WIND

WE PUT KNOWLEDGE TO WORK

DTU Wind Energy

Published on the occasion of the 40 year anniversary of DTU Wind Energy

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DTU Wind Energy

WIND

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DTU Wind Energy

Refshaleøen, Copenhagen.

PHOTO: MELISSA ØRNSTRUP

CONTENT

PHOTO: KIM DAHL

Happy 40th anniversary

By Peter Hauge Madsen, Head of Department, DTU Wind Energy

The history of modern wind energy is the story of politicians and authorities recognizing the perspectives of renewable energy and creating the basis for a green energy system through support and ambitious energy plans.

It is the story of individuals, wind turbine guilds, and the wind turbine industry investing in an untested green energy technology. It is also the story of creating confidence in wind energy and a basis for large-scale investments and international energy companies' development of large onshore and offshore wind farms.

However, it is also the story of a generation of young researchers in their research laboratories and of universities taking up the challenge of an unknown technology. Through research, development, testing, and training, they laid the foundation in the form of knowledge, models, and tools for designing a reliable and cost-effective energy technology and exploited it under different conditions globally. Part of the latter is the history of DTU Wind Energy, which began 40 years ago.

In 1978, the Test Station for Small-Scale Wind Turbines was established at Risø. The first foundations for erection of wind turbines were cast in the area that still houses DTU Wind Energy's research wind turbines, and where the first test station employees were hired. The test station was part of the Ministry of Trade's Energy Research programme phase two, which also contained other basic initiatives in the wind energy sector in Denmark such as the Gedser turbine measurements, establishment and measurements on the Nibe turbines, and preparation of the Wind Atlas for Denmark. Composites for blades and aerodynamics were also developed in these years. Although DTU and Risø employees had already been actively involved in the Tvind turbine, wind energy organisations, and preliminary examinations, 1978 is the year in which the foundation was laid for what is today DTU's Department of Wind Energy, DTU Wind Energy.

40 years later, the few dedicated employees at Risø and DTU in 1978 have developed into DTU Wind Energy, one of the largest and internationally most recognized wind energy departments with 250 employees, half with international backgrounds. The department is working to make wind energy even more cost-efficient, reliable, usable, and system friendly through research, teaching, innovation, advice, and testing aimed at creating a sustainable energy supply and making the world a better place. The following is the story of DTU Wind Energy, the technology applied, names from the past to the present, and the international collaboration with other institutions and enterprises.

The story has only just begun, but this book has been written to take stock of the first 40 years and to remind us all that continuous and trusting collaboration between industry, politicians/authorities, and universities/research institutions can move mountains and develop a technology and an industry that are well on the way to meeting a significant part of the challenge of global sustainable energy supply.

Wind turbine at Nørrekær Enge with two lidars. May 2015.

PHOTO: ANDERS ROUSING VESTERGAARD

DTU Wind Energy

PHOTO: MELISSA ØRNSTRUP

CHAPTER 1 | **METEOROLOGY**

"Industry collaboration has been crucial"

DTU Wind Energy at Risø has prepared a global wind atlas, and the detailed knowledge about wind and weather has synergized with other technical competences, resulting in international exports running into billions.

Customers for the detailed wind atlases include wind turbine installation companies, countries, the World Bank, and the UN.

DTU Wind Energy's software and models are today leading products in research and are used for calculations of wind turbine sites globally.

> **The coupling between wind conditions and wind turbine design is one of our key competences at DTU Wind Energy**
>
> Peter Hjuler Jensen, Deputy Head of DTU Wind Energy

Since the end of the 1970s, DTU and Risø ('DTU Wind Energy') have worked to develop the technological possibilities for exploitation of wind power via research, approval, testing, and authority assistance. Throughout the period, the department has had close and unique collaboration with the industry.

DTU Wind Energy approved wind turbines for erection in Denmark from 1979 to 1995, and was responsible for the approval scheme until 2016, when the Danish Energy Agency took over the task. Since 1980, DTU Wind Energy has continuously conducted research projects with the industry.

Danish industry's wind turbines were tested at Risø from 1979, later at Høvsøre Test Centre in 2002, and finally at Østerild Test Centre from 2012. Other experimental facilities have continuously been established. Most recently, a new national wind tunnel and a large-scale test facility have been established. They are both designed for research purposes and industrial use.

The industry collaboration has grown steadily over time, and today 40 per cent of DTU Wind Energy's revenue is generated via work for the industry. Another 40 per cent comes from publicly funded research projects with the industry as participant. DTU Wind Energy has worked with meteorology since the late 1970s. Meteorology research cannot be overestimated in any way in terms of its importance to wind power and wind turbine development. The field is important to the relevance of wind turbines, and wind knowledge is highly important. This comprises knowledge about where the wind comes from, and how strong it is.

Essential knowledge

Today, it has been proved that the energy content of the wind may be twice or three times as high along coasts as inside a forest, and this type of knowledge is essential to how wind energy is developed.

It is crucial to wind energy utilization that the industry has efficient tools to determine the wind energy content at the individual site chosen for the wind turbine or wind farm before the wind turbines are erected. It is also essential to have methods for mapping maximum wind speeds when designing the wind turbine and calculating how strong it must be. Accurate wind mapping is highly important to both the volumes of wind resources exploitable by the individual country and prioritization of wind energy comparing with other energy sources.

"We operate with different wind classes in our design of turbines, and the coupling between wind conditions and wind turbine design is one of our key competences at DTU Wind Energy. We cover all facets essential to the decision-making, from wind farm planning and right up to when it can be commissioned," says Peter Hjuler Jensen, Deputy Head of DTU Wind Energy. 40 years of intense work with research and development of new wind power technologies have produced advances and unique tipping points. Peter Hjuler Jensen has been involved since the very first pioneering days at the first test station at Risø and has his very own personal favourite picture: "It's

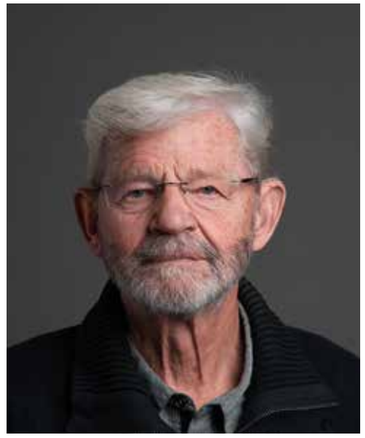
PETER HJULER JENSEN

Deputy Head of DTU Wind Energy, employed at the first test station in 1979.

Responsible for the approval scheme in the 1980s.

Responsible for establishment of the test centres at Østerild and Høvsøre.

PHOTO: BAX LINDHARDT



ERIK LUNDTANG PETERSEN

Employed at DTU since 1970.

Head of the Meteorology Section from 1977.

Head of the Test Station for Small-Scale Wind Turbines from 1980.

Head of Research Centre Risø's Wind Energy Department from 1985 to 2009.

Research Professor and Professor Emeritus from 2015.

a picture that describes the technology development in recent years. An aerial photo of a football pitch."

"Previously, the available technology allowed us to measure wind conditions in front of a wind turbine – equal to the wind conditions on the small white dot in the middle of the football pitch. Where the kick-off is and where the whole pitch corresponds to the area swept by the wind turbine. Today, we can measure wind conditions on the whole pitch with great accuracy. We refer to this as the rotor plane in front of the wind turbine, which illustrates the development in this field. We can use wind measurements throughout the rotor plane in wind turbine response calculations, and thus refine and improve both design basis and optimization possibilities in the development of the technology. With new measuring methods via the so-called lidars, we can now see the wind," explains Peter Hjuler Jensen.

Good ideas often come at night

In 1977, the Meteorology Section and the Danish Meteorological Institute (DMI) were asked to prepare a so-called wind atlas for Denmark. The idea was to prepare a large collection of maps showing wind speed distributions across Denmark at a number of heights.

Former Head of Department, now Professor Emeritus, Erik Lundtang Petersen was involved from the humble beginnings. He clearly remembers waking up one night and thinking: "All those maps simply won't work. There must be another way. Hopefully, by developing a useful method for calculating wind conditions at a given site based on an overall wind climatology and the site's topography."

Immediately after arriving at work at Risø, he contacted his colleagues Ib Troen, Søren Larsen, and Niels Otto Jensen, and together they started further developing the idea of the wind atlas method, which is today known and used worldwide.The researchers were aware of the importance of the wind turbine being in a coastal location or, for example, near windbreaks or buildings.
One of the important sources of this new knowledge was Dr Phil. and Dr. Tech Martin Jensen, whose many projects included technical responsibility for construction of the new Little Belt Bridge.

Here, he had calculated extreme wind speeds from different measuring stations, which became of great importance to the development work done by Erik Lundtang Petersen together with Ib Troen for the Danish wind atlas.

DMI analysed 15 years of pressure measurements in Denmark and its neighbouring countries and established the climatology for the so-called geostrophic wind, the undisturbed wind at approx. 1000 metres height.

"We combined this climatology with our knowledge of how the wind behaves over different terrain types, such as simple agricultural land to coastal areas, hills, and forests. We obtained this knowledge from boundary layer meteorology. It is a field in which the Meteorology Section had been conducting research since 1965. For example, we had participated in several large international experiments," says Erik Lundtang Petersen.

