Danish Research Consortium for Wind Energy

Wind energy research strategy

This research strategy presents DFFV's general strategic recommendations and the most important research areas for wind energy as well as a prioritization of the research fields

DFFV
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Wind energy research strategy

by Danish Research Consortium for Wind Energy

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Introduction

The Danish Research Consortium for Wind Energy (DFFV) has as part of its continued effort to coordinate and develop the medium to long-term research effort in Denmark developed this research strategy, including a set of general recommendations and challenges for the strategic development of the publicly funded research in Denmark. Based on an assessment of the challenges for the wind energy sector, DFFV has formulated a set of recommendations for the sector and R&D funding programmes in Denmark and Europe which we expect can develop the Danish wind energy sector – industry and research – to continue to be one of the leading wind energy regions in the world.

The Danish Research Consortium for Wind Energy (DFFV) is a network of public research organizations in Denmark within wind energy, consisting of the Technical University of Denmark (DTU), Aalborg University (AAU), Aarhus University (AU), DHI, FORCE Technology and DELTA.

The purpose of the Consortium is through a coordination of research and development, innovation and education to strengthen research and technology development in combination with market development of wind energy in the energy system globally. The consortium supports the Danish and European policies concerning security of supply, global warming and growth and acts as the national node in the European Energy Research Alliance Joint Programme on wind energy.

Part 1 of the strategy encompasses the set of recommendations for the sector and R&D funding programmes in Denmark and Europe. Part 2 has specific research strategies for 9 key research fields with an analysis of the present state-of-the-art research, key challenges, research gaps and recommendations. In appendix A, the groups and people who contributed to the strategy are listed.

We hope this research strategy can form the basis for the politicians' formulation of tomorrow's research goals for wind energy and research programmes for wind energy research in Denmark, as well as the wind energy sectors' prioritization of the research programmes in Denmark and finally form the basis for a dialogue between the industry, research society, research agencies and politicians concerning future research needs.

PART 1

How can Denmark continue to be one of the leading wind energy regions in the world?

Background for a new Danish research strategy

Denmark has a long-term vision for an energy system independent of fossil fuels. In 2035 the Danish heat and power sector should entirely rely on renewable sources and by 2050 the total energy system should be decarbonized and wind power should supply 50 per cent of the Danish electricity consumption.

Wind energy is on course to become a leading electricity generating technology in Europe. In 2014, the wind energy sector reached 129 GW of installed capacity with 121 GW onshore and 8 GW offshore. In an average wind year, this would be enough to cover 10 per cent of EU's electricity consumption. In Denmark in 2013 wind generation accounted for 32 per cent of the national electricity demand and in 2014 the wind generation was 39 per cent of the demand. In 2014 the Danish wind industry had an export of DKK 53.5 billion and employed 28,676 people. This has been made possible only with significant R&D efforts from the industry, the research community and a decisive political support at national and European levels. This strategy will outline measures to reinforce and develop this.

Progress on industrializing wind energy has already been achieved in the past 25 years, but there is still a massive potential for improvements in terms of cost reductions, reliability and environmental and social impacts, through research and technology development and market development. The research community and industry are collaborating to achieve innovations to drive down costs which will accelerate the transition towards low-carbon economy and to sustain and develop the leadership of the Danish wind industry.

The wind energy sector has a long history of close public-private cooperation on R&D and during recent years the number of highly skilled engineers employed in the sector has grown substantially and companies are increasingly looking at the global market for highly specialized expertise. The share of employees with a higher education has risen. It should therefore be a continued ambition to educate engineers and other highly skilled people to make sure that the sector maintains a technology lead in the global competition.

Wind energy research and interaction with industry

The framework for research funding and interaction between public funded research institutions and industry has been discussed in the Consortium and with the Advisory Board. The members of the relevant Consortium groups and the Advisory Board are listed in Annex 1. The outcome of the discussions has led to the following conclusions:

- **The overall goal** for the wind energy sector is to make wind energy one of the most cost-efficient energy sources in Europe. Based on this a research strategy is formulated with the aim to facilitate the use of state-of-the-art research results in the industry and in society.

- **Division of work between industry and universities.** Universities focus on medium to long-term, generic research and more short-term research and development is carried out together with the industry. Industry focuses mainly on short term research and application of knowledge from the research community in innovation and development. By nature the research community will not just address research benefitting specific companies, but also topics relevant for the sector as such or society in general. These are research areas aiming at establishing the basis for an overall cost-efficiency improvement for the entire wind sector; e.g. wind resource mapping and wake modelling, generic modelling of the wind turbine performance and dynamics and also non-cost related elements such as environmental and social areas. Typically, such research areas do not provide a competitive advantage for the individual industrial players in the sector but acts as an enabler for proprietary technology development. Another task for the research community is to develop software design tools and new experimental methods to strengthen the industrial development.

- **Research community and industry learning loops.** Continuous feedback from industry and other end-users is crucial for the focus of – and priority-setting of the research. This is necessary for both development of new technologies, and for the refinement of existing technologies towards more cost-effective solutions.

- **Fewer funds to long term research and trend towards more industry led research.** Internationally there is a trend that research projects should always have an end-user in the project and it is often preferred that a private industry company leads the projects. The trend is seen both in industry support schemes and also in more basic research schemes. This development limits the opportunities to finance long term basic research – due to the more short term industry focus – and thereby the sector does not fully benefit from the potentials of the research and development of the technology to get more cost efficient wind energy in the long term.

- **Maturity of the wind energy technology opens up for a more aggressive knowledge driven industrial development.** The onshore wind turbine technology is now a competitive technology on high wind sites and the offshore technology is becoming increasingly competitive. With increasing maturity of the technology the competitive advantage of wind turbine industry depends strongly on how efficient the industry can perform the technology development through implementation of research results in the products. This leads to new and more ambitious requirements for the research community with respect to quality, relevance and impact. An ambitious R&D strategy for Denmark can create the foundation for positively benefitting from the increasingly competitive situation.

- **The international competition between countries and regions.** This competition is visible from differences in how countries and regions (wind energy hubs) offer positive research environments, publicly funded infrastructures e.g. wind turbine test stations and other test facilities, local market stimulation programmes requiring a share of local production and strong research and education environments at universities. In this context Denmark is seen as a wind energy hub. The Danish framework conditions are regarded as very competitive but under increasing pressure.

- **A research strategy for wind energy research is not a niche strategy but a strategy for a globally leading wind energy hub.** Denmark is not a global leader in many sectors and therefore Danish research strategies are often "niche strategies". In the area of wind energy, Denmark is world leading and an ambitious national research strategy should be developed reflecting this fact. It is important to ensure that there is a consistent set of instruments to support the competitive strength of the Danish wind energy sector developing a strong research environment from full scale to nanoscale and the relevant infrastructures targeted the whole industry from wind turbine manufactures to suppliers, developers, wind turbine owners and operators.

- **Cooperation between research and industry.** It is a trend in the market that wind turbine manufacturers focus on core technology areas and have an interest in moving non-core technology areas to sub-suppliers and component manufacturers. Efficiency of cooperation in industry both vertically and horizontally together with the universities is seen as one of the elements that can give competitive strength to countries and regions. The most recent industry initiative is "United Industry" proposing R, D&D clusters that could be one of the vehicles for short term research cooperation between industry clusters and the research community.

- **Need for support to develop next generation of wind turbines.** The next wind turbine generations are expected to be 10 to 15 MW and there is a need for support from the R&D programmes to cope with the many challenges the technology upscaling implies. The research community should be a driver behind the development of the scientific and engineering basis for the industrial technology upscaling. This challenge is not only a question about demonstration, but will require a long-term, concerted effort by the whole sector – universities and industry together. The Danish research community should do its utmost to develop the needed knowledge and new technologies and innovations to facilitate this development. In 2 the detailed research challenges and opportunities are described.

Recommendations for the strategic development of the public funded research and development programs

DFFV has formulated the following recommendations regarding publicly funded research and demonstration programmes in Denmark and EU:

- So far Denmark has been leading in research and technology development in all parts of the value chain, but this situation can only be maintained and further developed if we continue to focus on R&D to underpin the desired technology development. These efforts **should focus on areas where the potential for improved cost-effectiveness are most evident and where Denmark has a strong knowledge base** in the industry and in the research community. This strategy will point to several of these issues which have been identified by the partners in DFFV. Specialization both in research and industry should be considered in the prioritization.

- The overall goal for the Danish research programmes should be to **strengthen the global leading position of the Danish wind energy sector.** It is both the Danish wind energy research and the wind industry that are leading globally and the prioritization of public resources in Denmark allocated to research and development should be discussed and adopted continuously to keep the competitive strength under the assumption that Denmark has a leading role globally.

- Emphasis on short term technology implementation focusing on knowledge generation and making science applied in the industry can be

a threat to the long-term research based technology development, if the trends of requiring end-user lead in research projects are continued or even further strengthened. **Therefore, focus should also be on the long term. It is important to develop large-scale research initiatives which are not only defined and led by industry.**

- The Danish research community is well integrated in the European R&D community, the European Energy Research Alliance (EERA) and in the European Wind Energy Technology Platform (TP-Wind). In order to develop the Danish leadership role in these partnerships it is recommended that **DFFV and national funders such as the Danish Energy Agency and the Innovation Fund coordinate more closely** to develop and implement national projects that are aligned and coordinated with similar projects in other countries to facilitate the implementation of the politically agreed European Strategic Energy Technology Plan (SET Plan).

- **Education needs to be supported by research.** Therefore, it is important that there is a research activity in the relevant education areas targeted towards wind energy. This calls for a broad and not too narrow prioritizing of the funding in research programmes and at the universities.

PART 2

Specific key wind energy research strategy recommendations

The specific recommendations formulated by the Danish Research Consortium for Wind Energy are aligned within the following 9 research fields where working groups have analysed the present state-of-the-art research, key challenges and research gaps. Based on this a specific research strategy has been formulated in the following research fields:

1. Wind resources, external design conditions and wind energy forecast
2. Aerodynamics, aeroelastics and aeroacoustics
3. Structural design, machine elements and materials
4. Electrical design
5. Power system integration
6. Offshore wind energy
7. Experimental test & measurements
8. Environmental issues
9. Societal issues

In the roadmap on page 12-13 is a summary of the key priorities for each research field.

The roadmap contains general recommendations. Single project proposals with an excellent potential which are not mentioned in the roadmap should be considered positively. In the succeeding chapters of the strategy you will find the detailed description, analyses and recommendations for each field.

	2016	2017	2018	2019	2020
METEOROLOGY					
Coastal winds	■				
Wind at tall heights		■	■		
Wind farm wakes		■	■	■	
Far-field noise modelling				■	■
Uncertainty modelling	■	■	■	■	■
AERODYNAMICS, AEROACOUSTICS and AEROSERVOELASTICS					
Wind tunnel methods	■				
Transition modelling/validation		■	■		
Aerodynamic devices			■	■	
Wind tunnel measurements	■	■	■	■	
Full scale measurements	■	■	■	■	
Include electrical sub models	■				
Floating turbines		■	■		
Wind turbine/wind farm control			■	■	
Stability and optimization tools					■
STRUCTURAL DESIGN					
Multi scale design methods	■		■		■
Coupled load effects	■				
Manufacturing processes	■	■	■	■	
Composite material fatigue			■	■	■
New materials	■	■	■		
Testing methods		■		■	
Reliability and life time assessment			■	■	
Surface treatment					
ELECTRICAL DESIGN					
Converter design and control	■				
Generators		■	■		
Switching transients			■	■	
System design and test					■

	2016	2017	2018	2019	2020
POWER SYSTEM INTEGRATION					
Wind power plants	■				
System stability		■	■		
Grid connection and transmission			■	■	
Market integration					■
OFFSHORE WIND					
Modelling tools	■				
Design of structures		■	■		
External conditions			■	■	
Control of large wind farms					■
O&M strategies	■	■	■		
EXPERIMENTAL TEST					
Site conditions	■	■			
Turbine measurements	■	■	■		
Plant measurements			■	■	■
ENVIRONMENTAL ISSUES					
Data collection	■				
Underwater noise	■	■			
Birds and bats		■	■		
Reef effects					■
Uncertainty quantification modelling	■	■	■	■	■
Environmental siting modelling		■			
Decision support systems			■	■	
Noise models				■	■
SOCIETAL ISSUES					
Engagement and acceptance	■				
Market access		■	■		
Price regulation/support schemes			■	■	
Policy impact				■	■
Planning					

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Part 2

1. Wind resources, external design conditions and wind energy forecast

1.1 Scope

For all wind farm projects it is of high importance to estimate the precise level of the wind speed at each location of the wind turbines in the wind farm. The wind speed relates directly to the amount of energy which can be extracted from the wind. Furthermore, the absolute level, dynamics and extremes of the wind on scales relevant for the turbines determine the loads and fatigue on the turbines. These external conditions determine the design basis for a wind farm. The wind resource and loads are therefore important characteristics which directly affect the economy of a wind farm; i.e. the wind resource determines the AEP (Annual Energy Production) which is the income. The extremes and dynamics of the wind determine the design and thereby the cost of the manufacturing of the turbines, and atmospheric conditions including wakes determine the fatigue and thereby affects the expenses of the O&M (Operation and Maintenance) of a wind farm.

For planning, operation and integration of wind farms in the power system, especially with a high penetration of wind energy, the knowledge of the variability of the wind on short-term time scales (from seconds to a couple of days) up to seasonal scales is of equal importance to ensure a reliable power system.

Estimation of the atmospheric flow is therefore one of the main drivers for the topics within the area of wind farm planning. In addition, the atmospheric flow and terrain properties also determine the propagation of noise generated by the turbines, which again has an impact on the environmental assessment of a wind farm. Therefore, the following sub areas have been identified:

- **Measurements of wind and turbulence** are needed to validate and calibrate the different models for wind resources and loads. A key point for the improved understanding of the interaction of the atmospheric boundary layers and wind turbines/wind farms on various scales (single turbine wakes, multiple wake effects inside a wind farm, far wake of a wind farm) is an extension of corresponding measurement capabilities.

