WIND POWER

ANNUAL RESEARCH AND INNOVATION AGENDA 2018

MEGAVIND

ANNUAL RESEARCH AND INNOVATION AGENDA
October 2018

Publisher: Danish Wind Industry Association // Megavind

Authors:
- Christina Aabo, Ørsted
- Jørn Scharling Holm, Ørsted
- Peter Hjuler Jensen, DTU Wind Energy
- Mattias Andersson, DTU Wind Energy
- Edit Lulu Nielsen, Danish Wind Industry Association

Photo cover: By courtesy of Ørsted. Crew vessel at turbine foundation transition piece
Graphic design: Koefoed/Aegir
Download the electronic version at: www.megavind.windpower.org

ISBN: 978-87-970265-1-9
EAN 9788797026519

CONTENTS

PHOTO: THE CLIMATIC WIND TUNNEL CAN ACCOMMODATE TESTS AT TEMPERATURES DOWN TO -10 DEGREES CELCIUS (AT 25 M/S) AND OBTAIN A MAX. FLOW VELOCITY OF 32 M/S. IN THE WIND TUNNEL FORCE TECHNOLOGY TEST SECTIONS OF WIND TURBINE WINGS OR BRIDGE CABLES FOR ICING AND HOW IT AFFECTS THE AERODYNAMIC PERFORMANCE OF THE WING OR CABLE.

INTRODUCTION

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

This Research and Innovation Agenda is an annual update of the research and innovation landscape for the Danish wind energy sector. It communicates emerging trends in wind energy RD&D and policies and gives strategic recommendations that are essential to Danish (and European) public and private stakeholders.

It is the hallmark of wind energy technology development that it has continuously exceeded the expectations – even of experts. The turbines have become bigger, the electricity cheaper and the electric grid able to absorb much more wind power than even experts expected.

We should continue to exceed expectations.

That is why the headline for a new vision in this year's Research and Innovation Agenda is:

EXPLOIT THE FULL POTENTIAL OF WIND ENERGY.

The industry firmly agrees that we can go much further in making wind energy cheaper, more reliable and more integrated in the energy system.

Since the publication of last year's Strategic Research and Innovation Agenda, the Megavind partners have had constructive dialogues with policy makers, politicians and our sector community. The feedback received during these discussions has been used as a cue to this report.

This year's agenda outlines the framework needed for Denmark to stay at the forefront of the industry and wind power technology. The agenda starts with a short summary that outlines the framework, followed by a section that elaborates on each of the four building blocks of the framework:

· Megatrends
· Innovation drivers
· Research and innovation themes
· Test facilities and human resources

Lastly, the agenda provides the Megavind recommendations to a balanced national strategic programme for RD&D for wind energy. The receivers of these recommendations include both public funding institutions as well as universities, companies and innovation bodies e.g. the new innovation network Energy Innovation Cluster.

We hope that this year's annual strategic research and innovation agenda will inspire the continued discussion among Danish (and European) wind energy stakeholders of how we collectively can exploit the full potential of wind energy.

PHOTO: DETAILS OF ONE OF THE MEGA-NEWTON-METER LINK-ARM COUPLINGS AT LORC'S NACELLE TEST FACILITIES

EXPLOIT THE FULL POTENTIAL OF WIND ENERGY

For decades, the holy grail of wind energy development has been to become competitive with fossil fuel on market conditions. Onshore wind has achieved this in markets with good wind resources and well-developed electrical grids. In parallel, offshore bottom-fixed wind power plants are undergoing the same development curve and are in some cases competitive on market conditions.

So how did we get there?

Over the past 40 years, wind energy has undergone two paradigms and is now moving into a third.

There are plenty of challenges but also plenty of opportunities in making wind energy even more reliable. It requires a new, shared ambition that allows us to support the industry of today while enabling the industry of tomorrow.

In recent decades, wind energy has become much cheaper and more reliable, but the sector and industry can go much further. The wind energy sector is still relatively young and the potential for research, development and demonstration of new solutions is vast. The Danish society does not lack an incentive to continue the development. Last year, the Danish wind energy sector had a turnover of 144 billion DKK and employed more than 30,000 people, so it is a big business.

1ST PARADIGM

In the first paradigm, the aim was to develop and deliver renewable energy. The technology was developed through public RD&D programmes, industrial innovation and an active civil society involvement.

2ND PARADIGM

In the second paradigm, the aim was to make wind energy cheap. Economy of scale, an experienced supply chain and advanced technologies have made onshore wind the cheapest forms of new electricity generation.

3RD PARADIGM

In the third paradigm, which we are now moving into, the aim is to make wind energy a reliable backbone of the energy system. As the technology moves from being a niche production to be the backbone of the energy system, wind energy needs to address well known and often discussed challenges about reliability due to the variable nature of wind power.