> **"While we were working on the new method and models, the PC was invented, making it possible to disseminate the work**
>
> Erik Lundtang Petersen, Professor Emeritus

PHOTO: BAX LINDHARDT

HANS EJSING JØRGENSEN

Programme Manager and Head of Section at DTU Wind Energy.

Has conducted research in atmospheric boundary layers. Subsequently Head of Section for Meteorology and today Head of Section for Meteorology and Remote Sensing, and Programme Manager responsible for coordination of DTU's siting and integration research strategy.

The result was Wind Atlas for Denmark, consisting primarily of a collection of graphs and a method description for how to combine the graphs to calculate the energy production of a given wind turbine at a given site. The calculation method was to determine the nature of the terrain in the eight wind directions, and after selecting the corresponding graphs, the method could predict the wind turbine's production over its 20-year service life using a simple pocket calculator.

"Today, we have loads of documentation that the method gives good results in terrain that isn't too complicated," notes Erik Lundtang Petersen.

The groundbreaking idea led to the models and methods used today, and also resulted in the EU Commission asking DTU Wind Energy to head the work to draw up a European Wind Atlas. Altogether, the work took eight years. Due to the mountains, DTU Wind Energy's researchers could not apply the method of pressure measurements they had used for the Danish wind atlas. Therefore, they came up with another pioneering idea.

> **In future, we will be dealing with completely new energy systems**
>
> Hans Ejsing Jørgensen, Head of Section and Programme Manager

"We quite simply went in another direction. We discovered that based on the many local measurements – in particular from airports – we could create a picture of the overall climatology and then use it as in the Danish wind atlas," explains Erik Lundtang Petersen.

He also reminds us that time was on the researchers' side in this period. To begin with, they worked on large mainframe computers, and while working on the new method and models, the PC was invented, making it possible to disseminate the work and make it available for everyone, because all the models and methods became the PC software WAsP, marketed since 1987. According to energy economists, the publication of the European Wind Atlas in six languages in 1989 had a great effect. Politicians realized that wind energy could be used throughout Europe.

Open data and global outlook

After working with the Danish and European wind atlases, DTU Wind Energy has continued its groundbreaking work to the benefit of all those engaged in wind power. Current Head of Section Jake Badger highlights a number of essential advances for the role of meteorology in wind power.

"Firstly, I want to mention the global reanalysis data setter, which is a description of the atmosphere through decades. It began around 30 years ago, but it's continuously improving, and we have gone from very rough resolutions to fine resolutions with better time data, and it's becoming increasingly accessible to everyone," says Jake Badger.

Today, everyone has access to the material, and all the data is global. It is used at DTU Wind Energy and is very important to the department's academic field.

When Hans Ejsing Jørgensen became Head of Section, the researchers could make wind atlases based on the models, and the wind atlas method was developed. The department is still working to make the method more precise. The researchers have continuously involved more and more, increasingly advanced elements.

DTU Wind Energy

> **If others catch up with us at some point, they will not have our experience and track record**
>
> Jake Badger, Head of Section

"Because we have been in the game for many years, we today possess massive knowledge and plenty of advantages in this field," says Hans Ejsing Jørgensen. He stresses that collaboration with the industry has been crucial. The enterprises have been the users of DTU Wind Energy's products.

Jake Badger also points to the development of mesoscale models, and particularly the models, which are today publicly available, and can thus be used by more researchers and developers. They are today accessible to anyone worldwide, which has meant that the whole field has become highly dynamic.

"We tell the surrounding world how we think the new knowledge should be applied. We are, after all, a university. We want to be transparent, so that others can see how we do it. This has made us an active part of a large community which uses mesoscale models, and we have developed a special model chain, which allows switching from one system to the other with many different users," explains Jake Badger. He mentions so-called microscale modelling, which enables researchers to get right down to the precise spot at which a wind turbine or several wind turbines in an overall wind farm are to be erected. DTU Wind Energy has contributed to making the relevant models usable by everyone and ensuring that they are connected.

Lightning-fast calculations

Jake Badger highlights the computing power DTU Wind Energy has at its disposal today. For example, the department has ensured that the crucial supercomputers are today available to more researchers, and "we will get a brand-new supercomputer with even more power in spring 2019," he points out.

Hans Ejsing Jørgensen explains that the main reason why researchers started working with wind atlases is the availability of fast calculating tools for establishing meteorological conditions.

"To begin with, our results were based on regular measurements at a height of maybe ten or twenty metres. We then had to convert the measurements into wind resources in the terrain, and here the WAsP calculation method revolutionized our work," notes Hans Ejsing Jørgensen. Quick tools were developed which could function on an ordinary computer. Back then, it took maybe 10 or 15 minutes to make a calculation. Today, it takes one second. A simple tool which performed a complex task, and which could be used by ordinary engineers.

"It was one of our major contributions. For the meteorology group, this was a serious tipping point, and it merely got better when our previous boss, Lars Landberg, realized that the tool should be integrated in Windows, making it a standard tool," says Hans Ejsing Jørgensen. Meteorologically, more advanced models were continuously developed, which meant that DTU Wind Energy allocated more manpower to working with these models.

Lidars have been vital

"Traditionally, we had used a classic cup anemometer to measure

PHOTO: BAX LINDHARDT

JAKE BADGER

Head of Section. Resource Assessment Modelling.

Educated in Physics (BSc) at Imperial College, London, and holds a PhD in Meteorology (PhD) from University of Reading.

Came to Denmak in 2000 to work on wind energy meteorology and resource assessment.

DTU Wind Energy

DTU WIND FACTS

DTU Wind Energy employs an average of 40-45 PhD students.

DTU Wind Energy is a multicultural workplace.

38 different nationalities work in the department.

PHOTO: MELISSA ØRNSTRUP

wind. It was expensive to move out into the terrain and erect a mast with a height of perhaps 100 metres. However, you should bear in mind that it was extremely important to determine wind speed in a given place for a wind farm. The error on a wind speed that you measure may perhaps not be raised to the third power, but it will be raised to the second power if everything is included. So if we made a mistake of one metre per second, it was exacerbated, because the energy you produce on a wind turbine is measured in a power curve that depends on the wind speed," notes Hans Ejsing Jørgensen.

He explains that it is important that the measurements are based on precise results, and it is thus today necessary to measure at a height of 80 to 150 metres, as this is the height of today's wind turbines. How do you get up there? Well, you must either use some large and expensive masts, or you can use remote sensing.

To be sure, measurements must be done on site. It is no good returning home with results that are 10 per cent lower than the reality, as this will automatically affect the project economy, and a 10-per cent margin could be crucial. There are examples from Germany where calculations showed that the owners would get 100 units out of some new wind turbines, but it turned out that they only achieved 67 units. They thus lost 33 per cent of the expected income.

"It's therefore important to be able to make accurate and reliable calculations, and we have made a living from this for many years," says Hans Ejsing Jørgensen.

About 15 years ago, DTU Wind Energy started working with light detector and ranging lidars and newly developed measuring instruments. This made it possible to measure not only at a single site, but at several sites and over a long period, which meant that the researchers achieved unprecedented fantastic measurements. Furthermore, the precision at the individual site was on a par with a cup anemometer. Instead of raising a high, expensive mast, you could light up into the atmosphere at a height of 100 metres and make the necessary wind speed measurements.

"This possibility has helped move us forward. We have since worked to develop highly advanced measuring instruments that can handle measurements of this type at lower costs and more precisely, because we cover larger areas," explains Hans Ejsing Jørgensen.

Big data challenge

Access to raw computer power and new measuring methods creates a number of new challenges. Head of Section Jake Badger believes that one of the current challenges for DTU Wind Energy is about how the department uses its available computing power.

"How do we use all the data at our disposal? It is not enough to just collect data. We can do many things with new methods. In terms of terrain and heights, we have a wide variety of data from satellites, which helps create pictures of what the landscape looks like. This may be buildings, forest, agriculture, cities, and desert. We face many challenges in finding out how we best utilize all this data on wind turbines with available or new methods. And it requires us to focus all our resources and capacities in the right direction," he points out.

Jake Badger finds that another current challenge is that the department must prove that it is among the best in the world. It is therefore important to maintain the quality and values together with DTU Wind Energy's partners, and he does not think that it is difficult to hold on to the department's competent researchers.

"The people who work here find it exciting. We work in an environment with much applied research, and it is my impression that all researchers here are interested in their research being used to solve problems relating to the energy challenges we are facing today. I think it's all about us working closely together with the industry, and the employees experience the dynamics of the collaboration with the industry as highly positive," says Jake Badger.
Hans Ejsing Jørgensen believes that one of the major current challenges for DTU Wind Energy is about getting a grip on turbulence. He points out that this is an important element in meteorology

DTU WIND FACTS

252 people work at DTU Wind Energy.

21 per cent of the employees are women.

48 per cent have an international background.

The average age is 42 years.

PHOTO: DTU WIND ENERGY

about which researchers do not yet have sufficient knowledge.

"Unlike with mean wind speeds, we cannot precisely calculate turbulence levels and diverse gust events, especially in complex terrain," ascertains Hans Ejsing Jørgensen.

Wind speed fluctuations due to the overall dynamics of the atmosphere have not yet been mapped.

Complex models are required to meet this challenge, and the model results must then be made usable, as they are important to the industry's design of wind turbines. What must a wind turbine be able to withstand? It must not be better and more durable than necessary.

