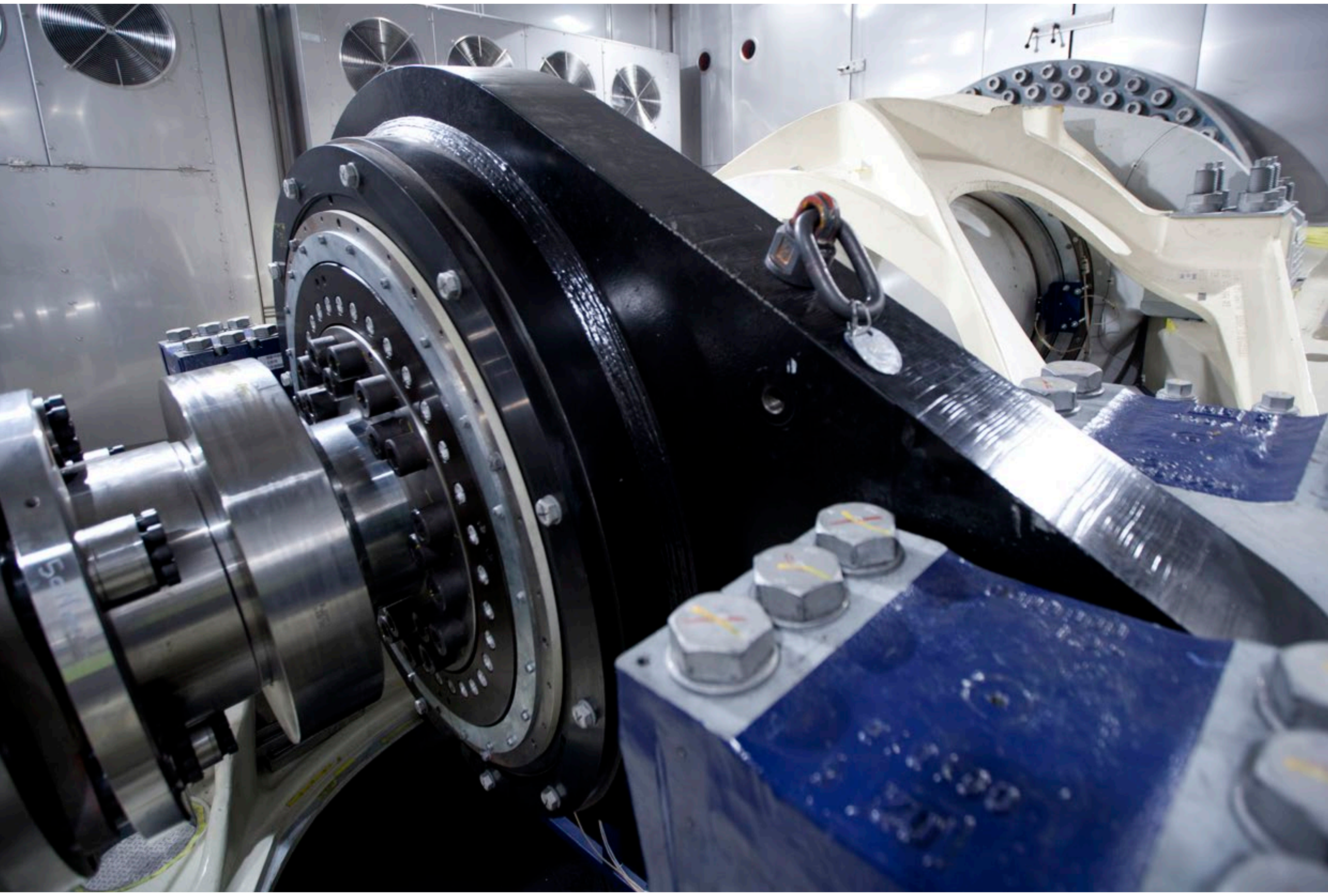
REPORT FROM MEGAVIND
JANUARY 2016



Test and Demonstration Facilities for Wind Energy Needed to Promote a Competitive Wind Industry in Denmark

MEGAVIND

Front page: Courtesy of Vestas Wind Systems A/S

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Østerild - National Test Centre
for Large Wind Turbines
Credit: OpenHouse/DTU

1. Preface

Megavind is Denmark's national partnership for wind energy, and acts as a catalyst and initiator of a strengthened strategic agenda for research, development, and demonstration (RD&D).

Megavind was established in 2006 with the aim of strengthening public/private cooperation between the Danish state, businesses and knowledge institutions in order to accelerate innovation processes within the wind industry.

Megavind's vision is for Denmark to continue to develop its position as the hub of globally leading companies and research institutions within the field of wind energy and to enable them to be the first to deliver competitive wind energy solutions in the world's main wind energy markets.

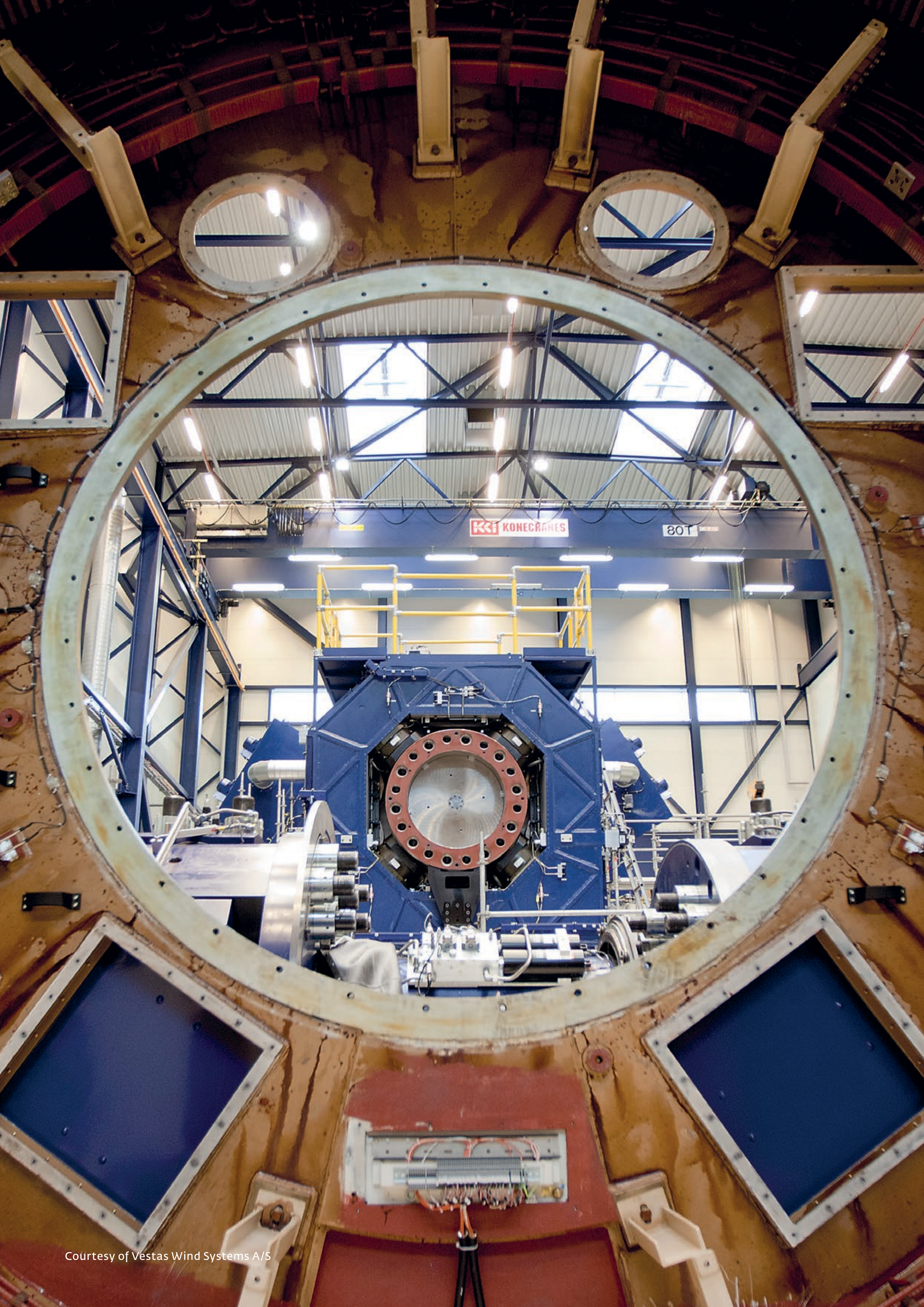
In this strategy, Megavind offers strategic recommendations for future test and demonstration facilities and competencies in Denmark along with a catalogue of ideas for the relevant activities and a global mapping of competing international test facilities.

The content of this strategy has been developed by a working group consisting of the following group of experts:

- Per Hessellund Lauritsen, Siemens Wind Power A/S
- Jesper Aagaard, Vestas Wind System A/S
- Peter Hjuler Jensen, DTU Wind Energy
- Kim Bertelsen, Global Lightning Protection Services
- Carsten Thomsen, DELTA
- Thor Ugelvig Petersen, DHI
- Erik Steen Jensen, blaest
- Lars Stylsvig Rasmussen, LORC
- Jakob Lau Holst and Emilie Kærn, Megavind Secretariat

The working group has received input from a large number of national as well as international stakeholders in the wind industry, using surveys and workshops to guide the analysis, and to ensure that the recommendations are a reflection of common priorities of knowledge institutions and companies located in Denmark.

The resulting working group analysis has been peer reviewed, and final agreement on priorities has been confirmed by the Megavind Steering Committee.



