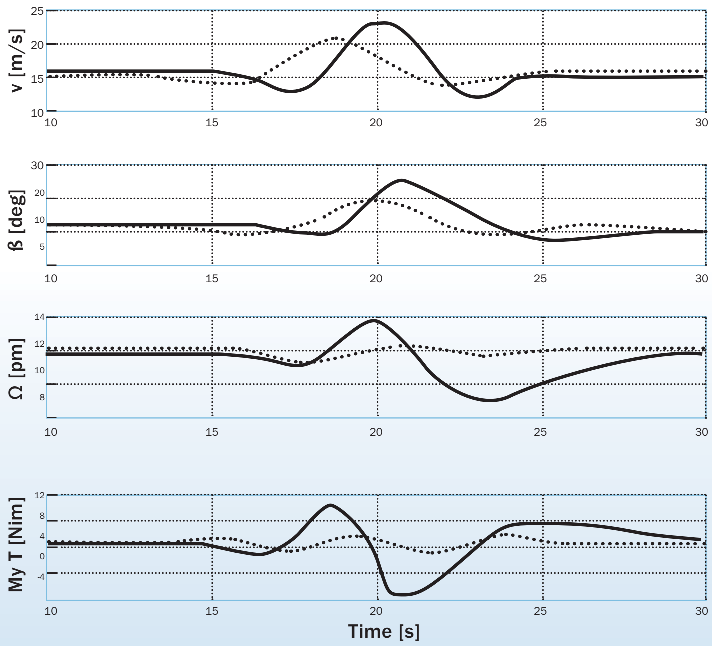

Figure 26: **Amelioration of gust response with LIDAR feed-forward**

LIDAR assisted collective pitch control
As WP6 shows, the accuracy of LIDAR systems has increased to the point where it may be feasible to use them for wind turbine control, by providing a preview of wind disturbances at various distances in front of wind turbines.

This information can be used to improve control performance using a predictive feed-forward control structure. To estimate the load reduction of extreme and fatigue loads by LIDAR assisted pitch control, LIDAR measurements were simulated with *Bladed* and the UpWind controller was extended by an additional pitch rate demand increment calculated from these simulated measurements. An example is shown in Figure 26. The upper plot shows the actual wind gust (black) and LIDAR measurement (grey). Below this are the collective pitch angle, rotor speed and tower base fore-aft bending moment for the UpWind controller only (black) and with LIDAR-based feedforward (grey), showing significant improvement.

Validation of load reducing controllers in full-scale field tests

An important task of the UpWind project is to use field tests to demonstrate that the very significant load reductions predicted with individual pitch control (IPC) can really be achieved in practice. Previously the only published results came from simulation models, so field test results are vital for increasing confidence of turbine designers to use IPC in their new designs. Field tests of an advanced controller were carried out on the two-bladed 'Controls Advanced Research Turbine' (CART2) at NREL in Colorado, USA. This demonstrated conclusively that both IPC and fore-aft tower damping work effectively and as predicted. Figure 27 shows spectra of the measured shaft bending moments during similar wind conditions with and without IPC, clearly demonstrating the elimination of the 1P load peak. By calculating damage equivalent loads, for 127 campaigns of up to 10 minutes each and binning these against wind speed, Figure 28 clearly demonstrates the consistent reduction in fatigue loading with IPC ON compared to OFF. No adjustment of the as-designed controller was required, demonstrating the robustness of this technique.

The field tests also provided the opportunity to test a fore-aft tower damping algorithm, and as shown in Figure 29 this also showed excellent performance, with a large reduction of loading at the first tower frequency.

This field test programme is now being extended to the three-bladed CART3 turbine. Field tests are also being completed on a REpower turbine to test both fore-aft and side-side damping algorithms.