A strategic framework

Megavind has identified four elements on which a successful strategy should build in order to exploit the full potential of wind energy.

- Firstly, we need to understand and navigate the current *megatrends* affecting the industry globally.
- Secondly, we need to update the criteria for assessing the potential impact of new innovations, which will function in an integrated energy system. We call these criteria for *Innovation drivers*.
- Thirdly, we need a programmatic approach to public-private partnerships and investments in wind energy, based on commonly agreed *Research and Innovation themes* that supports the entire lifecycle of wind power systems.
- Fourthly, it is critical to maintain investments in the training and education of *human resources* as well as in *state-of-the-art test and demonstration facilities* to support the development of new innovative solutions.

Megavind invites policy makers, funding agencies and other wind energy stakeholders to join efforts to deliver on the ambition to exploit the full potential of wind energy for the benefit of Danish growth, job creation and the global fight against climate change.

PHOTO: PERSPECTIVE VIEW OF THE 8 METER LONG MEGA-NEWTON-METER LINK-ARM COUPLING OF THE LORC HALT TEST FACILITY

MEGATRENDS, INNOVATION DRIVERS AND RESEARCH, DEVELOPMENT & DEMONSTRATION THEMES

Megatrends

- Competitive, industrialised and global industry
- Subsidy-free and technology neutral tenders
- Integrated energy systems based on distributed generation sources
- Digitalisation

Innovation drivers

- Increase performance and efficiency
- Decrease technical and financial risks
- Increase the system value of wind power
- Shorten the time to market
- Address environmental and regulatory barriers to the market

Research, development and demonstration themes

Research, development and demonstration themes

- What Megatrend(s)?
- Which Innovation Driver(s)?
- Incremental or radical innovation?
- High or low Technology Readiness Level (TRL) research?
- Short/long time and budget frame?
- Where in life cycle phase?

Any research, development or demonstration project should fit in the matrix below and address these questions

Research, development and demonstration themes	Onshore	Offshore	Floating
1. Wind, waves, soil and siting			
2. Wind turbine technology			
3. Foundations & substructures			
4. Electrical infrastructure & grid integration			
5. Environment & consenting			
6. Logistics & decommissioning			

Supported by human resources and test and demonstration facilities.

MEGATRENDS

To understand the scale of the challenges and opportunities that the sector faces in the third paradigm of wind power technology, where focus is on system reliability with high wind penetration, it helps putting it into the context of the four megatrends identified in Megavinds Annual Research and Innovation Agenda 2017. Megatrends are global socio-economic trends that affect the entire business and all stages of the wind farm lifecycle with profound consequences at technical, economic and human resource level.

PHOTO: NDT INSPECTION IS A USEFUL METHOD TO "SEE" WHAT IS HIDDEN BENEATH THE SURFACE. CONTACT BASED BLADE INSPECTION WITH ULTRASOUND USING DRONE TECHNOLOGIES IS THE NEWEST INVENTION FROM FORCE TECHNOLOGY IN THIS AREA.

A COMPETITIVE, INDUSTRIALISED AND GLOBAL INDUSTRY

Within the last five years, the wind industry has witnessed a string of mergers and acquisitions that brings the main manufactures head-to-head in a global competition for market shares. In this business environment, global presence and well-established supply chains at industrial scale have become essential for companies to stay competitive. At the same time, sub-suppliers experience a significant pressure to deliver higher quality at lower costs.

The competition is increasingly fierce in the on/offshore sector. Denmark was a first mover in offshore wind energy. Today, offshore wind energy is a global market, forecasted to grow exponentially in the coming decades. As a consequence, new players are entering the market, bringing with them the significant financial weight and organisations with years of experience in offshore energy production.

SUBSIDY-FREE WIND POWER AND TECHNOLOGY-NEUTRAL TENDERS

Until recently, renewable energies have been dependent on dedicated public support mechanisms to compete in the energy market. The rapid decrease in costs for wind and solar PV is changing that. In several high-wind-resource and high-power-price onshore markets, wind energy is subsidy free and tenders for new power capacity are changing to technology-neutral tenders.

Offshore, there have been several zero-subsidy bids in Northern Europe within the last 2 years. The zero-subsidy bids are depending on a number of factors, such as high electricity prices, the development of larger turbines and grid infrastructure. . The development is changing the requirements of wind energy and puts pressure on the manufactures and the supply chain to deliver reliable solutions at lower costs.