Courtesy of Vestas Wind Systems A/S

2. Key recommendations

Testing wind turbines, partial systems and main components under realistic conditions are necessary elements of evaluation and optimization of established and future turbine concepts. Succesfull testing and demonstration of concepts help shorten innovation time and secure development activities.

Testing is a key part of reducing the cost of energy (CoE) from wind energy, and therefore a key element of maintaining a competitive edge for wind energy, and for companies delivering solutions in this market.

Almost any part of a wind turbine can be tested in Denmark. From materials to blades, welding, the drivetrain and large components such as nacelles as well as full-scale turbines. However, as this report shows, there is still a considerable scope for increasing our knowledge and building upon the competencies already present.

Megavind's key recommendations on future national priorities within testing and demonstration of wind energy solutions are:

Facilities:

- **Ensure availability of additional test pads for full-scale wind turbines**
- **Further develop and strengthen Danish facilities and capabilities for full scale nacelle testing**
- **Develop a converter-based grid test facility for test of wind turbine generators (WTG's)**
- **Build test facilities for 100+ metre blades**

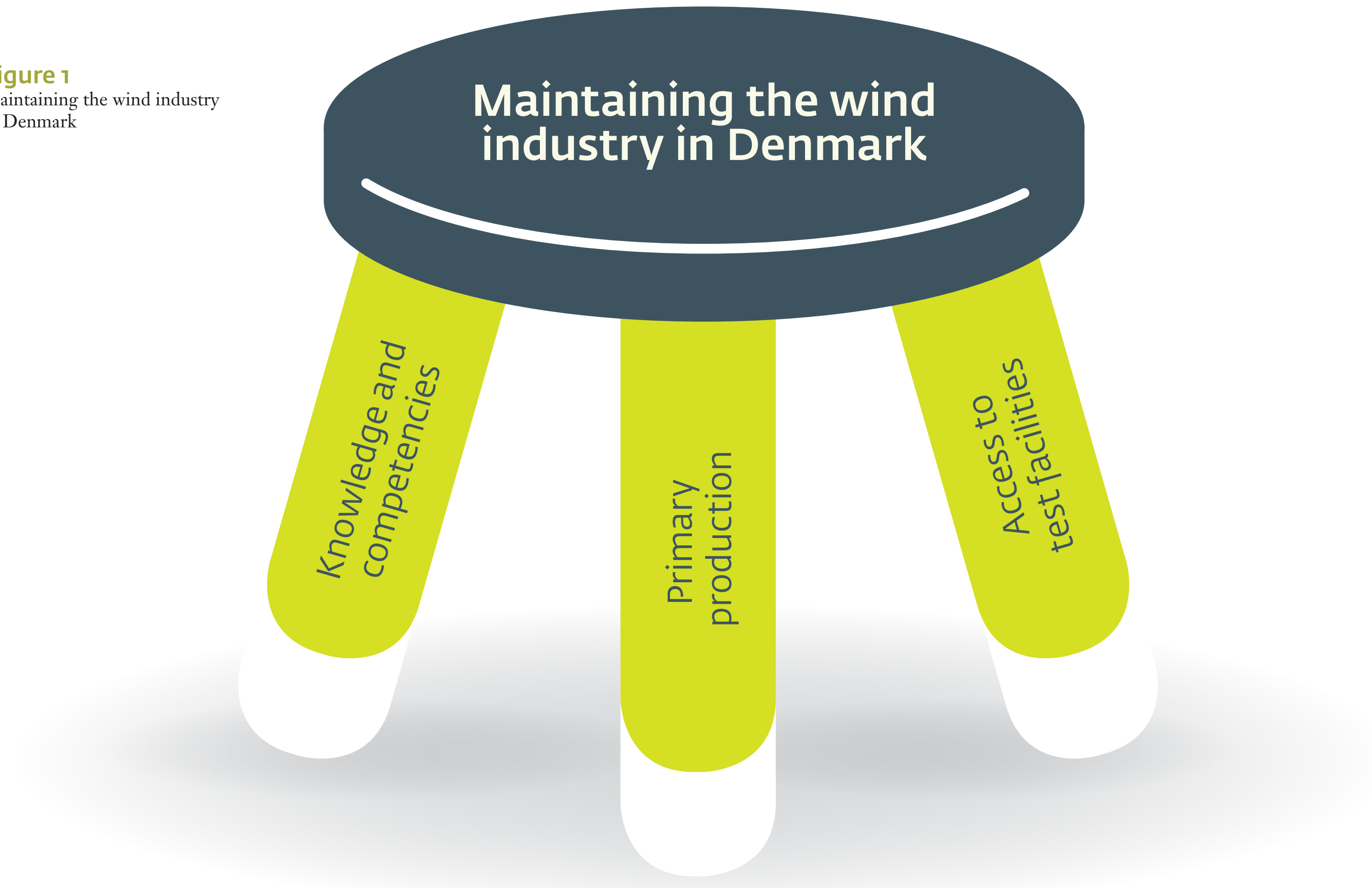
Competencies:

- **Improve our understanding of operational environmental conditions and develop more efficient, accelerated test methods.**
- **Develop more efficient methods for measuring offshore wind conditions**
- **Faster and more efficient, advanced blade-test methods**
- **Strengthen higher education in testing**

3. Mapping the priorities for test facilities and competencies in Denmark

The present strategy rests on the historic understanding, that there is a close interdependency between primary production of wind turbines in Denmark (and a stable home market), access to test and demonstration facilities, and a general level of knowledge and competence. These pillars are like the three legs of a milking stool upon which our competitiveness as wind energy hub rests. This is illustrated in the figure below.

Figure 1
Maintaining the wind industry in Denmark



If all three legs are regularly re-enforced, the position as leading hub can remain strong, and will accelerate the industry's ability to reduce cost of energy and be in the race to deliver the competitive wind energy solutions on market terms in the principal wind energy markets.

Access to test and demonstration is an important prerequisite for R&D departments to stay in Denmark. R&D departments are again closely linked to primary production facilities – the engineers benefit from being located closely to where turbines are built.

The wind industry is characterized by fierce global competition between several nations aspiring to be home to leading companies. To maintain Denmark's position as a global hub for wind energy, it is essential that Danish-based companies continue to have access to relevant state-of-the-art test and demonstration facilities and test competencies.

If one leg of a miking stool becomes weak, it looses it's balance. If opportunities for test and demonstration in Denmark becomes insufficient, R&D functions may begin to move to other places. If R&D begins to move out, there is a correspondingly higher risk of production being relocated.

If all three legs are regularly re-enforced, the position as leading hub can remain strong, and will accelerate the industry's ability to reduce cost of energy and be in the race to deliver the competitive wind energy solutions on market terms in the principal wind energy markets.

As the Danish wind energy hub is relatively advanced and strong, public research funding for test and demonstration of wind energy has historically been more than matched by private investments in research and development. Danish statistics show that every time public research funds and programs invest DKK 1 in wind energy research, development, demonstration and test, private companies invest DKK 5[1]. On a national basis DKK 1 of public research funding is matched by DKK 2 from the private sector.

The mapping has identified several areas where Danish companies and knowledge institutions have comparative strengths, and where it is of strategic importance to stay ahead.

The detailed mapping and a full catalogue of ideas can be found in annex A and B to the strategy. The recommendations are inherently different in scope and meets the demands of various stakeholders. The stakeholder process has resulted in eight prioritized key recommendations, that falls into two categories: Facilities and competencies.

The recommendations are detailed in the following chapters.

"Danish statistics show that every time public research funds and programs invest DKK 1 in wind energy research, development, demonstration and test, private companies invest DKK 5"

1 DAMVAD, Forsknings- og erhvervsmæssige styrkepositioner i den danske vindenergisektor, May 2014.

4. Methodology

In May 2013, Megavind published a revised main strategy that outlined the overall status of the RD&D environment in Denmark requiring separate strategic processes. This strategy responds to the recommendation “develop a new and revised, comprehensive innovation, test, and demonstration facilities strategy, including a benchmarking report containing a comparative analysis and mapping of available test and demonstration facilities globally”.

The present strategy is also a continuation of the 2008 Megavind strategy entitled “Testing and demonstration of wind turbines”, which analysed the need for demonstration sites in Denmark and made recommendations for planning and other initiatives relating to demonstration sites. Including recommendations for further separate thematic strategy processes. This strategy covers the recommendation.

The need for test and demonstration facilities covers the whole development chain from prototype and pre-series production to optimization of the early series production. On top of that, the need for testing and demonstration can be divided into short-term and long-term requirements – both being equally important.

To determine the industry interest for test and demonstration facilities, Megavind has received input to the strategy from a survey among The Danish Wind Industry Association's (DWIA) more than 250 members. In addition, interviews have been carried out with key players.

To get input for the final prioritization, Megavind ran a full-day workshop with more than 50 company representatives.

The global mapping of test infrastructure received input from the following test infrastructure partners: Aachen, Aalborg University, AEWC, BLAEST, CENER, Danish Technological Institute, DHI, DNV GL, DONG Energy, DTU Wind Energy, Energy research Centre of the Netherlands (ECN), FORCE Technology, Fraunhofer IWES, Global Lightning Protection Services, Lindoe Offshore Renewables Centre (LORC), Marine Renewables Test Centre, MassCEC, MTS, National Research Council Canada, NREL, ORE Catapult, SC&G Energy Innovation Centre, SGS, Technical Research Centre of Finland (VTT), ForWind & University Hannover, The Knowledge Centre for Wind Turbine Materials and Constructions (WMC), University of Stuttgart.