"It's about constantly going to the limit to cut costs, and turbulence is an element that we need to get a better grip on. Today, we can measure turbulence, but there are still too many uncertain elements," admits Hans Ejsing Jørgensen.

He also points out that the ability to predict wind and wind forces is another challenge. Based on the current energy system design, electricity is inexpensive when it is very windy and expensive when there is not much wind, as other energy sources or stocks are then needed.

Today, wind energy has become so competitive that it is possible to produce wind energy cheaper than power from a power station with coal, oil, or natural gas. However, it remains important to try to push prices down and produce cheaper power with the right design.

"We're driven by a desire for more accurate models. We must become better at predicting 24-hour variations, and we must be able to forecast better to ensure more efficient revenue management. It's highly complex, but we're constantly working to meet the challenge," says Hans Ejsing Jørgensen. As Programme Manager across the different research branches, his responsibilities include combining large model chains to enable the department to develop new wind turbine designs using highly advanced or simple models.

It is about enabling the researchers to predict the volume of energy that can be generated based on a given location and offtake. How this may be combined with batteries, and possibly solar energy plants, in a complex solution, and with extensive knowledge about all details of all parts and the coordination between sun and wind. The researchers must know how we dispose of the energy or how the energy can be stored.

"In future, we will be dealing with completely new energy systems. Via meteorology we must predict with the greatest possible precision the wind we can expect, despite large fluctuations in speeds and times," Hans Ejsing Jørgensen concludes.

Sustainable energy

Jake Badger is certain that sustainable energy is here to stay. He is convinced that the future will bring a lot of work for the researchers at DTU Wind Energy.

"I expect that 20,000 wind turbines with a total capacity of 50 gigawatts will be installed in the coming years, and there will be a need to examine around 80,000 locations each year in this connection." There will thus be a great need for valuation of wind resources and wind conditions, which means that wind energy will have a large volume in the future, and DTU Wind Energy will be able to contribute with many aspects.

"Right now, we have the overall unique knowledge in many facets of wind energy, but I don't know how long we can maintain this unique position. However, if others catch up with us at some point, they will not have our experience and track record," stresses Jake Badger. Hans Ejsing Jørgensen finds that the researchers at DTU Wind Energy must maintain the good collaboration between the various disciplines in the respective sections. The researchers must continue to adapt and meet the needs of the wind energy sector.

"We need to understand all the important aspects of wind energy and know how we integrate wind in a sustainable solution in the future," says Hans Ejsing Jørgensen.

40 YEARS WITH DTU WIND ENERGY

1978: Test Station for Small-Scale Wind Turbines is established at Risø

1979: 1st approval scheme (under the Ministry of Housing)

1980: The Danish wind atlas is published

1981: 2nd approval scheme (under the Ministry of Energy)

1987: IEC standardization is commenced

1989: The European wind atlas is published

1995: EllipSys software

2002: Test Centre Høvsøre is inaugurated

2005: BLAEST is inaugurated

2012: DTU Wind Energy is established

2012: Test Centre Østerild is inaugurated

2015: The global wind atlas is published

2017: Large Scale Facility is inaugurated

2018: The national wind tunnel – Poul la Cour – is inaugurated

> **Looking back over the last 10 years, becoming a part of DTU has strengthened our competence profile and reach significantly**

Peter Hauge Madsen, Head of Department, DTU Wind Energy

> **Our research in wind energy is a strong global brand for DTU. When I travel around the world to talk about DTU, there is one thing that people know about us, and that is DTU Wind Energy**

Anders Bjarklev, President DTU

LARGE SCALE FACILITY

Inaugurated November 2017.

Enables testing on a very large scale.

Makes it possible to conduct research in strength and fatigue of large structures exposed to complex loads.

A test hall of 1560 square metres with reinforced floor and three test stands.

The facility enables testing of blades and other slender structures in three different scales: 45 m, 25 m, and 15 m.

PHOTO: DTU WIND ENERGY

DTU Wind Energy

TUHFE GÖÇMEN

Tuhfe Göçmen (30) has worked at Risø for almost six years.

She is a qualified aerospace engineer from Ankara in Turkey and wants to focus on big data and data science in the future.

Tuhfe lives in Valby with her boyfriend and two cats, and she plays the drums in two bands in her spare time.

PHOTO: BAX LINDHARDT

The woman behind groundbreaking model for measuring energy from offshore wind turbines

The PossPOW project, Tuhfe's PhD work, has come up with a methodology for estimating the potential power production of wind farms in periods with down-regulated wind turbines. The aim is to calculate what is lost because of the down-regulation.

The down-regulation is preferred more and more frequently, as control of the wind farms helps keep the electricity grid stable in connection with wind power production, and knowing the 'losses' by doing so is important for being paid a fair amount by the power system for this service.

Tuhfe has worked with fast and robust models to simulate the flow between the turbines. The follow-up project, Concert, aims to take it to the next level and develop strategies to control that flow by tuning the turbines smartly. Thus, the overall production of the wind farm is maximized with increased lifetime and decreased uncertainty while it will still be able to offer the service of down-regulation in return for a fair compensation.

Her main involvement in the Concert project is to quantify and reduce the uncertainty in the estimated power in the wind farm at practically every second. In other words, her job in the project is to use the information recorded in the wind turbines' control systems (SCADA: Supervisory control and data acquisition system) to estimate the effect of turbine-turbine interaction in terms of overall power production within a certain interval.

Tuhfe Göçmen is currently a Postdoc in DTU Wind Energy focusing on the uncertainties involved in quantification and validation of SCADA-based flow modelling and control.

She investigates fast and robust methods to model the flow within large offshore wind farms, especially during non-optimum operational conditions.

She studies large data sets for both validation and model training purposes, including the integration of highly variable wind power with large-scale electricity systems. She received her PhD on real-time possible power estimation of down-regulated offshore wind farms, PossPOW framework.

> **"For me, Risø is the perfect mix of research and business**
>
> Tuhfe Göçmen

PHOTO: TIM KILDEBORG JENSEN

Mr. Windpower

The grand old man of wind energy, Henrik Stiesdal, on the achievements of the past 40 years and their importance to global wind energy.

On the current challenges faced by DTU Wind Energy and future requirements.

PHOTO: DTU WIND ENERGY

If anyone, Henrik Stiesdal has lived his life for wind power. He invented his first wind turbine at the age of 19 and helped build up the Danish wind turbine industry three years later.

After several years heading wind turbine manufacturer Siemens, Henrik Stiesdal has decided to retire, but this does not prevent him from continuing to invent things.

As he says, he will not stop until he is forced to, and he is still in demand by organisations, departments, and enterprises worldwide.

Henrik Stiesdal has a two-blade speedster stored in the basement of his home in Odense. This wind turbine was one of his very first inventions and it made him truly embrace wind power nearly 40 years ago. Since then, he has taken out more than 200 personal patents in wind technology, and Henrik Stiesdal must be regarded as one of the most significant pioneers in wind turbine technology.

We asked him about DTU Wind Energy's role in the past, present, and future of Danish wind turbine development.

What would you pick as the most important highlights from 40 years of DTU Wind Energy?
"Well, there are many, so here are just a few: Firstly, the establishment of system approval in the early years, which formed the basis of the industry's growth without too many setbacks due to growing pains. This meant that we gained a much stronger position on export markets than suppliers from countries without system approval schemes. Secondly, the professionalization and application-orientation of the research up through the 1980s gave us a huge edge on nearly all other countries, where the research was mostly a purely academic activity without any real dialogue with the industry. Thirdly, the conversion of research into tools up through the 1990s, probably best illustrated by the Wind Atlas and WASP, which eliminated many of the uncertainties of the commercial projects. Finally, the establishment of the Høvsøre and Østerild test centres made it possible to test new wind turbines without too many obstacles."

Is there one particular tipping point you want to mention?
"No, not really. DTU Wind Energy and the department's predecessors in the form of the Test Station for Small-Scale Wind Turbines and others have always been of essential importance to the Danish wind power adventure, so if I were to mention a single tipping point, it would have to be the actual establishment in 1978."

What have been the biggest challenges for DTU Wind Energy in its collaboration with the wind turbine owners and the industry?
"Over the years, there has been a certain decoupling between what the industry deemed necessary to focus on and what interested the researchers. This was occasionally very conspicuous in the 1980s and 1990s, but it's generally now a thing of the past."

> **"The biggest gains have probably been the approval schemes and their coupling with research**
>
> Henrik Stiesdal, Consultant

What have been the biggest gains to the industry?
"The biggest gains have probably been the approval schemes and their coupling with the research. This occurred in the decisive years in which Denmark established itself as the leading wind power nation. In a more long-term perspective, it has been of invaluable importance that DTU Wind Energy has constantly sought to establish and improve its competences in key areas in this field, wind resources, characterization of wind fields, aerodynamics, structural dynamics, materials, management and control, etc. This meant that the industry always had a place to turn to when difficulties arose or when there were new ideas where feedback from dialogue partners or development partners was needed."

What have been the biggest conflicts?
"There were some conflicts in the early years about the focusing of activities at the Test Station for Small-Scale Wind Turbines. They were settled amicably."

From your professional point of view, how does the collaboration function today?
"The collaboration functions brilliantly."

What do you consider the most positive aspect of the current collaboration between DTU Wind Energy and the wind energy industry, the wind turbine owners, and manufacturing industry?
"DTU Wind Energy has succeeded in maintaining its position as the absolutely unique competence centre for wind power, in both Denmark and globally. Having absolute star competence right next door gives the industry some very favourable terms for knowledge sharing and knowledge building."