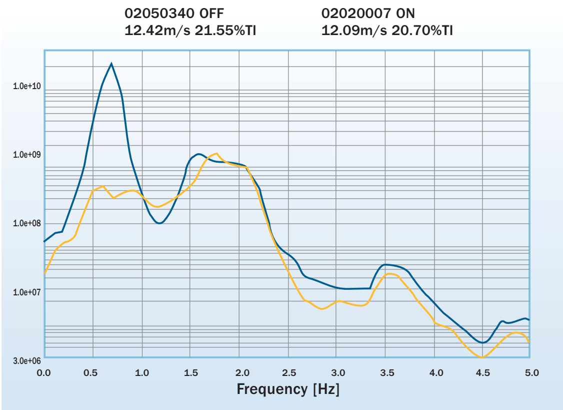

Figure 27: Spectra showing reduction of 1P shaft bending moment with IPC

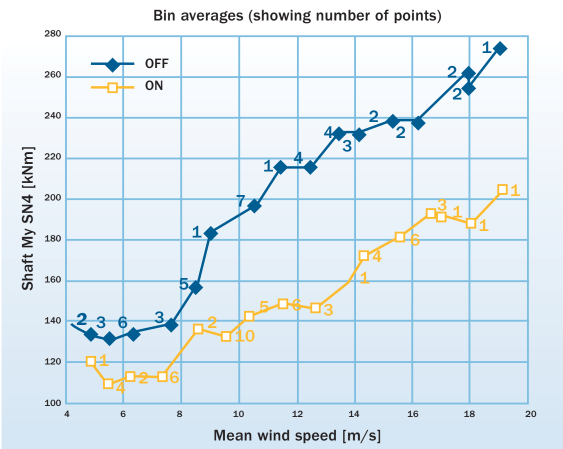

Figure 28: Binned results showing reduction of damage equivalent loads with IPC

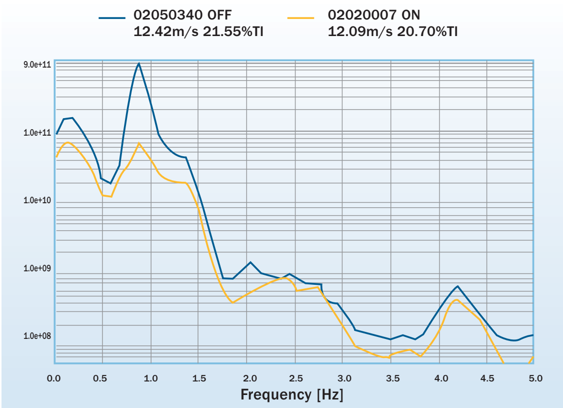

Figure 29: Spectra showing reduction of fore-aft tower bending moment

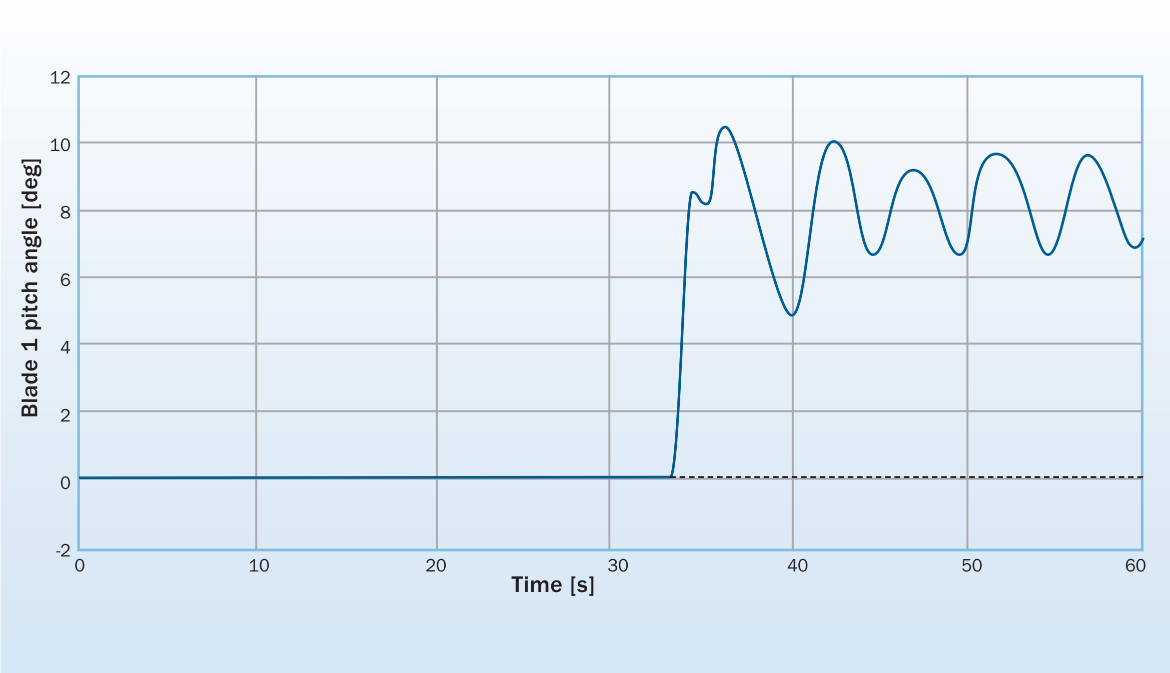

Figure 30: **Comparison of hardware-in-the-loop simulation (black) against pure simulation (blue) in turbulent wind.**

Hardware-in-the-loop testing of pitch actuators

Simulations with hardware-in-the-loop can verify the system performance much better than a pure computer simulation. A test rig has been set up with the IWES pitch actuator test bed providing three real pitch actuators, linked to a *Bladed* computer simulation of the rest of the turbine and the incident wind field using the *GH Hardware* Test package to provide a convenient interface. A MATLAB/SIMULINK simulation of the pitch bearing and gearing uses blade loads from the real-time *Bladed* simulation to transfer the load to the actuator test bed via xPC-Target. With this setup, more confidence can be gained in understanding the impact of individual pitch control on the pitch actuator performance, but the technique has the potential to improve understanding also of other wind turbine components. Performance of the pitch system under several wind conditions have been run using the hardware-in-the-loop pitch actuators, and validated against a pure computer simulation in the same conditions. The comparison of turbulent wind simulations in Figure 30 shows that excellent agreement has been obtained.

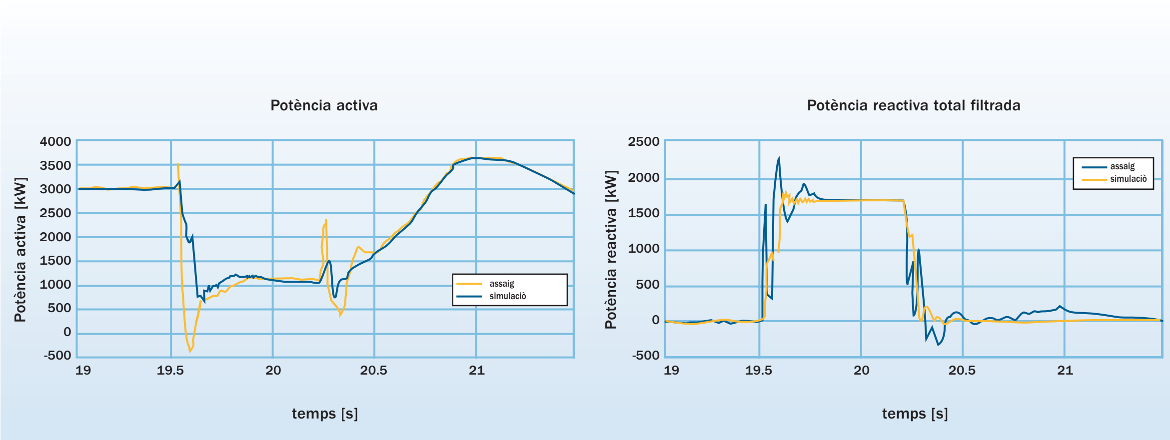

Figure 31: **Comparison of measured and simulated active power (left) and reactive power (right)**

Riding through grid faults

Doubly-fed induction generators (DFIG) have been widely used on wind turbines because of their well-known generator and power converter technologies and a relatively low cost. To ensure fulfilment of the different grid code requirements while simultaneously ensuring that load envelopes are not exceeded in grid fault situations, it is important to be able to model the DIFG accurately in conjunction with the aerodynamics, structural dynamics and controller dynamics of the wind turbine. To achieve this, a model of the electrical and control parts of the DFIG has been developed and linked into a Bladed model of the turbine using the DLL interface provided. As well as the generator and converter controller, the model includes a chopper resistor which is switched in and out according to DC link voltage, and a crowbar protection system which cuts in if a further over-voltage is detected. The combined model has then been validated using field measurements of voltage dip ride-through tests on an actual ECO100 turbine and comparing the measurements against simulated results for these cases. Good agreement has been obtained, giving some confidence in using this model to optimise the performance. Figure 31 shows a comparison of measured and simulated active and reactive power.

Impact of the drive train on wind farm VAR Control

Wind farms can be utilised to provide voltage control for the network to which they are connected. A supervisory VAR controller has been developed for a large-scale wind farm to control the voltage at the point of interconnection (POI) with the grid. Its use in conjunction with different types of generator and converter systems has been investigated, including doubly-fed induction generators (DFIG) modelled on the GE 1.5/3.6 MW systems, and synchronous generators connected to the grid through a full converter as on the GE 2.5 MW machine. This has also been compared to a directly-connected synchronous generator system. For synchronous machines, both static and brushless excitation systems were investigated, and two different VAR control strategies were investigated. The study has shown that grid short circuit ratio is an important consideration, and also that it is important to monitor the number of wind turbines connected at any one time. With well-tuned control parameters, the VAR control performance with the conventional synchronous machines could have similar time responses to that obtained with the DFIG machine type with power electronics grid interface or full power converter interfaces.

