Research Alliance
Wind Energy

JOINT RESEARCH FOR THE AGE OF RENEWABLES

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EDITORIAL

Dear Reader,

Just started in 2013 as an unconventional and untried alliance between state and federal research entities the German Research Alliance Wind Energy (FVWE) is already coming of age. The joint mindset of the 600 DLR, ForWind and Fraunhofer IWES researchers – to deliver excellent and innovative R&D support to the national and international wind energy community – has created a trustful atmosphere in which new concepts, models and technologies have been conceived in fast and successful manner.

The first joint research project SmartBlades has been a success from the very beginning and the follow-up project SmartBlades2.0 has just started. The considerable funding of the German Federal Ministry for Economic Affairs and Energy allowed us to transfer the compiled knowledge and skills to a level, where industry partners have shifted their position from observers and advisors to full project partners, which make active use of the new findings. This brochure gives you a compact update on FVWE's SmartBlades activities.

Inimitable and dedicated research and test infrastructures have been and will continue to be a unique feature of FVWE. The most recent additions to our laboratory pool are the Dynamic Nacelle Testing Laboratory (DyNaLab), the Generator Converter Laboratory (GeCoLab), or the Large Turbulence Wind Tunnel (WindLab), which all can be used for purposes ranging from fundamental R&D to industrial testing. The in April inaugurated Center for Industrialized Rotor Blade Manufacturing (BladeMaker) – briefly introduced in this brochure – is an excellent example, how we transfer knowledge from fundamental findings (e.g. nano modified materials in rotor blades, see LENAH article) to touchable results.

We are very happy that our efforts and goals – supporting the wind energy industry – are recognized and welcomed by partners from industry, science and politics. Feeling honored by the North German Science Award, which we received in 2014 for FVWE's outstanding cooperation, we are also pleased to see that our ambitions are perfectly in line with the ideas and concepts of a European Energy Union, as you can read in the interview with EC vice-president Maroš Šefčovič.

Watching our ideas, results and findings coming to live is our driver. If we can support you and your business, please challenge us!

Best regards,
the FVWE Steering Committee

FVWE Steering Committee: M. Wiedemann, B. Rollert, R. Rolfes, A. Reuter, A. Wagenknecht, S. Barth, M. Kühn, K.-D. Thoben, B. Milow, J. Tessmer (missing: S. Keller, J. Wenske)

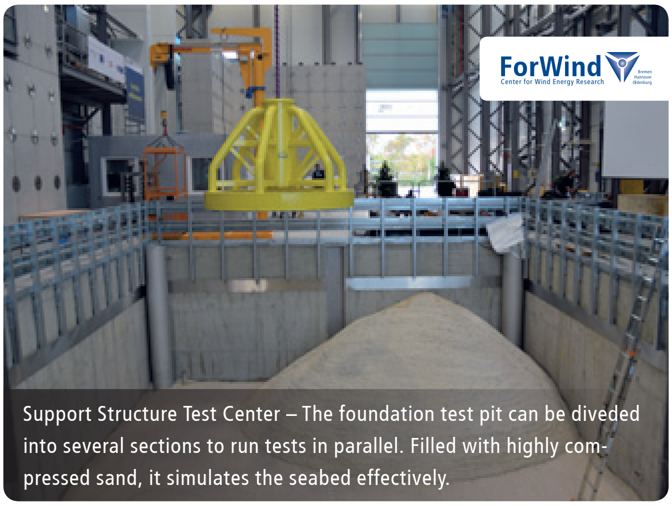
Content

The Research Alliance Wind Energy, founded in 2013, combines the know-how of more than 600 scientists and generates groundbreaking stimulus for the energy supply of the future. The three partners – German Aerospace Center (DLR), ForWind – the Center for Wind Energy Research of the Universities of Oldenburg, Hanover and Bremen and Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) North-West – are able to successfully carry out major long-term and strategically important projects, thanks to their manpower and strong ties to major industry players, politics and research institutions. The three partner collaboration enables uncomplicated access to a world-wide unique infrastructure, assures the technological transfer from the aeronautical industry and guarantees the link to university research and teaching.

►► www.forschungsverbund-windenergie.de

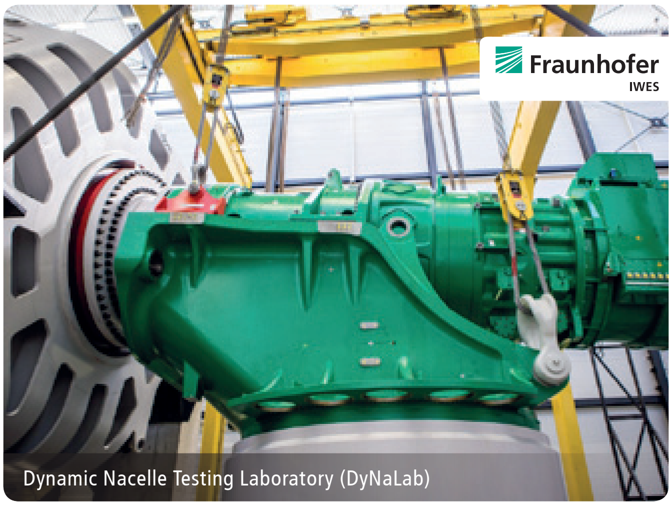
Center for Lightweight Production Technology (ZLP)