Where can DTU Wind Energy do better?
"You should probably focus a little harder on offshore. Not least on the infrastructure, including foundations, grid systems, etc. There is also a need to expand a little more to actual energy systems, including smart grids, platforms, and energy storage."

At DTU Wind Energy, they perceive themselves as having a unique global position in wind power. Do you share this view? Do you think the outside world holds the same view?
"Yes, I share this view, and it's my experience that it's also held internationally. Roughly speaking, everyone is jealous of the special advantages the Danish industry enjoys because of its close collaboration with DTU Wind Energy."

PHOTO: DTU WIND ENERGY

HENRIK STIESDAL

Henrik Stiesdal is a Danish inventor and executive in the modern wind power industry.

In 1978, he designed one of the first wind turbines representing the so-called Danish Concept, which dominated the global wind energy industry through the 1980s. Until 2014, Stiesdal was Chief Technology Officer in Siemens Wind Power.

DTU Wind Energy itself highlights two strengths in its work as an explanation of its unique global position: High academic competence and openness. Do you agree with this?
"Yes."

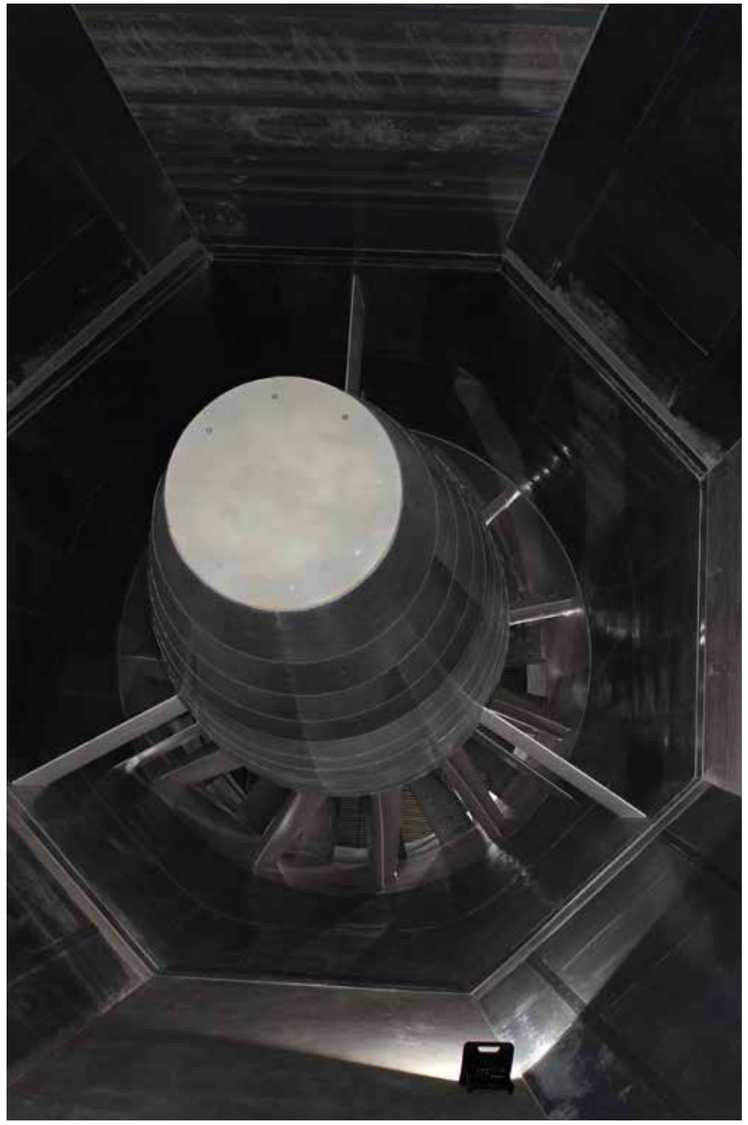
Can DTU Wind Energy maintain this position?
"Yes, it obviously requires constant efforts, but I don't see why they shouldn't be able to maintain this position."

Do you find that the researchers at DTU Wind Energy are sufficiently good at listening and paying attention to inquiries from the industry?
"Yes, absolutely."

What should DTU Wind Energy do to improve its collaboration with the industry?
"They have to remain open to input from the industry, including listening to the industry's focus points. But I actually think they're good at that."

What role should DTU Wind Energy play in the future?
"The same as today, with a twist. Be the absolute competence centre in wind power, and then diversify into mastering energy systems in a broader sense as well."

PHOTO: DTU WIND ENERGY



FACTS WIND TUNNEL

Inaugurated in April 2018

Is expected to be commissioned in the first half of 2019.

One of the largest university-owned tunnels in the world.

The combination of test options makes the wind tunnel unique, not just nationally, but also globally.

Makes it possible to expose part of a wind turbine blade to wind speeds of up to 105 metres/second or 378 km/h.

This corresponds to three times hurricane force.

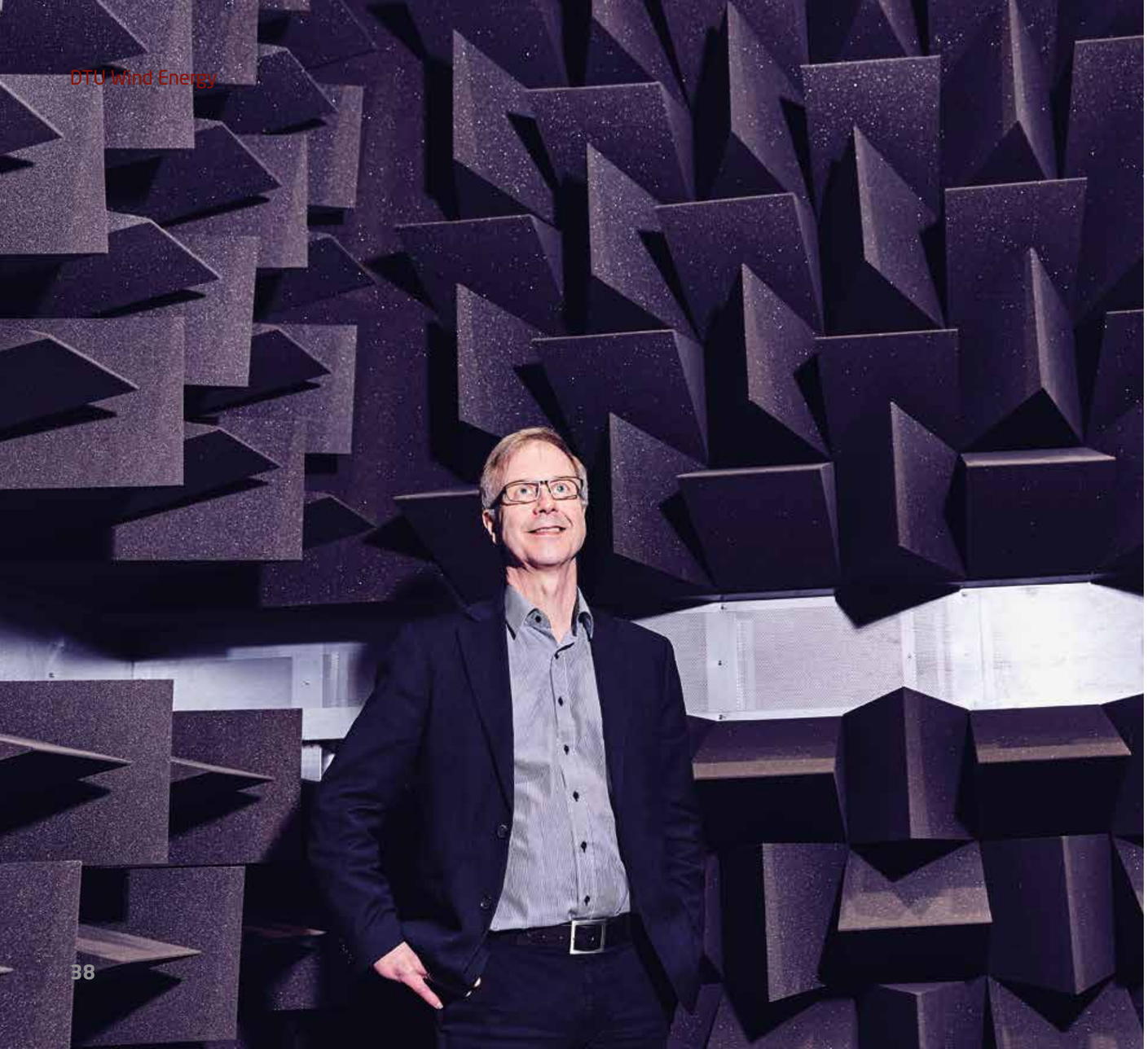


PHOTO: LARS BECH

CHAPTER 2 | **THE WIND TURBINES**

"Our work holds huge potential"

The wind turbine in Tvind, the world's first test station in a ploughed field at Risø and today's largest onshore and offshore wind turbines all form part of the continuous development of Danish wind energy.

For 40 years, wind energy researchers have kept a constant focus on innovation, technology, and tests at the facility at Roskilde Fjord.