AN INTEGRATED AND DISTRIBUTED ENERGY SYSTEM

An integrated and distributed energy system creates opportunities and challenges for wind energy generation. Integrating today's large amounts of clean wind power into the grid changes the role of the wind power plant from simply delivering electricity to providing additional services to the system. Nowadays, wind farms are referred to as wind power plants, precisely because they must deliver services comparable to a traditional power plant, e.g. frequency and voltage support.

It is an important part of the new role of wind power plants to be able to deliver green, cheap and reliable power in an ever more integrated energy system.

DIGITALISATION

The application of digital technology influences all parts of wind power projects from early planning → through consenting → design → manufacturing → transportation → installation → operation → maintenance → decommissioning on a large and complex set of data. The immediate challenge is to organise and use the data intelligently in order to take advantage of the wealth of opportunities for learning and new digital solutions. For decades, the industry and academia have developed so-called numerical models to calculate the properties of wind resources and wind power plant components and systems. Now, the combination of embedded sensors creating an internet of things (IoT) and high-performance computers opens up new possibilities such as creation of digital twins from the scale of wind turbine blades and up to wind power plants.

With digital twins, a digital copy is created of the physical component or system, for example to help predict damages and thereby allow so-called preventive /predictive maintenance.

INNOVATION DRIVERS

Today, public RD&D funding programmes for energy often target the reduction of the Levelised Cost of Energy (LCoE) when deciding on funding - and rightly so. LCoE remains the overall driver for research, development and demonstrations (RD&D) in the sector. However, the requirements of a competitive technology to deliver reliable solutions to an energy system are becoming increasingly complex and market conditions are changing. Therefore, there is a need for additional criteria used to measure the impact of RD&D projects. Megavind has identified 5 such criteria:

- Increase performance and efficiency
- Decrease technical and financial risks
- Increase the system value of wind power for society and for market
- Shorten time and cost to market
- Reduce environmental and societal impacts

These are key parameters that are used in the wind energy sector to assess the relevance and potential of new solutions to drive innovation. That is why we call them innovation drivers.

SHORTEN TIME AND COST TO MARKET

In a highly competitive wind energy market, speed is essential. Translating research into new products and solutions that provide a competitive edge is of paramount importance. Every day that an innovation process of developing a new product or service can be shortened has a value in € and $. As an example research, development and demonstration that focus on better and faster design processes, more tests and measurements or digital twins to reduce the need for physical testing, are key to maintain and develop the wind industry and the wider sector in Denmark.

REDUCE ENVIRONMENTAL AND SOCIETAL IMPACTS

The industry can develop cheap and reliable technology solutions, but if the environmental requirements, public acceptance or regulatory requirements are not met, no wind power will be built. In many European markets, wind energy must coexist with other businesses (e.g. shipping, fisheries, aquaculture and tourism) as well as neighbouring communities, natural habitat and animals. Research in this area adds significant value by enabling wind power by lowering its negative impact on humans and nature and by opening new markets.

INCREASE PERFORMANCE AND EFFICIENCY

Optimisation of the performance and efficiency of the individual turbines and the combined wind power plants continues to be a key innovation driver for the industry. It is about making products better, cheaper, lighter, stronger etc. A wind turbine is not simply a wind turbine; it needs to be tailored to specific site conditions ranging from onshore turbines for flat terrain to offshore turbines that can withstand earthquakes and typhoons. The design of the turbine and foundation needs to be integrated to ensure optimised designs of both.

DECREASE TECHNICAL AND FINANCIAL RISKS

There are two major factors to consider when developing commercial wind projects: The cost and the risk. Uncertainty about the capital, operational or development costs of a wind farm will increase the cost of financing the project. Similarly, uncertainty about the risk of critical failures or the lifetime of components increases the need to increase the safety factor and consequently affects cost and production capacity.

Example: If a developer are uncertain about the effect of waves on the foundation, they will order a heavier foundation to avoid critical failures; when the wake effects on turbines in a wind farm is unclear, heavier turbines, which are more expensive and less productive, will be chosen.

Technical and financial risks are reduced for example by better understanding the underlying physics through advanced models of wind farm layout or the wear and tear on wind turbine blades from wind, water and UV rays.

INCREASE THE SYSTEM VALUE OF WIND POWER

Today's wind turbines and wind farms are advanced electricity generation systems working in an increasingly integrated system that generates, stores, transmits and consumes energy. As described in the Megatrends, the build-out of the renewable energy capacity is moving towards technology-neutral tenders in which wind energy is competing head-to-head with other renewable technologies. Therefore, we are seeing companies moving towards delivering hybrid solutions consisting of e.g. wind, solar and storage facilities in order to best meet the demands for low cost, stable power generation and deliver reactive power and ancillary services.

The ability to fit into this new trend is a major innovation driver.

Increasing the system value of wind can also be achieved by adapting the technology to produce more power when prices are high. In markets with high penetration of wind energy, that is during periods with low wind resources.