The Center for Lightweight Production Technology (ZLP), Stade (Germany) of the DLR Institute of Composite Structures and Adaptive Systems, Braunschweig (Germany) is performing research on the automated production of composite parts in an industrial scale. Herein the focus is put on the realization of higher production rates, improved part quality and lower production costs. In the last years the investigation of processes for the manufacture of rotor blades has become an important field of research at ZLP. Today, the infrastructure comprises a 20 m research rotor blade tool, equipped with numerous sensors for quality monitoring, and a Direct Roving Placement facility for the automated manufacture of dry fiber rotor blade preforms. This infrastructure allows to perform full-scale research in a pre-serial production environment.



Support Structure Test Center – The foundation test pit can be diveded into several sections to run tests in parallel. Filled with highly compressed sand, it simulates the seabed effectively.

The Test Center Support Structures for onshore and offshore wind turbines is located in Hannover-Marienwerder and offers two large-scale test facilities for industry and academic research: the foundation test pit for exploration and evaluation of support and foundation structures and the span for large-scale support structures for examining their fatigue behavior using multi-axial loading. Additionally the GeCoLab (test bench for generators and converters) is available. In order to be able to fulfill preliminary tasks and accompanying examinations, the test center has special laboratories for steel, concrete, composites and geotechnical studies. Furthermore it is equipped with an autoclave, a resonance test machine and a salt water spray chamber. By using support structure designs which are technically reliable and economically efficient, plant availability and thus cost efficiency is achieved.



Dynamic Nacelle Testing Laboratory (DyNaLab)

In 2015 Germany´s first test facility for complete nacelles of wind turbines has started operation. The DyNaLab offers wind turbine manufacturers reliable tests under realistic conditions in the laboratory, contribute to the evaluation and optimization of established and future turbine concepts. The aim of tests on the test bench is to considerably shorten the certification process. With the grid and the hardware-in-the-loop wind load tests, loading scenarios can be simulated in a reproducible manner. As such, operational management and control can be optimized and models validated. This makes an important contribution to increasing the reliability and availability of turbines and, at the same time, also reduces maintenance and repair costs.
Beside the nacelle test rig the DyNaLab offers the possibility and infrastructure to execute customized component tests (e.g. fatigue tests of main shafts).

INTERVIEW WITH MAROŠ ŠEFČOVIČ
VICE-PRESIDENT OF THE EC IN CHARGE OF THE ENERGY UNION

In the future energy system wind energy will play without any doubt an important role. Where do you see advantages and challenges with respect to this technology?

Wind is a renewable energy source that will without a doubt continue to play an important role in global energy systems, and its role is only bound to grow. One of the leading advantages of wind power is that its driving source is available all across the globe, yet its intermittency leads to problems of volatility, system instability and higher costs for producers. Fortunately, new research and development in this area has helped produce solutions for many of these issues, so technology and innovation are keys for the success of wind energy in Europe and worldwide.

Hence, EU policy and the energy market stakeholders need to fully capitalise on these developments in order to fully accommodate for potentials and challenges of wind energy in electricity grids, especially in light of developing a fully integrated EU energy market. In terms of policy, promoting interconnectors and creating the right market design and conditions for renewable energy sources will greatly benefit the generation and supply of wind-based electricity. While interconnectors will allow Member States that have less windy metrological conditions to access energy from Member States with more favourable wind conditions, revising the energy market design will step up regional cooperation between Member States and drive investment through accurate price signals. We should also not forget the storage systems which deal with network stability or safety of energy supplies, whereas promoting smart energy systems will go a long way to ensuring optimal access for wind energy into the electricity grids. This means that technology and innovation are the keys for success of wind energy in Europe and worldwide, and I am confident that Europe will keep its leading role in research and innovation of wind energy related technologies.

These policies have been reflected in the Energy Union framework under which the European Commission will deliver a revision of the Renewables Directive and legislative proposals on the Electricity Market design and the regulatory framework by the end of 2016.

In an Energy Union all member states have to work together in order to build a renewable European energy system and so does the energy research community. For the wind energy sector the European Energy Research Alliance and the European Academy of Wind Energy are two major platforms for international cooperation. Would you say that those platforms are good examples for international joint research?

The European Energy Research Alliance (EERA) is a showcase example of the EU's Strategic Energy Technology Plan. It brings together 160 research organizations from across Europe that build on national initiatives, yet pool and share research between the organizations. EERA also cooperates with European industrial platforms in order to align research and innovation priorities. Moreover, not only does this research platform work on European level, yet it also cooperates with non-EU research partners as part of its Joint Projects.

Similar things can be said for the European Academy of Wind Energy (EAWE), which connects numerous European academics and research institutes specialising in wind energy. I also had the pleasure of meeting their representatives in Oldenburg during my Energy Union Tour.

Both are clear examples of how Europe can be stronger by bringing together and sharing its different strengths. One could say it is an example for the EU's motto „united in diversity".