A workshop with presentations from CENER, IWES Fraunhofer, Aachen, DTU, LORC and Blaest, together with a panel discussion with Siemens Wind Power, Vestas and Envision which mapped the international expertise in testing and demonstration.

In the prioritization, the working group used a schematic breakdown of a wind power plant taken from the Megavind strategy entitled “A Strategy for Wind Turbine Components and Subsystems”.

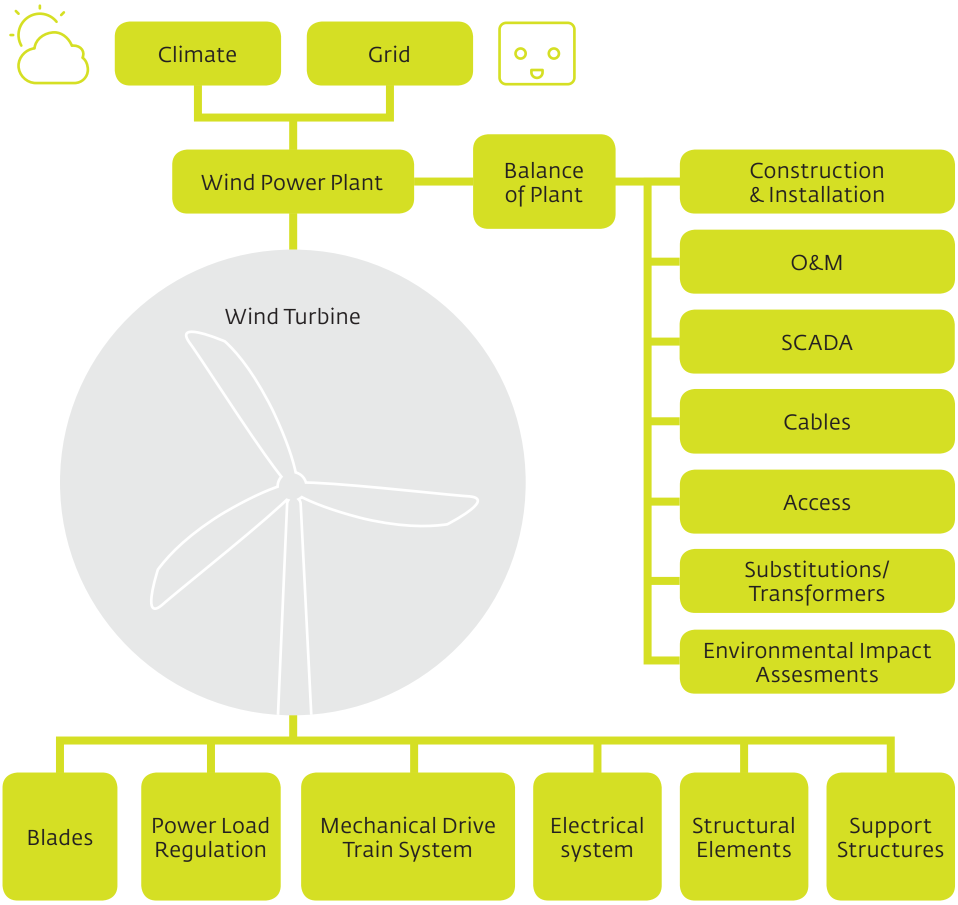


Figure 2
Breakdown

Category	Definition
Climate	Environmental impact, collection of data on external conditions
Grid	Grid test equipment relating to the physical net and system as well as wind integration in the grid
Wind Power Plant	Test on plant level
Balance of Plant	▪ Construction and installation ▪ O&M, including training facilities ▪ SCADA ▪ Cables (both onshore and offshore) and voltage levels ▪ Access, i.e. roads and harbours ▪ Substations/transformers ▪ Environmental impact assessment
Wind turbine	▪ Blades ▪ Power load regulation, i.e. advanced control systems within the turbine ▪ Mechanical drivetrain system (hardware) ▪ Electrical system, including the transformer, generator, converter, auxiliary systems, control system and condition monitoring ▪ Structural elements, including the hub, spinner, nacelle mainframe and housing, crane structure ▪ Support structures, including towers and foundations

Figure 3
Definition of categories

5. Priorities for test facilities in Denmark

Maintaining Denmark as a wind energy hub requires state-of-the-art test facilities. In order to maintain and develop the Danish position as a globally competitive wind energy hub and home to the world's leading companies and research institutes, it is vital to ensure that Denmark is home to competitive test facilities. Megavind considers the following four recommendations for investment in new test infrastructure to be important for the industry.

5.1 Ensure availability of additional test pads for full-scale wind turbines

The industry estimates that in the near future there will be a need for further new prototype test pads for full-scale wind turbines, similar to the existing.

Today we have two national test centres for testing full-scale wind turbines, at Høvsøre and Østerild. As both are fully booked several years into the future, manufacturers have no further ways of testing their new prototypes in Denmark.

Prototype testing is an important factor for industry competitiveness, and it is crucial for manufacturers to have access to a sufficient number of test pads near their development departments, as they continuously run measurement programmes and tests on their prototypes.

The increased need for new test pads is the result of an accelerated development of new and more competitive products. The market demands several different variants of these products, which again increases the demand for field testing in order to obtain certification. To ensure a minimum time-to-market for new products, several of their variants have to be tested concurrently, which requires more test pads. Thus the largest turbines can only be erected and tested at the Østerild - National Test Centre for Large Wind Turbines, as the availability of its test pads is reasonably predictable. The current capacity is consequently a limiting factor for the industry.

An insufficient number of test pads in the local area increases the risk that R&D activities will be moved outside Denmark – and hence also the jobs involved. Megavind thus recommends setting up additional prototype test pads.

5.2 Develop a converter-based grid test facility for test of wind turbine generators

Simple short-circuit equipment is currently sufficient to verify wind turbine grid compliance with the grid code requirements. Although converter-based equipment is more expensive, it can also be used for much more advanced tests. This is well understood by the US National Renewable Energy Laboratory, which has already established a converter-based test equipment known as the Controllable Grid Interface (CGI).

With an increasing focus on grid compliance, it is likely that future grid codes will require tests which can only be performed on converter-based equipment. As already stated in previous Megavind strategies, converter-based technology is needed for testing and verifying the response of wind power plants to frequency disturbances in the AC grid. Converter-based test equipment can additionally be used to test and verify interactions between wind turbine and HVDC converters. Such preliminary tests have already been carried out using the NREL CGI. It is extremely valuable to test the prototypes of new large offshore wind turbines in this way before they are used in large offshore projects.

The figure below illustrates how the proposed test facility could be connected for testing turbines. The grid emulator consists of the converter and software which controls the converter in real time so that it can emulate the specified grid conditions.

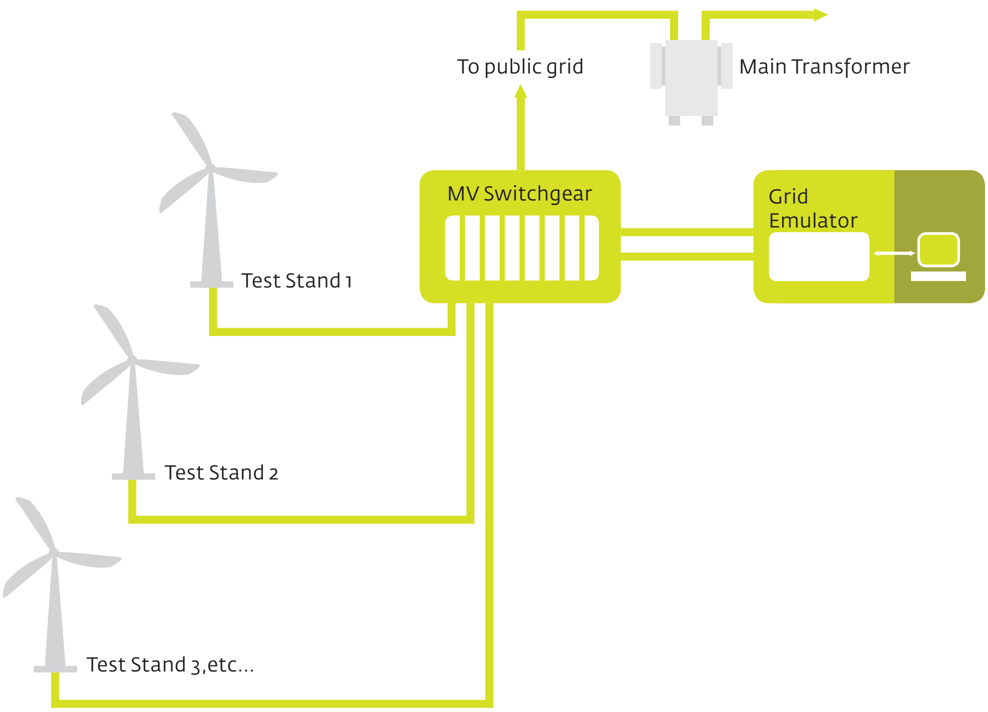


Figure 4
Proposal for converter-based grid test facility

Overall, this facility will contribute to ensuring that the necessary research, development and verification of system-supporting characteristics will take place in Denmark. Megavind therefore recommends the establishment of a converter-based grid test facility for WTG's.

5.3 Build test facilities for 100+ metre blades

Blades of up to 85 metres can currently be tested in Denmark, however as technology develops it will not be uncommon to see blades of more than 85 metres – especially for offshore turbines. At the moment, blades longer than 100 metres can not be tested at their full length anywhere. Such blades are already being developed, so a demand for testing them must be expected in the near future. There is therefore a need to establish a national test centre that can handle these types of blade tests.