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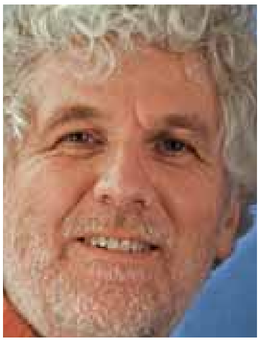

"Can remote sensing techniques substitute for conventional towers with the precision required by the IEC standards?

In my opinion, yes, definitely, but the first step will probably be to use remote sensing instruments together with shorter masts. Upwind has been working actively on the current revision of the IEC standard for power curve measurement in order to achieve this aim.

How do we best exploit the freedom to measure detailed profiles offered by remote sensing techniques?

We are using the profile information to measure more accurate and more repeatable power curves. This will ultimately reduce the uncertainty in estimating energy production. LIDARs mounted on wind turbines will also be able to see the exact 'shape' of the incoming wind and pro-actively control the blades to reduce loads or even to maximise the power. UpWind has been a core element for LIDAR technology development, testing and validation.

Resource assessment projects using LIDAR measurements are readily bankable as long as a suitable strategy is agreed with the banker's consultant. In the future, Recommended Practices in part based on the work of Upwind will be used to standardise and formalise such agreements"

Mike Courtney, Risø DTU, Work Package Leader, National Laboratory for Sustainable Energy

4.5 Work Package 6: Remote sensing

Challenges and main innovations

As wind turbines get larger, making conventional hub-height wind measurements becomes ever more costly as the masts get higher and higher. The challenge of UpWind is to research remote sensing methods as a more cost effective alternative to tall masts. One possibility is SODAR (an acoustical version of Radar), which measures wind speed by detecting the Doppler shift of sound waves reflected from temperature in homogeneities at different heights. LIDARs are based on a similar technique but use instead coherent laser light backscattered from suspended particles (aerosols). LIDARS are much faster and potentially much more accurate than SODARs. Recently new wind LIDARs have appeared on the market, designed for performing wind measurements over height ranges relevant to wind turbine applications.

More specifically, the objectives of UpWind are to answer the questions – can remote sensing techniques substitute conventional towers with the precision required by the IEC standards, and how do we best exploit the freedom to measure detailed profiles offered by remote sensing techniques? UpWind demonstrated the following points:

- With LIDARs, power curve measurements can be performed on very large wind turbines without masts. The best LIDARs measure wind speeds with an accuracy close to that of cup anemometers. Within UpWind, a verification procedure for comparing LIDARs to mast-mounted cup anemometers has been developed.
- For very large turbines, wind shear should be taken into consideration in power curve measurements. The equivalent wind speed method developed in UpWind, achieves this aim and improves power curve repeatability. IEC 61400-12-1 will probably be modified to account for the effect of shear using an equivalent wind speed and allowing the use of remote sensing to measure wind profiles.
- Including speed profiles in power curves for large turbines will also require full profile measurements for the resource assessment. LIDARs are ideal for this task, particularly when the power consumption and reliability issues have been tackled.
- LIDAR errors in complex terrain are now well understood and can be predicted if the local flow can be modelled reasonably well. Complex terrain 'correction' tools are now standard options with commercial wind LIDARs.
- An important and emerging aspect of LIDAR technology will be the use of nacelle-mounted LIDARs. Wind turbines may in the future, incorporate LIDARs in their design, allowing pre-emptive control of the blades based on the details of the approaching wind, hence reducing the blade loads. Another important application for nacelle-mounted LIDARs will be for measuring reference wind speeds in connection with power and load certification.

Results

UpWind has contributed very significantly to the development of remote sensing for wind energy. Important results have been accomplished, in particular in the areas of SODAR calibration, bi-static SODAR design, LIDAR testing, the use of LIDARs in complex terrain, power curve testing using remote sensing and the understanding of the turbulence sensed by LIDARs. Ultimately many of these advances have contributed to the improvement and modernisation of standards and best practices, most notably the IEC 61400-12-1 power performance standard revision.

Apart from the more formal work, UpWind has functioned as an important European remote sensing forum, especially within the field of LIDAR development. Work package meetings have included a number of participants from outside the project group, both from industry and other research institutes.

SODAR–calibration and design improvements

A central aim has been to develop techniques for the in-situ calibration of SODARs. One idea that has been developed in the project is to build a transponder system that simulates the acoustic response of the atmosphere to the transmitted signal under different speed and shear conditions [8]. This system has been found to be a useful tool for laboratory quality control and investigation of SODAR behaviour but has practical limitations in real-life field environments. A much simpler system that can measure the effective beam tilt angles by using in-situ tilting of the SODAR has been proposed and tested with promising results [3].

Bi-static SODAR designs, where the transmitter and receiver are physically separated, are much more sensitive than mono-static SODAR and can have significant advantages in complex terrain. Under the auspices of UpWind, a scanning bi-static SODAR design has been proposed [1]. Successful testing has been carried out in flat terrain and the system will soon undergo trials in mountainous landscape. Several commercial bi-static SODAR designs are now beginning to emerge.

LIDAR testing in flat terrain

Comparisons of measurements from remote sensing devices with mast measurements are our main tool for assessing the performance of LIDARs and SODAR. In flat terrain, the assumption of flow homogeneity inherent in the design of SODAR and LIDAR profilers is fulfilled, giving the best possible comparison to mast-mounted instruments. Concentrating on wind LIDARs that are still rather new and technologically immature has been a major task in UpWind and has provided important synergy to other EU projects using LIDARs, notably NORSEWInD and SafeWind.

Indisputably, the LIDAR testing carried out under UpWind has provided important feedback to the LIDAR manufacturers. For example it has been identified that the deflection angles of the prisms used in both the major wind LIDAR types were too imprecise. New procedures for individually measuring the prism cone angles have resulted in significant improvements in LIDAR precision. Thorough analyses of LIDAR error sources have been undertaken within UpWind [6] and these findings have been used both to improve LIDARs and to improve the LIDAR testing procedure. In flat terrain, many wind LIDARs provide consistently high correlations to reference cup anemometers [4].

As LIDARs have improved, so too has the demand for accurate testing. The need to validate a whole wind speed profile as opposed to a speed at a single height imposes unprecedented demands on the accuracy of boom-mounted cup anemometers. A new scheme using two cup anemometers mounted on two identical but differently pointing booms at one height has recently been proposed [7] which significantly reduces the uncertainty of boom-mounted cup anemometer measurements.

LIDAR measurements in complex terrain

Wind LIDARs use an assumption of horizontally homogeneous flow in order to calculate the horizontal wind speed. Whilst this is a good assumption in flat terrain, in complex terrain the flow is rarely horizontally homogeneous and consequently significant errors can occur in the measurement of the horizontal wind speed. A major result for UpWind has been to propose a scheme using flow models to predict and correct for the error [2]. Major wind LIDAR manufactures now offer such an error correction scheme based on CFD modeling as optional services for their products.