> **We saw the first large wind farms in Denmark 25 years ago, but it's only in the past five to ten years that we've reached a large capacity**
>
> Peter Hauge Madsen, Head of Department

The Test Station for Small-Scale Wind Turbines was set up in 1978 at Risø Research Centre to promote the technical and financial opportunities for exploitation of wind power in Danish energy supply.

There has been a huge national and global development since the researchers ascertained in connection with the 10th anniversary of the test station in 1988 that Denmark could receive 10 per cent of its electricity supply from wind turbines in 2000. The researchers also pointed out that wind turbines could become one of Denmark's most important exports if the opportunities were exploited correctly.

The researchers probably could not have imagined the explosive development for offshore wind turbines, including the work with floating foundations.

"It certainly has the potential to become larger than the market for conventional offshore wind turbines we know today," says Peter Hauge Madsen, Head of DTU Wind Energy. Like large onshore wind turbines, floating offshore wind turbines entail a number of potential conflicts.

There are many interests in play at sea: Fishing, military, and environmental interests, but it is basically about exploiting waters which are so deep that it is not profitable to erect normal offshore wind turbines, fixed to the seabed.

The majority of the world's population live along coasts, so if the objective is to establish offshore wind farms near the customers, they must be floating farms, because of the deep waters off many of the densely populated coasts, e.g. in the Mediterranean and along the coasts of the USA.

Ten years ago, the first demo project with floating offshore wind turbines named Hywind was established in Norway, and DTU Wind Energy participated in the commercial project, funded by the then Statoil.

"One of the great advantages of floating wind turbines is that their foundations are the same, unlike fixed turbines where the individual foundation is designed and adapted to the specific location. The identical foundations make floating turbines an obvious choice for batch and mass production," explains Peter Hauge Madsen. Extensive research is being conducted into floating wind turbines, in the industry and at DTU Wind Energy. Most recently, DTU has conducted a series of tests in DHI's wave tank for consultant Henrik Stiesdal.

"Stiesdal is deeply involved in the work to develop new types of foundations, and he has come far in studying the requirements for flexibility, control of fluctuations, and modelling, among other areas. Today, there are many different concepts, but it remains unclear after ten years of work what the end result will be and which standards we will see as winners," says Peter Hauge Madsen.

Equinor (formerly Statoil) and several power companies are very active in developing floating wind turbines, and a number of start-ups are also working intensively with these turbines. One of the first projects - Hywind Scotland - was installed off Aberdeen, Scotland,

DTU Wind Energy

PHOTO: MATTIAS ANDERSSON

PETER HAUGE MADSEN

Head of Department at DTU Wind Energy since 2012.

Previously responsible for the Wind Energy Department at Risø.

Board member of the Danish Wind Turbine Owners' Association since 2017.

2005–2006: Research Manager at Siemens Wind Power.

DTU Wind Energy

PHOTO: MATTIAS ANDERSSON

FLEMMING RASMUSSEN

Head of the Aerodynamic Design Section and Programme Manager for Wind Turbine Technology at DTU Wind Energy department, focusing on the research, development and application related to aerodynamics, CFD and CFD structure coupling and software design and optimization tools for blades, wind turbines and wind farms.

Flemming Rasmussen was employed at DTU in 1978. M. Sc. in fluid mechanics from Technical Univ. of Denmark.

in 2017 by the then Statoil, but no one has yet produced decisive large-scale solutions.

Peter Hauge Madsen believes that the market for floating offshore wind turbines may become much larger than the market for conventional offshore wind turbines. However, he believes it will take more than 10 years for the market with floating wind turbines to mature.

"We must remember in this connection that we saw the first large wind farms in Denmark 25 years ago, but it's only in the past five to ten years that we have reached a large capacity. It takes a long time to develop, and we will see the same pattern with floating turbines," predicts Peter Hauge Madsen.

Research project on floating foundations launched

In the Norwegian Hywind concept, wind turbines are placed on a floating buoy with ballast at 80 metres' depth, moored to the seabed. In a different concept – the French Ideol – the floater is designed as a barge on the surface. Several pilot plants have shown that floating turbines work just as well as conventionally anchored offshore wind turbines in shallower waters.

> **"When we started, there were 15-kilowatt wind turbines, now we're talking about 10 megawatt turbines**
>
> Flemming Rasmussen, Head of Section

The FloatStep project has just been launched with a grant of DKK 15.8 million from Innovation Fund Denmark in 2018. This new project is the next step towards actual industrialization of floating wind turbines. In collaboration with leading enterprises, researchers from DTU Wind Energy are to optimize the design of the floaters for positioning of offshore wind turbines in deep waters.

Offshore wind turbines are gaining ground worldwide, but, as mentioned, the sea is too deep in many places to fix the turbines to the seabed.

Floating offshore wind turbines are therefore being developed and tested. They are to optimize the tools and methods used to design and launch the floaters on which the wind turbines are erected. One goal is to make it cheaper and easier to produce platforms and adapt turbines to them.

DTU Wind Energy has gathered the leading Danish researchers and companies in floating wind turbines to develop and test new and better models for calculating and designing floaters for wind turbines. The Danish wind power sector has been a pioneer in offshore wind energy and thus has every opportunity to become the leader in floating wind turbines as well.

"We will contribute to this in the FloatStep project," says Project Manager and Professor at DTU Wind Energy, Henrik Bredmose. The researchers will develop new engineering models for calculating how heavy waves affect the floater and its mooring. In the work with floating wind turbines, DTU Wind Energy has longstanding collaboration with the industry, in EU projects, and through model tests.

"We look forward to validating and targeting our calculation models in a strong consortium that includes both the industry and knowledge-intensive players. With a combination of model tests, advanced calculations, and full-scale data analyses, we cover the full range," says Henrik Bredmose.

DTU Wind Energy

In the Norwegian Hywind concept, wind turbines are placed on a floating buoy with ballast at 80 metres' depth, moored to the seabed.

ILLUSTRATION: STATOIL

TetraSpar is the Danish floater developed by Henrik Stiesdal in the company Stiesdal Offshore Technologies, and it forms part of FloatStep as a general calculation example.

Henrik Stiesdal's contribution includes data from the first full-scale version of the floater. The TetraSpar concept will be further developed in collaboration with Aalborg University and Siemens Wind Power.

"TetraSpar is designed to enable installation of offshore wind turbines in water depths greater than 50 metres at competitive prices. We hope that the concept will become a game changer in offshore wind power," says Henrik Stiesdal.

Constant progress

Although floating offshore wind turbines are currently receiving much public attention, much of the research at DTU Wind Energy still focuses on classic wind turbine challenges.

Head of Section Flemming Rasmussen, DTU Wind Energy, ascertains that it is today extremely important to preserve, maintain, and expand the necessary knowledge and make it available. "For example in relation to the USA, we have created constant progress in our research, and we're good at exploiting our resources efficiently," says Flemming Rasmussen. For many years, DTU Wind Energy has built up knowledge and has developed aeroelastic programs for calculating blade response and stability and ensuring that they do not vibrate.

"We started with calculations for a profile, then a rotor with three-dimensional relations and rotational effects. This has been further developed so that it now includes the whole turbulent inflow. We have recently coupled this with structural wind turbine models, bringing everything to a much higher level. The new methods make calculations for the whole wind turbine flow, and it's much more sophisticated," says Flemming Rasmussen.

From the mid-70s, materials researchers at the former Department of Materials Research at Risø Research Centre (now part of DTU Wind Energy) have worked on developing manufacturing processes, materials insight, and testing methods for load-bearing materials in wind turbine blades. A development which has made it possible to help the industry build the world's longest blades.

Right from the start, glass fibre-reinforced polymers were chosen because of their exceptional fatigue properties. A wind turbine blade is one of the man-made structures that must resist the most cyclical loads during its life, while weight and price must be kept down. This has not been achievable with metallic materials.

"I must ascertain that glass fibre composites have proven to be an exceptional choice of material," says Senior Development Engineer Jakob Ilsted Bech.

"We have participated in making continuous small materials and manufacturing improvements in close collaboration with blade manufacturers and their materials suppliers. Through this development work, we have succeeded in increasing the blade length from 20 metres, used for the 600 kW wind turbines of the late 1970s, to the ten times as large 6 MW wind turbines with 75-metre blades now being used. This has been achieved concurrently with the production price for wind turbine electricity having plummeted to a level at which it can outcompete fossil fuels on market terms while helping support sustainable energy production," says Jakob Ilsted Bech.

However, the development of wind turbine sizes has not been stopped here. By helping the industry to introduce carbon fibre in a mix with glass fibre in a hybrid composite, it is now possible for the industry to produce blades with a length of nearly 90 metres. In the very near future, a length of over 100 metres will be achieved. A development that may push down the price of wind turbine electricity even further. Throughout the history of wind turbines, blade manufacturer LM Wind Power has repeatedly set new world records in building the world's longest blade. The first copies of the record blade of 88.4 m were produced in 2016. The hybrid technology that makes this possible has been developed by LM together

PHOTO: DTU WIND ENERGY

Sky River wind farm in the USA, DTU Wind Energy performed a measurement programme and approved 247 V27 wind turbines 225 kW.

with DTU Wind Energy and the University of Aalborg in the Blade King research project.

Test of fibre composites

Research into improvements of the composite materials used has had a marked experimental element in which new discoveries have been made in close collaboration between materials researchers and research technicians.