5.4 Further develop and strengthen Danish facilities and capabilities for full scale nacelle testing

Testing of WTG nacelle under realistic conditions in test benches are efficient and necessary elements of validation, evaluation and optimization of existing and future turbine concepts and systems. Successful nacelle testing shortens the time for innovation, development and testing, helps design validation and documentation, and supports certification.

In Denmark, at Lindo Offshore Renewables Center (LORC), nacelle testing can be carried out for nacelles of up to 10 MW. LORC Nacelle Testing (LNT) is designed as a split test bench facility, with two docks for testing. One dock is a functional tester, testing the functionalities and performance of the nacelle as a fully integrated systems design, including test of software and communication signals to and from systems and components within the nacelle. Along with grid simulation, the functional tester, can also be used for certification purposes. The other dock is a mechanical tester, planned for 2016, with HALT test capabilities, that enables customers to reliably verify the expected lifetime quality level of a wind turbine nacelle as 20 years of operation can be simulated in less than 6 months.

The LORC Nacelle Tester is among a select handful of facilities globally, that offers full scale testing of wind turbine nacelles. Some of the other nacelle test facilities offer full scale test of even larger WTG nacelles and offer more support for testing. For all of the established nacelle test facilities, securing access is difficult and is therefore only possible for bigger players in the market.

While LORC offers world class services and is an undisputed part of the Danish competitive position, global competition is fierce. Therefore Megavind recommends to further develop and strengthen Danish facilities and capabilities for full scale nacelle testing.

Measurement of wind conditions
Credit: OpenHouse/DTU

6. Priorities for test competencies in Denmark

It is not enough to invest in infrastructure alone. The Danish facilities include all elements of the value chain for both onshore and offshore wind turbines as well as their installation. This full coverage also implies an unrivalled understanding of the overall turbine system and its interaction with the grid.

In order to develop and maintain this strong position and overall system understanding, it is important to eliminate potential bottlenecks and gaps in our knowledge of different areas. Megavind identifies the following four recommendations for investment in competencies and knowledge to be necessary for the industry. The recommendations are not listed in order of priority.

6.1 Improve our understanding of operational environmental conditions and develop more efficient, accelerated test methods

We currently have a good infrastructure for testing environmental conditions in a climatic chamber. However, many component suppliers do not have access to the knowledge about how exposure to different environmental conditions affects the whole turbine.

There is consequently a need to improve our understanding of the link between environmental conditions (e.g. wind, sand, dust, waves and atmospheric salt content) and the test specification, and to translate this knowledge into more efficient and faster, accelerated lifetime tests that demonstrate the operating life of the component in the field. Relative differences between designs are not at issue here – as the absolute lifetime and maintenance schedules need to be defined. The defined test specifications need to produce repeatable test results in order to provide reliable lifetimes.

These could include an analysis of the impacts from the conditions to which the wind turbine is exposed. This would give a better insight into which specifications would best demonstrate the real lifetime in a climatic chamber test, leading ultimately to the accelerated development of industry test standards in this field.

Megavind therefore recommends more analyses of operational environmental conditions so that the resulting knowledge can be used for more efficient lifetime tests of components.

6.2 Develop more efficient methods for measuring offshore wind conditions

Advanced methods for measuring offshore wind conditions, using techniques such as for instance LIDAR or meteorological towers, would be able to measure wind conditions directly and allow all the collected measuring data to be available publicly in a database.

As wind conditions are one of the most important variables in calculating the yields of future wind farms, it is very important to collect reliable data. This will ultimately lead to higher security and fewer risks for investors, resulting in lowering the CoE.

The aim is to measure and record wind speed, wind direction, temperature and pressure fluctuations in order to establish a more rugged and reliable design basis for offshore wind turbines, enabling the development of optimal and more cost-effective designs with respect to safety and long-term reliability. The design basis includes wind conditions as well as sea current and wave measurements, giving a more precise foundation for future wind turbines in the North Sea as well as a more reliable description of the environmental conditions in the other seas around Denmark. These could then be used to produce wind resource estimates and design calculations for future offshore sites.

6.3 Faster and more efficient advanced blade-test methods

Structural blade fatigue testing is normally carried out in two successive tests – a flap-wise test and an edge-wise test. However, this type of test does not correspond very well to the loading of the wind turbine blades in the real world, where the blade is exposed to simultaneous bending and torsion loads in different directions, resulting in more complex load cases. The industry consequently needs to develop combined fatigue test methods that better match the loads to which the blade is exposed in its real operating environment. An advantage of combined loading is that it enables more efficient testing of shorter duration which can cut the testing period by up to a half.

The main challenge of developing combined fatigue test methods is to control the load parameters (magnitude and direction) so that they reflect the loads to which the blade is exposed in its real operating environment. Moreover, it is an engineering challenge to develop reliable and cost-effective test equipment. The operation and control of a combined fatigue test with multiple axes will require at least two simultaneously operating advanced excitation mechanisms, whereas this currently uses one directional activator with a relatively simple electrically rotated mass.

A number of international test centres are already in the process of developing combined fatigue tests, and further development in this field is therefore essential if Denmark is to maintain its position as a wind power hub.

Specifically, there is a need to develop new test specifications and procedures for blades ensuring a more realistic load pattern that is closely related to the calculated loads. Strength verification criteria as well as more advanced test procedures and test equipment need to be developed. The primary task would be to develop test methods based on theoretical knowledge about the lifetime and strength verification of composites supported by practical experience of how the tests can best be conducted. These new developments must unfailingly be agreed with the certification bodies and related to the relevant certification standards.

This work would result in better and faster blade tests which would contribute to the faster market introduction and higher reliability of new blade types.
Megavind consequently recommends the development of methods and equipment for fatigue testing in multiple directions simultaneously in order to better mimic real conditions as well as to devise methods for speeding up fatigue tests.

Courtesy of Vestas Wind Systems A/S

6.4 Strengthen higher education in testing

Wind turbines are designed to operate continuously for at least 20 years. In particular, there is an increasing focus on the reliability of offshore turbines, as the costs of lost production and component replacement are extremely high.

Universities and engineering schools should be encouraged to generally increase their focus on education within reliability engineering and product verification methodologies. These are important competences for all design engineers.

Testing is a key verification method. There is currently a gap in the educational value chain, especially for engineers with testing knowledge, resulting in Danish companies starting to recruit qualified employees from other countries. The lack of competent resources causes bottlenecks at the test facilities and make it more difficult for suppliers to deliver orders. The shortfall in recruiting qualified employees poses a risk to the upcoming growth in the wind industry, so the industry must help by making it more attractive for engineers to specialize within test disciplines, for example by offering internships and masters/PhD projects.

In some countries, test engineering is a specific degree. Denmark is likely to be too small to offer such degrees, but its universities and engineering schools should establish relevant courses and other opportunities for specializing within test engineering. Test engineers need a balance between theoretical understanding and the ability to do hands-on work in the laboratory. Student collaboration with the industry is thus particularly relevant.

Wind turbine test engineers need competences within the following technical areas:
- Reliability engineering
- Scaling laws
- Test standards and methods
- Mechatronics and programming
- Control systems
- Measurement theory and systems
- Data management
- Reporting

Megavind recommends more focus on education within testing and verification at universities and engineering schools, thereby ensuring the training of more engineers with a strong understanding of the methodologies and competences needed to design, conduct and report tests.

7. Mapping global test and demonstration facilities

Other countries besides Denmark are investing heavily in long and short-term research programmes, demonstration programmes and test facilities, and also build knowledge networks to attract global wind energy companies. In the near future, Denmark may no longer be the only leading wind power hub. Northern Germany is building a wind cluster with a large supply chain capability while at the same time investing in test facilities (Bremerhaven) and knowledge networks, as well as having a huge home market. Some global companies who have looked into Denmark as their European head quarters have chosen Hamburg instead. Northern Germany is thus the most powerful competitor to the Danish wind power hub.

The competencies and facilities of other countries are more fragmented. In the United Kingdom (UK), however, the Carbon Trust (CT) has been quite successfully ramping up activities for several years. The UK offshore value chain is particularly attractive, partly due to the country's offshore market – currently the largest in the world – and its investments in offshore test facilities.

The mapping of global test and demonstration facilities and competencies shown below serves as a guideline for the ways and places now challenging Denmark as the world's sole wind-power hub, and also provides relevant companies with an overview of the available test facilities.

The overview is limited to test facilities serving western markets, and thus excludes those located in places such as China, India and South America. Moreover, only publically accessible test facilities are mapped, so test facilities for a company's internal use or research facilities at universities are excluded.

The list does not include training facilities. For an overview of these, please contact the Global Wind Organization (GWO).

The mapping is exhaustive for the Danish market, while only the main international test centres are included.

7.1 Test centres included in the mapping

- Aachen
- Aalborg University
- AEWC
- BLAEST
- CENER
- Danish Technological Institute
- DELTA
- DHI
- DTU
- DNV GL
- Energy research centre of the Netherlands (ECN):
- FORCE Technology
- Fraunhofer IWES
- Global Lightning Protection Services
- Lindoe Offshore Renewables Center, LORC
- Marine Renewables Test Centre (University of Dundee)
- Massachusetts Clean Energy Center's (MassCEC) Wind Technology Testing Center
- NREL National Wind Technology Center
- ORE Catapult's National Renewable Energy Centre (former NAREC)
- SC&G Energy Innovation Center (Clemson University)
- SGS
- Technical Research Centre of Finland (VTT)
- Test Centre for Wind Support Structures, Marienwerder (University of Hannover)
- The Knowledge Centre for Wind Turbine Materials and Constructions (WMC)
- University of Stuttgart, Institute of Aerodynamics and Gas Dynamics

The mapping of global test and demonstration facilities and competencies shown below serves as a guideline for the ways and places now challenging Denmark as the world's sole wind-power hub, and also provides relevant companies with an overview of the available test facilities.