Power curve testing

Power curve measurements require wind speed measurements at the hub-height of the wind turbine. As wind turbines increase in size and height, this requirement alone makes ground-based LIDAR or SODAR anemometry more attractive. At the same time, with increasing rotor diameter, the concept of correlating wind turbine power production to a single, hub-height wind speed becomes more and more suspect. It is now well accepted that the wind speed profile has a significant effect on the power production and an equivalent wind speed method has been proposed to include the influence of the speed shear [11]. Measurements have shown a significant reduction in scatter when the power is plotted as a function of the equivalent wind speed rather than the hub-height wind speed [12]. Uncertainty budgets show that a remote sensing device with a very high correlation to the reference cup anemometer is required.

Figure 32: **Commercial LIDARs undergoing test at Høvsøre, Denmark. UpWind has contributed significantly to wind LIDAR development and testing.**

IEC 61400-12-1 revision

Many of the results from UpWind are contributing to the modernization of the strategically important power curve standard, IEC 61400-12-1. For very large rotors, UpWind demonstrated that measuring the wind speed at a single location leads to significant errors in power curve measurements. Instead, the wind profile over the entire rotor should be taken into consideration. A method estimating the equivalent wind speed was developed and demonstrated. The equivalent wind speed method is proposed as a central component for the revised standard. Since remote sensors are obvious tools for measuring wind speed profiles, UpWind is also contributing concepts and methods for LIDAR verification including a rigorous proposal for LIDAR uncertainty [5].

LIDAR turbulence measurements

At a prospective wind energy site, the turbulence intensity is often as important to ascertain as the actual wind resource. LIDAR testing has shown that, even when the mean wind speed is highly correlated to a reference cup anemometer measurement, the standard deviations of wind speed are much less well correlated between the LIDAR and reference. In UpWind, this has been examined both theoretically and experimentally.

Firstly, the turbulence measured by a 'staring' LIDAR (one constant line of sight as opposed to scanning) has been compared with that measured from an adjacent sonic anemometer [10]. Good agreement was found. For a conically scanning LIDAR, several mechanisms combine to attenuate the wind speed standard deviation observed by the LIDAR. A model including the spatial averaging both along the lines of sight and around the scanning circumference has been proposed and compared to experimental measurements [13]. Whilst generally good agreement is found, the LIDAR and cup anemometer standard deviations are still very scattered. An even more rigorous model including the contribution from all three components of turbulence has recently been proposed [9]. Here it is found that the ratio between LIDAR and cup anemometer turbulence intensity varies markedly both with height and atmospheric stability. Using current LIDAR designs, it is impossible to accurately measure the horizontal turbulence intensity unless a sonic anemometer, giving the ratio between the three turbulence components, is present.

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"UpWind showed the pathway for improved wind turbine reliability. It developed the data acquisition hardware and the analysis tools to predict and detect failures in large offshore turbines. With the support of comprehensive fault statistics and load counting/ estimation tools, wind turbines and wind farms will be smart enough to support a cost-optimised operation and maintenance management. This is particularly crucial for far offshore sites, where access is difficult and faults cause long downtimes."

Jochen Giebhardt, Work Package Leader, Fraunhofer Institute for Wind Energy and Energy System Technology (IWES)

4.6 Work Package 7: Condition monitoring

Challenges and main innovations

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

UpWind results contribute to the development of reliable and durable load measurement equipment on the basis of optical Fibre Bragg Grating (FBG) sensors for temperature, strain and acceleration. Sensors must be as reliable as the component which they are monitoring; FBG sensors show promising results in lab and field tests to fulfil a 20-year life cycle, especially when embedded in the matrix of FRP structure components.

The development of an operation & maintenance (O&M) management tool will allow the estimation of remaining life time of components by life-cycle load counting, and therefore enable predictive maintenance planning. A database of fault statistics was developed, and UpWind results will help to identify technological weak points in large turbines.

The outcomes of this work will reduce the electricity generations costs, in particular of large offshore wind turbines and wind farms, through:

- reduced downtimes of turbines by enabling an operation level with reduced power output in case of a developing fault;
- avoiding severe consequential damages on components;
- providing support of O&M activities: planning data for logistic (spare parts, heavy equipment, personnel) and optimised time scheduling for O&M activities.

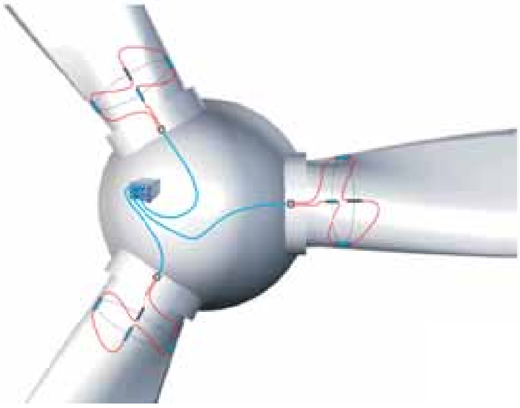

Figure 33: **Schematic of the fibre optic (FBG) strain sensors mounted on the rotor blade roots**

Results

Optimised condition monitoring systems for use in wind turbines of the next generation

With the increasing size and developing technology of the next wind turbine generation, new approaches for measurement equipment as well as for signal acquisition and evaluation will be required to perform condition monitoring and fault prediction tasks. This subtask investigates the required improvements and new developments of the condition monitoring systems (hardware and software) for wind turbines. UpWind established the following points:

- A review of principle philosophy of condition monitoring in wind turbines and an investigation of the faults and reliability of wind turbine components has been prepared and is available at http://www.upwind.eu in the WP7 publication section.
- A fibre optic strain and acceleration measurement system, based on the Fibre Bragg Grating (FBG) effect, has been installed in a 2.5 MW turbine (Figure 33). The functionality and the performance of the FBG sensors have been demonstrated successfully. Techniques were developed to detect the failure of sensors.
- In close co-operation with the UpWind activities on materials, laboratory tests have been carried out. Within these tests, the stress and fatigue behaviour of the GRP material itself and of the applied FBG sensors has been determined simultaneously. The results show promising approaches to integrate embedded FBG sensors in rotor blades.

"Flight leader" turbines for wind farms

The planning of O&M measures and the estimation of its cost requires extensive knowledge about the load applied to the individual turbine in a wind farm during its life time. To save investment costs, only selected turbines, the so called “flight leader turbines” (a term used in aircraft technology), at representative positions in the wind farm will be equipped with load measurement sensors. 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 investments for sensor and data acquisition equipment is possible. The performance of the “flight leader turbine” concept has been demonstrated by applying it to a simulated 5x5 offshore wind farm and by a field test installation in a model wind farm.