"Already in 1983, our materials testing laboratory became accredited for testing fibre composites, which meant that we could perform measurements for certification of new materials. This became very important in the 1980s, when Danish wind turbine manufacturers sold thousands of blades to wind turbine projects in California," says Jakob Ilsted Bech.

"I was employed at Risø in 2003 by Povl Brøndsted, one of the pioneers in applied research in blade composites," recalls Jakob Ilsted Bech.

"Povl emphasized that we should have fun while we pushed the materials technology forward together with the materials and blade manufacturers. My first assignment was to develop a testing method for measuring the compressive fatigue strength of aligned carbon fibre laminates. A testing method that was to be used for certification of future generations of large carbon fibre-reinforced blades. The test was a success, and we subsequently tested large quantities of carbon fibre for materials suppliers and wind turbine manufacturer Vestas, and the new large blades took off," he says.

Jakob Ilsted Bech says that DTU Wind Energy focused increasingly on also involving producers of fibres and polymeric systems in the following years.

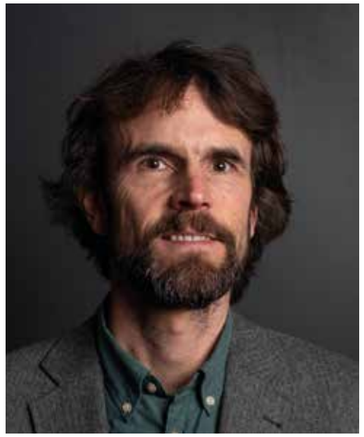
One result of this collaboration was a JEC Innovation Award in the Sustainability category in 2014 for a new composite system developed in collaboration with materials suppliers 3B Fibreglass and DSM Resins, as well as wind turbine manufacturer Siemens Wind Power.

DTU Wind Energy is a world leader in fibre composites research and has a team of more than 20 materials researchers and engineers as well as highly advanced laboratories for manufacture, characterization, and testing of composite materials and sub-structures where 15 highly specialized research technicians perform the experimental work.

Deputy Head Peter Hjuler Jensen points out that modern technology is based on calculations of strength, performance, and efficiency. With an established industry follows standards for how to calculate formulas and new models; when DTU Wind Energy started developing wind turbines at Risø, such standards did not exist. At DTU in Lyngby, they worked early on with relatively advanced modelling, for example for the Tvind turbine and the power industry's turbines.

The researchers calculated how much they vibrated. Based on a given service life, it was calculated how strong they were to be. From today's perspective, however, the basic assumptions for all the calculations made at the time were admittedly incredibly uncertain.

PHOTO: MATTIAS ANDERSSON



JAKOB ILSTED BECH

Senior Development Engineer at DTU Wind Energy. A qualified mechanical engineer and PhD from DTU.

Since 2003, he has worked at DTU Wind Energy with testing and development of composite materials for wind turbine blades in close collaboration with the industry.

His focus is currently on contributing to meeting challenges with rain erosion on wind turbine blades through several interdisciplinary research projects.

DTU WIND FACTS

DTU Wind Energy has well-equipped production laboratories and accredited equipment for mechanical testing of composite materials for wind turbine blades.

PHOTO: MELISSA ØRNSTRUP

"We had descriptions of aeroelastic models and the physics, but no one had a sufficient basis for integrating the available knowledge in usable models. The industry could not use our models, as no one could interpret the results," says Peter Hjuler Jensen. The industry with companies like Vestas, Nordtank, Bonus, which later became Micon, had maybe one or two engineers employed at the factories at the time.

They could not use the tools available from DTU Wind Energy, which led to the first so-called load paradigm being designed in the early 1980s. All conditions concerning a wind turbine were calculated in a simple manner.

Old measurements from the 1930s showed how large the pressure on the wind turbine was when it was at a standstill, and how large the pressure was when it was running.

Using the current knowledge of dynamics and adding lots of safety, the researchers gathered a simple set of design prerequisites for the maximum pressure and for the load to which the wind turbine would be exposed during its service life. Overall, this was called a load paradigm.

"What we did back then was used as a basis for designing the wind turbines which were sent to the USA, and I must admit that some of it was done on something resembling the back of a napkin," says Peter Hjuler Jensen, and adds:

"In the 1980s, we didn't need large fancy models. We knew that there were loads of uncertainties connected with them anyway. We therefore added a lot of safety, and the first wind turbines were probably five to ten times more resistant than they actually needed to be. But they lasted," he says.

In the following phase, DTU Wind Energy and the industry could use the so-called aeroelastic models, implement them, and make calculations for them based on the available knowledge of vibrations, wind forces, and turbulence.

Flemming Rasmussen was among the very first employees at DTU Wind Energy. He recalls that the first wind turbines in Denmark were made by pioneers and master smiths. And that the researchers at DTU Wind Energy helped start a development process.

At the time, it was all done at a very low-tech level. Many felt that it had to be done in popular terms, but if it were to become an industry, the researchers stressed that the technology level had to be raised, if the objective was to use the technology in energy supply in the long term. The purpose of the test station at Risø was to establish collaboration with the industry.

A scientific approach

The first researchers tried to adopt a more scientific approach by developing calculation programs and thus create a design basis for wind turbines. This made no sense without interaction with the industry, as the vision of using wind power for energy supply was to be realized through this collaboration.

The researchers were to prepare tools, incl. software for the industry. They were to help the industry with knowledge of, for example.

PHOTO: BAX LINDHARDT

ATHANASIOS BARLAS

Senior Researcher at DTU Wind Energy.

He originally graduated as a mechanical engineer from UTH in Greece in 2004.

He has been a Senior Researcher at DTU Wind Energy since 2014 with focus on active aerodynamic control and morphing structures.

> **It's quite simply the best place to work. We have a good culture, I have lots of good colleagues, and we're good at working together**
>
> Athanasios Barlas, Senior Researcher

PHOTO: DTU WIND ENERGY

aerodynamics, which it could use in its design processes. It quickly became clear that it was a very complex matter.

Aerodynamics, structural dynamics, control, and power were to be combined in a wind turbine. Therefore, the first researchers developed aeroelastic programs describing the interaction between wind and turbulence, and aerodynamics and structural response.

"We were to calculate this entire complex context, and we soon found out that we needed to think long-term," says Flemming Rasmussen.

Much of the initial research at DTU Wind Energy was experimental, but Flemming Rasmussen observes that it was quickly acknowledged that more theoretical research was needed.

"We decided to develop Computational Fluid Dynamics, CFD. We made load measurements on wind turbines during turbulence, and we especially examined stall-regulated wind turbines; wind turbines with fixed blades, which do not pitch the blades. Based on our interaction with the industry, we were constantly aware of where the problems were. We also had an overview of what wasn't working, and we tried to explain why something broke, and why there were unintended vibrations in a specific wind turbine," says Flemming Rasmussen. To him, the most important thing has been the close interaction with the industry.

It has meant that the researchers have always been aware of the principal points of research required to develop the new programs containing the new knowledge.

Basis for optimizing wind power

Flemming Rasmussen points out that the situation is now completely different for wind power.

"Today, everybody talks about the target of a 100% sustainable energy system, and wind energy must be a part of this. I think wind energy is the cheapest option and even if solar energy is developed further, wind energy will always be needed. We started with 15 kW wind turbines, and we are now talking about 10 MW turbines. Behind this development is a huge effort from the industry and the research community, which have jointly created a solid basis for optimizing wind power and developing new concepts," says Flemming Rasmussen. He believes that DTU Wind Energy must continue the important interaction with the industry.

"We must demonstrate the new opportunities that we have constantly established with our research and calculation programs. We must document where we can go, and where we can do things better and cheaper. I am convinced that we still have an enormous amount of opportunities ahead of us. We need to focus on what the companies are not so good at. We should be the best at organizing the research and looking ahead in collaboration with the industry."

Flemming Rasmussen is convinced that there will still be something called DTU Wind Energy in 40 years. "I can't imagine a better model than the one we know today. There will be industry in Denmark and research here at DTU also in the future. Our work holds huge potential. I often hear that we must surely now have finished developing the wind turbine. No, far from it. There's a long, long way to go," he says.

"And I can imagine many new concepts which require increasingly advanced, complex calculations and models."

Deputy Head Peter Hjuler Jensen points out that one central element in the future will be new high-performance computer systems, which have made it possible to calculate the flows around profiles much more precisely. In future, it will be possible to calculate the service life of a wind turbine in a turbulent wind 20 years ahead. Today, we can dissolve a blade into five million points. Overall, a wind turbine can be divided into perhaps 20 million points with descriptions of the load to which all these points are exposed.

"It requires great computing power, but we have that today," says Peter Hjuler Jensen.

In the future, computers will be so powerful that they can describe all parts of a wind turbine, calculate all types of load, and map how wind turbines and all materials react to the load. This will

PHOTO: DTU WIND ENERGY

Østerild houses Østerild Test Centre for large-scale wind turbines with facilities for testing seven wind turbines of up to 250 metres. The test centre is being expanded with another two test stands, making it possible to test wind turbines of up to 330 metres.

lead to far more advanced load models and materials models in the wind turbine mark 2.0 or 3.0 of tomorrow.

"This is the future we're gazing into," says Peter Hjuler Jensen.

Greek super talent plays key role

Athanasios Barlas has a Bachelor's degree and a Master's degree in mechanical engineering from Greece, and he became seriously interested in wind power while doing his PhD in the Netherlands.