- **Modelling of inflow conditions and wind resources for turbines.** Activities for this objective include further development of high-resolution microscale models coupled to mesoscale models, with special emphasis on profiles of mean wind and turbulence to heights that are relevant for modern turbines. The models need to account for atmospheric stability, coherent structures, wind gusts and extremes, directional veer and wind speed shear, inhomogeneous and non-stationary conditions; and the models should cover siting in offshore, coastal, hilly and forested areas.

- **Modelling of wind farm wakes.** Activities for this area aim at characterizing the flow within the wind farm on timescales that can describe the turbulence as well as the farm-to-farm interaction. The objective is to better model the loads and winds created by the wind farm itself and thereby create better tools for siting, wind farm planning and control.

- **Modelling of noise propagation.** Activities in this area aim at developing new models for predicting the noise in the far field from wind turbines/wind farms. The new models will include knowledge of e.g. the atmospheric conditions, noise emission, amplitude modulation in time and the reflection, refraction, diffraction and absorption of noise due to both the atmospheric conditions and surface characteristics. Full scale measurements should be carried out to investigate and understand noise sources and propagation and validate simulation models.

- **Forecast modelling of wind.** Develop models for data assimilation of different sensing techniques (e.g. remote sensing) into the meteorological models for a better representation of ramp events in the forecast modelling. Focusing on the offshore case, and especially near-coastal areas where most large offshore wind farms are expected to be built, the importance of better understanding of local wind conditions is crucial, as our knowledge here is more limited than for the onshore case. Especially the dynamics of wind profiles, the interaction between the wind turbines/farms with the atmosphere (i.e. wake, turbulence and energy deficit), and wind-wave interactions.

- **Uncertainty modelling.** With collaboration between flow modelers and experimentalist, a scientifically based method for quantifying the uncertainty for resource assessment and other siting parameters for wind farms needs to be established. The uncertainty stems from different sources, ranging from the characterization of the input data to the uncertainty parameters of the models; which again are based on different physics in the models. There is a need to quantify these different sources of uncertainty.

1.2 Knowledge gaps

In the following, knowledge gaps in the different sub tasks have been identified.

Measurements of wind and turbulence

- Knowledge on wind statistics such as mean values, fluctuations and distributions above 100 meters is limited for all types of terrain including offshore, mainly due to the lack of datasets for evaluation and proper modelling techniques.
- How do we create cheaper and innovative measurements for validating models? As an example, offshore measurements are sparse and very expensive. Therefore, challenges are to develop innovative methods and instruments that can provide reliable, cost-effective measurements offshore.
- Advanced remote sensing techniques have become available, but still there are challenges in the interpretation of e.g. turbulence measurements.

Modelling of inflow conditions and wind resources for turbines

- How different scales in models interact, i.e. coupling of different types of models (global climate, mesoscale, microscale) .
- How can the ocean wind and wave conditions be characterized and modeled through coupled ocean/meteorological models on different time and space scales?
- Understanding and accurate characterization of atmospheric turbulence on large and small scales over all types of terrain and climates, including offshore.
- Interaction of the large turbines and large wind farms with the atmospheric flows on turbine and wind farm scales.
- Understanding the effect of variations due to the different atmospheric timescales as well as length scales, e.g. variations such as the diurnal cycle due to the properties of the atmospheric response to radiation.
- Understanding the effect on power production and loading of wind turbines caused by wind shear and changes of wind direction with height, including a realistic description of the statistics of wind shear and wind veer at taller heights.

Modelling of noise propagation

Coupling of the noise source with the atmospheric variations of wind shear and temperature due to the topographical heterogeneity to capture the physics causing the amplitude modulation of noise caused by the atmospheric flow.

Forecast modelling of wind

- How atmospheric and wind turbine data can be utilized in data assimilation to improve short term wind forecast and wind resource assessment.
- For lead times between 3-4 hours and 10-15 days, the largest contribution to the final prediction error comes from the lack of accuracy of meteorological predictions. Therefore, there is a need for interaction with the meteorological forecasting community in order to improve the forecast accuracy within the meteorological models.
- Crucial aspects relate to the assimilation of more surface observations, coming from various types of measurements such as radar images, LIDAR

profiles, and more classical measurements from meteorological stations. These observations may be assimilated more easily in mesoscale and limited-area models than in global ones. In all cases, they will require some form of filtering, as well as the improvement of data assimilation methods. For instance, the recent advances in using new covariance structures, extended Kalman filters, etc. may be beneficial in the short to medium term, though implying a substantial increase in computational costs. Regarding the filtering of these new types of measurements, it will certainly be well supported by a better understanding of local wind conditions. The physical and numerical schemes used in these models may also need enhancements, based on the better understanding of the dynamics of local wind conditions.

Uncertainty modelling

- Investigation of the differences in the different types of models; both mesoscale and microscale.

- Investigation of the inputs to flow models, such as the variation in characterization of land cover types and the corresponding influence on the modelled winds.

- Influences from climate variability on the wind resources on timescale from months to the lifetimes of the wind farms (approximately 30 years).

- Establish methods that can quantify the uncertainty of wind resource modelling, i.e. what is the uncertainty of measurements, power curve in different flows, flow modelling, wake modelling, availability, technical losses, etc.

- Knowledge of the extremes for the whole range of atmospheric conditions with the aim of better load characterization.

- Establish the prober transfer functions for comparison of the data with models, as the models often refer to a simplified version of the reality.

1.3 Research priorities

The following research priories are focused in the Danish employment of wind energy:

- Research on coastal winds for near-shore wind farms. The gradients in coastal winds are larger than further offshore. Turbulence, atmospheric stability and roughness changes due to fetch are significant. Thus, to enable improved quantification of the wind resource and wind variability in near-shore areas, it is recommended to strengthen research by using innovative new observations methods, including remote sensing, floating instrument concepts and satellite remote sensing. In addition, a flow model suite effectively combining wind farm wake scale, micro- and mesoscale is an important next step for assessing with sufficient accuracy the dominant length- and time scales involved.

- The cost of tall meteorological masts offshore is high. Therefore, alternative methodologies to assess in particular the wind resource and the temporal wind variability offshore are required. The research is focused on alternatives with promising new technologies observing for shorter periods of time, e.g. remote sensing from wind profiling lidars on floating platforms, long-range horizontal scanning from nearby installation spots, airborne observations, etc. This research emphasises three aspects of atmospheric modelling of statistics due to sampling for less than one year and disjunctive sampling through various periods. These aspects are:

    - correlations of seasonal wind statistics
    - disjunctive data series wind statistics
    - long-term inter-annual statistics

  Establishing knowledge and method to characterize the external conditions at higher heights 100-300 m (i.e. statistical distributions of wind veer, shear, turbulence, etc.) through measurement with e.g. remotes sensing.

- Large offshore wind farms and clusters of wind farms stimulate a concept of power plant operation. To ensure optimal strategies of power plant operation, the wind variability at very short time scales down to minutes is relevant information. Research on improving physical and statistical forecasting methods, using new technologies installed at or near the wind farms is a strategic new area for operation of the individual wind turbines as well as a wind farm clusters.

- Accurate noise modelling in the far field of a wind turbine, which includes the amplitude modulation in time, is necessary to get a realistic noise simulation which describes the annoyance which is experienced by neighbours to large turbines. This requires a coupling of time-varying atmospheric conditions, a noise model for the emission of noise from a turbine and an advanced noise propagation model.
- Establishing scientifically-based uncertainty modelling of both loads and wind resources.

1.4 Application of research results

In general, improved modelling and understanding of the wind conditions will lower the cost of energy based on the following improvements:

- The reduced uncertainty of the estimations of wind resources will lower the cost of capital due to more reliable estimates of the economy in a wind project.
- More precise estimations of the external design criteria (such as extreme winds, wind shear, veer and turbulence) enable turbine manufactures to construct turbines closer to the design limits and thereby reducing the cost of the turbines. Furthermore, more precise estimations of external conditions will result in a less conservative approach in site assessment and application of suitable turbines for a specific site.
- Better forecasting of the wind power production will enable a larger portion of the wind power production to be utilized in the grid at a lower cost.
- Reliable physical models for turbine loads and resources can be used within operation of large wind farms to optimize the O&M. As an example, model outputs can be compared to real-time SCADA data from wind farms to identify malfunctions of the turbines and also to accumulate the loads into fatigue parameters for an optimized maintenance of the turbines.
- Advanced noise models will enable a regulation of the turbines, so that noise levels can be reduced during special atmospheric conditions again enabling a better neighbour relation between wind farms and inhabitants near the wind farms.

1.5 Commercialization of research results

The methods developed can to a large degree be integrated into software packages (existing and new). The research performed so far in the wind conditions area has already been implemented with a high degree of success in applications used by the industry, planners and developers. Examples are the wind resource software tool WAsP which has been incorporated into windPro and WindFarmer and used for nearly all existing wind farms in the world. The turbulence models developed are incorporated as standards in the IEC-61400 (ed 3). The wind atlas methods developed are commonly used in World Bank projects, and the methods have become de-facto standards. The methods for statistical forecasting are commonly used in the forecasting of wind power and the Wind Power Prediction Tool (WPPT) is the backbone in Energinet's forecasting of wind power in Denmark.

The software tools developed so far are:

- WAsP (WAsP CFD): Wind resource assessment
- WAsP Engineering : Wind conditions (loads & extremes)
- windPRO: Wind farm planning
- DELTA: Acoustic model Nord2000
- ENFOR: Short-term forecasting

2. Aerodynamics, aeroacoustics and aero-servoelastics

2.1 Scope

Aerodynamics, aeroacoustics and aero-servoelastics are key competences for the wind energy industry. The research level within this area has developed during the last 30 years hand in hand with the development and maturing of the wind turbine industry towards a higher technology level. This makes it very important to keep and further develop know-how and tools within these fields in order to maintain and further develop a strong research, innovation and development environment that are able to constantly push the technology development and thereby maintain the existing manufacturers in Denmark and make it attractive for other international companies to open offices in Denmark.

Aerodynamics

Due to its computational speed the Blade Element Method (BEM) is foreseen to be used in aeroelastic simulations for many years and tuning and calibration of this method is going to continue in future research projects. The results from Computational Fluid Dynamics (CFD) and experiments have been used to calibrate the engineering models in the basically steady BEM code. Research and development of more sophisticated aerodynamic tools such as full 3-D CFD or panel methods have also been going on for many years. CFD (as the code EllipSys) is state of the art for airfoil, wind turbine rotors, wake and flow over terrain simulations. CFD is under continuous development to cope with advanced turbulence modelling, transition from laminar to turbulent flow and grid generation. This includes unique models for simulating the generation and emission of aero-acoustic noise. In some versions the effect of the rotors on the flow is modelled through volume forces determined from airfoil data and angles of attack estimated from the 3-D velocity field. These techniques called Actuator Disc (AD), or Actuator Line(AL), eliminates computing the boundary layers on the blades making the flow computations fast, enabling actual aeroelastic computations to take place. Coupling of AL and full CFD with aeroelastic codes is already operational.

Aeroacoustics

The research in wind turbine noise includes sound source characterization and control, sound propagation and interaction and the human perception of noise. Below these issues are briefly described.

Sound source characterization and control:

- Models of aerodynamic noise sources are developed and investigated to predict the aerodynamic noise emission from the blades. This implies noise emission from the blade leading edge and trailing edge, but also emission when blades are separating and stalling. The amplitude modulation of the source strength is another important topic where major progress has recently been obtained.

- Wind tunnel measurements are carried out to investigate and understand noise sources and to establish data bases to validate models simulating the noise sources.

- Full scale measurements are carried out to investigate and understand noise sources with correlation techniques such as microphone arrays.

- Aerodynamic noise reduction techniques are investigated like trailing edge serration, brushes, vibration-isolating mounts, fibreglass panels, etc. and control strategies to reduce the emitted noise (e.g. pitch- and yaw control).

Sound propagation and interaction:

- Models for predicting the noise in the far field from wind turbines are investigated and developed. This includes knowledge of e.g. the atmospheric conditions, the noise emission, amplitude modulation and the reflection, refraction, diffraction and absorption of noise.

- Full scale measurements are carried out to investigate and understand noise sources and propagation and validate simulation models.

- Based on the knowledge of the underlying mechanisms of noise sources and propagation it is investigated how silent wind turbines and wind farms can be designed.

Human perception of noise:
The annoyance due to low-frequency noise, amplitude-modulated noise, as well as impulsive noise needs to be further explored to ensure an up-to-date knowledge of these phenomena both for individual turbines and wind farms. In addition, the dose-response curves for wind turbine noise which show an extremely high sensitivity to wind turbine noise compared to other noise sources such as aircraft, trains or road traffic, need to be revisited since previous studies were made at a time (early 2000's) when wind turbines were much smaller, and not as widely disseminated as today.

Aero-servoelastics

The upscaling, optimization and thus increased flexibility of wind turbines has called for advanced aero-servoelastic tools that can handle a large amount of freedom and the nonlinear effects arising from large deflections and pitch or distributed control actions. Such models have been developed, refined and validated during recent years. The aero, servo and hydro-elastic tools can simulate in-time domain the deflections and loads of a given turbine exposed to a prescribed turbulent inflow, a prescribed sea state and a given controller e.g. a floating spar type wind turbine with various mooring systems. The prediction of design loads on wind turbines requires not only aero-servo-elastic simulations, but also stochastic modelling of the system dynamics to determine long-term extreme and fatigue design loads. An integrated dynamic simulation environment for analysis and control of wind turbines has been developed over the last years for the bridging of electrical, aeroelastic and control. Such simulation platform facilitates an integrated dynamic analysis and thus a thorough insight of the complex interplay between wind turbines and the electrical grid, accounting for relevant aeroelastic, electrical and control aspects.

2.2 Knowledge gaps

Important research gaps are related to:

- The prediction of flow characteristics for thick airfoils at increased Reynolds numbers and at high speed (compressibility effects) and furthermore including the integrated effect of aerodynamic flow devises. This covers prediction of transition for airfoils and full rotors and the impact of atmospheric turbulence characteristics and operational conditions on this process.