My experience during the Energy Union tour has shown me that Europe needs such research alliances in order to overcome the mostly national approaches that we have been experiencing. In my view alliances such as these also represent one of the main ways the EU can achieve three objectives of a clean, secure and affordable energy system. Therefore, I am always happy to see the research community working together across European and international borders.

The individual national wind energy research activities and the respective funding are the backbone of joint European research. How do you evaluate the German wind energy research and where do you see its position and focus in the next decades?

Germany performs above EU average in terms of research and innovation areas of the Energy Union. These activities were fostered by a strong national wind energy market that recently gained momentum including for off-shore installations. In 2015 the net increase in installed wind turbine capacity was the second highest in history: 3.5 GW by 2015 after 4.4 GW in 2014. Moreover, German leadership in renewables is particularly striking in terms of innovation, where Germany stands at much higher levels than any of the major competitors.

The recent ambitious agreement concluded in Paris calls for a speed-up of the electricity market transformation process on European level, including in Germany. Concerning R&D activities within the ongoing German 6th Energy Research Programme, the Federal Ministry for Economic Affairs and Energy (BMWi) provided 38,51 million EUR of funds for 63 new research projects in 2014. The efforts intend to lower the costs by increasing the yields and making wind farms' operation more reliable.

The German Aerospace Center, the Center for Wind Energy Research - ForWind, and the Fraunhofer Institute for Wind Energy and Energy Systems Technology form the German Wind Energy Research Alliance – a collaboration of approximately 600 researchers, who operate massive research infrastructures, e.g. rotor, nacelle, and substructure test stands, wind tunnels, super computers, etc. What do you expect from such an alliance in a European context?

The German „Forschungsverbund Windenergie" is a lighthouse alliance of research organizations in the sector originating from different German states. It has supported the development of relevant technologies, such as Smart Rotor Blades that do adapt more effectively to wind flows. It was awarded the North-German scientific prize 2014 for outstanding cooperation in energy research, the „Norddeutscher Wissenschaftspreis 2014 für herausragende Kooperationen in der Energieforschung".

Increased world-level competition in line with a move towards larger wind turbine dimensions and thus the need for larger, more complex and higher cost wind turbine components and test equipment may require a higher level of specialization and a more coordinated research approach of European research centres in the medium-term. In this context it is good to see that Forwind, Fraunhofer and DLR are playing an active role in the European Energy Research Alliance Joint Programme on Wind Energy and that Forwind is leading the European Academy for Wind Energy. In this way they strengthen the whole European Wind Energy community. It is important to work together to keep a competitive advantage in the highly competitive wind energy sector.

The export of wind energy technologies is an important part of the business too. Where do you see auspicious markets and chances for the European industry and R&D sector?

As a leader in developing innovative renewable energy technologies, Europe needs to continue seeking out new markets around the world for exports of these technologies. National climate pledges in emerging markets and the ambitious deal in Paris could spark an export boom for the European wind industry. China, India, Morocco, Brazil and Turkey are a few of the countries that have made post-2020 national pledges on the deployment of wind energy in the coming years.
Europe is now home to three of the world's five largest wind turbine makers with installed wind capacity able to meet over 10% of electricity consumption across the continent. Nevertheless, to keep this position European industry should consider the specificities of these markets. As an example: we are leaders in the offshore wind energy market but this is limited to relatively shallow waters. Floating offshore wind might be much more interesting for other markets. For both fixed and floating offshore wind there is a need to realise cost reductions and the European industry and R&D sector can contribute to this. However, despite the clear economic benefits, there is a risk that a potentially limited ambition from EU countries on renewables post-2020 puts a big question mark over whether Europe will realise its huge export opportunities.

In your opinion, where could the wind energy community learn from other sectors and also vice versa?

I believe that the wind energy community, especially here in Europe, has achieved something wonderful and truly amazing. Whereas 20 or 30 years ago it was a small group of people who believed in wind power, now it is a blooming industry with a global potential. They have managed to prove their potential and success, even though an overwhelming majority of the population, including some decision-makers, did not see their potential for a great breakthrough. I believe there is a great drive in the wind energy community to face any challenges head on – I even remember one engineer in Denmark who told me during the Energy Union Tour: give us a challenge, tell us what you need, we'll find a solution! So, what we can learn from the wind energy community is to believe in what you are doing, to not give up, and to believe in the potential of research, technology and innovation for your business.

On the other hand, there has to be a business case and a clear demand. While subsidising the use of new green technologies is certainly important, even best idea doesn't help if no one is ready to implement or buy it. Everything depends in the end on the people who shall use it. But I can see that these considerations are fully taken into account by the wind energy community. Therefore, I am convinced that wind energy is part of the solution to our triple challenge of sustainable, secure and affordable energy.

Jan Tessmer (DLR), Antje Wagenknecht (Fraunhofer IWES),
Maroš Šefčovič (Vice-President of the EC in charge of the Energy Union), Stephan Barth (ForWind)

SMART BLADES

New ideas for making rotor blades more efficient

In the Smart Blades project new concepts for intelligent rotor blades are developed which can adapt efficiently to different wind conditions. Smart Blades was a three-years research project, funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) with € 12 million.