ORE Catapult's National Renewable Energy Centre (former NAREC)
Fraunhofer IWES
Energy research centre of the Netherlands (ECN)
Aachen – Center for Wind Power Drives
Massachusetts Clean Energy Center's (MassCEC) Wind Technology Testing Center
NREL National Wind Technology Center
SC&G Energy Innovation Center (Clemson University)
AEWC
CENER
Østerild National Test Centre for Large Wind Turbines
AAU
BLAEST
Høvsøre National Test Centre for Large Wind Turbines
GLPS
Lindoe Offshore Renewables Center LORC

7.2 Test centres by topic

Full scale test pads

Denmark
- DTU: Østerild
- DTU: Høvsøre
- DTU: Campus Risø

France
- Le Havre (WIN 1)

Germany
- Fraunhofer IWES: Wilhelmshaven
- Fraunhofer IWES: Sylt
- Fraunhofer IWES: Heligoland
- Fraunhofer IWES at the Weser estuary
- GL Garrad Hassan: Janneby

Spain
- CENER: Alaiz

The Netherlands
- ECN Wind Turbine Test Site Wieringermeer

United Kingdom
- Aberdeen Statoil's 30 MW floating (Scotland)
- Beatrice Demonstration Centre (Scotland)
- Hunterston Test Centre
- NAREC: Blyth

United States
- NREL field test sites

Nacelle test

- Aachen
- CENER
- DTU
- Fraunhofer IWES
- Global Lightning Protection Services (electrical tests)
- LORC
- NREL
- ORE Catapult
- SC&G Energy Innovation Center

Blade testing

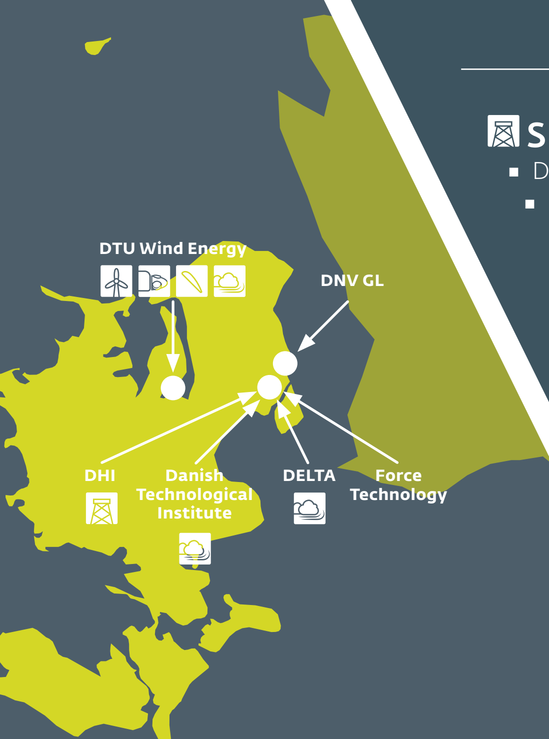
- AEWC
- BLAEST
- CENER
- DTU
- Fraunhofer IWES
- Global Lightning Protection Services
- Massachusetts Clean Energy Center's (MassCEC) Wind Technology Testing Center
- NRC National Research Council of Canada (wind tunnels)
- ORE Catapult
- SGS
- WMC (part of ECN)

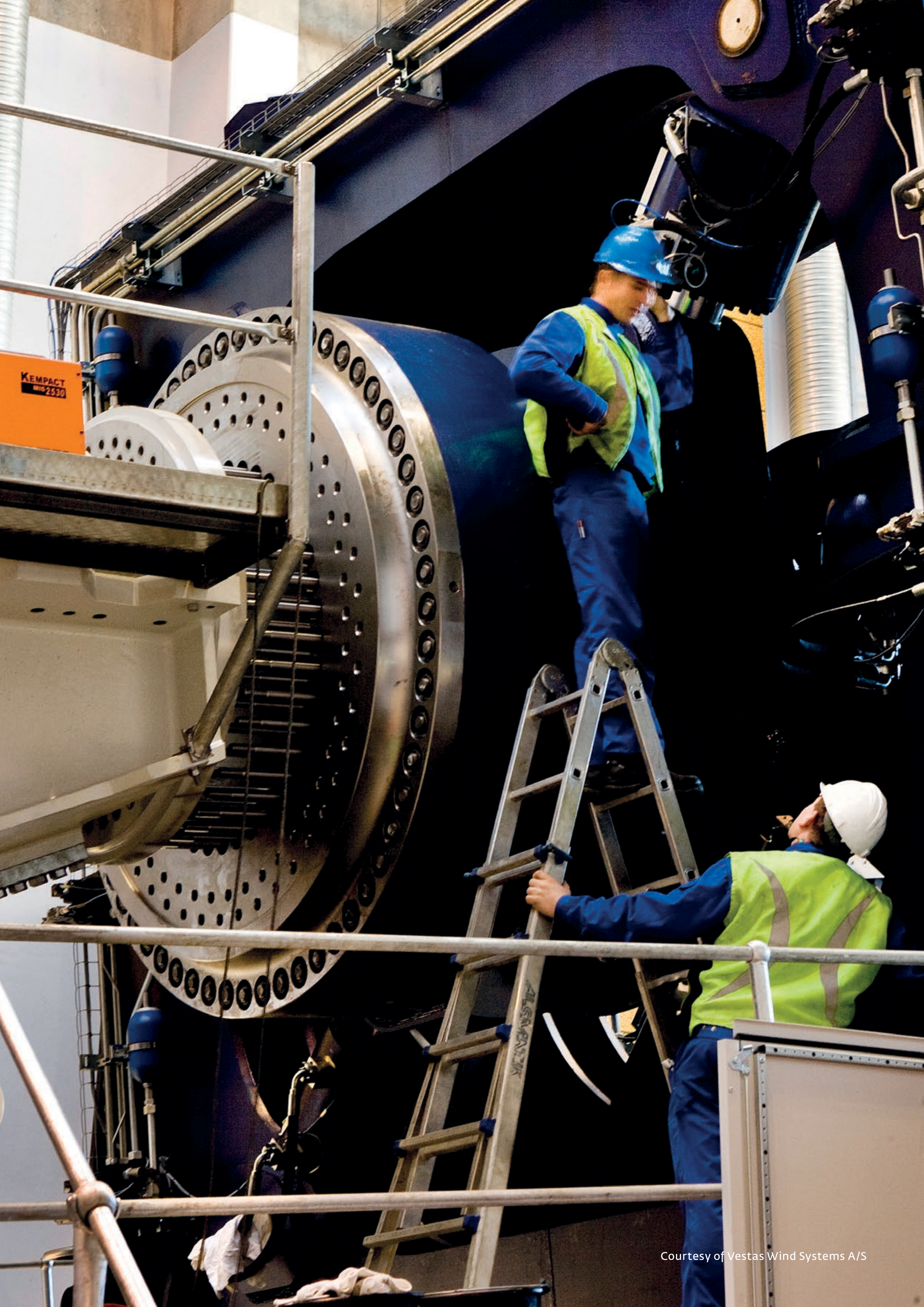
Support structures

- DHI
- LORC

Climate chambers

- AAU
- AEWC
- Danish Technological Institute
- DELTA
- DTU
- Fraunhofer IWES
- LORC





Courtesy of Vestas Wind Systems A/S

8. Appendix A: Detailed mapping of global test facilities

Aachen - Center for Wind Power Drives

- 4 MW-WT system test rig for onshore wind turbines
- 1 MW system test rig for onshore wind turbines
- Back-to-Back gearbox test rig

Aalborg University

- The Center of Reliable Power Electronics (Corpe) provides test facilities for testing the lifetime and ruggedness of power electronics components and systems for wind turbines.

AEWC

- Reinforced concrete test stand capable of testing wind blades, towers, foundations, and other structures up to 70 m in length in both static and fatigue testing modes.
- Heat solutions environmental test chamber capable of simulating the extreme temperatures and other conditions of offshore environments.
- Immersion Tank: Allows cyclic corrosion testing, such as testing varying degrees of salt exposure over a short period of time.

Blaest

- Blaest performs full-scale structural tests of blades: External test, Stiffness test, Static test, Fatigue test, Model analysis, Thermographic analysis, Acoustic Noise Emission. Blaest has four test rigs with a capacity of up to 85 metre blades.

CENER

- Blade Test: Performs structural tests on blades up to 75 metres for both static and fatigue conditions, as well as static tests on blade sections up to 100 m.
- Powertrain Test Bench: Tests of powertrain and optionally of the electrical equipment of wind turbines of up to 8 MW, including accelerated lifespan tests on mechanical parts.
- Generator Test Bench: Performs tests on generators and electronic power equipment integrated into wind turbines up to 6 MW.
- Nacelle Test Bench: Performs tests on the cooling system, noise measurements and EMC
- Nacelle Installation Bench: Performs nacelle assembly tests

Danish Technological Institute

- Test of joints: Standardised and customer-specific mechanical testing of bolted, welded and riveted joints including friction testing.
- Slip-factor determination: Test to determine the slip factor or other specific tests.
- Anchoring point test: Standardised and customer-specific anchor point testing both on-site or indoor at the test centre. The test centre handles components up to 40 m long on a reinforced concrete floor. High-temperature testing up to 300°C in a specialised oven for components up to 3 m long.
- Mechanical test centre: Tensile testing of construction steels, welding and bolted joints, Charpy impact testing (down to -196 °C), hardness and corrosion testing of welds and base materials. Fatigue testing and Crack Tip Opening Displacement (CTOD) tests on steel and special alloys for towers and welded components.
- Climate chamber: Test of wind turbine components in climate chambers, including torsion testing of cables in extreme conditions, temperature testing of generators and air breathers etc.
- Air distribution design: Design of air distribution systems in the generator or other hot spots in the nacelle using CFD software and other thermodynamic calculation tools.