He was employed in a postdoc position at DTU Wind Energy in 2011, and after a spell back in Greece to do his military service, he returned to Denmark in 2013, this time for a job as project manager at Siemens Gamesa in Brande.

"For me, it was a good learning experience to see the industry from the other side, and I returned to Risø in 2014. It is quite simply the best place to work. We have a good culture, I have many good colleagues, and we are good at working together. In my work, I have free access to the world's leading experts, so I definitely expect to remain here," says Athanasios Barlas. He is a good example of some of the great talents who come to DTU Wind Energy from all over the world to continue their careers; in Barlas' case to develop what you could perhaps best characterize as the wind turbine of tomorrow:

Athanasios Barlas' project at DTU Wind Energy

"My work at DTU Wind Energy focuses on developing the new generation of wind turbines. Future wind turbines with extremely large rotors will have new types of blades, which will feature actively deformable (morphing) parts and complex optimized tips. One could imagine similar capabilities as the wings of a bird of prey. Athanasios has been working on this for the past ten years, and two recent projects have already made the leap for industrial implementation. Small directly implemented innovations with high impact are needed to achieve the next technology leap in modern wind turbine rotors, and Athanasios is helping to develop highly innovative blade tip and flap concepts which can be a grand solution for Danish wind turbine innovation."

In the future, wind turbines will talk to each other

Deputy Head Peter Hjuler Jensen believes in a future with wind turbines that can communicate internally and thus constantly optimize production. With communication, he means that the wind turbine itself registers wind load, wind speed, and all other important conditions. This makes it possible to monitor how large the load has been, and the load to which the material has been exposed.

"We have the opportunity continuously to measure the load on the materials and monitor how they break down over time, and whether they deteriorate and lose strength over time. Another key challenge will be wind turbines in the electricity grid of tomorrow.

How do we meet the challenge of more than 100% electrical power from wind energy? Today, this can be handled together with other countries, but how can this task be performed in Denmark alone? How do we establish an energy system based entirely on renewable energy sources?

"It's a great challenge," says Peter Hjuler Jensen. He points out that researchers have discussed the storage problem for 30-40 years, and it is the same in many other countries.

We need to constantly have two to three days' energy consumption in stock next to the wind turbines, so the power from the wind turbines can be used when needed.

"I think there will be several different solutions. It could be fuel cell solutions or a heated stone warehouse; solutions that were not in sight just 10-20 years ago. Now modern technology makes it possible," says Peter Hjuler Jensen.

He also believes there is a need for greater efficiency. The industry is under constant competition and price pressure, and it will be a great challenge to create lifelong efficient delivery of power at as low a price as possible. For Denmark and Europe, this will be a decisive element in the competition with China, which has ousted Europe on, for example, the solar cell market.

"Today, all solar cells are produced in China," says Peter Hjuler Jensen. "If we're to maintain a high share of the global wind turbine industry in Europe, including Denmark, in the future, we must be able to match and address these challenges. We need to be competitive on turbines and technology, and we must supply the electricity at as low a price as possible."

PHOTO: BAX LINDHARDT

OSCAR GERARDO CASTRO ARDILA

He received a BSc degree (2009) and an MSc degree (2012) in Mechanical Engineering at the Universidad del Valle, Cali, Colombia.

This year (2018), he received his PhD degree in Wind Energy, and he is currently working as a Postdoctoral Researcher.

He has worked as a researcher at the University of Delaware (2013), USA, the Technical University of Berlin (2014), Germany, and the University of Padova (2017), Italy.

"My goal is to improve the fatigue performance of wind turbine blades"

Oscar Gerardo Castro Ardila (33) works as a postdoctoral researcher at DTU Wind Energy.

"My research activities regarding fatigue in wind turbine blades focus on three main areas: Development of experimental techniques at the blade length scale to make the fatigue tests efficient and closer to reality. This work is currently part of the BLATIGUE (Fast and Efficient Fatigue Test of Large Wind Turbine Blades) project funded by EUDP.

I work on identification of fatigue damage mechanisms and quantification of their effects on the stiffness and bearing capacity degradation, and the final failure of the blades. This work started during my PhD project and will continue in the newly funded EUDP project RELIABLADE.

This project aims to develop and demonstrate techniques to create a Digital Twin for each individual wind turbine blade in order to improve their reliability by updating their current damage state and predicting their future damage evolution.

In the project, I work at developing multi-scale damage-based fatigue lifetime prediction models based on experimental and numerical observations at the different length scales. This work started during my PhD project and will continue in the RELIABLADE project."

Oscar Gerardo Castro Ardila has been at DTU Wind Energy for four years. He took his Bachelor's and Master's degrees in Columbia and has completed his PhD at DTU Wind Energy.

"I plan to stay here for many years, but I would probably like to return to my native country to work with wind power at some point. Columbia today has a single pilot project with a wind farm, but wind energy does not currently play any major role in Columbia."

As part of the new Materials and Structures Programme, my colleague Martin Alexander Eder and I are working on defining a strategy that allows DTU Wind Energy to positively influence the development of the wind power sector. This involves improving the fatigue performance not only of the wind turbines that are already installed but also of future wind turbine designs.

This work has been developed in conjunction with the different sections of DTU Wind Energy and guided by Ignacio Martí, who is the head of the Materials and Structures Programme.

> "I feel I have all possibilities here at DTU Wind Energy, which – for me – is the world leader in wind energy
>
> Oscar Gerardo Castro Ardila

PHOTO: HENNING BAGGER

CHAPTER 3 | **SOCIETY**

"We have been highly successful in putting knowledge into play"

For 40 years, DTU Wind Energy has played a crucial role for the surrounding society, in Denmark and internationally.

Throughout the globe, groundbreaking research from Risø has had an impact on the diffusion of wind power and the related industry.

The future challenges concern maintaining and developing known research areas and building up new ones, including e-learning and research in social and environmental conditions.

> **The Danish Embassy in Pretoria – which has supported the collaboration with South Africa – compared the wind atlas project with digging for gold**
>
> Jens Carsten Hansen, Head of Section

Knowledge of the role of wind energy to the development of society has changed markedly over time. Today DTU Wind Energy leads the way with, for example, international MSc programmes and online e-learning.

DTU Wind Energy is currently a national and international consultant in a number of fields. In Denmark, the department is adviser to energinet.dk., among other energy companies. However, the sky is not the limit. With increasingly bigger wind turbines dominating the landscape, popular opposition has increased.

Therefore, DTU Wind Energy has integrated social science perspectives in its wind turbine development to understand the reasons for the opposition and to identify solutions.

Important work with standards and approvals

The first major task to the benefit of society has been the work with standardizations and approvals of technology and design. Two areas of responsibility that have played dominant roles for DTU Wind Energy over the years. The work with approval of wind turbines began in August 1979 via a subsidy scheme under the Ministry of Housing, and it continued under the Danish Energy Agency in 1981.

The overall work at Risø with approving, testing, and subsequently establishing the first standards has been of huge importance to the technology in international wind power, and the work has secured Risø a unique global position.

To begin with, the approvals were based on ordinary engineering assessments, and the work really took shape with the first regulations for design and load paradigms.

"I can't claim that it was a complete, cohesive system. This only followed in the 1980s, prepared together with the Danish wind turbine industry and often based on unfortunate breakdowns, which made the wind turbine owners and the industry demand new methods to enable them to avoid future breakdowns," says Peter Hjuler Jensen.

The wind turbines did not necessarily always produce the power they were supposed to deliver, and the researchers at Risø were then asked to find the reason. One of the reasons was that the wind resources had not been studied sufficiently.

DTU Wind Energy received all the complaints, and DTU Wind Energy was responsible for the approvals. The department was to work to make the turbines safer, increase their performance and quality, and develop the technology. On this basis, DTU began developing recommendations for the different areas that make up the design of a wind turbine.

"We made our first standardization work under the Danish Society of Engineers in the mid-1980s," says Peter Hjuler Jensen.

A brilliant decision

Head of Department Peter Hauge Madsen: "It was a brilliant decision that, from the outset, we were subject to approvals and standards known from the construction industry. In retrospect, I can see that

PHOTO: MATTIAS ANDERSSON

JENS CARSTEN HANSEN

Head of Section for Integration and Planning since 2002.

Responsible for several international projects and partnerships since 1985, most recently in South Africa and Mexico, among other countries.

Has been employed at DTU Wind Energy and Risø since 1982.

PHOTO: DTU WIND ENERGY

The test centre for large-scale wind turbines is located at Høvsøre. The test centre has facilities for testing five wind turbines of up to 165 metres. The test centre is being expanded with two further test stands, making it possible to test wind turbines of up to 200 metres.

it was equally brilliant that, from the start, we decided not to work only with Danish standards. From the beginning, we focused on establishing international standards. It was also definitely an advantage that the first international committee for standards in 1987 was chaired by a Dane, Jørgen Christensen, who headed the test station at Risø at the time."

International standardization work

In 1987-88, the international standardization work commenced, and at that time, DTU Wind Energy had come far in Denmark with quality assurance and requirements for implementation and certification.

The department had described in detail how to measure a wind turbine's power curve and performance, and the load situations that were to be examined to ensure that the wind turbine was good enough and safe enough.

The work was performed under the Danish approval scheme, and projects were also performed at EU level in which the Danish standards were coordinated with the rest of the EU.