- The understanding of the aerodynamic noise generation mechanism and modelling of noise sources and propagation and its dependency on turbine operational- and atmospheric conditions, as well as the correlation with measurements in the near field and the far field.

- The prediction of aeroelastic stability and transient conditions for large flexible turbines, and the validation of the complex interaction between the flow and the highly coupled blade deformations do have gaps. This includes validation of a full CFD-structure coupling that is considered necessary to model this interaction in sufficient detail, as well as the integration of control actions.

- The integration of a large number of prediction tools into an integrated design tool that covers the real operational condition for wind turbines in wind farms, including multi-level control and turbine interactions. In a systems engineering context this feed-back determines the design conditions for the individual components.

- The interaction of the mechanical behaviour of a turbine and the electrical components and system is an area of minor focus, despite the fact that this interaction can be crucial for the design driving load cases. A concurrent design and optimization of this interaction can play an important role in the future needed reduction in cost of energy.

2.3 Research priorities

Aerodynamics

An important focus point is transition modelling and thick airfoils. Predicting correctly the transition location is known to have a significant influence, not only on the viscous drag, but also on the onset of separation. The increasing Reynolds number with size causes uncertainty on this. This also includes compressible effects and aerodynamic devices including models for Vortex Generators, slatted airfoils and resolved VG's. Additionally, the existing coupling between CFD and aeroelastic codes should be expanded. Furthermore the development of a dedicated rotor code based on a panel method coupled with 2-D viscous-inviscid airfoil code is believed to be a strong tool in future rotor design. Various devices for controlling the boundary layer on wind turbine blades exist and especially vortex generators are used on almost all modern blades. The purpose of the devices is to increase maximum lift or increase the maximum ratio between lift and drag. The latter is to increase the aerodynamic efficiency of the rotor and the former is used to enable producing a more slender blade that yields the same loads as a wider and thus also heavier blade without vortex generators. Other devices such as e.g. Gourney flaps, multiple airfoil blades, suction or blowing active jets into the boundary layer exist, the work on numerical modelling of aerodynamic devices needs to be continued in order to make the techniques mature enough for direct inclusion in the design/optimization process.

Specific priorities are:

- Development of measurement methods in the wind tunnel

- Transition models from laminar to turbulent flow will with the aim of implementing it into the flow solvers.

- Transition characteristics on a full scale rotor and the influence of atmospheric turbulence using the DAN-AERO data set + new experiments.

- Thick airfoil aerodynamics: Modelling, design and test.

- Further development and validation of panel codes.

- Investigate the performance of various boundary layer manipulators, as Vortex Generators, suction, small jets etc. for assessing their potential use on wind turbine blades.

- Research on aerodynamic devices including the BAY model for Vortex Generators, slatted airfoils and resolved VG's.

- Investigation of the use of winglets.

- Inclusion of compressible effects for high tip speed rotors.

- Impact of erosion, icing and roughness of blades.

- Impact of uncertainties of aerodynamics in wind turbine prediction codes (measurements and modelling).

- Aerodynamic engineering models and assumptions.

- Atmospheric (full scale) tests.

Aeroacoustics

Design of silent wind turbines and wind farms with high aerodynamic performance is of primary importance for the further development of wind energy. Designing wind turbines includes the understanding of the mechanisms for generation of noise obtained from measurements and also the modelling of noise sources and the propagation to be able to predict the noise emission. This includes strategies for aerodynamic blade design, airfoil design, the application of noise reduction devices and the development of control strategies to decrease noise without influencing the power production significantly.

Measurements of noise:
Measurements of noise both in full scale conditions and in wind tunnels are important in order to understand the underlying mechanisms for noise emission. The establishment of the National Wind Tunnel, which includes aeroacoustic measurements and which is a national research infrastructure within the wind energy research, is an important facility to increase the understanding of aerodynamic noise, develop measurement methods and develop the knowledge and competences also within simulation of noise. Full scale measurements will increase the understanding of the underlying mechanisms of noise sources and noise propagation.

Portable test facilities using multiple, wireless synchronized sensors will enable the analysis of cause-effect relationships between any and all elements of a wind turbine or multiple turbines in a wind farm. The sensors can acquire signals from transducers such a microphone, force and strain gauges, accelerometers, wind sensors, meteorological data, and electrical signals, and time stamp the acquired data with up to 50 ns precision. This is particularly relevant for analysing the relationship between noise sources and propagation to arbitrary measurement points including offshore noise propagation. With large numbers of sensors, directional beam forming arrays can be created, and fine meshed measurements of noise can give a better picture of its spatial variation in the far field.

Aero-servoelastics

Specific priorities are:

- Bridge the gap between aero-servo-hydro-elastics and the electrical components and system
- Model floating wind turbine foundations numerically (Wamit in aeroelastic tools; nonlinear wave forcing)
- Full coupling of CFD and the AC Line/Disk with aeroelastic codes.
- Improve and integrate various structural dynamic tools, including super-elements and methods for predicting structural damping in existing aeroelastic tools.
- Advanced controller design development for system level integrated wind turbine optimization. This will integrate and design different types of state space controls schemes such as model based control, disturbance accommodation and feed forward compensation for optimal turbine performance and load mitigation.
- Development of models specifically for control design in contrast to models for simulations. This must include data driven modelling/ system identification, state estimation, linearization and model reduction of linearized models based on aeroelastics.
- Further development of aero-servoelastic stability tools, validation and understanding and mapping of turbine stability and

control characteristics including distributed blade control.

- Fast Frequency domain based extreme and fatigue loads estimation for integration within a structural optimization framework for wind turbine conceptual design.
- Studies on load reducing control during disturbances from the electrical grid side
- Wind farm control is further developed with regard to: modelling and estimation of the wind field and fatigue, optimal model based design, development of simulation tools.
- Design and topology optimization at wind turbine system level, wind farm level and wind turbine components interaction level.
- Further development and application of airfoils and rotor optimization with couplings between aerodynamic, aeroelastic and structural models optionally including models for cost and material

2.4 Application of research results

- Aerodynamics: The research leads to the development of new airfoils and blade design including passive and active flow devises for application in the industry. This is obtained both directly from research and by implementation of new methods in the design tools that are implemented in the industry. Larger rotors with distributed control, operating at higher tip-speeds will be the intended outcome.
- Aeroacoustics: Research in design of silent wind turbines is directly applicable to the manufacture of wind turbines and wind turbine blades. New and silent airfoil designs, guidelines to the aerodynamic design of blades and application of noise reduction devises will be a direct input to future wind turbines. The present noise reduction control strategies will be significantly improved, because the state-of-the-art goes hand in hand with a significant loss of AEP.
- Research in measurement methods and data processing will create a more detailed picture of the noise emission from wind turbines and increase the understanding of the underlying mechanisms. This understanding can be used for controlling the turbine to operate even more silently.
- Aero-servoelastics: The research results are continuously implemented in the aeroelastic design and stability tools that are already used in the industry. A common framework for integration with other tools is being under development. This will further facilitate the application for direct optimization which makes it possible to handle an increased number of dependent variables in the design phase. This makes it realistic to incorporate the advanced characteristics like coupling between deformations and actively distributed blade control and wind farm control into the design. This represents a new era in wind turbine design for wind power plants.

2.5 Commercialization of the research results

Results from the research in design of silent wind turbines and measurement methods can be used for design of future and silent wind turbines. The research will give input to the design of wind turbines in terms of airfoil design, blade design, drive train design and control strategies. In the following process of validating the wind turbines, the research will give input to accurate measurement methods, how to erect wind turbines also in wind farms and how the noise is perceived by people.

3. Structural design, machine elements and materials

3.1 Scope

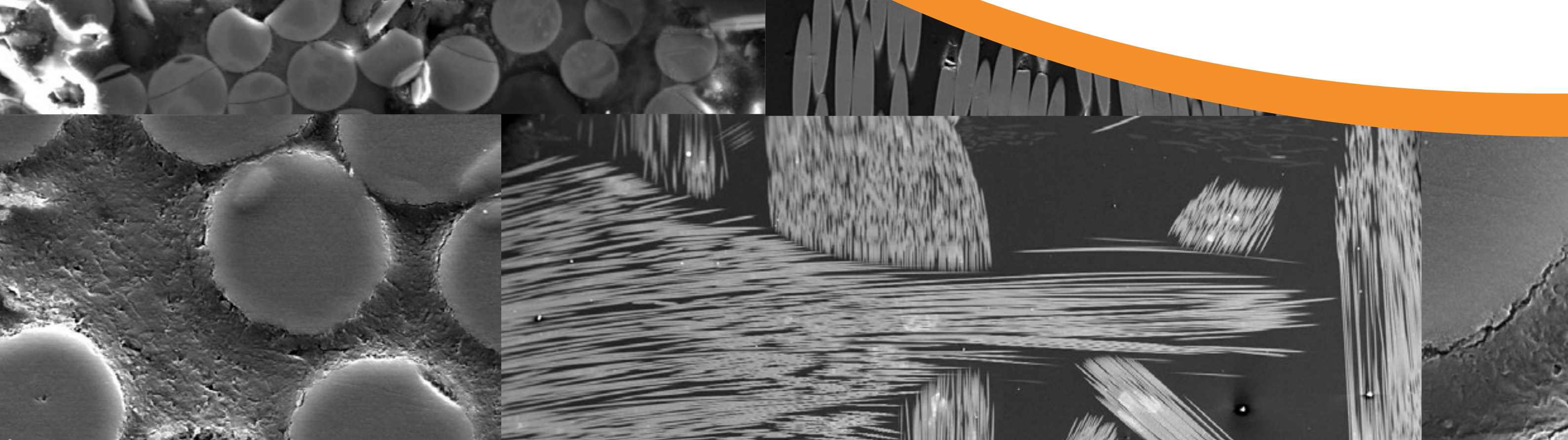
In a broad sense, structural design, machine elements and materials encompass classical mechanics, in particular continuum (solid), damage, fracture and probabilistic mechanics of materials, machine elements, structures and turbine systems as well as manufacturing processes in tight integration in particular with aerodynamics, aeroservo-elasticity and other research fields. From a systems engineering point of view this includes all physical systems such as foundation, tower, nacelle, blades, hub, bearings, shaft, frame, gearbox, generator, yaw, pitch and brake systems, etc.

3.2 Knowledge gaps

The length scale challenge or size effect is of essential importance in turbines due to the sheer size of present and future wind turbines. The properties at the structural scale are determined by small length scale features and mechanisms and taking size effects into account is essential for safe prediction of strength of large structures. Even though it may be possible to carry out full-scale qualification or failure tests, they only represent a one-off test and they do not give any information about the underlying variation of the load carrying capacity for the given system produced with the given tolerances and quality. Knowledge and description of variations, underlying the safety factors, are obtainable only by proper multiscale understanding of the complete product value-chain from material tests, design methods, manufacturing processes, linking failure modes across scales (size effects) with manufacturing tolerances and quality.

In combination with the length scale challenge, the turbine and its subsystems must endure ultra-high ($>10^7$ (=10.000.000) cycles) and non-proportional (very high load irregularity) cycle loading causing fatigue damage under multi-axial stress states. Phenomenological fatigue strength prediction models for metallic and composite materials in the low to high-cycle domain is greatly matured, however the failure mechanisms are poorly understood. For composite materials no fatigue life prediction methods exists and in consequence of this, the state-of-the-art method is inspired by uniaxial loaded fatigue life prediction methods used for homogenous and isotropic materials. In general non-proportional and alternating multi-axial stress states (including effects of load sequence, R-values etc.) are not understood. For example state-of-the-art design of laminated composite blades is based on the first principles of composite mechanics such as linear-elastic classical lamination theory and first-order shear deformation theory, which do not account for the nonlinear behaviour of progressive interlaminar and intralaminar failures.

In order to be able to develop innovative and novel designs for wind turbine applications taking into account these challenges, there is a need to develop methods for multi-scale design and advanced materials characterizations. State-of-the-art design techniques are based on homogenization approaches whereas multi-



scale (spatial and time) methods are needed to gain a holistic and top-down understanding of physical phenomena at turbine system and subsystem level by combining the underlying physical mechanisms, variations and multi-physics coupling. Exploring further advances in turbine design such as load reduction while increasing turbine output either in the form of advanced passive or active aerodynamic intervention calls for further development in load prediction at the turbine system level. E.g. the passive aero-elastically tailored blade can be achieved by innovative design features on different length scales. The tailored blade will lead to load coupling effects on the turbine level introducing a more dominant multi-axial and non-proportional loading state on the blade level as well as others subsystems, which in turn will lead to more complicated fatigue damage processes in the metallic and composite materials. The coupled effects of grid, aero- and/or aeroservo-elasticity in combination with the non-linear behaviour of large blade response are also examples of important effects that need attention for improved dynamic design load estimation.

These shortcomings in state-of-the-art methods result in uncertainty levels that lead to turbine systems of unnecessary high weight, cost and non-optimal material, structure and system designs. Understanding these shortcomings can ultimately render future turbines to a lower levelized cost of energy (LCOE) by lower cost and higher energy yield, while having higher reliability, which in an optimal design are two counteracting objectives. Characterization of uncertainties at all length scales is needed to improve reliability of wind turbines in the future. The fundamental question is how to overcome the length scale challenge in design of reliable wind turbines.