This has important implications for research and innovation.

- Firstly, it means that innovations should not only deliver electricity at the lowest Levelised Cost of Energy. It should also deliver electricity when it has the highest system value.

- Secondly, new solutions enabling the wind turbines to contribute and benefit from system requirements or existing solutions that previously were uneconomical are now becoming competitive due to new requirements.

PHOTO: POUL LA COUR WIND TUNNEL AT DTU WIND ENERGY. A SECTION OF THE 6000 WEDGES IN THE CHAMBER WITH LENGTH 13M, WIDTH 11M AND HEIGHT 11.5M THAT SURROUNDS THE TEST SECTION TO ABSORB THE NOISE AND THAT CREATE THE ANECHOIC CHAMBER.

4

RESEARCH, DEVELOPMENT AND DEMONSTRATION THEMES

Wind energy research, development and demonstration should be supported by a programme-driven approach that covers all the phases of the life cycle of wind power plants (design, sourcing, manufacturing, installation, operation, maintenance and decommissioning) and supports all wind energy technologies (onshore, bottom-fixed offshore, floating and, in the long term, airborne).

This is why Megavind has identified *six research, development and demonstration themes* that are developed to ensure that priorities are directly aligned with the wind energy sector's multimillion investments in research, development and demonstration.

WIND, WAVES, SOIL AND SITING

It is essential to have the best possible measurements and modelling of the elements that a wind farm is exposed to (wind, waves, soil) when optimizing the detailed design, layout and O&M of wind farms, foundations and electrical systems. New complex models using high performance computers and novel technologies to provide measurement data are opening up new opportunities.

Examples of current challenges are: broaden the use of LiDAR technology; better understanding of turbulence; modelling and experimental verification of inflow conditions in complex terrain; qualifying alternative wave measurements to buoys; wake modelling for next generation of large size turbines; better understanding soil properties.

WIND TURBINE TECHNOLOGY

Wind turbines taller than the Eiffel tower, turbines floating far ashore, multi-rotors or wind turbines operating in extreme weather conditions such as ice and snow. What are the next steps for future generations of sophisticated high-tech turbines in terms of size, materials, system complexity including control systems and use of big data and grid interaction?

Improved reliability of critical components such as blades, power converters and hydraulic systems; improved lighting protection, new designs for very large rotors.

FOUNDATIONS AND SUBSTRUCTURES

For the offshore wind power market there is a need for solutions that are suitable for larger turbines and to local conditions such as earthquakes, supply chain, etc.

Examples of current challenges include:
Design tools and validation of models for main foundation concepts; improved coating and corrosion protection systems; improved solutions for noise mitigation during installation; improved methods for measuring soil characteristics.

ENVIRONMENT AND CONSENTING

The wind industry is global, but wind-farm related environmental -and stakeholder issues are local. The industry needs to understand the environmental issues in the new markets.

Examples of challenges are: methods to minimise impact on protected and endangered species of sea mammals and birds; special planning to optimise the sea areas for offshore wind power and other purposes; addressing noise from the turbine itself or from the construction phase on nearby dwellings.

ELECTRICAL INFRA STRUCTURE AND THE GRID

The distance from shore, size and electrical infrastructure complexity of offshore wind farms are increasing. This requires continuous evolution of grid code requirements and technical solutions to also address growing penetration of wind power. New wind farm analysis methods (including transients, converter stability and harmonics), electrical components and overall infrastructure optimization are needed to accommodate challenges introduced by new projects and markets.

Furthermore, design and operation improvement can be further achieved by measurements, diagnosis and condition-based monitoring.

LOGISTICS AND DECOMMISSIONING

This headline covers onshore and offshore transportation, assembly and installation as well as transportation in the O&M phase and decommissioning of wind farms.

Current challenges include development of: vessels and methods for installation of next generation WTGs and foundations; hybrid/electric crew transfer vessels; application of drones and unmanned vessels for specific processes; decommissioning processes and recycling of materials from wind farms.

HUMAN RESOURCES AND TEST FACILITIES

New innovations do not spring from thin air, they are inspired and developed by a skilled workforce, and the road to commercialisation of new products requires rigorous tests and demonstrations at state-of-the-art facilities. A long history of developing wind energy technology and solutions and a significant commitment from both politicians and CEOs has ensured the necessary investments in both human resources and world-class test and demonstration facilities in Denmark. A journey that has to continue in the years to come.

HUMAN RESOURCES

Our ability to attract, train, educate and employ a highly skilled labour force is no doubt an important part of the story about how Denmark has been able to maintain its unique position in the global wind energy industry. The high quality education that we can deliver in Denmark is yet another result of the unique public-private partnership. Students are educated and trained in an environment that encourages them to explore radically new ideas and engage in the improvement of existing solutions; and employees are offered a wide range of opportunities for in-job training or further education at academic or vocational level.