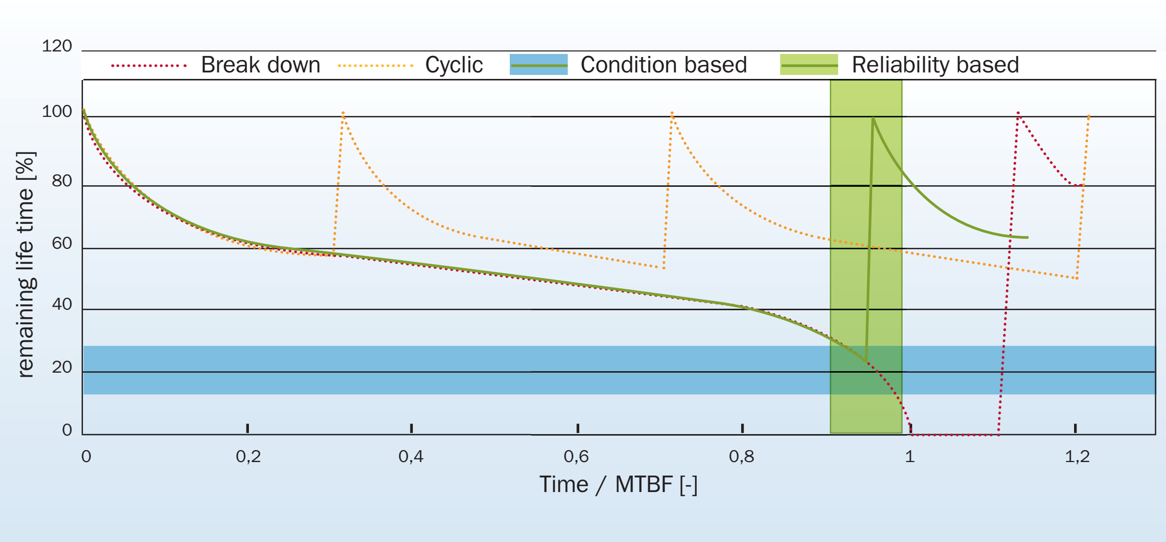

Figure 34: Maintenance and repair strategies with respect to condition/reliability based approach

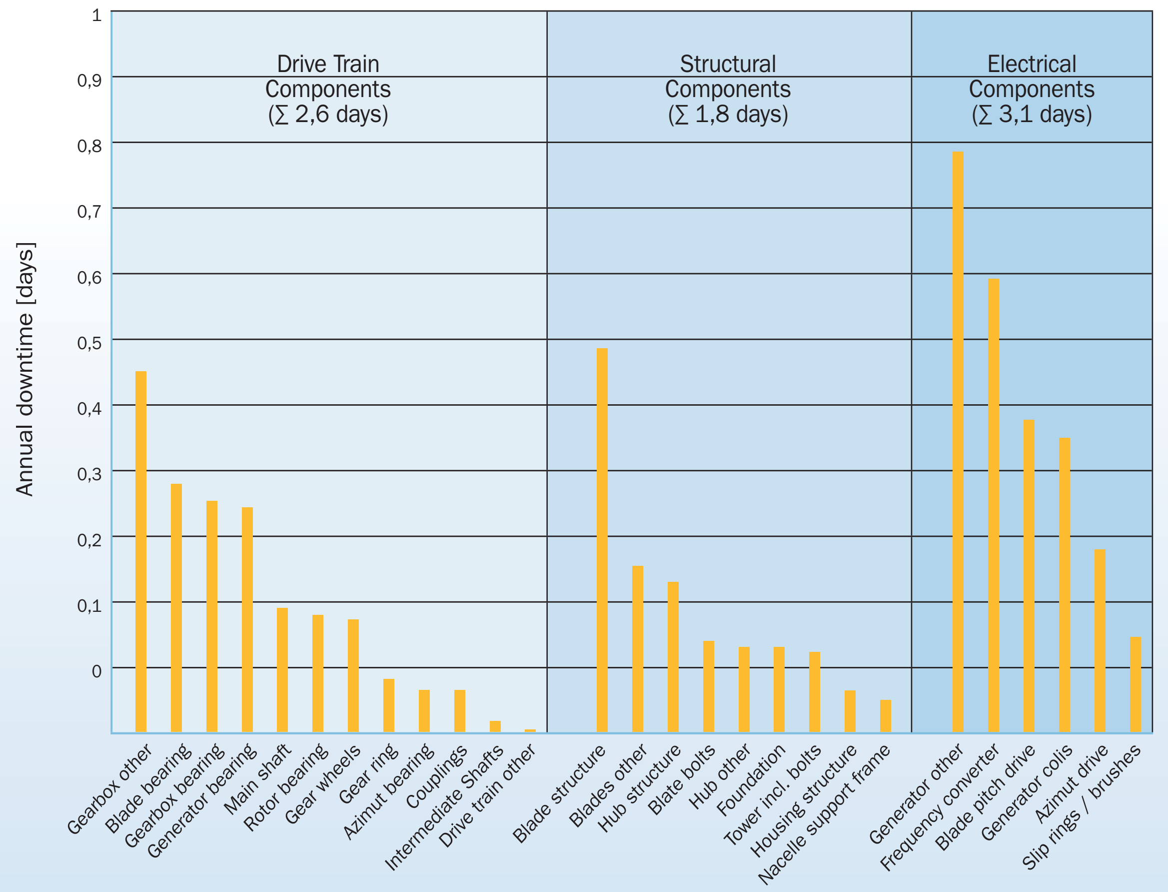

Figure 35: Components of variable speed wind turbines and their reliabilities

Fault statistics

Fault statistics are used as a starting point for investigations in new diagnostic methods, materials and wind turbine concepts. They are essential to identify weak points in the design of wind turbines and their components and to establish new O&M strategies. Most suitable will be a combination of condition-based and reliability-based O&M concepts (see Figure 34).

Based on the results, a component reliability ranking has been worked out, as shown in Figure 35. Within this sub-task, fault statistic data from several data bases have been evaluated. It showed large variable turbines do not only have the "classical" component fault problems, but could also show significant problems with electrical components. Fault statistics data bases are still not fully established. A high interest was noticed within the sector but confidentiality issues need to be addressed.

Detailed fault statistic data base analysis has delivered 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.

Standardisation

In recent years, several national, European and international standards have been established or are currently under development. Within this task, the implementation of the standards has been observed. Selected results of the work package have been communicated by personal attendance of WP members in the respective standardisation work groups and have been partly integrated.

Conclusions

The overall outcome of the research and technical development activities under WP7 "Condition monitoring" shall be an O&M cost optimisation concept for the next generation of offshore wind turbines with power outputs beyond 10 MW. The results have been fed into the integration work of other work packages in the project. Basic scientific and technical results have been made available in international publications and conferences as well as in the form of materials for the educational part of the project. Technical knowledge has been communicated to relevant international standardisation work groups.

The results of WP7 Condition monitoring will contribute to establish a cost-optimised, condition- and reliability-based operation and maintenance strategy for large offshore wind turbines. Selected results have been presented at several international conferences. Reports are available to the research community via the public UpWind project web site: http://www.upwind.eu in the WP7 publication section.