3.3 Research priorities

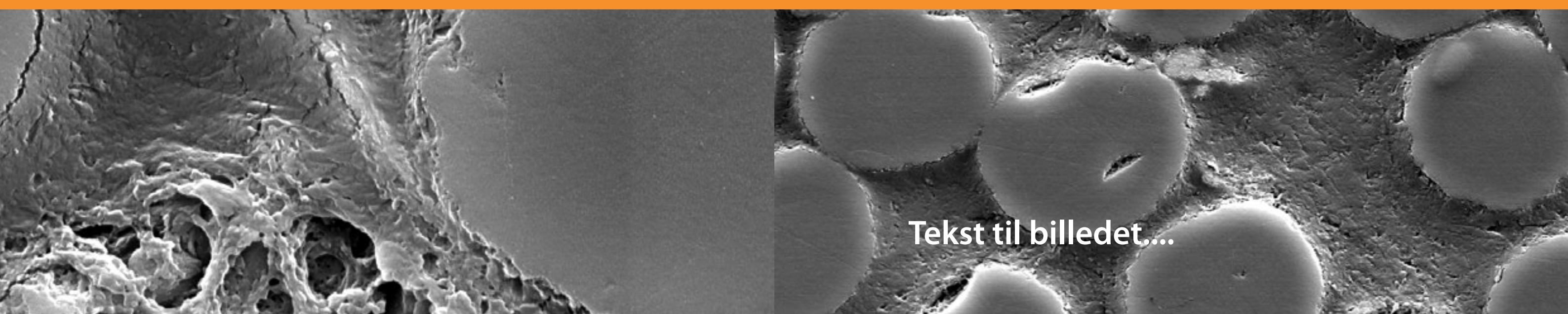
The research priorities are considered in a downstream fashion of the product-life cycle of the wind turbine. It starts at the top-down level of turbine design and ends at the operation and maintenance.

Multi-scale design methods

Developing multi-scale design methods is required to address the fundamental questions. It should be a priority to develop advanced fatigue models based on the real physical fatigue mechanisms linked to large-scale structural design methods and optimization techniques with fatigue constraints for structures undergoing non-proportional and alternating multi-axial loading such that innovative and cost effective structures can be sought after in a rational manner. This includes optimization of materials and manufacturing processes.

Advanced turbine load estimation models for coupled effects

Load calculation is often performed either as a preliminary load estimation for a new designs or in an iteration cycle with component development. At best, load simulation models capable of performing large time series turbine operation events in reasonable computational time, are based on low fidelity multibody models with linear assumptions for the deformation of flexible components. With increasing blade length, geometric nonlinearity, and blade material nonlinearity further development of time domain multibody simulation techniques are needed for improved dynamic load calculation and better understanding of structural response, drivetrain modelling and optimization of materials. There are several areas of interest, including, but not limited to, improved non-linear modelling of large blade subsystems for time domain simulation, dynamic stress recovery in multibody models, improved drivetrain modelling, aero-elasticity and control algorithm development. Furthermore, taking advantage of recent developments in multi-physics simulation, electrical performance of the machines along with advanced grid modelling will yield invaluable insight to coupled effects which previously have been left to partial coefficients in safety margin computation or neglected in the design basis.



Manufacturing processes

Traditionally, strong focus has been on the design of perfect and ideal structures with advanced numerical models. The application of similar numerical tools within the production of wind turbine parts has not been matured in the same degree, even though to a large extent the generic base for such tools has already been developed. Consequently, a focal point is the further development and application of advanced numerical simulation methods for the various manufacturing processes involved in the production of the different parts of wind turbines. Some of the most important are drivetrain components (forging, machining, etc.), hub, frame, housings, etc. (metal casting), blades (vacuum assisted resin transfer moulding, prepreg, etc.) and towers (welding). In particular, research in welding materials, design, geometries, tolerances and corrosion influence for different welding joint types is needed in combination with automated manufacturing and inspection methods for e.g. hybrid laser welding. Also research in manufacturing of metallic and composite materials and understanding of why and how imperfections develop as well as quantifying the level of residual stresses in the structure after manufacturing is of essential importance. In the long-term perspective simulation of manufacturing processes should be coupled to the iterative design process of wind turbine systems when evaluating multi-scale design sensitivities and statistical load capacities based on manufacturing tolerances and quality.

State-of-the-art blade production has elements based on manual fabric layup with a high labour cost, high variability in quality and material placement resulting in a low reproducibility, high degree of imperfections and repair work as well as a large amount of material waste. Research in flexible manufacturing systems with automation adapted to the wind industry for extremely high material mass placement per hour on complex doubled curved (concave and convex) surfaces with high reproducibility, e.g. with inline control, better material properties and strengths is recommended to improve high performing blade structures with increased energy yield at same weight and lower cost. Automation and parallel manufacturing processes, e.g. with pre-fabricated elements, is a mean to achieve this goal. This should not lead to a one-sided design-for-performance as the design strategy should be balanced with design-for-manufacturing to make technology leaps towards lower cycle times, especially for small production series of large offshore wind turbine blades. Besides new material placement technologies and design methods, the way to achieve high quality standards for the new manufacturing technologies is to do research and development in new materials and architectures for the processes, e.g. securing and preserving the material placement, homogenous matrix infusion as well as heat transfer through the thickness of the material, the curing degree and residual stresses which all govern the mechanical properties of the final blade.

Fatigue behaviour of blades and components in composite materials

There is a need for a deeper understanding of fatigue mechanisms at different length scales, enabling the development of more physical based fatigue laws for metallic and composite materials, e.g. account for microstructural features such as defects, impurities, local heterogeneities, local fibre distribution, ply-drops, interfaces at plies, laminates, sandwich structures and adhesive joints. For metals fatigue damage should be correlated with the local microstructure. For composites fatigue damage laws should be developed which are suitable for ply-to-laminate predictions of arbitrary layups undergoing non-proportional and multi-axial loading such that they can be readily implemented in the design and optimization of large scale structures.

New materials

The current development trend of increasing size of wind turbine rotor blades can lead to the need for use of carbon reinforced polymers with high specific stiffness and strength. While it is not feasible to manufacture blades solely out of carbon fibre, hybrid composites are of much more interest. Hybrid composites of carbon and glass fibres can be mixed on various levels (fibre level, bundle level, lamina level) and it is yet unclear which type of hybrid is performing the best. Research is thus needed in manufacturing and processing, microstructure characterization (microstructure and microscale damage evolution) modelling (micromechanical modelling) and mechanical characterization (compression, fatigue, and delamination) in order to determine the best way of creating such hybrid composites.

Metal parts in wind turbines also require a significant research effort in the development of new and advanced metals in order to increase the strength and durability without significant increase in cost. Important areas of research include failure analysis and development of techniques for detection of defect formation and propagation as well as development of optimal surface treatments.

Characterization and testing methods

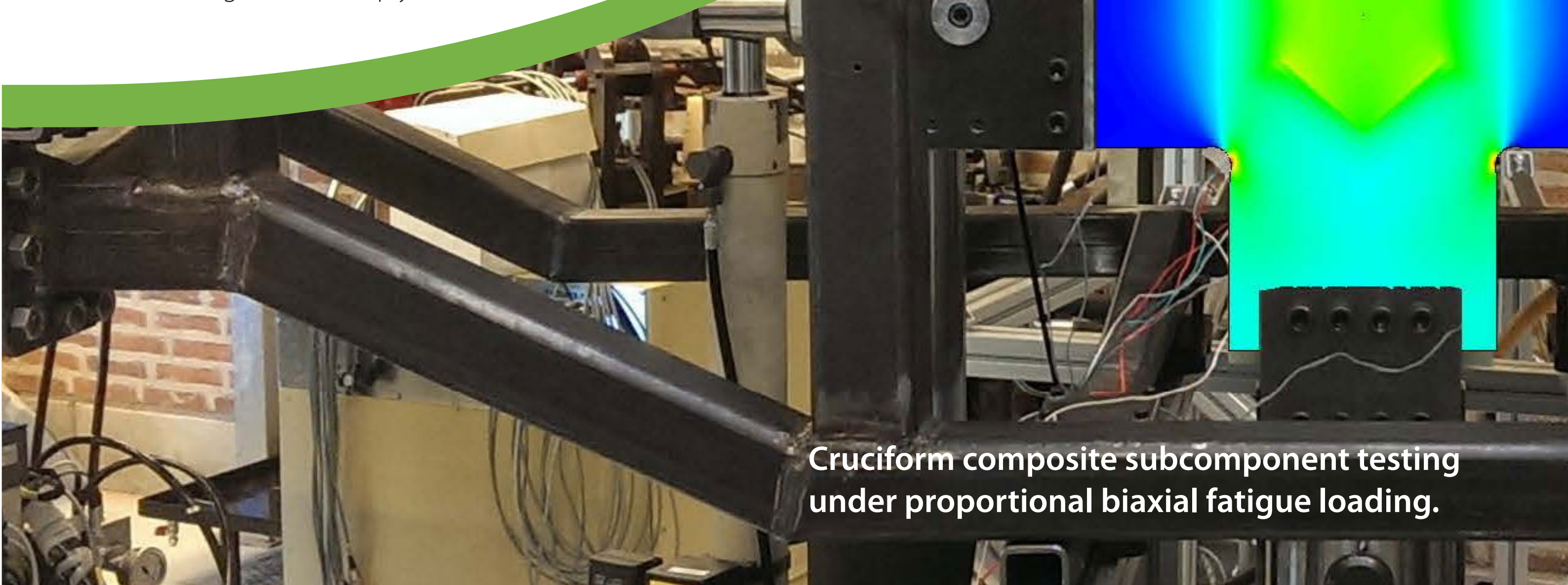
Performing composite static or fatigue testing is not straightforward if one is taking a physical approach of classifying the failure mechanisms. A simple but vital concern is getting the test specimens to fail inside the gauge area and away from parasitic effects. If it fails prematurely outside the gauge area, the resulting strength is not the true strength sought after. Therefore, there is a need for the development of better testing and characterization methods allowing for multiple strength recordings per test specimen and statistical data mining. This can be accomplished through a detailed stress analysis of test specimens eventually leading to new, optimized specimen geometry. In-situ testing while observing the microstructural development (including crack formation and evolution) is considered essential. Compression testing both in static and fatigue is a challenge in particular for composite materials since many competing failure modes exists. Therefore, it is of great importance to develop better laws for the description of compression strengths.

Test methods for blades traditionally focus on small and full-scale testing. However, sub-component testing needs to be explored to demonstrate new concepts to improve strengths of design details in blades, e.g. fatigue resistant ply-drops, thickness, material and geometric transitions and terminations, etc. Down-scaled prototype blades are envisioned to be used for demonstrating new concepts, e.g. new aerodynamical feature (blades with moveable parts, slots and slats), twist-bending coupling, use of embedded sensors for damage detection, blade repair technologies, new materials (e.g. bio-based composites and hybrid composites), blades made is parts, joined by adhesive bonds, etc. Scaling effects need to be better understood in order to develop the full potential for using sub-component and down-scaled testing.

Reliability and life time assessment

With the larger turbines, it becomes increasingly important that the structures are damage tolerant, i.e. that the first mode of damage does not lead to system failure or collapse. This concerns all length scales, materials (metals and composites) and interfaces between materials (e.g. resistance to delamination) as well as structural design aimed at creating stable as opposed to unstable damage or crack growth.

Tools for prediction of residual life of metallic and composite structures with damages and cracks are important in



Cruciform composite subcomponent testing under proportional biaxial fatigue loading.

order to increase reliability of components and large wind turbine blades. These tools involve materials characterization (damage evolution, crack growth), materials models (fatigue, cohesive laws) and structural models (covering the range from molecular dynamics to the finite element method).

In order to do reliable operation conditioning, e.g. monitoring and assessing structural damages in wind turbine blades, it is a necessity to develop reliable and robust structural health monitoring systems with embedded sensors. Current research within the field of vibration-based structural health monitoring is mainly focused on developing more sophisticated and robust methods that e.g. include advanced signal processing and statistical analysis of chosen damage features. Especially statistical approaches based on pattern recognition and machine learning techniques are studied extensively at present, and the preliminary results suggest that these methods can be further developed to become applicable for detecting, localizing, and assessing structural damages.

The size effect has an important influence on the manufacturing flaws and defects, which in turn have a great influence on the structural damage tolerance. There is thus a great need for scientific based criteria for sorting out which defects are critical and which are not critical. This requires substantial knowledge on how damage initiate from processing flaws as well as reliable tools for the prediction of stable and unstable damage growth. This constitutes a huge challenge for composite materials as the interaction of many failure modes and countless of failure sequences exist combined with many types of defects e.g. in the form of porosity in adhesive bonds, fibre rich domains, un-wetted/dry fibres, fibre wrinkles and waviness, thermal-induced transverse cracks, debonds and delaminations etc. This is also a challenge in corrosion and cracking mechanisms in different zones of offshore foundations, which also require development of corrosion control options such as coating, cathodic protection, corrosion allowance and materials selection. In addition to this, research in leading edge erosion, in particular in offshore applications, is needed in order to establish better understanding, solutions and possible innovation in new materials and repair methods for damaged blades.

In repairs and/or life extension several issues are of importance. First, structural health monitoring and assessment is essential, so the use of sensors for the detection of damage and corrosion control should be developed, e.g. monitoring of structural behaviour of wind turbine blades in order to better capture structural phenomena important for design and failure of wind turbine blades. Next, robust and creditable damage or facture mechanical models

Double cantilever beam test specimen for interlaminar cohesive law characterization of composite laminates under mode I loading.

should be used to assess the damage and corrosion criticality. Repairs should be done according to procedures that are scientifically sound, i.e. well documented and controlled by mechanical tests or assessed by creditable damage or facture mechanical models. Methods for life extension should be developed for non-destructive evaluation of the damage state of a component, i.e. by identifying the presence of damages and assessing their lifetime.

3.4 Application of research results

In general multi-scale design methodologies will bring new rational and innovative designs to the wind industry with higher durability and energy yield at lower cost and thus decreasing the LCOE. A detailed understanding of the fatigue damage evolution will enable the development of more fatigue resistant structures and materials. E.g. in blade design this will lead to longer blades for the same weight. The extreme lightweight blades will truly be optimized for non-proportional loading of time history loads and complex deformation states with passive aero-elastic tailored response.

Improved damage tolerance and rational repair and material state monitoring in wind turbines will ultimately reduce costs of components and extended lifetime, e.g. in integrity management, production control of foundations and sub-sea in-service inspection of large off-shore wind turbines.

The research effort will ensure extensive dissemination of scientific results and high-quality education of researchers and engineers as well as knowledge sharing and input to international standards and regulations. For example taking improved realistic scenarios into account in the design phase could also open up for a dialog with the accreditation authorities about removing unnecessary conservative safety margins as well as probabilistic design for safety factor calibration.