There is currently a high demand from the Danish wind energy sector for all competencies, from skilled labour to highly qualified RD&D specialists in areas such as ICT. Megavind therefore reiterates last year's recommendation to the sector to develop a better and more nuanced common understanding between industry and the educational institutions about the competences required.

TEST AND DEMONSTRATION FACILITIES

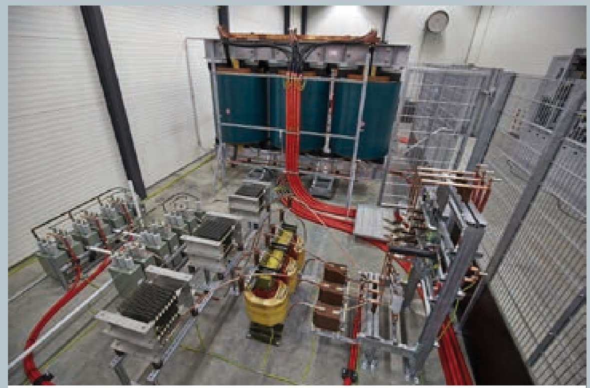
In 2018, the Danish parliament gave the green light for the extension of the national test sites for very large wind turbines at Østerild and Høvsøre. Østerild is now one of the very few places in the world where turbines of up to 330 m heigh and with a rotor diameter of 280 m can be tested onshore before they are fully developed and deployed offshore. Combined with other major test facilities, these facilities offer the Danish wind energy sector a significant competitive edge in developing the next generation of advanced wind turbines and wind farms.

Denmark has been able to construct and run these state-of-the art facilities due to the intelligent use of various different models to finance the facilities. Facilities such as LORC, BLAEST and Østerild are all developed and run by combining public and private investments in a dynamic way.

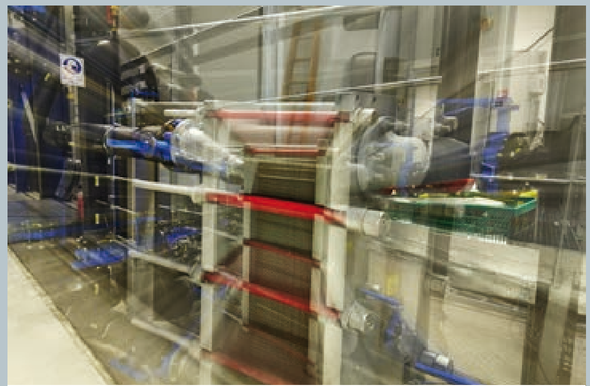
Looking ahead, Danish wind energy test facilities cover most of the current needs. But several of our test facilities will have to be upgraded and expanded to keep up with the technological development and requirements in years to come.

BY COURTESY OF MHI VESTAS

TEST FACILITIES



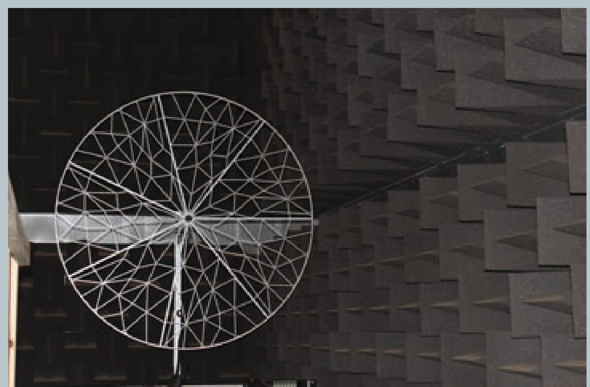
Filter installations at the grid emulator part of LORC´s nacelle test facilities.



Distorted view of the cooling infra-structure at one of LORC´s nacelle test facilities.

Transformer-converter connections at the LORC HALT test facility.

In the wave basin at DHI, researchers from DTU are mounting a model of a 10 MW turbine on a model of the Stiesdal TetraSpar floating.

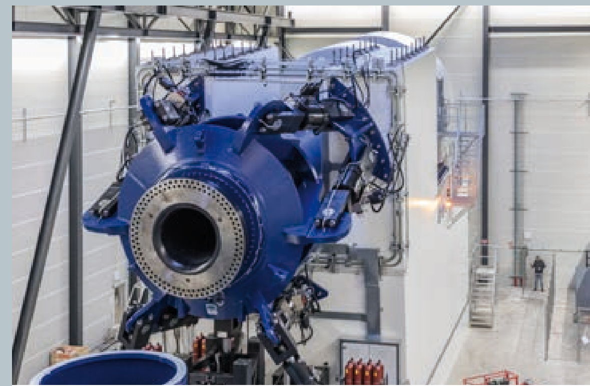


Poul La Cour wind tunnel, DTU. The microphone array measure the aerodynamic noise from the models that are tested.