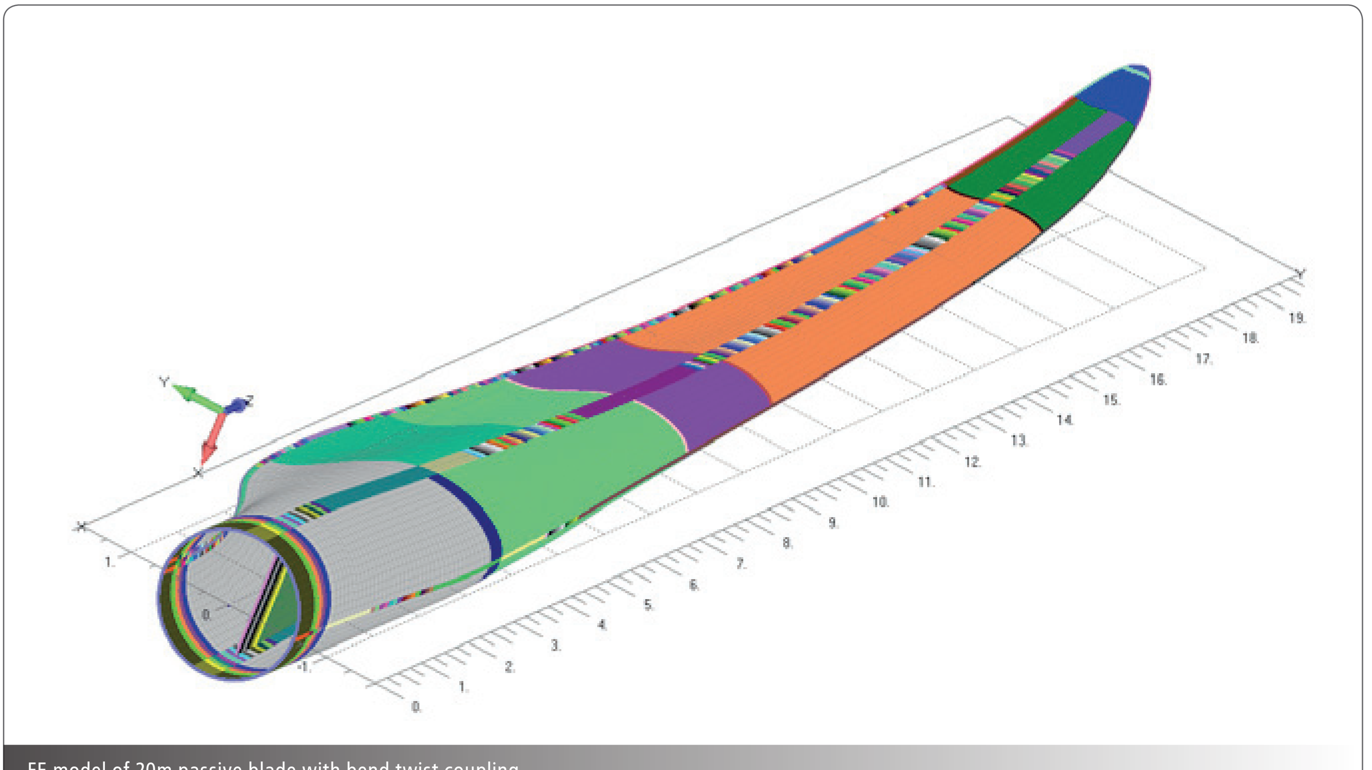
Nowadays, wind turbine rotor blades can reach up to 85 meters in length and the turbines themselves can tower more than 200 meters above the ground. Consequently, rotor blades are subject to severely fluctuating wind loads due to the difference in wind distribution close to the ground and at the top end of the turbine. The result is high loads for the rotor blade material and an enormous challenge when it comes to the control system. In the case of storm winds in particular, the wind load can be so large that turbine operators are even forced to power the systems down in order to avoid damage. From a cost-efficiency perspective that is particularly bad, as stronger wind translates to higher energy yields. The ideal solution would be rotor blades, which are able to adapt their geometry to suit the local wind conditions. This is made possible by active and passive technologies which allow individual rotor blades to adjust to the prevailing wind conditions – so-called smart blades. The Smart Blades project – in a joint effort between researchers from the German Aerospace Center (DLR), Fraunhofer IWES and ForWind, the Center for Wind Energy Research of the Universities of Oldenburg, Hanover and Bremen – aimed at investigating the effect of these technologies. The findings of this project offer turbine developers and operators new information and tools allowing them to launch more effective, more cost-efficient and more reliable system designs on the market.