3.5 Commercialization of research results

The potential in innovative blade designs based on this research strategy and including aspects of aerodynamics and aeroservo-elasticity can have a major contribution to LCOE reduction. Developing novel and advanced multi-scale structural analysis and optimization techniques can significantly reduce the cost as well as extend the life span of new innovative wind turbine components and structures.

Research in modular based concepts for welding and corrosion control of offshore wind farm (gravitational, bucket, monopole and tripod) foundations will gain access to the emerging offshore market for large wind turbines in respect of integrity management, production control of foundations and sub-sea in-service inspections. Long-term integrity assurance based on on-site monitoring systems and tailored sensors and instrumentation to suit individual project requirements will prevent failures and make better decisions for maintenance planning, generate cost savings and ultimately feedback to improved know-how-based designs.

4. Electrical Design

4.1 Scope

Overview

The design of electrical parts in wind turbines and wind power plants are driven by high efficiency, high reliability, high functionality and a constant pressure to reduce system costs including weight. The power electronics technology has now fully entered into the wind turbines by controlling the full power range in most cases to enable much better control of the wind turbine and give fully compliance with the constant changing grid codes. The functionality of a wind turbine and a wind power plant is coming closer in its operation to a conventional power plant – and even in many cases it is much more advanced. The power electronics technology is constantly under pressure as the power rating is increasing and there is a demand for new innovative solutions without compromising the demand for low cost, low weight and high reliability. The complete wind turbine drive train also seems to be challenged as wind farms are being planned to handle DC internally and this opens up for new wind turbine topologies/concepts having DC as output. At the same time there are still technological issues about whether the partial scale power converter in combination with the doubly-fed induction generator will continue to be in the market and how to scale up this technology and at the same time comply with the grid codes.

Converter design and control

As the power rating is still rising as well as the power devices improve their performance – a continuous circuit topology investigation exist – should they continue to operate below 1 kV and then parallel a number of power converters (lower prize, redundancy) or move into voltages higher than 1 kV by using new power devices/modules and also circuits topologies e.g. multi-level converters. This demands new protection procedures and schemes in the wind turbine. Further, the power electronic devices might see a paradigm shift towards wide-band-gap devices (SiC) where the losses and switching performance might give a new generation of power converters. Within the next 6 years the power converter should have a 30 per cent better efficiency. The controllability of the wind power plant is also enabled by power converters as well as advanced digital controllers can be implemented. It includes basic control of generator and interconnection to the grid but also ancillary functions specified in the grid codes as well as diagnostic features on the drive train and monitoring functions to the grid for the power system operator. New challenges have appeared on the grid system as many active power converters are working on the same grid and might in some cases introduce harmonic instability. Also, more sophisticated control software is possible like increasing the life span during operation or monitor it and in that way using prognostic methods.

Generators

A number of generators exist for wind turbines – a few years ago the game changer was the slow rotating permanent magnet generator based on rare-earth magnets and avoiding the gear-box. However, due to the risk of high magnet prices alternative generator solutions now are necessary master technically and be able to introduce. The solutions are low speed, medium speed and high speed generators and constant efficiency, cost and total weight are the key-parameters to benchmark between the systems. Further on for very large scale generators the first applications of super-conducting generators are explored and could be an interesting alternative to the permanent magnet generator. As the power electronics technology is enabling operation higher than 1 kV, new medium voltage generators are of interest and need to be investigated

Switching transients

In order to ensure a reliable drive train the electrical system needs to be designed for all kind of transients in the system. It can appear both at the generator side and from the grid side. Protection equipment is needed to avoid damage/destruction of the electrical system and here modelling, worst case scenario analysis as well as different isolation coordination schemes, are important to enable a continuous operation of the wind turbines – also after the switching transients from the grid side. Often the most life span determining factor is the severe situation during switching transients and they need to be identified.

System design and test

Multidisciplinary design of generator, drive-train, power converter and grid is already done in research and development. However, new tools enable more complete system design and optimization of all components together in order to do virtual prototyping. Software tools and their interplay still need to be improved. This also includes the possibility to simulate the reliability stressors such as humidity, temperature and vibration so it becomes easier to design for reliability in a wind turbine drive train by including the various mission profiles a wind turbine sees. The designs need to be validated by large test drive-trains or by testing with RTDS systems or Hard-Ware in the loop (HIL) to ensure the new systems works properly, identify severe situations and improve the overall system before the first prototypes are installed.

4.2 Knowledge gaps

The electrical design of wind turbines is constantly striving towards lower cost in order to reduce the overall cost of energy. This includes less material cost, high reliability in order to have low operational and maintenance cost and at the same time an up-scaling in power is on-going. Therefore, different knowledge gaps exist. One is the discussion about whether the electrical system should be low voltage or medium voltage – constantly new topologies for medium voltage are proposed but the wind turbine manufactures are still using low voltage – the voltage-change is a paradigm shift for the electrical installation and bottom-line is always cost. The interesting thing is that medium voltage is used in many adjustable speed drives e.g. in mining, propulsion for ships and trains. Another area is whether new power device technology will move the voltage even higher and thereby enable the possibility to avoid the "low-voltage" transformer by operating at even higher voltage – in this discussion there is also a knowledge gap to change the power distribution system in a wind farm to become DC and avoid too much power conversion – which technology and voltage to use – and at the same time have a high efficiency.

The selection of generator technology is also under discussion – with high speed, medium speed or low speed generator – at the same time the risk in the cost of permanent magnets is forcing wind turbine companies to have solutions which are not too risky. As a more long term technology – super-conducting generators are still not demonstrated in a larger scale – and how to make the technology feasible in a long term needs a lot of R&D.

Finally, all issues are driven by reliability and the technology needs to be assessed and designed for that. There is a need for better to be able to transfer the real mission profile of the electrical system into figure of merits in terms of reliability and then use this for an optimization of the overall electrical system taking both Capex and Opex into account.

4.3 Research priorities

Converter design and control

Intelligent power electronic modules for wind turbines which could include new wide band gap devices, higher operating temperature, intelligent sensing of temperature and other states in the power converter, intelligent driving – both seen from a protection view but also from an efficiency point of view. The modules should also be designed for a specified reliability given a certain application (Mission profile). Integrated cooling methods to shrink volume and weight need also to be explored to lower the overall cost.

New power converter topologies need to be developed and explored for + 10 MW wind turbines. Will the solutions be paralleling of low voltage converters or will the voltage increase e.g. above 5 kV in the DC-link. It includes study of different multi-level converters, the impact of new power semiconductor devices and power modules, protection schemes, drive train layouts including the passive filters to reduce harmonics. The goal is to develop a system with a lower cost of existing technology and reduce the volume by 25 per cent.

A new "DC"-generator drive-train for interconnecting to a DC-grid in a wind farm. It could involve new generator concepts, medium frequency galvanic isolation, transformer design and system control. Prototype systems are important to realize in order fully to benchmark the new technology.

Life span modelling of power devices, electrical components and circuits for enabling a better design for reliability in wind turbines. The modelling includes stressors like temperature, humidity, cosmic radiation, dust and vibration. The approach should both be based on physics of failure as well as detailed study through experiments (HALT, CALT and other). The models can then be used for new power converter designs.

A functionality of active damping of harmonics in the grid is necessary due to severe resonance issues locally in the wind farm but also in the grid are seen in different locations. Both systems have a power electronics interfaced grid structure with active controllers and passive filters and their interaction can be critical by entering resonances – new control means must be developed as well as better design tools to predict which harmonics might cause problems in the systems.

Development of new advanced control methods for the generator and the grid which in general improve performance of the wind turbines system. It could be active control of the generator to dampen system resonances but also control of the whole system in specific severe situations. It could also be to comply with the grid codes as well as operate the system to maximize the life time of the whole wind turbine.

Generators

More efficient generators which have reduced need for permanent magnet need to be developed to reduce the dependency of permanent magnet prices. The power rating is below 10 MW and they should be overall competitive with permanent magnet generator solutions with a certain prize of permanent magnets.

Study and design of 10-20 MW generator drive train systems where permanent magnet generator, induction generator, doubly fed induction generator, synchronous generator and maybe others are developed and compared in terms of weight, cost, efficiency and reliability. It involves low-voltage and medium voltage generators as well as low speed to high speed generators. The goal should be to find the best solution to lower the generator costs with 30 per cent.

Super conducting direct drive generators in large wind turbines using integrated design might be seen in the next 10 years. Issues like generator design, super conducting "magnets" and their reliability, manufactur-

ability, cost as well as the applicable power converter for the concept are of importance.

Switching transients

Some of the most challenging events in a wind turbine happen with lightening strokes and by the switching devices in the electrical system. In some areas it is the root cause for most failures in wind turbines. Detailed study and modelling of the impact of the switching transients on electrical components are needed and should also be validated towards real events in order to better protect and monitor the wind turbine system. Life time models of the components in the severe events will make it possible better to predict new failures in the wind turbines

System design and test

More concurrent design optimization of wind turbine components is enabled by a number of software tools which have their advantages in different disciplines (electrical, thermal, power electronics, magnetics, power system, reliability). At the same time, the calculation power is increasing in computers and it is possible to comply with more multidisciplinary designs in order to design the electrical parts in wind turbines better. The design criteria will be lower cost, increased reliability, and improved system performance both on the generator side and to the grid side. The system engineering tool can be further expanded to develop a more comprehensive toolbox which designs for reliability based on the real mission profile of a wind turbine. An already integrated design platform to assess the impact of grid code requirements on wind turbine loads and components life span can form the platform for such a study.

More demands exist for the wind turbine to fulfil advanced power control. Therefore, the impact of the power control methods on the wind turbine (electrical, drive train, tower) are of importance and it is also interesting to study the value of a limited energy storage (capacitor, super-cap) in such a system to minimize loadings of the whole wind turbine system. It could give a longer life span of the whole drive-train.

New electrical designs (grid structure) of future topologies when looking into a wind farm. It could be a DC-grid and how to design and lay-out such systems including drive train. It could also be wind turbine systems without an ac-transformer e.g. operating at 10 kV AC as an internal grid structure. Cost of energy will be the main driver in selecting the final topology in such a future design.

New developed hardware and control methods need to be full scale test and/or validated by hardware in the loop. The electrical design and control concepts might first be explored at a common small scale test site (e.g. 100 kW) and subsequently transferred to real-scale test-benches. In between real time simulation systems for wind power drive trains could be a competitive platform to be developed.

4.4 Application of research results

Most of the research is rather application oriented, so innovation and ideas will naturally be explored in close collaboration between research institutions and companies in the wind turbine industry. There is also a need for more basic research but there is a tradition for a close collaboration in the above mentioned areas. This is valid both from a component level and up a more sophisticated system level and there is a strong need for this synergy as the wind turbine industry has important field experience which can be used for the component and system design. Some of the research will also have simulation tools and experimental facilities as output – those should be maintained as well as used by research institutions and the wind turbine industry.

4.5 Commercialization of the research results

A part of the research will be directly related to improvement of components which can be commercialized by the wind turbine companies and their sub-supplies. Also, we are seeing new companies being started in the field of power electronics as design centre and even manufacturing. Also, in the case on DC-technology and super conducting generators there might be a possibility to form setups for commercialization. Further, tools developed in the different research activities could later be released as commercial products as well as test facilities might be used on a commercial basis. Finally, smart ideas in control are often patentable and having a commercial value as seen today with a couple of examples.

5. Power system integration

5.1 Scope

The national and international targets for renewable energy development in general and wind energy development in particular raises new technical and market related challenges to ensure a secure and economically efficient development and operation of future power systems. This wind power integration strategy focuses on identification of the R&D areas which have a specific and significant relevance for large scale integration of wind power, appreciating that in parallel with this, there are strategies for a more general development towards smart grids and flexible consumption and production technologies, which can be used as important enabling technologies for wind power integration.

A key element in integration of wind power is the continued development of ***wind power plants***, which will be able to serve as electricity generating units while at the same time participate to the insurance of a stable and secure operation of the power system. The contribution to power system stability and security is vital to enable the partial or complete replacement of conventional thermal plants with wind power and other renewables.

The development of wind power plant capabilities should be matched by development of new solutions to ensure ***power system security and stability*** wind large scale wind power. Deterministic approaches must be combined with probabilistic approaches, which can ensure that sufficient and yet not redundant reserves are available at any time. There is also a need to develop new ways of ensuring frequency and voltage stability in systems where thermal plants using directly connected synchronous generators are replaced by wind power plants using power converters.

The development towards increasingly large wind power plants and the need to transport the power over long distances places new demands to ***grid connection and transmission***. Especially the massive offshore wind power development including wind power with long distances to the coast raises new challenges to the transmission of the wind power.

The ***market integration and value of wind power*** is influenced by the development of wind power plant capabilities enabling the participation in new markets for ancillary services as a supplement to the power traded on spot markets. The structures of the markets are also of very high importance for the value of wind power.

5.2 Knowledge gaps

The continued successful development of wind power calls for a continued effort to ensure a cost-efficient and sound development of the wind power technology.

First of all, the responsibility of wind power for the power system stability is increasing along with the increased penetration of wind power in the system. The traditional way of ensuring a stable and reliable power system is very much dependent on ancillary services provided by conventional power plants using synchronous generators. Modern wind power plants are already capable of delivering many of those ancillary services, but the grid operators still need "must run" conventional power plants running at any time to ensure the stability. Moving towards steadily increased penetration of renewable energy in the future power systems, this must-run strategy is not only costly, but also a barrier towards reaching the ultimate 100 per cent renewable generation. Therefore, the development and validation of enhanced ancillary services from wind power plants are key technical challenges for the future.

Also, the market integration of larger scales of wind power calls for new solutions to increase the flexibility of the power systems. Increased flexibility can be obtained either by development of the transmission grid integrating different market areas more efficiently, or by flexible consumption and storage solutions.