FORCE. Lindø Component and Structure Testing.

The transformer hall at the LORC HALT test facility.

The 13MW drive-line of the LORC HALT test facility.



Front-end view of the wind-load unit of the LORC HALT test facility.

Filter installations at the grid emulator part of LORC´s nacelle test facilities.

The transformer hall at one of LORC´s megawatt nacelle test facilities.

NATIONAL STRATEGY FOR RESEARCH, DEVELOPMENT AND DEMONSTRATION

The Danish Energy Agreement of 29 June 2018 is establishing the framework for research, development and demonstration until 2024. The budget volume will increase gradually from 580 mio. DKK in 2020 with approximately 100 mio. DKK a year until 2024. This means that in 2024 Denmark will get back to the budget volume known in 2010 – 2013 of 1 billion DKK.

Megavind welcomes the reestablishment of the “energy billion”, however, regrets the slow implementation that will mean that Denmark has deprioritised research, development and demonstration within energy for 10 years (2014 – 2024).

It will be essential to implement a National Strategy for research, development and demonstration based on the framework agreements set out in the Energy Agreement of 29 June. A National Strategy for Energy should take into consideration the renewable energy sector’s hands-on experience with the public-funded framework programmes, because taking the hands-on knowledge into consideration will maximise the outputs of the public research, development and demonstration budgets.

A future National Strategy for research, development and demonstration for Renewable Energy Sources (RES) should consider the headlines listed below:

Balanced ambition level between incremental and radical innovation

Modern wind turbines, systems and wind farms are primarily developed through incremental innovation at an overall level and a combination of incremental (main part) and radical (small part) innovation in detail.

Paul La Cour, the Danish wind energy pioneer, concluded already in the 1890s that the optimal number of blades on a turbine is 3 – this has not changed over the last 125 years. Paul La Cour also worked on using hydrogen for storing electricity, and large companies like Siemens Gamesa Renewable Energy still work on this technology. This goes to show that wind turbine and storage technology is to a large extent developed through incremental innovation, i.e. continuous development of small improvements.

The *radical innovations* create an explosion of growth and possibilities within a relatively short timeframe. These innovations are typically original, complex, expensive and time-consuming to develop.

The *incremental innovations* ensure a continuing refinement and improvement of the existing technology. These innovations are typically, in comparison with most radical inventions, less original, less complex, less expensive and less time-consuming to find and develop.

Research and innovation environments that nurture both radical and incremental innovation create the most efficient stepping stones for technological leadership – such as recognised by the Danish wind energy sector.

Balanced ambition level between big and small projects (both in timeline and budget)

It is important to prioritise both small projects (that give relatively quick indicators of an ideas potential) as well as big flag-ship projects.

A National Strategy for research, development and demonstration should consider the necessary flexibility for how expensive and how time-consuming a

1) https://efkm.dk/media/12222/energiaftale2018.pdf

project can be, since tight regulations risk to "strangulate" innovation.

Smaller and quicker projects serve knowledge and innovation in one way where big flag-ship projects serve knowledge and innovation in another way. Both are equally important for progress.

Balanced focus between more mature technologies and more immature technologies

There is an increasing perception of wind turbines being a relatively simple and fully developed "plug-and-play" technology that can be installed wherever there is a political will to do so.

This is a misconception. Modern wind turbines and wind farms are high-tech and complicated structures that are developed from cutting edge technology.

The first wind turbine saw the light of day only 40 years ago and the technology continues to develop rapidly. In comparison, the development of the aviation sector did not stop its development 40 years after Ellehammer's first prototype in 1906.

As the decrease in cost for wind turbines combined with increasing efficiency continues – there are still a need for massive development in the wind energy industry. The most significant inventions in the industry may not even have seen the light of day yet.

If Denmark stops developing the more mature wind technologies (such as onshore wind) in the belief that these technologies no longer can or should develop from the level they have today, Denmark loses its technological leadership in this area.

In general, the more developed a technology is, the more sophisticated and complex questions can be asked in a research, development or demonstration project.

There is a need for research, development and demonstration (RD&D) within both the more mature and the more immature areas of wind energy.

Balanced budgets between low and high Technology Readiness Level (TRL)

Reasonable ambition level in budget volume is important. Equally important is how the budget is spent. It is important that it is considered how the budget is distributed between all maturation levels in the Technology Readiness Level-chain going from research-to-development-to-demonstration. Thus, prioritisation of budget in: idea phase → competence building phase → laboratory testing phase → testing in real environment in small scale phase → testing in real life environments in large scale phase etc.