Intelligent structures react to wind turbulence

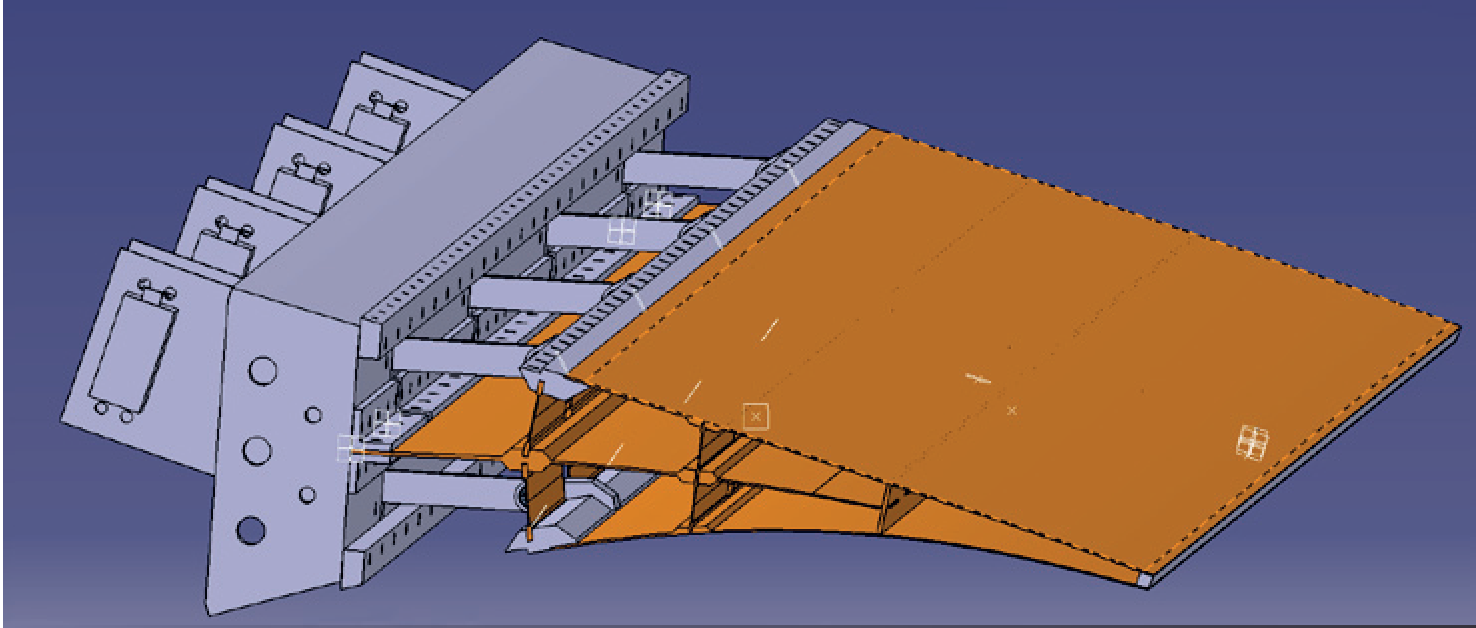
When a rotor blade – subject to high wind – turns in such a way that it offers the wind a smaller contact surface, researchers speak about end-twist coupling (BTC). As this bending is initiated by the force of the wind alone, it is described as a "passive" mechanism. The investigation focused on two approaches which produce this effect. On the one hand, a crescent-shaped geometry was examined and, on the other, a particular structure was employed for the material composition of the rotor blade. In this structural approach, the glass fibres within the rotor blade layup are arranged in such a way that they induce local drilling rotations on top of the global blade pitch at different wind speeds "The advantages of the mechanisms are that the blades can be built with a less robust design and are therefore lighter. Both processes have the potential to improve the energy utilization of wind power systems," says Alper Sevinc, who was Smart Blades technology coordinator for the bending-torsion coupled rotor blades at Fraunhofer IWES. The researchers now hope to be able to investigate the mechanisms tested in the simulation on already designed demonstration rotor blades in the upcoming project SmartBlades2.0.

Active control elements in the rotor blade

Another approach pursued by the scientists applies active mechanisms which adapt the trailing edges of a rotor blade and which system operators can use to control the aerodynamic loads on a rotor blade. In this respect, the researchers examined both flexible and rigid trailing edge flaps. The concept was inspired by the aviation industry and is comparable to the flaps on the wings of aircrafts. The investigations revealed that both



FE model of 20m passive blade with bend twist coupling



Structural concept for active trailing flaps

options effectively reduce the load on the rotor blade. However, the maintenance efforts required for rigid trailing edge flaps are so high, due to the soiling of the moving parts, that the advantages of flexible trailing edge flaps outweigh them substantially. The construction of demonstration blades for this concept is also planned at a later point. However, in a next step within SmartBlades2.0 this technology shall prove its effectiveness and reliability on segment level under real environmental conditions.

Flexible leading edge flaps create an optimal profile

The researchers also considered whether a flexible leading edge flap on a rotor blade can improve the efficiency of wind turbines subject to heavily fluctuating, turbulent wind conditions. This mechanism enables optimal use of a rotor blade in a large wind speed range. "The advantage in this respect is in the reaction speed of the flexibility of the leading edge flap, which allows on rapidly influencing the active aerodynamic forces in turbulent influx conditions," says Michael Hölling, Smart Blades technology coordinator for rotor blades with flexible leading edge flaps at ForWind, commenting of the potential of the adaptive leading edge flap. The concept of the flexible leading edge flap was tested in a wind tunnel during the past project and delivered very promising results for further investigations in the future project.