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"Large wind farms of 500 MW and more will be common in the near future, but in an array, wake-induced losses can be up to 20% of the total power output. UpWind provided the industry with more accurate wake models and advanced wake mitigation strategies to generate more electricity with the same number of turbines."

Rebecca Barthelmie, Work Package Leader, Risø DTU

4.7 Work Package 8: Flow

Challenges and main innovations

Wind farms or arrays containing large numbers of wind turbines are particularly challenging to model. The impact of multiple-turbine wakes (interactions between the flow downwind of turbine and the atmosphere) are of critical importance to the wind energy industry because they directly impact both the power output and the turbulence level that determines turbine lifetime. Because wake effects are influenced by both the environment (wind speed distribution, shear, veer, turbulence etc.) and wind farm characteristics (turbine type, spacing etc.), they are complex systems (Frandsen et al. 2009). Since power losses due to wakes can be between 5 and 20% of total power output there is considerable benefit to improving wake and wind farm modeling to assist in developing optimised wind farm layouts.

UpWind performed a comprehensive model evaluation of wakes in large offshore wind farms, and improved the performance of many of the models. Within UpWind, several wake-reducing approaches have been investigated that aim to optimise the performance of the entire wind farm. A way forward could be to sacrifice some performance of the upstream turbines to lower wake effects and increased performance of the downstream turbines which can (over-)compensate for the loss in performance of the upstream turbines. An intermediate approach lies in upscaling, since the rated power of a wind turbine increases with rotor diameter squared while wake losses decrease linearly with diameter. Also, non-conventional wind farms were investigated, e.g wind farms which consist of turbines with unequal size.

Results

An important task in UpWind has been to analyse data for model verification and to categorise turbine wake losses to identify the most important parameters based on SCADA data, which was recorded on three types of wind farms ranging from a small onshore wind farm (five turbines) located in flat terrain, a complex terrain wind farm (43 turbines) and three large offshore wind farms (80 turbines, 72 turbines and 36 turbines). The offshore climate analysis shows a clear correlation between atmospheric stability, ambient turbulence and power deficit (e.g. Hansen et al. 2010). For example, the maximum power deficit for three different wind turbines spacing shows a consistent relationship decreasing with increasing turbulence intensity.

UpWind performed a comprehensive model evaluation of wakes in large offshore wind farms using the data described above and the range of models (shown in **Table 2**). During the course of the project, the performance of many of the models was improved (e.g. (Rathmann et al. 2007, Schlez & Neubert 2009)). An example result is shown in **Figure 36** (Barthelmie et al. 2010). The main finding can be summarised as acknowledging that wake losses in the centre of large wind farms offshore are larger than modeled using standard wind farm model parameterizations but, once corrected, model results were improved in comparison with data from existing data sets.

Name	Company	Type
WAsP	Risø DTU	Engineering
WindFarmer	GH	CFD-Ainslie
“Canopy”	Risø DTU	Under development
Wakefarm	ECN	Parabolised CFD
CFDWake	CENER	CFD
CRES-flowNS	CRES	CFD
NTUA	NTUA	CFD

Table 2: **Wake and wind farm models evaluated in UpWind**

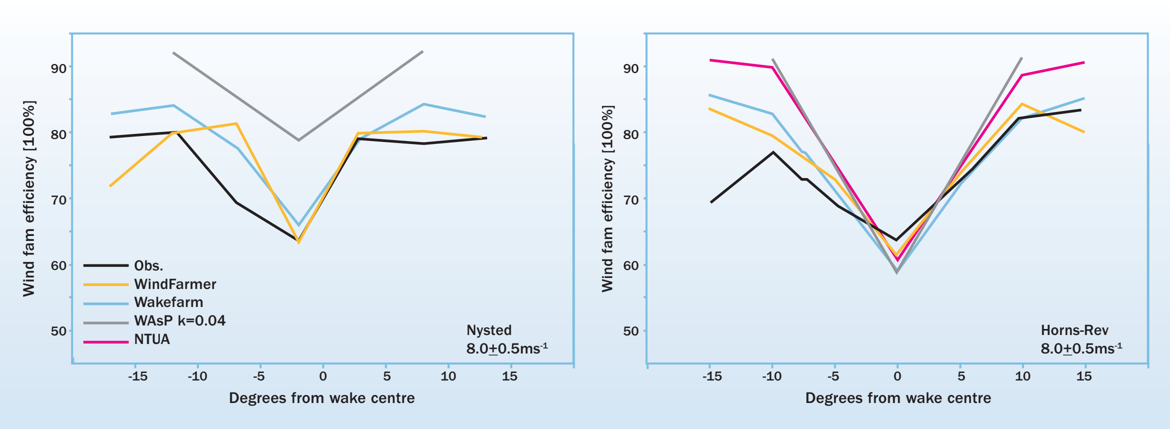

Figure 36: **Summary wake model evaluation for specific wind speed of 8.0±0.5 ms-1 and directions at Horns Rev and Nysted. The wake centre refers to 270° at Horns Rev and 278° at Nysted (according to Barthelmie et al. 2010).**

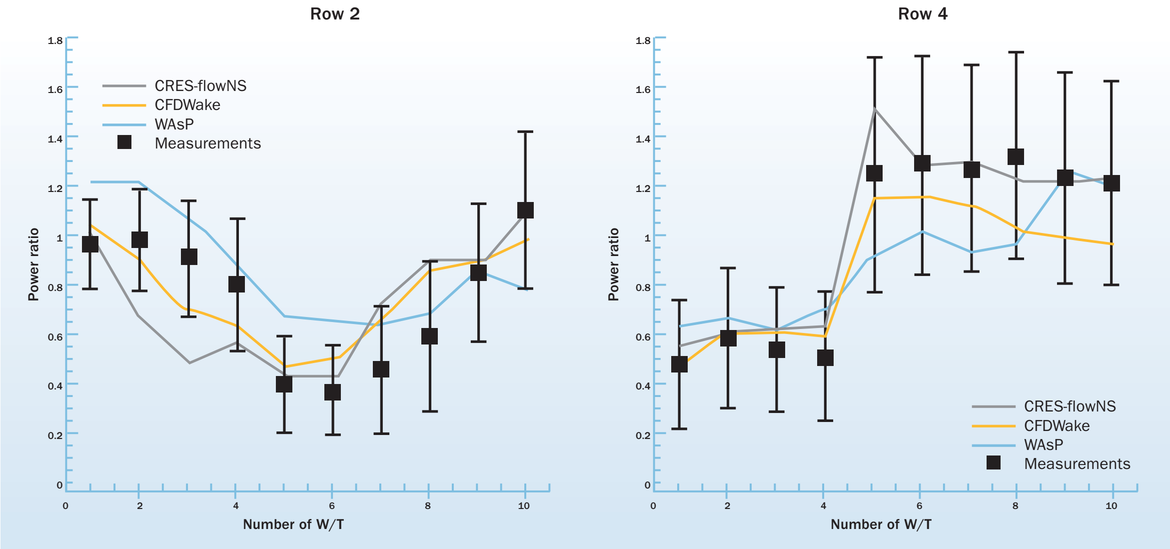

Figure 37: **Power ratios of the Wind Turbines in the second and fourth rows of a large wind farm in complex terrain for wind direction 327o. The reference is to the average power of the seven Wind Turbines of the first row, for the complex terrain wind farm. CRES–flowNS, CFDWake and WAsP predictions are compared with operational data.**