Maintaining the volume of projects that go through all development phases helps ensuring the quantity -and quality of projects that can lead to commercialisation. It is precisely the quantity -and quality of new energy products -and systems that will secure growth, job creation and export for Denmark in the future.

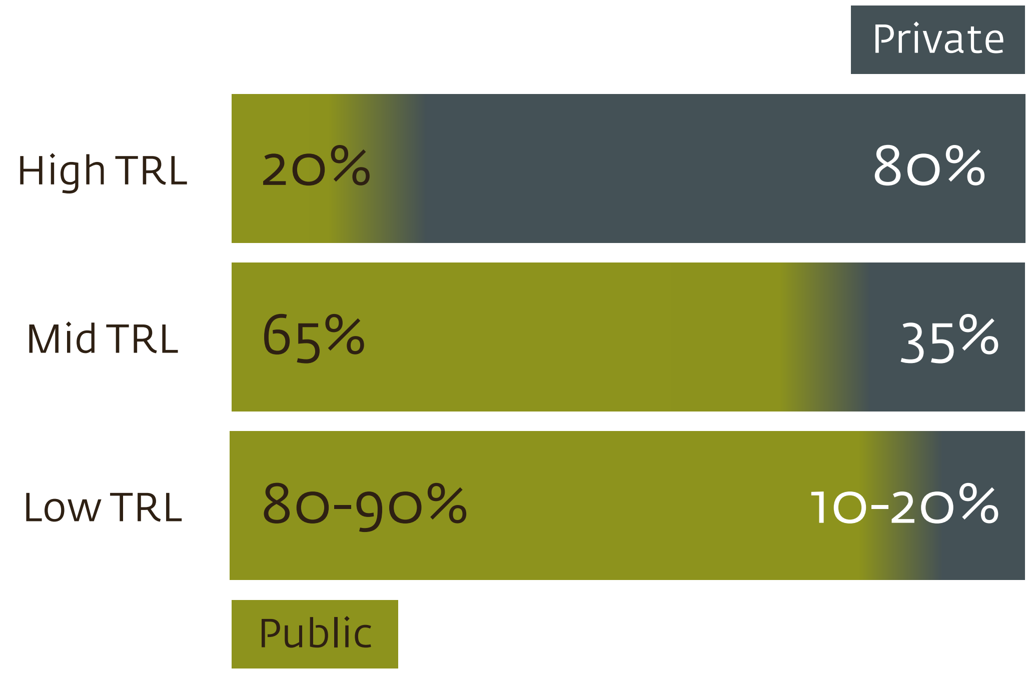
Currently, Denmark's research, development and demonstration budgets are unbalanced with too little focus on lower Technology Readiness Level (TRL). Megavind recommends considering the split between public and private research, development and demonstration (RD&D) budgets as illustrated in the figure on next page.

Prioritised programme for the supply chain

Megavind recommends that public framework programmes target the Danish energy supply chain more efficiently in their strategies and way to measure success. It is of significant importance that the public framework programmes support research, development and demonstration of products -and services at all levels of the value chain – including tier two and tier three level.

Few publicly funded projects have consortia where companies from the supply chain (and SME layer) are present.

However, the Danish technological leadership on wind energy arises from the sector's ability to collaborate across all levels of the value chain (research institutions, supply chain and large enterprises):



- Several Danish universities and private research institutions are globally acknowledged as leading institutions within wind energy. Denmark hosts a variety of publicly and privately-owned test facilities such as Lindø Offshore Renewables Center (LORC), Høvsøre test station for large wind turbines, Østerild National Test Center for large wind turbines, BLAEST blade test center in Aalborg, Poul La Cour wind tunnel etc.
- Three of the leading wind turbine manufacturers are located in Denmark: Vestas Wind Systems, MHI Vestas and Siemens Gamesa Renewable Energy.
- The Danish energy developer and utility, Ørsted, is globally leading in offshore wind farms. Companies such as E.ON and Vattenfall are also developing and running offshore wind farms from their base in Denmark.
- Denmark is headquarters for large 'tier one' wind power enterprises.
- Denmark has a large number of enterprises in the 'tier 2' and 'tier 3' category in the wind industry.