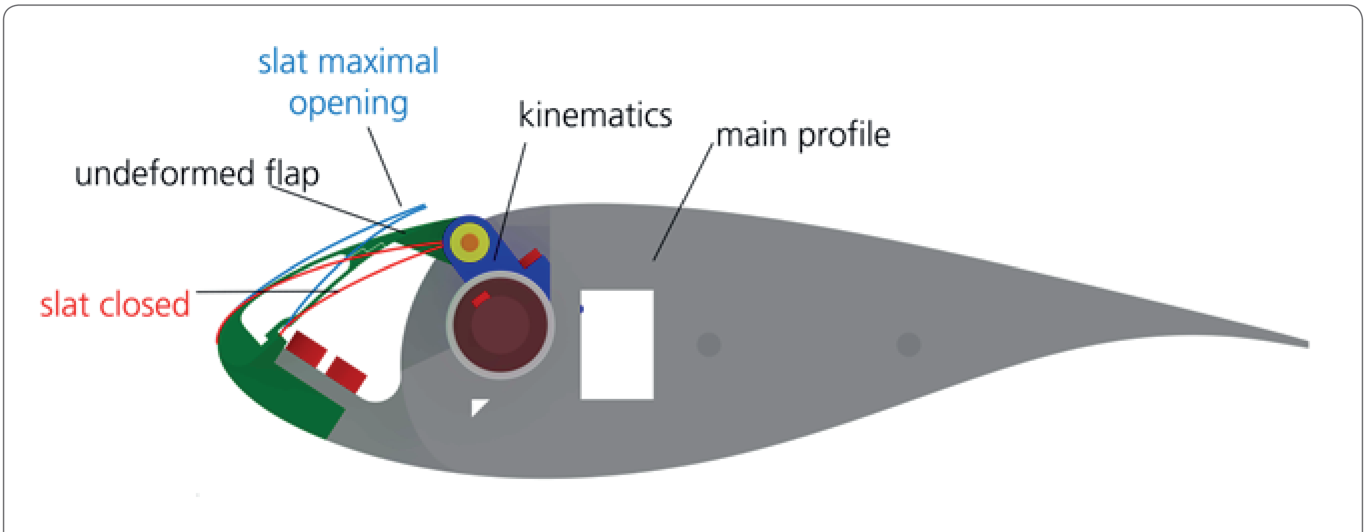
In addition, the researchers also assessed the cost-efficiency of the technological developments. They compared all the mechanisms with a state-of-the-art reference system with an 80-meter-long rotor blade in simulations and came to the conclusion that many of the examined mechanisms could lead to improved rotor blades in the future. In a next step, the researchers plan

Daniel Schäfer
Henkel AG & Co. KGaA

The Smart Blade concept, with its innovative rotor blade design, is a very current research topic which requires a flexible and versatile bonding process. In order to better understand future composite bonding needs in the wind industry, Henkel is working closely with the Smart Blade Project Partners, supporting with its high strength polyurethane adhesives engineered under the Loctite brand.

Dr.-Ing. Johannes Rieke
Nordex Energy GmbH

The understanding of aeroelastic phenomena - especially dynamic aeroelastics - not only at the rotor blade level but on the whole system is of major importance for the further development of wind turbines. From our point of view the Smart Blades II-Project team is a unique composition of partners from fundamental and applied research and from industry and gives a good opportunity to improve knowledge on aeroelastics of wind turbines. Therefore we expect that the numerical and experimental investigations will help us to improve our design methods and tools for future blades.



Blade profile with leading edge flap

to test their results on full-scale rotor blades.
The Smart Blades project was one of the first large research projects conducted by the research alliance founded in 2012 to be completed successfully. "The outstanding cooperation within the group is reflected in the promising results delivered by the project. The project has shown that the different skills offered by the various partners complement each other and fit together ideally," stressed Ceyda Icpinar, Smart Blades project manager from the DLR Institute for Composite Structures and Adaptive Systems. The successful completion of the project has not only cleared the way for further joint activities in the field of intelligent rotor blades, but has also laid solid foundations for future projects in the wind energy sector as a whole.

In the upcoming project SmartBlades2.0 it is planned to manufacture and test a rotor with BTC-blades in order to validate concepts and methods developed recently. The team of researchers of the FVWE will be enhanced by several industrial partners. This will assure investigations and developments with a clear focus on affordable performance and industrial usability.

►► www.smartblades.info

Dr. Fabio Bertolotti
SSB Wind Systems
GmbH & Co. KG

SSB Wind Systems has been, and continues, to be a leading supplier of blade pitch control systems for the entire span of wind turbines in the market, as well as blade sensors for blade aerodynamic and structural performance evaluation. SSB Wind Systems is proud to supply its BladeVision system to the Smart Blades Project for accurate blade torsion measurements, as well as flap and edgewise deformation, along the span of the passive flat-twist coupled blade that will be field tested in Phase II of the Project.

Dr.-Ing. Andree Altmikus
WRD GmbH

After observing the research on ambitious precompetitive active blade technologies in SMARTBLADES fulfilling our role as industrial observer, WRD gained interest in a more active role in order to verify research assumptions on operative industrial level. The envisioned technologies imply an even stronger interdisciplinary collaboration of development engineers and design methods. SMARTBLADES 2 ambitions thus call for a stronger teaming-up and networking between leading research institutions and industrial stake holders, which WRD is pleased to foster on behalf of ENERCON.