Regarding transmission systems development, the main knowledge gaps are related to the development of reliable and secure offshore transmission technologies, which can interconnect power system areas with different generation technology mixes, and also enable connection of offshore wind power with long distances to land. This strategy recommends R&D in the interaction between wind turbine converters, wind power plant controllers and HVDC converter in HVDC connected wind power plants. There is also a need for more general R&D in design and operation of multi-terminal meshed HVDC systems, but this should be coordinated with other strategies. Finally, Dynamic Line Rating of overhead transmission lines depending on wind speeds and temperatures can increase the thermal capacity of the transmission systems significantly, but there is a need to develop this into a reliable approach which the wind energy community should contribute with development of probabilistic methods to estimate the distribution and uncertainty of wind speed, wind directions and temperatures along the overhead lines.

The development of flexible consumption and storage technologies is at present outside the scope of this strategy, but the assessment of the value of existing and future large scale technologies for integration of large scale wind power is an important part of the strategy. Already with the present 39 per cent of wind in 2014 in Denmark, such solutions will have a positive impact on the value of wind power, but the horizon of such assessments should be very long, covering the entire roadmap towards 100 per cent renewable energy systems.

5.3 Research priorities

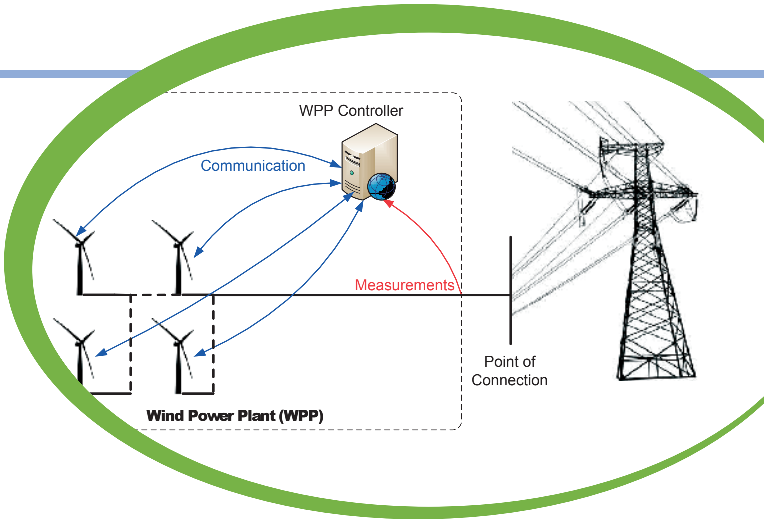
In order to be able to understand the extent of wind power integration challenges, it is necessary to develop scenarios including detailed description and quantifications of the expected medium to long term development of renewable energy technologies, energy consumption and new enabling technologies such as large scale storage.

Wind power plants

The following R&D priorities have been identified to support the development of wind power plants:

- Development and simulation based verification of enhanced ancillary service capabilities of wind power plants based on electrical models and control

- Development of advanced integrated operation and control strategies for wind power plant ancillary services aiming at maximizing energy yield and reducing operational costs while providing the ancillary services. Such strategies should use forecasts in probabilistic solutions



- Development of generic methods for testing and verifying ancillary service capabilities of wind power plants (pre-standardization)

- Modelling and aggregation of wind power plants for power system stability assessment

Power system security and stability

The following R&D priorities have been identified to support the development of power system security and stability with large scale wind power:

- Optimization of spinning reserves and other reserves – inclusion of forecasts and special focus on additional needs for reserves in high wind cases

- Wind power reliability at power system level

- Power system stability assessment with large scale wind power and other renewables - match wind power plant capabilities with system needs

- Power system security, stability and protection with low system inertia

Grid connection and transmission

The following R&D priorities have been identified to support the development of grid connection and transmission solutions:

- Grid connection to "new" transmission technologies (HVDC / LFAC / hybrids)

- New integrated solutions for design and control of wind turbine, grid connection, wind plant power collection and transmission

- Interaction between wind turbine converters, wind power plant controllers and HVDC converter in HVDC connected wind power plants
- Assessment of the value of dynamic line rating of transmission lines depending on the ambient wind speeds and temperatures along the lines. This assessment should take into account the wind speed profiles along the lines and wind speed forecast uncertainties
- Improved generic methods for testing and assessment of power quality emission from wind power plants

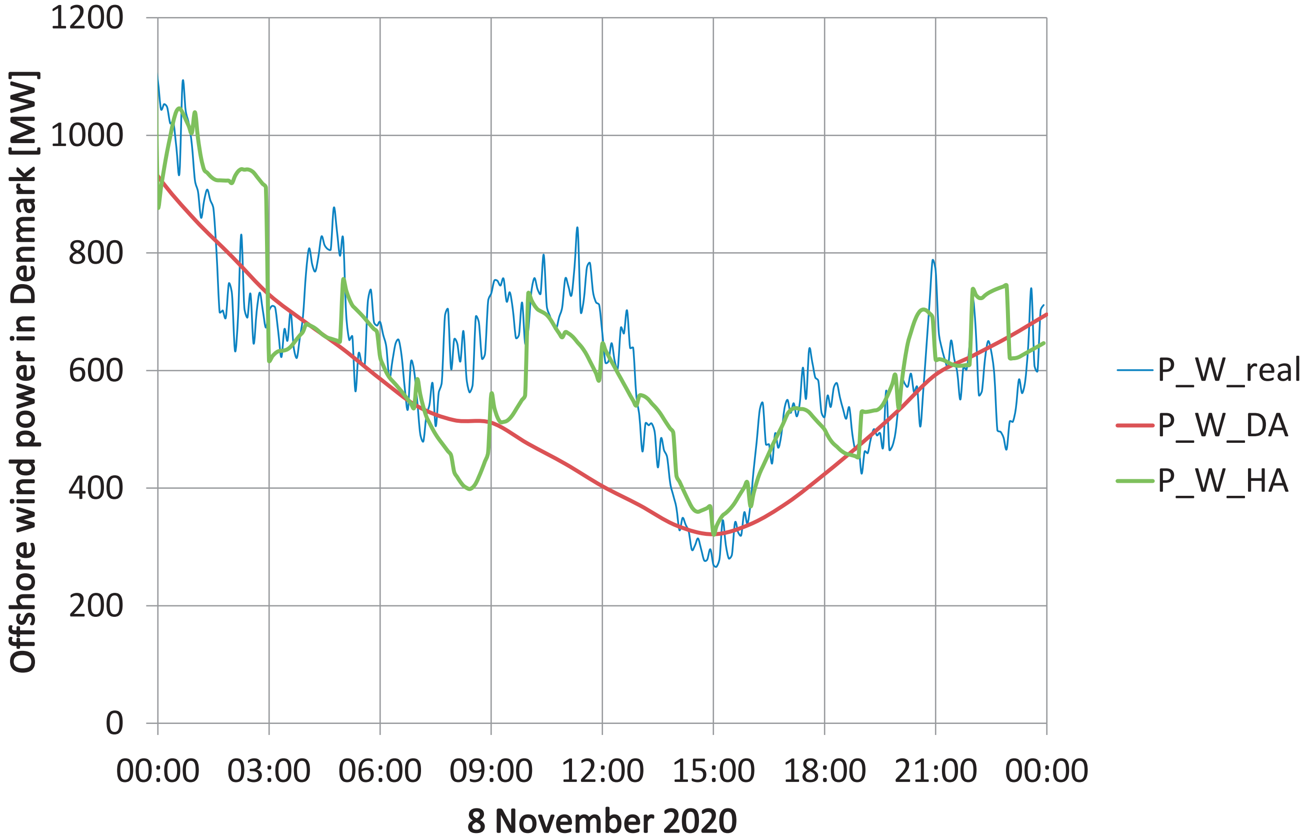
Market integration and value of wind power

The following R&D priorities have been identified to support the market integration and value of wind power:

- Assessment of the value of large scale storage technologies and other flexible units for wind power integration. Special focus will be on the integration of power and heat systems, where the technology of heat pumps and electrical boilers are well developed, but regulatory issues prevent the large scale deployment. Also, the value of newly proposed large scale technologies based on heat storages in sand or concrete should be assessed.
- Modelling and validation of wind power variability in present and future power systems (impact of offshore concentration on generation patterns, impact of future larger rotor vs. capacity ratios, aggregation of wind turbines over power system areas, uncertainties in terms of forecast errors). These models are intended as input to assessment of the need for reserves in the future power systems towards 100 per cent renewables and for sizing of future large scale storage technologies and transmission network development

Modelling of variability of wind power production

(P_W_real) together with day-ahead (P_W_DA) and hour-ahead (P_W_HA) forecasts.



- Assessment of economic benefits of providing ancillary services and power balancing from wind in present and future power systems
- Use of probabilistic wind power and price forecasts in wind power trading and asset management
- Advanced wind power energy management systems – based on prediction / prediction uncertainty / variability and IT, close to real time

5.4 Application of research results

The R&D priorities are all selected to support the development towards integration of a massive scale of wind power. Thus, the priorities are very application oriented. The main stakeholders will have the following applications:

- TSO applications ensuring a secure and stable system operation at minimum costs
- Regulator applications supporting the development of future power markets
- Utility (owner and operator) applications to increase the value of wind power
- Wind turbine manufacturer applications to make wind power more competitive by reducing the costs and increasing the value of wind power plants.

6. Offshore Wind Energy

6.1 Scope

Wind power plants at sea are to some extent based on the same technology and are facing similar challenges as onshore wind. However, the development today is heading towards technologies and methods specialized for offshore conditions. There is a tendency towards larger turbines at sea that can provide lower relative costs for installation and operations and better withstand the harsh environments. Installations at increasing depths may open new possibilities but also require new technologies to accommodate the changed conditions. Offshore wind energy spans a wide range of topics. Some are specific to offshore application while others are shared with onshore wind turbines. In the present context, offshore wind energy is defined to cover the areas :

- Offshore wind resources
- Wind and wave loads
- Optimization of offshore wind power plant layout
- Design and optimization of support structures including soil-structure interaction
- Optimization of installation, operation and maintenance of offshore power plants

The electrical system and grid connection of offshore is described in section 4 and 5.

6.2 Knowledge gaps

To decrease the cost of energy, offshore wind turbines are of large capacity and rotor diameter, the largest commercial offering of 7MW and exceeding 170m in diameter. Plans for turbine ratings of 10MW and beyond are also being made for the near future. However, offshore wind turbine designs are based on limited validations of design conditions and design loads and thereby the offshore wind turbine design can possess large uncertainties related to metocean models, wind turbulence, extreme waves, soil conditions, the interaction of the rotor with the wind and damping of the turbine support structure. Further, there are many failure problems associated with turbine components that are yet not fully understood, such as blade edge erosion, pitch bearing degradation, grouted joint failure, gearbox failure, inclination of the sub structure, etc. This gap in knowledge of the design conditions and the failure modes of the turbine need to be addressed rapidly to ensure reliable wind turbine designs that minimize the cost of energy in the near future.

At the typical depths of offshore wind farms, the waves are not deep-water waves, as known in the oil and gas industry. The limited depth is associated with stronger nonlinearity which leads to steeper waves and more impulsive wave impacts. This still holds for the deeper sites of 40-45 m where extreme wave loads are often dimensioning for the substructure. Recently, ringing and springing due to wave nonlinearity have been pointed as a design-effect that needs further investigation. The wave load models applied in today's design, however, are best-practice engineering models that do not take the physical effects of 3D wave spreading, currents, sea bed slope and nonlinearity of irregular waves fully into account.

The limitation of today's models and the application process of these have a direct and significant impact on LCOE through the uncertainty and associated risk. The improvement of today's design models and closure of the knowledge gap is thus a direct potential for cost saving.

Jacket structures are expected to play a major role at the deeper sites where the monopile is not cost-efficient. While the main hydrodynamic forces are relatively well described due to the slenderness of the structural members, many load phenomena are not well covered or even understood. This includes local fatigue-damaging vibrations induced by vortex motion, viscous high-Reynolds number flow around complex geometries and current blockage effects where the presence of many structural members induces a global and load reducing reduction of the flow speed. There is a strong need for qualified research in jacket loads at intermediate depth where also wave breaking can still occur.

Offshore installation of wind turbines is highly complex both in planning and in executing. The use of special equipment is evident, and creates costly bottleneck if transformation and flow not are carefully planned.

6.3 Research priorities

Below is listed a number of research priorities. They are not listed in prioritized sequence.

- Wind turbulence at heights above 100m
- Extreme waves
- Loads measurements
- Probabilistic design of structures
- Damping of wind turbine components
- Reliability and risk assessment
- Soil-structure interaction
- Wind turbines support
- Wind farm wake effects
- Installation, operation and maintenance

Foto: DONG Energy A/S

Modelling and design tools

Reduction of cost of energy of offshore wind farms requires minimizing the uncertainties in the wind turbine design. A significant model uncertainty is the design tools used in prediction of the component loads, stresses and failure analysis. Research in the development of design tools include:

1. Appropriate met-ocean models that provide the right turbulence, wind shear distribution at different mean wind speeds and heights along with the prevailing wake flow that needs to be provided to aeroelastic codes

2. Long term statistics of the loads on wind turbine components should be predicted to appropriate levels of accuracy.

3. There is a need for integrated finite element models of coupled structural interactions such as the response of jacket sub structures coupled to the wind turbine structure and soil.

There is a need to acquire data on the behaviour of existing wind turbines. This information will support research into the development of improved design tools and techniques and better design standards.

In recent years a number of advanced wave models, capable of describing 3D nonlinear wave fields have been developed. Some of these models have the potential to be applied in design through utilization of GPU technology (graphics processing unit). They may also be combined with modern methods for numerical uncertainty quantification for a systematic assessment of sensitivity of input parameters.

CFD methods have shown strong progress in applicability to even breaking wave impacts and have been validated against experiments. More research, however, is needed here that addresses inclusion of turbulence and viscous effects. The advanced models can be used to calibrate simpler engineering models and to investigate the load effects of large uncertainty in detail. The modelling must be accompanied by experimental measurement campaigns and high-quality field data. For example, for large monopiles the Reynolds number for the extreme waves is of order 10 million which is outside the scope of most lab tests.