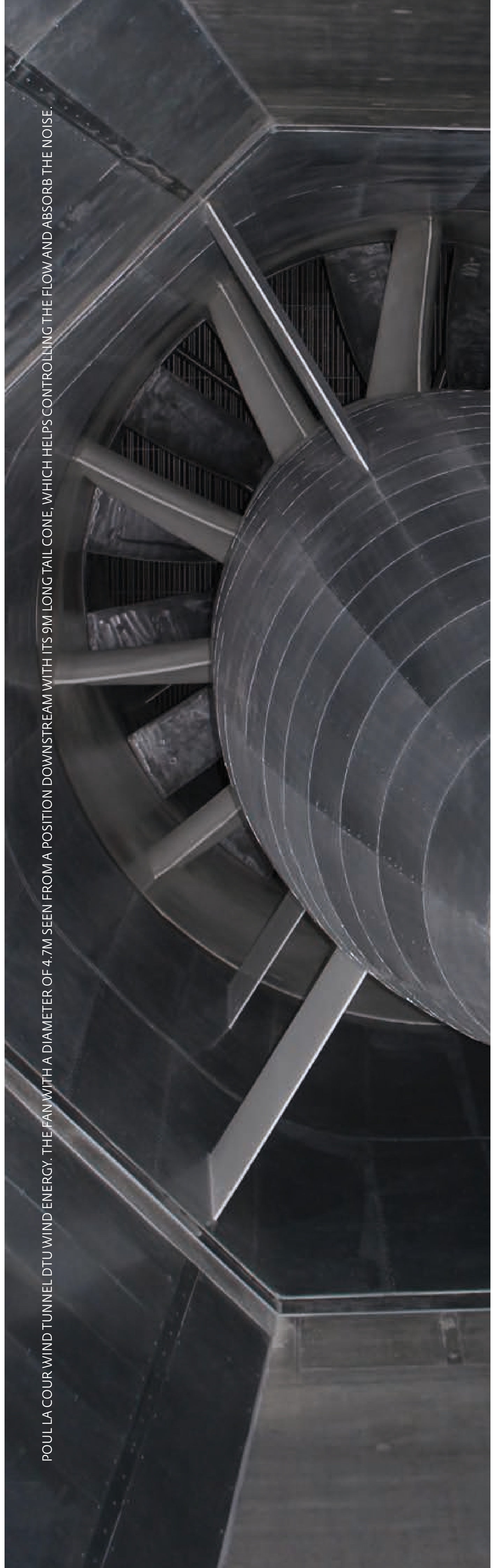
APPENDIXES

APPENDIX 1

What is Levelised Cost of Energy (LCoE)

LCoE expresses the ”levelised” unit cost of 1 MWh over the lifetime of the wind farm by taking the sum of the discounted lifetime costs relative to the sum of discounted energy production at the time of the financial investment decision. LCoE can therefore be expressed as:

$$\text{LCoE} = \frac{\text{Present value (cost)}}{\text{Present value (Production)}}$$



POUL LA COUR WIND TUNNEL DTU WIND ENERGY. THE FAN WITH A DIAMETER OF 4.7M SEEN FROM A POSITION DOWNSTREAM WITH ITS 9M LONG TAIL CONE, WHICH HELPS CONTROLLING THE FLOW AND ABSORB THE NOISE.

APPENDIX 2

Technology Readiness Level

Technology Readiness Level (TRL)

HIGH

TRL 9
Actual system proven in operational environment
(competitive manufacturing in the case of key enabling technologies; or in space)

TRL 8
System complete and qualified

TRL 7
System prototype demonstration in operational environment

TRL 6
Technology demonstrated in relevant environment
(industrially relevant environment in the case of key enabling technologies)

TRL 5
Technology validated in relevant environment
(industrially relevant environment in the case of key enabling technologies)

TRL 4
Technology validated in lab

TRL 3
Experimental proof of concept

TRL 2
Technology concept formulated

TRL 1
Basic principles observed

LOW

MEGAVIND

Danish Wind Industry Association

DFFV

Danish Ministry of Energy, Utilities and Climate

Vestas

Offshore Energy.dk

Siemens Gamesa Renewable Energy

Vattenfall

e.on

Ørsted

Øglænd System

GLPS

Mita-Teknik Great at Control

DNV·GL

MHI Vestas Offshore Wind

IB Andresen Industri

Energinet.dk

Scanel

Fritz Schur Energy

Aalborg Universitet

DTU

Aarhus University

Envision

SDU University of Southern Denmark

Global Lightning Protection Services

Liftra

House of Energy

PHOTO: BEFORE TEST: K-NODE JACKET STRUCTURE FROM OFFSHORE WIND TURBINE IS BEING TESTED IN THE MECHANICAL TEST BENCH AT LINDOE COMPONENT AND STRUCTURE TESTING A/S

BY COURTESY OF LM WIND POWER

Megavind
Vordroffsvej 59
DK-1900 Frederiksberg

Tel. +45 3373 0337
Web: megavind.windpower.org

ISBN 978-87-970265-0-2