A comprehensive model evaluation of wakes in complex terrain was undertaken using three different cases:

(i) Gaussian-type topographies where CFD models and wind farm models were compared for the case of one hill-top wind turbines to identify differences in the wake development between flat and complex terrain;

(ii) CFD models comparisons for the case of five turbines in flat terrain to evaluate the modeling of wind turbines in wake simulations;

(iii) CFD model and wind farm model simulations of a large wind farm comprising 43 turbines in complex terrain. The obvious breakthrough in this kind of application stems from the fact that is the first time that CFD tools are employed for power predictions in large wind farms in complex terrain (Cabezón et al. 2010, Politis et al. 2010). CFD predictions have been considerably improved in flat terrain. In complex terrain (see Figure 2), there is still room for improvement, especially in the application of the actuator disk technique (Prospathopoulos et al. 2010).

Within UpWind, several wake-reducing approaches have been investigated that aim to optimise the performance of the entire wind farm. One idea is that it may be beneficial to reduce wake effects by sacrificing some performance of the upstream turbines, e.g. using a non-optimal pitch angle/rotor speed, or a yaw misalignment that leads to lower wake effects and increased performances of the downstream turbines which can (over-) compensate the loss in performance of the upstream turbines. An intermediate approach lies in upscaling, since the rated power of a wind turbine increases with rotor diameter squared while wake losses decrease linearly with diameter. Also non-conventional wind farms were investigated, e.g. wind farms which consist of turbines with unequal size. It was found that all of the above mentioned approaches have potential but that the conclusions are based on calculations with large uncertainties (Schepers et al. 2010).

Typical wind farm layout optimisations operate by using the energy yield as a target function. While leading to layouts with maximum energy yield, this can be less than optimal for the project economics, due to increased turbine loading and associated cost. To optimise a layout for overall cost including loading, three new key concepts have been implemented. This allows us to optimise the layout of a large wind farm with respect to an economic target function, reduce the turbine loads and vary turbine types to find the most economic layout.

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"Wind turbine upscaling has little influence on grid connection costs. Larger wind turbines will require higher voltages in the collection grid, but that is basically an adaption of known technology, which will be driven by costs. The transmission system for offshore wind farms, however, depends on farm size and distance to shore rather than wind turbine size. Cost is a main driver for higher voltages or switch from AC to DC. DC connection is more competitive after 100 km, and is clearly the most feasible technology for larger distances. UpWind investigated various grid connection technologies and analysed the reliability of wind power in the power system."

Ole Holmstrøm, Work package Leader, DONG Energy

4.8 Work Package 9: Electrical grid

Challenges and main innovations

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 could impact 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.

The challenge is to identify means by which satisfactory system reliability can be achieved without excessive investment in transmission or distribution system reinforcement by planning and improving the power output controllability of wind power. There are increasing requirements for wind energy operation to comply with the capabilities of traditional power plants. The main issues are the flexibility and controllability of wind power:

- Active power and frequency control
- Reactive power and voltage control
- Fault-ride-through capabilities
- Extended operative ranges.

The aim of this UpWind activity has been 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.


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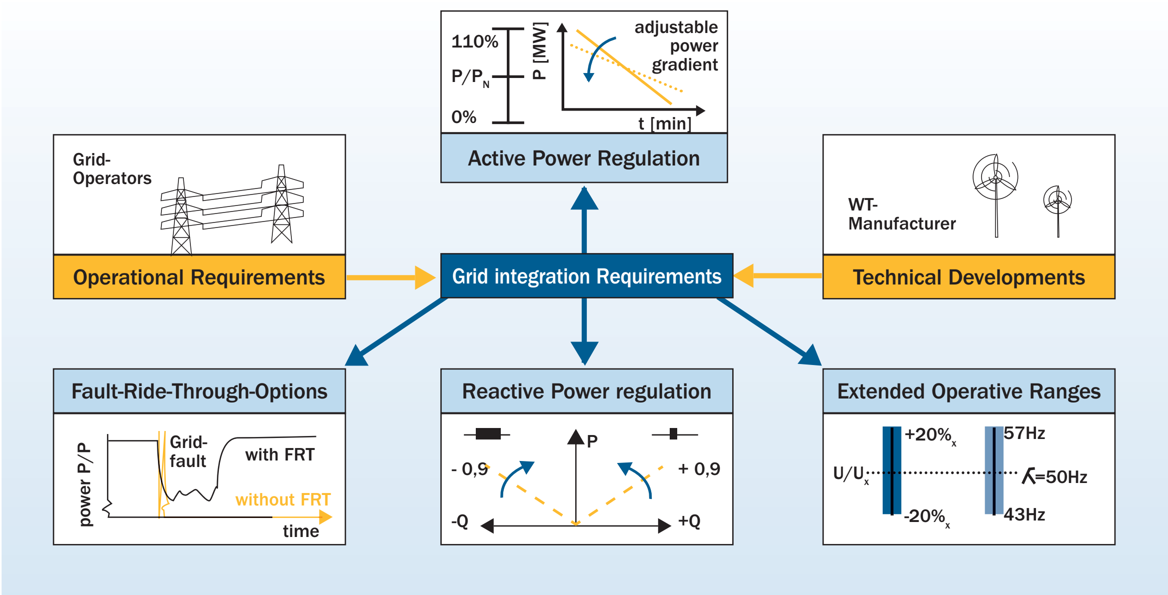

Figure 38: **Summary of grid integration requirements for wind turbines**

UpWind investigates operational as well as statistical aspects of wind farm reliability with a focus on offshore wind farms. 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 modeling.

UpWind considers future large wind turbines turbines of 5, 10 and 20 MW in very large offshore wind farms of hundreds of MW. Significant upscaling will have an impact on electrical design and may have significant influence on reliability and availability. Upscaling trends for cost modeling and technical and economical barriers in relation to electrical design of the wind turbine as well as the design of large offshore wind farms are investigated.

Results

The UpWind activities in this field are purely analytical and focus on the main subjects of reliability modeling and design criteria of future large wind turbines and on the subject of improved grid integration. To a large degree, the results are provided as results of modeling and simulation.

Wind farm reliability

Power producing units can be considered in two respects: the availability of the individual wind farm itself and the impact on the reliability on the overall electrical power system.