DELTA

- Accredited and non-accredited regulatory compliance testing, within
  - EMC, EMF: EMC at DELTA
  - Reliability – climatic test – mechanical test: Reliability at DELTA
  - Acoustics, noise and vibrations: Acoustics at DELTA Acoustics at DELTA

- Extreme testing, within
  - HALT and HASS HALT and HASS at DELTA
  - HACT: HACT at DELTA
  - Accelerated Life Testing (ALT) provides information about product lifetimes based on well-known acceleration models and mission profiling.
  - Calibrated Accelerated Life Testing (CALT) is a statistical method for lifetime prediction
  - Reverberation: Reverberation - EMC HALT and Radiated immunity
  - Salt mist: Salt mist test
  - Condensation: Condensation test

- Climatic tests: Testing of mechanical, electronic and electromechanical products. Simulation of product environment to ensure that the product meets the conditions to which it will be exposed. Typical test conditions are according to IE-C600-2-1, IEC600-2-2, IEC600-2-3, IEC600-2-14, IEC600-2-14, IEC600-2-78, IEC600-2-38, or customer specification (high temperature, low temperature, constant moisture, cyclic moisture, thermal shock, icing).

- Climatic testing equipment
  - Temperature and moisture chambers: 1-50 m3, -100°C to +250°C, 20% RH to 98% RH
  - Temperature variation from -100°C to +200°C, 5°C/min, but 60°C/min in the HALT or 2-chamber method
  - Thermal vacuum chamber: 1 m3, -40°C to +85°C, atmospheric pressure down to better than 1.3 x 10-3 Pa
  - Salt fog chamber: +30°C to +40°C, 98% RH, typically 5% NaCl
  - Dust chamber, free-settling dust, typically 6 g/(day/m2)
  - Artificial sun (UV simulation)
  - Corrosion chambers: SO2, H2S
  - Water seal, all IP classes and high-pressure testing
  - Dust tests with/without vacuum, IP 5X and IP 6X
  - Dust test with free-settling dust
  - Combined vibration and temperature: -70°C to +180°C
  - HALT: -100°C to +200°C, 60°C/min, 70 g (6-axis vibration)

- Mechanical tests: Sine vibration, random, sine on random, shock, free fall, bump, drop topple and stability, bounce, static load, compression, bending, combined vibration and temperature.

- Mechanical testing equipment
  - Electrodynamic vibrators with slip tables 31 kN and 35.6 (nominal force sine), 1-3000 Hz, max. amplitude 112 g, velocity 1.8 m/s, displacement ± 0.5-1.5"
  - Shock test machine, half sine, 10-3000 g, 0.2-50 ms
  - Fall test apparatus
  - Equipment for mechanical operating stresses
  - Demolition hammers: 0.5 Nm and 1.0 Nm

- Force and torque measurements:
  - Under constant or variable load applied to material samples, components, sub-assemblies, etc. An important use is to check the material or assembly strength in order to assess product or process quality. Measurements can be performed both in the lab and in the field.
  - In-house mounting of strain gauges on test samples and measurement equipment.
  - Impact strength testing of metal and plastics test specimens at controlled temperatures, typically according to DIN50115 or EN10045.

- Tensile strength
  - Measurement of tensile or compression strength is used to investigate the deformation characteristics of a material or connection.
  - Tests are typically based on DIN50125, DIN50145, ISO6892 or DS/EN10002-1

- Fatigue test
  - Test of mechanical fatigue strength and mechanical wear. Typical test specimens are material samples, component subassemblies or complete products. If applicable, tests are made in accordance with DIN50100.
  - Test of fatigue resistance to internal pressure pulsations. Typical test specimens are pressure vessels, valves and heat exchangers. These tests are often based on UL207.

- Corrosion test: Test of materials and surface protections against corrosive environments. Both material samples and complete products are tested. The adhesive strength of coatings and paints can also be measured. A typical test complies with ASTM B117, IEC 60068-2-30 ISO 60068-2-52, ISO 9227 or ASTM G85-A5.

  Coatings and paints are tested and analysed according to ISO 2409
  - Salt fog
  - SO2 test
  - H2S test
  - Condensation test

- Seal test: IP tests, immersion in water, drip test, dust test with/without vacuum

- Other environmental tests: Simulated sun test, height simulation, overpressure, rapid decompression, combined temperature, moisture and height simulation.

- Acoustics, noise and vibration test and measurement campaigns
  - Accredited noise measurement to harmonized European standard IEC-61400-11
  - Accredited noise measurements according to the Danish Environmental Protection Agency's statutory orders and guidelines.

- Test strategies – Regulatory Requirements Specifications

- On-site testing and troubleshooting of issues relating to EMC, reliability or noise

DHI

- Shallow Water Wave Basins: DHI performs testing of foundation structures, pipelines and cables, including flow-structure-seabed interaction; hydrodynamic forces on foundations induced by waves, currents and combined waves and currents; breaking wave impacts and non-breaking wave interaction with foundations; wave run-up, wave and wind interaction tests; scour and scour protections around marine installations, motion of floating structures; and vibrations of structural components (such as risers and pipelines).

- Offshore Wave Basin (deep water): Testing of foundations structures in short-crested waves e.g. testing the dynamic response of floating offshore wind turbines and installation of tests.

- Wave Flume: Testing of foundation structures for e.g. long crested waves involving force response in various sea states; wave impact on structural components (sustained and slamming); wind and wave interaction.

- CFD test facility designed to support and extend the physical modelling capabilities in relation to flow interaction with support structures for offshore wind turbines.

- Model testing for offshore developments and innovation.

DNV GL

- Materials qualification and testing, e.g. determination of corrosion properties, fracture mechanics and fatigue properties, mechanical properties (e.g. yield strength, tensile strength, toughness, hardness), metallographic features (microstructure, grain size, heat treatment), chemical composition.

- High-power/high-voltage testing: Short circuit laboratory for independent testing and certification for medium, high and ultra-high voltage transmission and distribution equipment. Also a commercially operated high-voltage laboratory.

- Failure investigations in fields such as metallography, fractography, optical microscopy and scanning electron microscopy; non-destructive testing, mechanical testing, chemical analysis; alloy composition and material/contaminant identification, linear and non-linear finite element analysis; advanced fracture mechanics, corrosion protection evaluation, fitness-for-purpose assessments.

- Full-scale testing for static and dynamic loading, combined loading conditions, external and internal pressure, cryogenic and elevated temperature as well as harsh or aggressive environments.

DTU (Technical University of Denmark)

- Test centres: Østerild with seven test pads for wind turbines up to 16 MW and 250 metres height, and the Høvsøre Test Centre for Large Wind Turbines with five test pads for wind turbines with a height up to 165 metres.

- Static blade test facility for 25 m (45 m forthcoming)

- Drivetrain test facility 1 MW

- Meteorological tower, 123 metres

- Calibration facility for LIDARs

- Wind tunnel (from October 2016)

- Computer clusters

- Mechanical testing

- Fibre lab

- Microscopy

Energy Research Centre of the Netherlands (ECN):

- EWTW test site (ECN Wind Turbine Test Site at Wieringermeer)

- Offshore LiDAR validation facilities

- WMC (Wind Turbine Materials and Construction): Blade testing facility up to 60 metres and a composites expert centre.

- Labs for material testing and characterisation

- Forthcoming: A second prototype test facility for very large wind turbines and other offshore tests

FORCE technology

- Testing and analysis of polymers and composites: testing the resistance to weather and light stability of materials under various conditions as well as the strength of joints and adhesions. Determining the adhesion of protective paints or coatings and performing accredited measurements of surface tension on solids and liquids.

- Surface characterization laboratory: Equipment for surface characterization and analysis. The equipment covers 3D-microscopy, electron microscopy and X-ray analysis.

- Materials examination – concrete and brickwork: microstructural analysis of thin sections or more extensively through scanning electron microscopy (SEM) as well as chemical analysis and physical testing to determine a material's remaining service life or suitability for a given purpose.

- Fatigue testing of materials and joints: test machines operating at high and low frequencies to generate fatigue curves for testing the ability of joints or other components to withstand the continuous influence of stresses and corrosion.

- Mechanical testing: from conventional tensile testing of materials or other products to advanced test methods such as Fracture Toughness Testing.

- Corrosion tests: salt chamber, weight loss, electrochemical, ASTM G48 tests

- Test of paint surfaces: adhesion, thickness, gloss, rust creepage

- Analysis and classification of steel and other metals: OES analysis (optical emission spectrometry), XRF analysis (x-ray analysis), SEM-EDX analysis and wet-chemical analyses to verify that steel and other metals meet the requirements.

- Strain gauge measuring: to measure the actual stress in the structure

- Wind tunnels: experimental investigations of issues related to civil engineering, including structures.

- Component & Substructure Testing Centre: full-scale climatic test chamber, realistic atmospheric sea conditions (temperature, humidity and salt water) can be simulated for small and large components.