Design of wind turbine structures

Offshore structural design aims to optimize the component design over its lifetime, reduce all uncertainties and to develop reliable, but cost effective components that are calibrated to site specific conditions.

As turbine sizes increase beyond 7MW, and the industry moves into waters deeper than 30m improved structural designs are required. The cost of wind turbines is to a large extent tied to the structural design and to the reliability and safety of the load carrying elements and components. There is a further need to extend the life span of structures, reduce costs through optimization and develop risk-based life-cycle approaches for future designs.

Different types of fixed support structures are expected to be developed until 60m water depths which may be extremely expensive due to the large influence of fatigue loads and soil conditions. Active and passive means to mitigate fatigue loads on sub structures need to be developed and implemented to reduce the cost of sub structures. Alternatives to welded joints on sub structure need to be developed so that the labour costs of sub structures are reduced.

External conditions

Today's wind turbine design is based on design load cases which are defined with basis in statistical extrapolations for the extreme wave and wind conditions. The associated statistical uncertainty has a strong impact on LCOE. More work is needed to provide more reliable statistical models for combined wind-wave climate. This must be supported by scientific physical models that link the statistical approaches to the real governing phenomena.

Control in large wind farms

Another way of decreasing LCOE is to increase AEP. This can be done by exploring advanced control strategies for load mitigation and power optimization: Use of wind sector (or regime) based control or LIDAR.

Operation and Maintenance strategies

The OPEX expenditures over the life span of an offshore wind farm amounts to a large part of the overall expenses. This can be decreased by making optimal scheduling of maintenance with regards to turbine life, security of supply, power prices. There is a need to develop more precise models for weather windows to support the optimal scheduling.

6.4 Application of research results

Within the above mentioned areas new and improved models and methods will be developed. Making improved models and methods will reduce uncertainties and will therefore lead to less conservative designs. Most of the mentioned models and methods will directly be applicable in industry or by authorities and will help reduce the LCOE through increased reliability, lowering capital expenditure and increasing power output.

6.5 Commercialization of the research results

The developed models and methods can be included in tools and be commercialized in this way. Constantly improving the tools through the newest model and methods will ensure that the parties using these tools are at the forefront of the development and thereby having a competitive advantage. In this way a pull from market will be generated to have the latest and most advanced tools.

7. Experimental Test & Measurements

7.1 Scope

Test and measurement and subsequent data analysis provide valuable information in the design, engineering validation, performance verification and operation of wind turbines, their individual components, as well as their system behaviour when integrated into wind farms and the power grid.

Improved and innovative sensor types, with integration in components and structures, and ability to operate under high loads and severe environmental conditions, provide significant value in contributing to a more efficient and reliable design. Their integration into monitoring systems enables scheduled maintenance, thus reducing operating costs. Data mining and advanced signal analysis of sensor data provide significant insights into operating conditions under various loads in addition to giving the classic validation of numerical models.

7.2 Knowledge gaps

A list of research areas are identified as research leading to invention of or improvement of sensors, technologies and methods within the areas of:

The wind

- Wind sensor calibration and classification methods (cups, sonics, lidars, etc.)
- Offshore wind measurements (floating lidars, satellites, nacelle lidars)
- Coastal wind measurements (scanning lidars, UAV)
- Wind measurements in complex terrain (scanning lidars, UAV)
- Wind farm measurements (lidars, scanning lidars and radars)
- Wind measurements from the wind turbine (nacelle, spinner, transition piece)
- Measurements of extreme winds and turbulence

The turbine

- Sensor and sensor mounting techniques for control and monitoring
- Test facilities for large component testing (Drivetrain, Blades)
- Kinematic measurements (Stereo vision, Fibre optics, new sensors)
- Light and strong materials (Fibre and Metals)
- Wind Tunnel aerodynamic and aero-acoustic measurements

The wind power plant

- Smart sensor networks (Synchronizing and sharing)
- Grid interaction

The surroundings

- Noise monitoring and control (at Source and Receiver)
- Shadow flicker monitoring and control

The measured data

- Handling, storing and analysing huge amounts of data
- Transmitting data
- Data mining methods for wind energy
- Novel methods for data analysis (fast data)

7.3 Research priorities

- **Wind resources and site conditions:** The increased focus on offshore and complex sites challenges our ability to measure with traditional masts and anemometry. Consequently, remote sensors, e.g. floating lidars, will be used more and more as the primary wind source. Whereas with traditional anemometry we have a good understanding of the measurements of turbulence and extremes, this is not the case for remote sensors. Fundamental research is needed to improve the quality and reduce the uncertainty of measurements from these instruments. Focus will also be on turbulence and statistical handling of measurement data.

- **Wind turbine:**
  Research to develop and apply new sensors can lead to reduced cost and improved reliability. New sensor types both for structural, inflow, noise and electrical measurements, can offer new and exciting possibilities for the control and monitoring of future wind turbines. Optical sensors shall be developed for deflection measurements. Increased focus shall be on the discipline of testing components, parts and turbines and to improve the scientific foundation of the area with a more methodic, mathematic and statistic approach to testing as a discipline including increased focus on education of engineers with these qualifications.

- **Wind power plant:**
  There is a general lack of knowledge about the flow in and around wind farms. This gives rise to over-conservative design and large uncertainties in the wind farm performance. The problem is exacerbated by increasing park sizes. Research is needed to develop measurement techniques that can quantify the spatial distribution of wind, turbulence, and noise in and around a wind farm and relate these to the measured loads and power on the turbines and meteorological conditions The results of this research can improve wind farm site planning and operation. Advanced data analysis methods including data mining can be used to extract new knowledge about wind farm systems parameters.

7.4 Application of research results

Reduction of LCOE, through science-based research and innovation is the overall goal and at the same time increase the share of wind energy into the grid. Research in improved sensor technique, measurement systems and data analysis will have their greatest value in improving reliability and reducing operating costs for off-shore systems.

In addition, all systems will be enabled for more efficient operation and lower environmental impact thanks to improved instrumentation contributing to a better design, and better control systems for more efficiency, low-noise operation.

7.5 Commercialization of the research results

Wind Turbine manufacturers and all sub suppliers will be able to design better systems by having consistent numerical models which have been validated by large scale system wide synchronous test. This speeds up the design cycle hence improving their competitiveness. New sensor types and mounting techniques developed by the research can be licensed to sensor and instrumentation manufacturers, while data analysis techniques provide business opportunities for software companies.

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8. Environmental issues

8.1 Scope

The research in environmental issues deals with a wide range of topics underpinning the impact assessment and monitoring activities related to wind energy planning and development. The scope of the research corresponds to the scope of an EIA report (VVM report in Danish).

8.2 Knowledge gaps

Mapping of sensitive species and habitats

Database and geographic information systems integrating available data on year-round dispersal and movements of relevant key species collected in connection with EIAs and monitoring programs through state-of-the-art monitoring methods are missing at both national and international levels.

Fine-scale predictive distribution and agent-based models are developed to improve baseline descriptions of spatio-temporal dynamics in animal dispersal and movements. Currently, impact assessments are often based on field data alone leaving large gaps in knowledge of dynamics.

Social and socio-economic impacts

Methods are needed for quantification of direct and indirect impacts on land-use, traffic, communication and commercial fisheries caused by establishment of a wind farm. Assessments in relation to fisheries are non-trivial due to potential positive counter-effects of closure of wind farm area from trawling activities.

Visual and landscape impacts are among the most prominent impacts realized in connection with land-based and near-shore marine wind farms, and often play a key role in the local acceptance of any wind farm project.

Species and human responses to wind farm

Noise is considered a major issue in relation to land-based wind farms, and includes development of models of the sound source, the propagation of the sound from the source to the receptor and finally models for human perception of noise. Also, evaluation of various techniques for noise reduction is included as well as techniques for measurements of noise. A special area with lack of research results is noise in the low-frequency area.

Responses of important land and marine mammals, land and marine birds as well as fish to air and underwater noise are quantified under different planned or established scenarios during constructions and operation of the wind turbines. Experimental designs may also be employed.

Responses of species of fish, mammals and birds to wind farms caused by disturbance effects are quantified using monitoring results as well as experiments. Responses include habitat displacement, barrier effects and collisions.

Attraction of species to wind farm constructions due to noise, illumination and food present around the constructions is quantified.

There is a general lack of knowledge of long-term changes of habitats located within the foot-print of terrestrial and marine wind farms, including artificial reef effects and effects of reduced fishing activity on local marine populations.

Knowledge of adaptation of initially affected populations to the new constructions is needed.

Assessment of cumulative impacts

Habitat degradation experienced for most species due to human anthropogenic construction work and use of natural resources have taken place for centuries. These detrimental effects have a cumulative nature which under the extreme conditions may lead to displacement or extermination of species or part of the ecosystems. The relative contribution of wind farms to the cumulative anthropogenic impact needs to be quantified.

Species passing through regions may easier be displaced from a region due the easier displacement possibilities and effects. Research in displacement of migratory species attempts to improve the assessment of whether the migratory species is displaced to less suitable habitats or to alternative unexploited habitats within the range of the affected species in question.

Quantification of the uncertainty associated with the assessment of impacts from wind farms is needed. Both inferences from field data and model predictions have some

built-in uncertainty that may be quite variable from case to case.

Cumulative impact scenarios increase the risk for creating environmental detrimental effects on the population level.

Simulation of optimization of environmental siting

Knowledge obtained through modelling of habitat preference of key species has the potential of determining areas of least biological importance.

Decision support systems which integrate biological information, simulations of wind resources, environmental impacts and cost estimates are lacking. This has created a situation where fast, reliable and efficient decisions on suitable sites for wind development are very difficult to make at local, as well as regional and national levels.

8.3 Research priorities

- International digital information systems integrating all available or new field data at regional and national levels by application of predictive modelling technology.
- Nature and significance of behavioural responses of marine mammals and fish to underwater noise emissions associated with construction of offshore wind farms (in particular piling of mono-pile foundations).
- Drivers behind the process of attraction of protected species of bats to land-based wind farms and terrestrial birds to offshore wind farm constructions.
- Quantification of micro-avoidance of flying birds and bats to individual rotor blades.
- Long-term reef effects and effects of reduced fishing activity on benthic and pelagic ecosystems.
- Application of probabilistic modelling of uncertainties in wind farm environmental impact assessments.
- Model applications for simulation of optimal environmental siting of wind farm development through a framework for assessing cumulative effects on population levels.
- Development of decision support systems for integration of simulations results for optimal environmental siting, wind resources and construction and operational costs.
- Development of models for low frequency noise
- Improved measurement techniques for noise

8.4 Application of research results

- Introduction of more comprehensive impact assessments for wind farm developments, based on all available data on sensitive resources, more detailed knowledge of specific behavioural responses and cumulative impacts, including quantification of density-dependent mortality and probabilistic modelling of associated uncertainties.
- Strategic impact assessment applications and tailor-made decision support systems for optimal siting of wind farms.
- The research will give input to the design of wind turbines in terms of airfoil design, blade design, drive train design and control strategies for noise reduction with less impact on AEP. In the process of validating the improved wind turbines, the research will give input to accurate measurement methods, how to erect wind turbines also in wind farms and how the noise is perceived by humans.

8.5 Commercialization of the research results

- The research within EIA issues will serve to create a firm basis for consultancy of wind farm developments based more on scientific evidence and models and less on 'expert judgment'.
- The research will create the basis for development of consultancy within Strategic Environmental Assessment (SEA) and apply this at local, regional, national and international levels.

9. Societal issues

9.1 Scope

With the increasing shares of wind energy in the energy systems, economic and social aspects become increasingly challenging. It is thus of utmost importance to understand and incorporate political and social aspects in the research, so that wind energy can continue to be a success story.

Therefore, the overall knowledge gap is the need to explore the major economic, legal and social challenges for wind energy now and in the future and to investigate how they can be addressed and mitigated. In addition, there is a need for coordination and a holistic perspective in the economic assessment of wind power generation versus other generation technologies, including all costs, benefits and impacts, since large amounts of wind energy influence the remaining system and actors

It has long been acknowledged that the development of wind power will not happen at an adequate scale or pace if left entirely to the market and private initiative; it requires some degree of intervention and support from governments at central and local levels. However, although many governments have set targets for their wind energy development, the sector has developed unevenly across countries. Thus, it is important to improve our understanding of how governments most effectively intervene to promote the development of wind power.

Planning for wind power, environmental assessment and public participation

Planning and environmental assessment procedures are well-known regulatory measures that ensure public participation in decision-making – not only for the purpose of improving the decision-making basis, but also for the purpose of ensuring local legitimacy and acceptance. It has in particular in relation to wind energy projects been put forward that the success depends on the degree to which planning regimes stimulate or impede collaborative approaches. While planning law and planning procedures may differ widely from one country to another, environmental assessment procedures have been subject to legislative initiatives at EU as well as international level. Public participation is a core element in environmental assessment procedures as reflected in both the EIA and SEA Directives as well as in the Aarhus Convention. The implementation of public participation and environmental assessment procedures – and their application in relation to wind energy projects – may however also vary from one country to another. Furthermore, environmental assessment procedures and public participation may often be seen as obstacles from a developer perspective. Thus, there might be tensions around the use of such procedures in general as well as in individual cases.

Local engagement and acceptance

A crucial challenge to the development of wind power is how to ensure local engagement or at least promote local acceptance. The achievement of political targets on the increased share of wind energy is facing serious impediments when it comes to local decision-making on wind energy projects due to local opposition. Several empirical studies have through case studies identified the main factors influencing local acceptance of wind energy projects. Among such factors is not only the visual interference, problems of noise etc., but also factors such as decision-making processes, including trust in decision-makers, as well as the ownership of a project. Thus, it must be acknowledged that local acceptance is a complex and multifaceted issue that also calls for a careful consideration and design of public decision-making processes as well as other policy instruments or measures.

Market access and connection to networks

With increasing market shares, wind power begins to have a decisive impact on the market prices that are forming on the European day-ahead spot markets. Because of the low marginal cost of wind power, it pushes market prices down (merit-order effect). Such effects threaten the functioning of the current spot markets because conventional generation relies on a higher price level to justify investments. It is important to analyse determinants for the merit-order effect and investigate their potential mitigation through changes in market design.