Industrialized rotor blade manufacturing

Rotor blades have a cost share of about 20 per cent of onshore wind turbines. The project "BladeMaker" has been set up to achieve savings of up to 10 per cent through more efficient production processes, the use of innovative materials and carefully selected automation approaches. A verified cost model that has been developed in close collaboration with a large number of blade manufacturers has confirmed the feasibility of this aim. In contrast to a purely automated approach, BladeMaker is focused on the industrialization of the entire process. In this context, new materials or the consistency of the semi-finished products have to be improved in order to open up further opportunities for reducing costs and manufacturing time.
In addition to an innovative process chain for rotor blades, Fraunhofer IWES and specialized partners have set up a direct tooling approach to shorten the time-to-market for rotor blade molds and blade prototypes. The BladeMaker project will end in fall 2017 with a full-scale process demonstration using a blade design developed by Fraunhofer IWES.

The BladeMaker demonstration center has been set up as an open platform to the industry for the joint development and testing of innovations together with Fraunhofer IWES and 15 partners. Blade sections measuring up to 25 meters (scale 1:1) for blades in the 50-meter class can be used in the workshop. Production processes can be tested in a reproducible way on a flexible gantry system. The carbon fiber framework design of the gantry system combines the precision of a milling machine with high speed operation at up to 2.5 m/s and a load bearing capacity of up to 400 kg. Thanks to the flexible and integrated CNC control, various production steps, which would normally be conducted at different machines, can be performed at the same workstation by simply changing the process head. Rotor blade molds, handling jigs, mixing machines and a textile cutter can be used to evaluate a large variety of different production processes. The project is funded with EUR 8 million by the German Federal Ministry for Economic Affairs and Energy.

Milling of a tool mold of a 40 meter blade

LENAH
Hybrid material for wind turbine blades

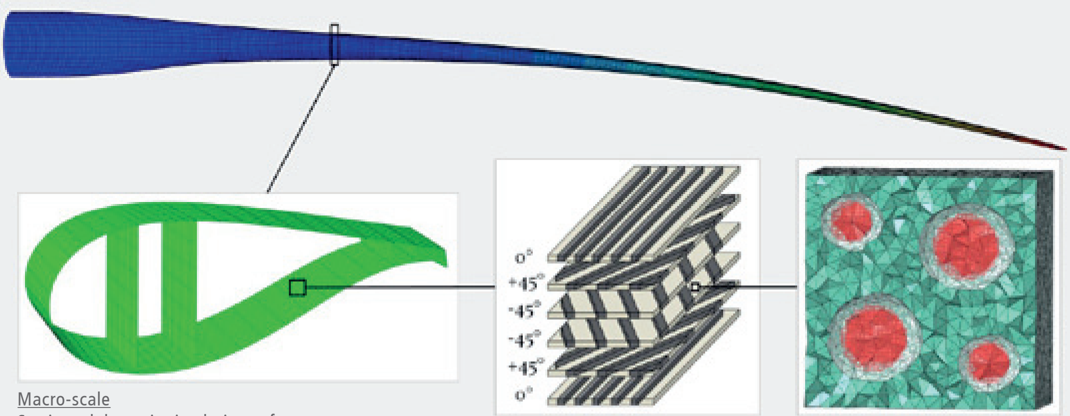
The economical success in establishing renewable energies in Germany and other countries heavily depends on the efficiency of the systems used for its generation. Therefore, increasing efficiency of the present systems is a major topic in international research. Considering offshore wind energy, which is and will be one of the most important sources for renewable energy, this increase of efficiency means to enlarge the length of the wind turbine rotor blades. Although today's blades can hold lengths up to 85m, the established materials, usually glass fibre reinforced polymers (GFRP), encounter their constructive limits.

One of the main problems concerning offshore rotor blades is the blade stiffness, which needs to be increased with increasing length. A large blade of insufficiently low stiffness may hit the tower under extreme loading conditions. A total loss of the turbine would be the result. A sufficient stiffness of future blades with today's established materials would either lead to very high weight in case of GFRP, or to inacceptable high costs in case of carbon fibre reinforced polymers (CFRP).

A second issue is the high fatigue resistance of the applied material, which is needed to withstand up to 100 million load cycles during a wind turbines lifetime of about 20 years. If the fatigue resistance of the materials applied is too low, cracks may grow within the blade, yielding its total loss at worst. The fact that future blades with lengths over 90m will have to withstand fatigue loadings of even higher amplitude than the largest blades of the present explains the urgent need for materials with an extremely high fatigue resistance. The application of traditional materials like GFRP or CFRP would again yield too heavy and too cost intensive constructions, respectively.
Within the LENAH project innovative material concepts are to be investigated, which offer the above characteristics. To do so, the project takes into account two important fields of material re-search: hybrid and nanomodified materials.