- Mechanical testing of sub-components: mechanical test bench for determining the simple strain robustness or fatigue resistance of large components. The test bench has a large strong floor and interrelated reaction walls along two sides of the plane, enabling it to test full-size structures with a three-dimensional stress set-up relevant structures exposed simultaneously to waves, wind and alternating rotating loads.

Fraunhofer IWES

- Blade test: With two test rigs for rotor blades of up to 90 m in length with uniaxial and biaxial static cycling testing.
- Support Structure Test Centre (TTH) tests all types of support structures (towers and foundations) on a scale of 1:10 and larger.
- Dynamic Nacelle Testing Laboratory (DyNaLab) for up to 10 MW including grid simulation and a main shaft bending test facility.
- Offshore test locations: Wilhelmshaven, Sylt, Heligoland and the Weser estuary - materials and components testing under offshore conditions.
- LIDAR buoy: for offshore wind measurement campaigns.
- Demonstration centre for industrialized rotor blade manufacturing with the vacuum infusion process (from 2016).
- Test Stand for Oil Sensor Systems: simulates the operating conditions of a gearbox oil circuit in a wind turbine.
- Main Shaft Bending Test Facility: accelerated fatigue testing of main shafts of 2 to 5 MW turbines.
- Test Stand for Rotor Blade Coating.
- Climatised Rain Erosion Test Stand (with a rotating arm): evaluates the resistance of rotor blade coatings to rain erosion, with blade tip speeds of up to 550 km/h.
- Climate chamber: simultaneously simulates the mechanical and environmental loads to which offshore wind turbines are subjected.
- HALT/HASS testing: load testing for manufacturers of mechanical systems, components or electronic systems.

Global Lightning Protection Services A/S (GLPS)

- Material testing: Electrical properties of conductive, semi-conductive and insulating materials; conductivity, permittivity, tracking, electrical breakdown strength, etc.
- High-voltage testing on blades, hubs, nacelles and smaller subsystems and components to simulate the mechanisms and impacts of lightning strikes. The facility can test blade sections and full blades up to 75 m indoors.
- High-current testing on blades, hubs, nacelles and smaller subsystems and components to simulate the mechanisms and impacts of lightning strikes: 2,100 m² test facility accessible via 9x9m gates (drive through).
- Testing is performed in accordance with IEC 61400-24 Ed 1.0 Annex D
- Test equipment: high voltage and impulse voltage: 3MV; continuous HVDC voltage: 700 kV; high current: 250 kA (10/350 µs) + 1,500 C (DC current).
- Larger samples can be tested remotely on the OEM production facility – or at another remote location.

- Large-scale and modular impulse current testing (1.2 MV and 200 kA) on full blades available by 2017.

- Lightning Striking Simulations; attachment point simulation, exposure risk assessment; current and voltage distribution simulations, model correlation with full-scale testing.

Lindoe Offshore Renewables Center, LORC (DK)

- Mechanic nacelle tests on a 10 MW test bench

- HALT test (Highly Accelerated Lifetime Testing). The HALT test will be available from the end of 2016.

- Climatic chamber with a size of 900 m³ measuring 14 x 8 x 8 metres. The chamber exposes structures and components to varying climatic conditions, primarily low and high temperatures, temperature cycles and corrosive environments.

- Strong floor of 20 x 9 metres that will be equipped with a number of generic load frames and actuators for static tension/compression, cyclic loading, bending and torsion.

- Welding centre with 32 kW laser-system.

Massachusetts Clean Energy Center's (MassCEC) Wind Technology Testing Center

- Blade test: Up to 90 metres

NREL National Wind Technology Centre

- Advanced Research Turbines: available to test new control schemes and equipment for reducing loads on wind turbine components.

- Wind Dynamometer Test Facilities: conducts lifetime endurance tests at various speeds at nacelles up to 5 MW.

- Wind Structural Testing Laboratory¬: office space for industry researchers, experimental laboratories, computer facilities for analytical work as well as space for assembling components and turbines for atmospheric testing.

- Wind Research High Bay: 225-kilowatt dynamometer for testing small wind turbine components and subsystems.

- Wind Turbine Field Test Sites: for testing prototypes.

ORE Catapult's National Renewable Energy Centre (former NAREC)

- Blade test: 50 m and 100 m blade test facilities cover structural testing of wind turbine blades up to 100 m in length (dynamic and static).

- Nacelle test: 3 MW and 15 MW powertrain testing facilities for full systems and components (including generators and converters). Both test rigs use a Non-Torque Loading (NTL) system to perform accelerated lifetime testing.

- Electrical systems: HV and flexible LV test laboratories/facilities for electrical, materials, mechanical and environmental testing and demonstration.

- Subsea trials and demonstrations: onshore saltwater location for all stages of technology development.

- Resource measurement and assessment: open access offshore anemometry platform facility for testing, calibrating and verifying remote sensor technologies.

SC&G Energy Innovation Center (Clemson)

- 15 MW test rig: drivetrain testing facility with full-scale highly accelerated mechanical and electrical testing of advanced drivetrain systems.

- Duke Energy eGRID (Electrical Grid Research Innovation& Development): for testing generator compatibility to 50 or 60 Hz electrical transmission grids.

- 15 MW Hardware-In-the-Loop (HIL) Grid Simulator: Allows wind turbine generator (WTG) manufacturers to test both mechanical and electrical characteristics.

SGS

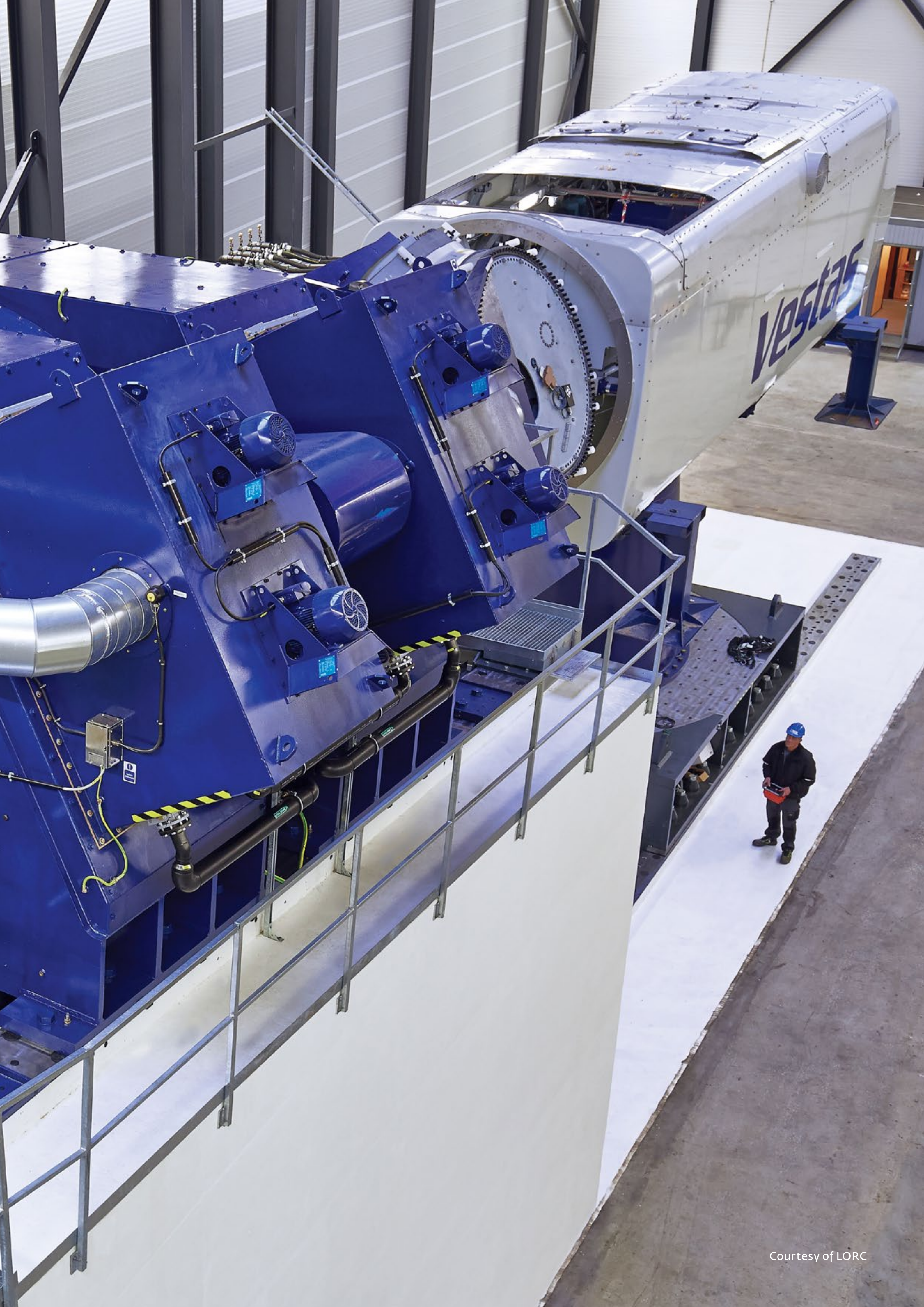
- Blade test: verifying the reliability of rotor blades while extending operational life

Technical Research Centre of Finland (VTT)

- Icing wind tunnel

University of Stuttgart, Institute of Aerodynamics and Gas Dynamics

- Wind tunnel for airfoil testing



Courtesy of LORC

9. Appendix B: Full catalogue of ideas for testing and demonstration

Besides the seven main recommendations identified here, Megavind has developed a catalogue of ideas on relevant test and demonstration facilities and competencies designed to support the Danish wind industry. Some of these will relate to both elements, namely competencies and facilities.