High shares of wind pose fundamental challenges to the current market set-up, not only through merit order effects, but also through other effects, including in a time and spatial dimension. Changing the gate-closure time of day-ahead markets could e.g. reduce forecast errors significantly and thus increase the efficiency of wind integration. Because of the widespread spatial distribution of wind energy as compared to conventional generation, ongoing discussions suggest that instead of countrywide power prices, each node in the power network should have its individual price. While this is efficient from a power system economics perspective, it might expose wind farm investors to considerably larger financial risks. Furthermore, radical changes in the market set-up might become necessary in future energy systems, such as e.g. the introduction of capacity markets to ensure adequate investments in new capacity.

Moreover, wind power has to compete in a market with conventional fossil fuel plants which were previously operating in a monopoly market. Even though liberalization of electricity markets goes hand in hand with deregulation of these markets under most models for electricity regulation across the globe, fully liberalized energy markets involve a high level of regulation to achieve such liberalization. Both deregulation and regulation of electricity markets thus involve legal interference, albeit of a different nature. Responses by the market can indeed require regulation, in particular if new market entrants have to break through in a sector that was dominated by monopolies, in which case discrimination against incumbents can continue despite regulation. Two key examples of where regulatory instruments are often used to intervene in the market are first the guaranteed or priority access to the electricity grid, and second the third party access.

Price regulation and financial support schemes

Economic incentives in the form of production support have played a key role in promoting the deployment of wind energy in Europe over the last two decades. The main categories of support mechanisms used in EU Member States include quota schemes, feed-in tariffs and feed-in premiums. These are frequently coupled with investment support, auction schemes and/or tax incentives. The frequent changes in support scheme design in many countries over the last years prove that further research is needed to refine the design features in order to better capture interrelated concerns and policy objectives.

With increasing penetration rates of onshore and offshore wind, economic incentives need to be adapted, in particular to foster next generation technologies, such as offshore wind located further from shore, in deeper waters and/or in combination with combined wind park and interconnectors. However, continuous adaptations and changes of design and level of support to wind energy can jeopardize investor confidence, and as a consequence, impact the rate of deployment of wind energy throughout Europe. A balance has to be found by policy makers.

When designing economic incentives through policy support, several aspects have to be considered. There will have to be a trade-off between preventing overcompensation and windfall profits, stimulating innovation, easing grid integration, exposing electricity generated from wind energy to market signals, and public acceptance.

The actual design of the measure differs from country to country and it is important to identify which design elements are the most regulatory efficient.

9.2 Knowledge gaps

Planning for wind power, environmental assessment and public participation

The legal and economic design as well as the actual practices of planning and environmental assessment procedures are very important in relation to how well they work in relation to reducing conflicts and increasing local acceptance. However, the current level of public involvement and consultation does not always result in satisfying all the interests concerned or in the support of local communities. The participation procedures are often perceived as being neither 'democratic' nor transparent. As a result, there is often a need to ensure that the legal framework provides for further incentives for enhancing public participation.

Local engagement and acceptance

There is a need for more open and transparent decision-making that takes into account the diversity of the stakeholders involved in or affected by proposed renewable energy projects. If local concerns are brushed aside or not sufficiently considered, there will be a risk that opposition to projects or conflicts between stakeholders will intensify, and that, from an overall perspective, general support for renewable energy projects will fade. Although most major renewable energy producing countries would probably argue that access to information and public participation are important and are already integral parts of their decision-making processes, renewable energy projects nevertheless increasingly meet local opposition which delays or prevents their implementation. This means that a well-planned project for a renewable energy project has no guarantee of either acceptance or successful implementation. Thus, there is a need for new legal instruments to encourage local acceptance.

In Denmark, there has been a distinct need to implement further incentives to achieve the planned growth of wind energy capacity. There is no doubt that, from a political perspective, the schemes introduced in the Renewable Energy Act have been very successful. In the period from 2009 to 2013 there has been a significant growth in both planned and installed capacity. However, local opposition continues to grow and the special-interest groups opposing new wind energy projects have grown significantly and have generally adopted a more professional approach. Consequently, there is a constant need to consider and reconsider both existing and new measures.

Market access and connection to networks

The fast increasing cross-border exchange in electricity emphasizes the need to take into consideration the market context to an even greater extent.

The existing market design has proved to be efficient in operation; however, the merit-order-effect of wind power is threatening the functioning of the current spot markets. It is important to analyse determinants for the merit-order effect and investigate their potential mitigation through changes in market design. Furthermore, radical changes in the market set-up might become necessary in future energy systems, such as e.g. the introduction of capacity markets to ensure adequate investments in new capacity.

While access of renewable electricity is important, at the same time non-discriminatory criteria for grid access are equally important. The energy suppliers cannot carry out their business without access to energy systems, and for that reason they are dependent on whether or not the system operators provide access to their systems. Moreover, the suppliers risk being discriminated against by system operators, because system operators hold a (former) natural monopoly position in the market for transport facilities and have incentives to abuse this position. This dependency and risk of discrimination means that equal competition between suppliers is only possible in the first place, if non-discriminatory third party access to energy systems is ensured.

Price regulation and financial support schemes

The newly adopted EU Guidelines on State Aid for environmental protection and energy 2014-2020 introduces

a number of fundamental policy shifts. Above all, a shift from feed-in tariffs to market premiums is introduced. Another fundamental change is a shift from statutory tariffs to competitive bidding processes. The frequent changes in support scheme design in many countries over the last years prove that further research is needed to refine the design features in order to better capture interrelated concerns and policy objectives.

The EU Guidelines on State Aid assume that national support schemes per se constitute state aid, while they remain silent on the fundamental issue of when these schemes contain aid in the first place. This is a question of immense importance for Member States that have carefully designed their national support schemes to avoid state aid issues.

The impact of different policy mixes on wind energy development

While previous legal research has aimed to isolate and measure the effect of single policy instruments, it is contended that it is important to study the interaction and impact of policy packages. Policies are seldom comprised of one single instrument but are packages of different instruments. Thus, the current picture of national policies is a patchwork of policy instruments and a critical lack of knowledge on how different policy instruments interact and work together. Thus, it is important to examine the impact of different policy mixes on wind energy development in order to identify effective combinations of policy instruments to further promote wind power development.

9.3 Research priorities

Planning for wind power, environmental assessment and public participation

How to improve the economic and legal design as well as the actual practices of planning and environmental assessment procedures

Local engagement and acceptance

How to develop incentives to enhance the local engagement or acceptance of wind energy projects in order to reach the renewable energy targets

Market access and connection to networks

- Assessing new market designs for day-ahead and intraday markets, as well as financial markets to support the integration of wind in systems with high wind shares
- Understanding and mitigating merit-order effects of wind energy on spot markets

- How to ensure competition while also ensuring fair access to the grid for new market entrants such as wind power producers

Price regulation and financial support schemes

- Which support mechanisms are best suited for the promotion of wind in the future European energy system?
- Which policy design specifications can help foster certain favourable technology developments?
- Design of technological as well as legal regulatory framework conditions, especially with respect to off-shore grids and wind parks
- How to cope with the significant limitation of the EU Member States' freedom to adopt and maintain national support schemes for renewable energy generation

The impact of different policy mixes on wind energy development

Analysing the impact of different policy mixes on wind energy development in order to identify effective combinations of policy instruments to further promote wind power development

9.4 Application of research results

The social science analyses will contribute to the identification of the overall regulatory constraints and ethical concerns that arise from the promotion of wind energy development. In particular, it may address the main barriers and highlight key promotional opportunities in order to ensure effective implementation of wind energy policies. The social science studies will contribute to an increased understanding of energy markets and provide thorough analyses of how trade and legal trade regimes may contribute to the establishment of sustainable production pathways that may also address other policy concerns such as energy security. Further, the analyses of energy and renewable energy markets and trade mechanisms may help to identify opportunities that should allow industry to maximize future market potential in this field. The analyses aim to establish an improved understanding of the types of policy and regulatory frameworks that can be both regulatory efficient and socially acceptable.

9.5 Commercialization of research results

The knowledge of how different policy instruments interact and how they work to promote wind energy development is sparse and only sporadically analysed, although the consequences of employing the 'wrong' policy-mixes are far-reaching. Such research would therefore make a significant contribution not only to policy analysis in general by generating a more sophisticated understanding of the interaction between different types of regulations and policy means and their impact, but also specifically to policy making aimed at developing wind power in a cost-effective, regulatory efficient and socially acceptable way.

Appendix A
Members of the Danish Research Consortium for Wind Energy

Advisory Board

Name	Job title	Organization
Christina Aabo	Head of R&D	Dong Energy
Hanne Thomassen	Advisor	Danish Energy Agency
Henning Kruse	Director Government Affairs	Siemens Wind Power
Jacob Lau Holst	Chief Operating Officer	Danish Wind Industry Association
Klaus Jacob Jensen	Senior Director	Rambøll Energy
Klaus Rosenfeldt Jakobsen	Research administration and funding	Innovation Fund Denmark
Lars Christian Christensen	Vice President	Vestas Wind Systems A/S
Lars Fuglsang	Vice President	LM Wind Power
Morten Basse Jensen,	Business Development CEO	Offshoreenergy.dk
Per Hessellund Lauritsen	Research Manager	Siemens Wind Power

Steering Committee

Name	Job title	Organization
Carsten Thomsen	Director of Engineering	DELTA
Eskild Holm Nielsen	Dean	AaU
Jens Roedsted	Director, Market and Innovation	FORCE
John Dalsgaard Sørensen	Professor	AaU
Jørn Rasmussen	Director, R&D and Quality Management	DHI
Leo Pedersen	Associate Professor	AU
Martin Greiner	Professor	AU
Peter Hauge Madsen	Head of Department	DTU Wind Energy
Peter Hjuler Jensen	Deputy Head of Department	DTU Wind Energy

Coordination Group

Name	Job title	Organization
Birgitte Bak-Jensen	Associate Professor	AaU
Carsten Thomsen	Director of Engineering	DELTA
Flemming Rasmussen	Head of Section	DTU Wind Energy
Florin Iov	Associate Professor	AaU
Frede Blaabjerg	Professor	AaU
Hans Jørgensen	Head of Section	DTU Wind Energy
Henrik Bredmose	Associate Professor	DTU Wind Energy
Henrik Carlsen	Head of Department	DTU Mechanical Engineering
Henrik Kofoed-Hansen	Head of department, Ports & Offshore Technology	DHI
Henrik Madsen	Head of Section/Professor	DTU Compute
Jens Carsten Hansen	Head of Section	DTU Wind Energy
Jens Nørkær Sørensen	Head of Section/Professor	DTU Wind Energy
Jens Roedsted	Director, Market and Innovation	FORCE
John Dalsgaard Sørensen	Professor	AaU
Lars C. T. Overgaard	Associate Professor	AaU
Leo Pedersen	Associate Professor	AU
Niels Leergaard Pedersen	Associate Professor	DTU Mechanical Engineering
Ole Steensen	Manager Innovation and Technology	DELTA
Ole Svenstrup Petersen	Chief Engineer at DHI and Civil Engineering Consultant	DHI
Ole Thybo Thomsen	Professor	AaU
Peder Klit	Associate Professor	DTU Mechanical Engineering
Peter Hjuler Jensen	Deputy Head of Department	DTU Wind Energy
Pierre Pinson	Professor	DTU Elektro
Poul Hummelshøj	Head of Section	DTU Wind Energy
Thomas Buhl	Head of Section	DTU Wind Energy

Work Package Leaders

Work Package	Name	Job title	Organization
1. Wind resources and climate design circumstances	Hans E. Jørgensen	Head of Section	DTU Wind Energy
2. Aero dynamics, aero acoustic and aero servoelastic design	Flemming Rasmussen	Head of Section	DTU Wind Energy
3. Structural design, materials and engine elements	Lars C. T. Overgaard	Associate Professor	AaU
4. Electric design	Frede Blaabjerg	Professor	AaU
5. Wind integration in the electrical system	Poul E. Sørensen	Professor	DTU Wind Energy
6. Offshore technology and O&M	Thomas Buhl	Head of Section	DTU Wind Energy
7. Experimental tests and measurements	Poul Hummelshøj	Head of Section	DTU Wind Energy
8. Societal aspects	Poul Erik Morthorst	Professor/ Head of Division	DTU Management
9. Environmental aspects	Henrik Skov	Consultant	DHI
10. Education	Jens Nørkær Sørensen	Professor/ Head of Section	DTU Wind Energy

About DFFV - The Danish Research Consortium for Wind Energy

Vision

The Consortium is the leading platform in Denmark in wind energy research and technology development and is the cornerstone of the interaction between industry and knowledge institutions in all areas of wind energy technologies including wind resource assessment and the environmental impact of wind energy.

The Consortium provides a framework for research and technology cooperation and innovation for the public and private sectors as well as experimental verification and demonstration, testing, education and training within wind energy. The collaboration aims to:

- contribute to the development of the wind energy industry and more efficient wind turbine technology to lower cost of energy
- provide research-based knowledge to change the energy system in Denmark to a coherent system based on renewable energy
- operate as an entry to international research networks in wind energy
- increase the value creation of the consortium members

Tasks

The tasks of the consortium are within the field of wind energy and in cooperation between the consortium partners to:

- develop and maintain research competencies in specialist areas of strategic importance for the industry, system administrators, public authorities, consultants and other key stakeholders
- conduct strategic research at a high international level
- conduct research and development in collaboration with or for companies or institutions
- ensure the quality and relevance of the research with the utilization of the partners' core competencies
- advise and conduct studies for public authorities
- contribute to the education of candidates, industry researchers (PhD's and post docs) or PhD's
- contribute to the training of staff
- run dissemination of knowledge activities, including seminars and continuing education activities
- hold wind energy conferences regularly
- develop and organize international master and PhD programs and courses

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Learn more about Danish Research Consortium for Wind Energy on **www.DFFV.dk**