The initial problem to be solved is to provide adequate general models and accurate data for the reliability and risk assessments of wind turbines and wind farms. These models are essential to enable comparison of different electrical-design and grid-connection options.

A survey of existing large offshore wind farms was performed considering grid events, electrical construction and protection. The results and conclusion show that specific wind farm component data is difficult to obtain due to restricted access to data and due to lack of statistics from offshore installations. The reliability database considering electrical components in wind farms was derived from data for onshore installations.

This served as the basis for the subsequent reliability model of wind turbines and wind farms. These were developed in different software tools: a general commercial reliability software and ECN simulation programme EeFarm. The models focus on the effect the electrical design has on the reliability of large offshore wind farms considering the characteristics of the wind. The developed reliability models are used in the evaluation of upscaling.

Extreme wind conditions influence the reliability when the wind speed drops fast or increases above the cut-out wind speed. This is particularly important if several large wind farms are geographically close. Models are developed which can quantify the probability of these events in terms of probability and amount of lost generation and used to study the influence of control system modifications, aiming at less abrupt cut-out of large-scale wind power generation. The analysis is based on re-analysis data for wind speeds from Max Planck Institute and from measurements from Danish wind farms.

Power system requirements

The overall power system requirements are reflected in the grid codes. In this context it is important to predict what can be the future requirements of the transmission system operators in order to integrate an increased amount of wind power in the system. These requirements have to be compared to the capabilities of the wind turbine technology available today and in the future. A state-of-the-art review of grid codes and a corresponding survey on wind turbine performance has been carried out, pinpointing the relevant requirements and design criteria in relation to operative ranges, active and reactive power control, and fault-ride-through. The review of grid codes shows important differences is the requirements across Europe. This results in gross inefficiencies for manufacturers and developers. This issue is now being addressed by the European Wind Energy Association, which states that there is an increasing need to develop a harmonised set of grid code requirements due to the increasing penetration of wind power.

The survey of the existing wind turbine technology reveals that today's wind turbine technology is capable of fulfilling the current grid code requirements for wind generation. This enables manufacturers to offer wind power plant solutions tailored to the different operational and connection requirements of different grids. It has also been found, however, that system operators often are not able to take full advantage of the capabilities already available by wind turbine and wind farm technology due to the lack of operational aggregated control systems for wind power plants.

The analysis of small island grids give valuable information about systems with high wind penetration pinpointing technical limits and measures that can increase the wind capacity. The results can be used to evaluate larger systems. First of all, constraints imposed by the conventional generators and security of operation considerations result in significant and frequent wind power curtailments. In addition, small island grids with high penetration of wind power depend more on the reliability of the wind energy than corresponding large interconnected systems. For this reason, island systems are used for modeling and simulations in order to investigate specific requirements needed for wind turbines operating in such systems, along with power and frequency control capabilities, to fully exploit the high wind potential available.

Wind farm electrical design and control

The impact of various electrical and control concepts of wind farms on reliability are investigated. The electrical designs need to comply with relevant grid codes and maximise reliability, observing reasonable cost constraints. Different designs of electrical systems for wind farms are evaluated with respect to the new design criteria from grid codes and their ability to participate in power control, including automatic frequency and voltage control. This is done for island (non-interconnected) systems as well as for large interconnected power systems.

As for the non-interconnected power systems, the response of different electrical configurations of wind turbines during transient events in the grid is investigated. The fault-ride-through capability of wind turbines is crucial for the secure operation of non-interconnected power systems. Power system inertia, protection relays settings, voltage and frequency stability have to be carefully analysed before the penetration margin levels are expanded. Due to reduced power system inertia under high wind power penetration, the issue of frequency control provided by modern wind turbine technology is crucial. Additional control methods developed in wind turbines, like droop, inertia and combined control, provide the capability to support the system frequency during events that affect the power balance. Therefore, penetration levels beyond the limit of 30% (often applied to isolated power systems) can be further expanded provided that sophisticated frequency control services are implemented in modern wind turbine technology.

The impact on interconnected power systems of large wind farms with different turbine technologies has been investigated. The investigation focuses on fault-ride-through, power control and voltage support control capabilities of different wind farm concepts. The contribution to grid support has been assessed and discussed by means of case studies and simulations with the use of a generic transmission power system model. Simulations showed that both variable speed wind turbine concepts can help nearby connected stall or active stall wind turbines to ride-through grid faults and can enable them to partly comply with grid code requirements, without any need to implement additional ride-through control strategy in the active stall wind farm.

Among the variety of additional aspects concerning wind farms' ability to participate in advanced voltage control schemes, one study focus on optimised performance for a coordinated control of a STATCOM and an ULTC transformer used to achieve a better voltage profile in the whole grid in steady state and in contingency situations. Further, the project has also shown that by using the control abilities of the future wind turbines and wind farms together with power electronic compensators in a different and more intelligent manner, new features regarding, for instance, the ability to help suppress SSR and power system oscillations in the network grid can be achieved, which are possibilities not yet described in the grid codes.

The internal transmission system of the future larger offshore wind farms considering new technologies may impact system reliability. Studies are conducted in order to investigate HVDC connections and electrical concepts with respect to their impact on system security and compliance with the new design criteria and grid code requirements.

Upscaling

The upscaling of wind turbines and wind farms is investigated, focusing on trends for electrical design criteria, technical barriers and grid connection costs considering up to 20 MW wind turbines and large offshore wind farms 500-1,000 MW.

First step is evaluation of upscaling trends for wind farm grid connection was made using the developed reliability model and an up-to-date data base with component parameters and investment costs. The results give trends as to choice of voltage levels, AC or DC solutions depending on wind turbine sizes, wind farm sizes and distance to shore.

Design criteria for the electrical infrastructure of future wind farms are analysed for both AC and DC solutions. HVDC is further detailed and different types of technologies used for HVDC. The operation, control and protection system was detailed in collaboration with HVDC manufacturers. Key components and risks of such systems were identified. Subsequently the electrical infrastructure focusing solely on DC networks was investigated. AC/DC converters are key components in a DC grid and different topologies are evaluated presently. When it comes to offshore installations, the converter platform design has to be innovated as to the function of the converter components and for redundancy reasons. The need for standardisation of components is pointed to be a major factor for the deployment of future DC connections.

A study of wind turbines design aspects focuses on the physical size and design. As wind turbines rated power output increase, a main barrier short-term for optimised design of an AC collection grid is the connection voltage in wind turbines. The investigation focused on this concludes that the electrical equipment (transformers and switchgear) already exists, so that the main issue is to adapt it for offshore wind turbines and to make it reliable and more cost effective.

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EWEA is the voice of the wind industry, actively promoting the utilisation of wind power in Europe and worldwide. It now has over 650 members from almost 60 countries including manufacturers with a 90% share of the world wind power market, plus component suppliers, research institutes, national wind and renewables associations, developers, electricity providers, finance and insurance companies and consultants.

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