This section is divided into the following main categories: Climate, Grid, Wind Power Plant, Balance of Plant and Wind Turbine. These are illustrated in figure 5.

The topics are not listed in order of priority.

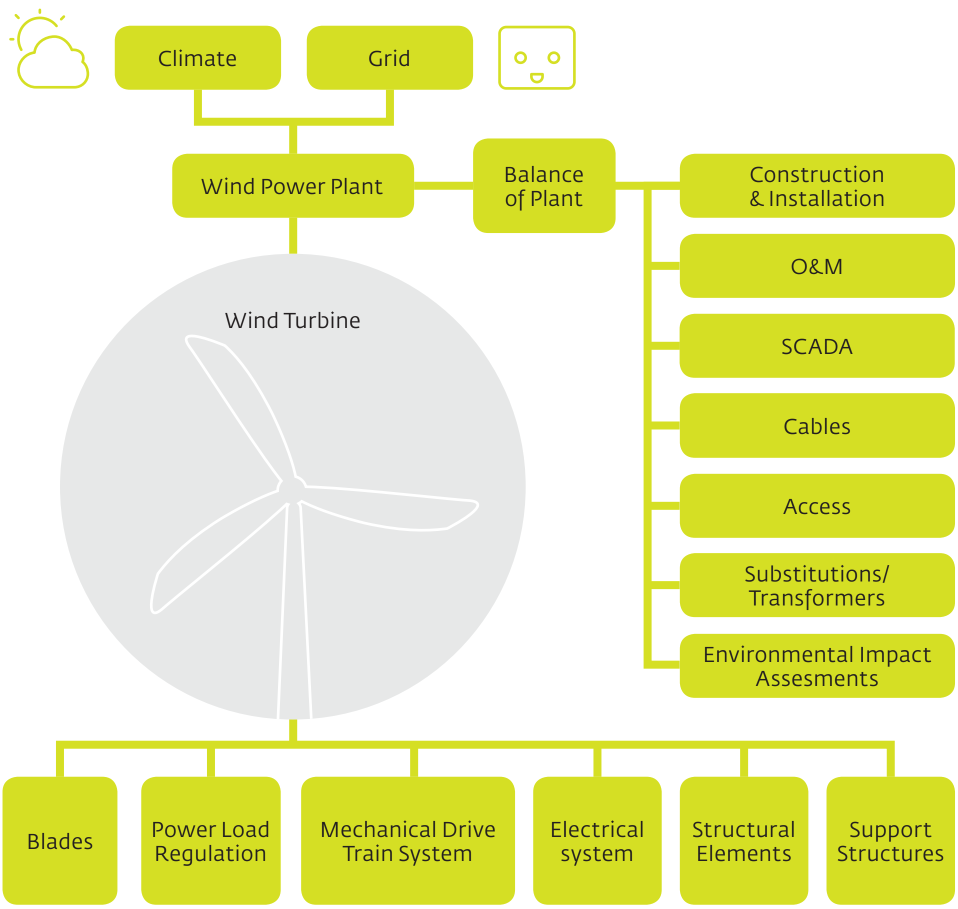


Figure 5
Breakdown

CLIMATE

Facilities

- Portable test facilities using multiple wireless-synchronized sensors for analysing cause-effect relationships between any and all elements of a wind turbine or multiple turbines in a wind farm.
- A cost-effective offshore platform for environmental data collection

Competencies

- Development of advanced methods of measuring offshore wind conditions (key recommendation).
- Low-frequency noise, amplitude-modulated noise, as well as impulsive noise need to be further explored.
- A lightning monitoring programme at The National Test Centres for Large Wind Turbines Høvsøre and/or Østerild
- A lightning database – e.g. a collection of data on extreme conditions and mean values
- Collection of knowledge about the environmental impact on foundations from the oil and gas industry in the 1960s and 1970s.

GRID

Facilities

- Develop a converter-based grid test facility for test of WTG's (key recommendation)
- Park (plant) level test environment - e.g. hardware/power in the loop
- Complete state-of-art standard test environment at Østerild - National Test Centre for Large Wind Turbines
- Grid testing facility (60 Hz)

WIND POWER PLANT AND TURBINE

Facilities

- Ensure availability of additional test pads for full-scale wind turbines (key recommendation)
- Test facility for modelling wind farms
- Upgrading and expansion of The National Test Centres for Large Wind Turbines Høvsøre and/or Østerild for large tip heights and noise limits
- Testing turbines, power curve testing, load measurements, acoustic measurements, net quality measurements, MW turbines operated by independent test centres allowing individual testing of component performance and integration.

Competencies

- Establish higher education in testing (key recommendation)
- Training, research and master degrees in testing and validation
- Test engineers specialized in testing, verification and Six Sigma
- Test and validation competencies at universities
- LIDAR experts
- LIDAR industry standard
- Globally accepted standards

BALANCE of Plant

ENVIRONMENTAL IMPACT ASSESSMENT

Facilities

- Establishment of a noise measuring institute
- Development of wireless synchronized sensors
- Light tunnel for measuring flight lights

Competencies

- Mapping of birds and marine mammals

- High-voltage engineers (for lightning)
- Offshore noise dissemination modelling

SUBSTATIONS / TRANSFORMERS

Facilities

- Grid code compliance / power quality / emission test facilities
- 66kV infrastructure at test facilities
- HV and HC test facilities

Competencies

- High-voltage engineers
- Measurement and monitoring of substations

ACCESS

Facilities

- Precision measurement

Competencies

- Chartered surveyors
- Process

CABLES

Facilities

- Lifetime testing of sea cables, e.g. temperature, harmonisation etc.
- Offshore cable installation test range
- Offshore installation technologies

Competencies

- Methods for calculating and verifying (mechanical) cable dynamics
- Analyses of possibilities for higher voltage levels
- Marine engineers

SCADA

Competencies

- Standard for testing electrical equipment mounted externally on the nacelle (lightning)
- Engineers for data analysis

O&M

Facilities

- Tower (e.g. 100 m) for training personnel in lifting operations in relation to safety
- 100 m tower for testing O&M and installations, with access from sea and land
- Offshore or onshore simulator to train crew transfer/step-over during day and night including procedures for getting dressed and walking to the transfer point. The simulator should take account of varying weather conditions such as wind, snow, rain and temperature.

Competencies

- Procedures and safety routines for different roles of all personnel involved
- Better weather forecasting with more accurate results based on more sources and dimensions - e.g. wind, waves, periodic functions etc.

CONSTRUCTION & INSTALLATION

Facilities

- An offshore demonstration site
- Better forecasting tools during installation and maintenance
- Test-feeder transport system

BLADES

Facilities

- Build test facilities for 100+ metre blades (key recommendation)
- Test methods and equipment for erosion (leading edge)
- Fatigue testing with realistic loads
- Turbine with exchangeable blades for testing repairs etc. with access to blades from different manufacturers.
- Wind tunnel
- Rain erosion tester with a rotating arm
- Equipment for more advanced 3D deflection measurements during structural testing

Competencies

- Faster and more efficient, advanced blade-test methods (key recommendation)

POWER CONTROL

Facilities

- Representative HALT tests of components
- 3D wind tunnel
- Dynamic HALT
- Test turbine for documentation of smart software algorithms
- Pressurized wind tunnel
- Environmental facilities to verify components for offshore use

Competencies

- HALT competencies
- Research on nacelle test
- TCCL optimization
- Knowledge of climate testing
- Knowledge of general test standards

MECHANICAL DRIVETRAIN SYSTEM

Facilities

- Test equipment to develop a recognized drive-test standard
- Test of drivetrain
- Hydrogen embrittlement, electron microscopy and mechanical testing
- Electron microscopy for surface and bulk structures
- X-ray tomography
- Testing of materials
- Lifetime testing
- Vibration testing on multiple axis

Competencies

- Measurement strategies – e.g. measurement systems & sensors, and data analysis
- Modelling & designing verification methods
- Centre with knowledge of test and vibrations in combination with a facility for vibration testing.

ELECTRICAL SYSTEM

Facilities

- Combined mechanical and electrical HALT testing
- Back-to-back test generator at 6-10 MW
- Accelerated AC power cycling
- Test set-up for lifetime modelling of power modules

Competencies

- Combined test programme for electrical systems
- Lifetime modelling of mechanical and electrical environments
- Knowledge of EMC (electromagnetic compatibility)
- Knowledge of ICT (Information and Communication Technology)

STRUCTURAL ELEMENTS

Facilities

- Internationally recognized test institutes
- Material testing
- Test at micro and nano levels

Competencies

- Improve our understanding of operational environmental conditions and develop more efficient, accelerated test methods (key recommendation)
- Education of test engineers and inclusion of students in industrial work
- NDT: Utilization of methods and translating data into failure rates
- Omission of regional requirements for the use of test facilities
- A centralized test community as a one-stop-shop
- Knowledge of permanent magnets

SUPPORT STRUCTURES

Facilities

- Full-scale demonstration site (near coast: 15-25 m and 35-40 m depth)
- Large 3D Shallow Water Wave Basin
- Full-scale offshore test of foundations
- Long 2D wave flume
- Large-scale test wave flume
- CFD wave flume facility
- Laboratory for wave (load) testing

Competencies

- Certification or classification system with procedures and standard for foundations
- Knowledge of metallurgy
- Design parameters for offshore constructions
- Inclusion of tender demonstrations

Courtesy of Siemens Wind Power A/S

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