Nanomodified polymers are created by mixing nano particles with an average size of about 50 nm and conventional polymers. The interaction between the polymer molecules and the nano particles, which have a huge cumulative surface ('nano effect'), lead to improved mechanical properties of the material. This beneficial effect can be applied for fibre reinforced polymers, as well as for pure adhesive polymers. Within the LENAH project nano particle reinforced polymers are investigated by experimental tests and multi scale finite element simulations. First of all, atomistic simulations on nano-scale are performed to derive the unknown material properties, followed by micro-scale simulations, as well as component simulations on the macro-scale (see picture below). The major aim is to understand and characterize the influence of nanomodifications on the material properties. With the knowledge gained materials can be designed that merge the positive characteristics of the base materials and allow a more efficient design of wind turbine rotor blades.

A similar idea holds for hybrid materials, where the ideal aim is to create a material which holds the advantages of all the base materials. Within the LENAH project hybrid laminates made from GFRP and steel as well as GFRP and CFRP will be investigated. Here, not only the optimization of the resulting material properties is considered, but also the manufacturability and the profitability. GFRP-steel laminates are to be used within the load introduction area, where the blade is bolted to the hub of the turbine. Due to the bolt holes local stress concentrations occur, which can damage the brittle GFRP massively. Local application of much stiffer steel foils in between the GFRP layers results in a smooth introduction of the loads into the laminate. Once a certain distance from the in-troduction area is ensured, the metal foils are substituted by regular GFRP layers. This procedure yields a higher embedding strength in combination with a sufficient fatigue resistance within the load introduction area. The application of GFRP-CFRP laminates is an efficient method to locally increase the stiffness of the load carrying parts of the blade. These parts are in particular the girths of the bending-beams, which are hidden under the blade skin and generate the overall stiffness of the blade. The connection between the girths may then be made from much cheaper GFRP, since these regions add no significant bending stiffness to the blade.



Macro-scale
Static and dynamic simulations of components

Micro-scale
Modelling of the laminate setup and fibre-matrix interaction

Nano-scale
Atomistic material modelling and simulation of nano particle reinforced epoxy resin

Hierachic modelling of composite structures – from the structural (left) to the nano level (right)

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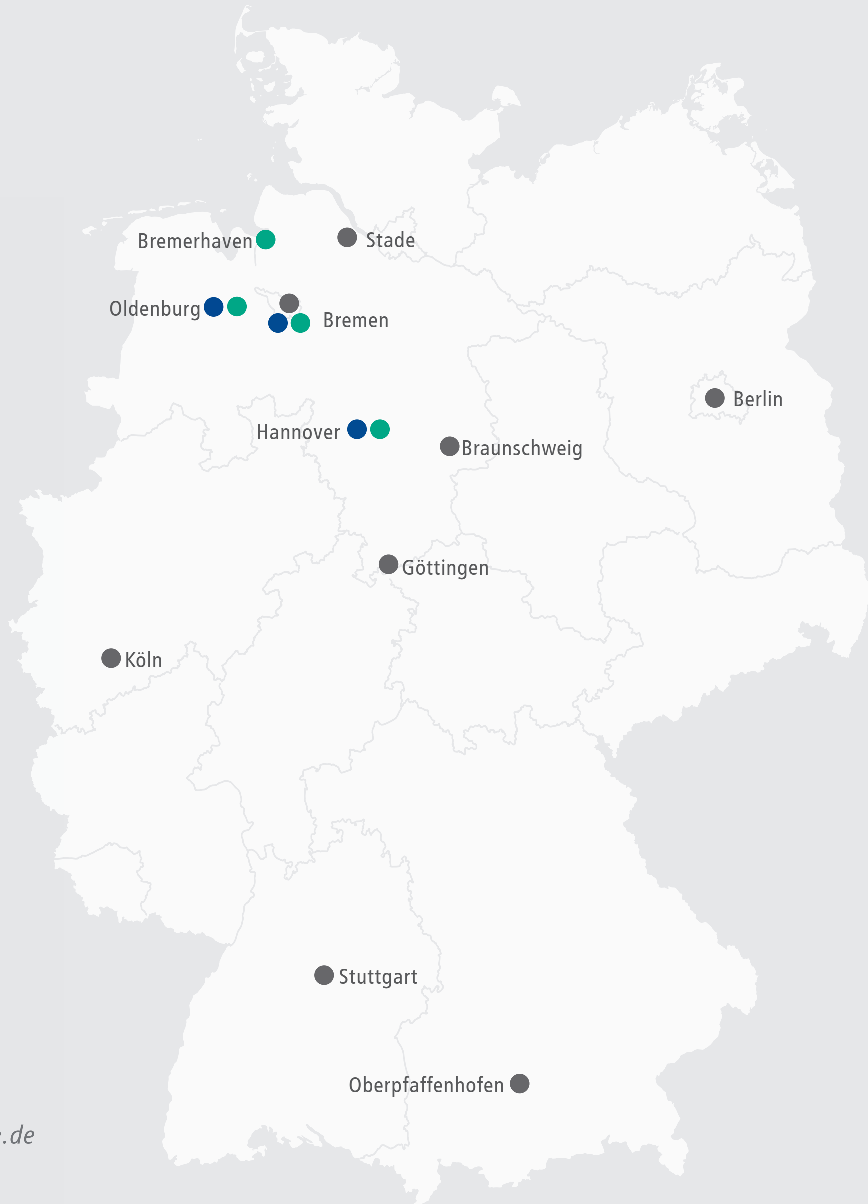

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