The other EU countries were interested in this, and DTU Wind Energy created recommendations for the EU standards. The basis for the current EU structure has been prepared in Denmark.

The researchers wanted to draw up the standards themselves, but the wind turbine owners and the industry demanded in the joint discussions that DTU Wind Energy became better at formalizing the documentation process for approval and common standards.

In effect, the work became an interaction between DTU Wind Energy, the wind turbine owners, and the industry.

"We aimed internationally, and we convinced the Danish Energy Agency of this. For many years, the Danish Energy Agency funded the international work with standards at DTU Wind Energy," explains Head of Department Peter Hauge Madsen.

After a blade breakdown, the researchers could see how they could improve their fault-detection methods. The set-up was strengthened by the wind turbine owners reporting faults meticulously. First to the industry and then to DTU Wind Energy, which together were to try to solve the problem to prevent the same fault from recurring.

"Our international collaboration has had an immense impact on committees working internationally with the challenges faced by the industry. This reason is that we had a detailed structure for standards and approvals at an early stage," explains Peter Hauge Madsen.

DTU Wind Energy is today being challenged due to the financial interests in standards and the resources which international companies can invest in the work.

"Our strength is that we are independent experts. We can supply the knowledge and experience that everyone uses as a reference, and in this way we can maintain our position," finds Deputy Head of DTU Wind Energy Peter Hjuler Jensen.

Jens Carsten Hansen, Head of the Section for Integration and Planning, has travelled around the world for DTU Wind Energy for many years, and he has in-depth knowledge of the extensive international cooperation that has always characterized the department's many specializations.

"Denmark is the absolute leader in wind power. We have significant expert knowledge benefitting society, technology, and research. In addition, we are known worldwide and respected for our research and knowledge. From the start, we undertook the role of technology expert, and we have maintained and expanded it." Jens Carsten Hansen remembers that he went on his first trip to the Cape Verde Islands south of the coast of West Africa already in 1983. The work continued for more than 25 years supported by the UN, Denmark, and the World Bank.

"The first step in the introduction of wind power was a technology centre with two Vestas wind turbines at the capital Praia. It was a success, and we established wind farms on the four large islands over the next decades. Cape Verde actually held the wind energy

DTU Wind Energy

PHOTO: DTU WIND ENERGY

world record with 25 per cent of its total electricity consumption covered by wind power, until Denmark claimed the record."

In Somalia, we managed to establish a technology and training centre. India was up next in 1985, where also the collaboration with Cowi and other consulting firms continued with professionalization of the development and establishment of wind farms.

The first projects included the first three wind farms in India. Two of the wind farms were funded by Denmark and one was funded nationally.

The collaboration with India continued for a number of years, with Danish funding to support the construction of a test station and a technology centre, where Peter Hauge Madsen, the current Head of Department at DTU Wind Energy, played a key role.

At the training centre, there is still today a tree with Peter Hauge Madsen's name on it.

"The Danish-Indian collaboration is a shining example of the link between past and present, because we have today just revitalized this collaboration. A new dialogue has led to an agreement that includes joint research projects in combined wind and solar power stations and offshore wind energy," says Jens Carsten Hansen.

Towards greater impact and global goals

Right from the start, DTU Wind Energy has also had close collaboration with key institutions on development and expansion of wind power in China.

"I was responsible for the choice of location, layout, and tendering of the first wind farm in China in close cooperation with Cowi. It was the result of well-functioning bilateral collaboration between China and Denmark.

In October 1988, they had a single wind turbine in operation. Based on production data from its first year and our measurement on site of its power curve, we determined the wind climate as well as the location and design requirements for the coming wind farm. It was a challenging assignment, which would normally take several months, but we managed to do everything in three weeks, including set-up and performance of measurement campaign. In 2000, South Africa became interested. Here, we participated with wind measurements and calculations for the national demo farm with Danish support. In 2009, collaboration was entered into with South African partners to map wind resources. This has been of central importance to the overall national planning of wind energy in South Africa, which today regards wind and solar power as the cheapest options for the supply of new energy towards 2050."

Local lobby groups in South Africa claimed that there was not enough wind in South Africa. The Wind Atlas documented that the wind was there and that it was distributed on many locations across the country, which is positive for the planning of wind farms and the electricity system.

"We were responsible for the very significant mapping, and I remember that the Danish Embassy in Pretoria, which supported the collaboration with South Africa, compared the wind atlas project with digging for gold. And they were right in that we found large values for small investments using our knowledge and tools," says Jens Carsten Hansen.

"Here, you can clearly see the impact of our research and work. South Africa has been a valuable development and demonstration location for DTU Wind Energy, and our work has helped set new standards for mapping and planning.

In the wake of the results from South Africa, a similar collaboration has been established with Mexico under the Danish-Mexican Strategic Sector Cooperation coordinated by the Danish Energy Agency.

The World Bank has also adopted the method from DTU Wind Energy. It has subsequently been rolled out in 11 countries, so far.

"This has been done based on the experience from South Africa, and it has then been further developed within the framework of a partnership agreement on establishment, development, and use of the Global Wind Atlases and knowledge we gain from the research.

MASTER OF WIND ENERGY

Courses run over 13 weeks beginning in early September or February each year.

- Wind Turbine Technology
- Wind Resources
- Materials for Wind Energy
- Wind energy in society: planning, social context, environment, economics
- Aerodynamics and Aeroelasticity
- Grid connection and integration of wind power
- Numerical Tools in Wind Energy
- Offshore Wind Energy
- Measurement Techniques in Wind Energy

The programme ends with a 15 ECTS final project given the specialization of each student.

To become a Master of Wind Energy, you must complete nine courses and a final project.

PHOTO: DTU WIND ENERGY

Wind turbines at Cape Town in South Africa.

The work in South Africa has documented that strategic research and international collaboration provide a significant contribution to the green transition," says Jens Carsten Hansen.

Online MSc programme and e-learning

Global online education is another, relatively new focus area for DTU Wind Energy. Senior Researcher Merete Badger has the overall responsibility for an online MSc programme and the extensive commitment to e-learning.

"We're committed to an online MSc programme and e-learning, because the international wind energy industry is growing. The growth is very high in Asia and in North and South America, and this was the reason why we embarked on a new strategy in 2016 under a new slogan: Wind Energy for the World. With the new strategy, we wanted to create a contrast, a counterpart to the Danish research and the Danish study programmes," she says.

"The objective is clear. We want to create study programmes for the entire industry globally. The background is a number of bottlenecks posing challenges for the industry. For example, it is difficult for Vestas to establish projects in Ethiopia because there are no people with competences in wind power. We thus support the Danish industry with these global study programmes," underlines Merete Badger.

The target for the MSc programme is 20 students each semester. In the very first semester in the autumn of 2017, there were 33 students.

"We're highly committed to e-learning as a modern and new approach in education. All international trends point in this direction, and I believe we must get used to educating ourselves throughout our lives via continuing and further education," says Merete Badger.

Research into opposition to wind turbines

Concurrently with the almost explosive growth in wind power,

PHOTO: MATTIAS ANDERSSON

MERETE BADGER

Senior Researcher at DTU Wind Energy.

She originally graduated as a geographer from the University of Copenhagen in 2002.

After several years as a researcher at Risø specializing in satellite images used for mapping wind resources, she switched to the educational area in 2011.

DTU Wind Energy

“The objective is clear. We want to create study programmes for the entire industry globally

Merete Badger, Senior Researcher

DTU Wind Energy has had to acknowledge that the time has come to react actively to the opposition that has been brewing.

Ethnologist Laura Tolnov Clausen conducts research into social aspects of wind energy. She especially focuses on the growing opposition from citizens. She works in collaboration with a German geographer, David Rudolph, two engineers, Tom Cronin and Niels-Erik Clausen from DTU Wind Energy, and Julia Kirkegaard, who has a background in China studies, market and innovation.

The group was established in 2015 and works with conflicts and social acceptance regarding wind farm planning. The wind turbines and projects are getting bigger and bigger, and citizen opposition has grown concurrently with this development.

The projects have typically gone from being minor local projects to being large-scale projects without local rooting.

Several municipalities have introduced a stop to wind turbine projects in response to the growing opposition from citizens.

“Our special focus is on the opposition in Denmark, because Denmark is a pioneering wind power country. We have a special history with many local wind turbine guilds, and there was previously great local support in many places,” says Laura Tolnov Clausen, and adds: “Today, we’re unfortunately seeing growing local opposition. We study the reasons for the opposition and work with socio-technical interactions, dynamics, and relations between society and wind energy. We also look at how wind power can contribute to a sustainable and socially acceptable green transition.”

Researchers examine the circumstances behind the conflicts to understand how people respond to wind turbines. They examine why citizens react negatively, but also look for openings and potentials for a positive attitude.

“We study what works and what doesn’t. We identify new methods for better citizen participation, and we look at the consequences of the political framework for wind turbine planning, EU policies, and national policies, and their importance to social opposition or acceptance.”

As part of their work, the researchers have conducted a large number of interviews with citizens, planners, and wind turbine developers to identify the core of the issues.

One of the conclusions from this work is that the actual planning may generate conflicts. There is consequently also special focus on possible improvements of the planning process and the identification of new angles and methods for citizen participation.

“We’re a success when we can point out possible solutions to the challenges we know; when we’re able to identify improvements in planning and development of wind turbine projects, and when these are implemented in practice. When we can develop specific tools, which municipalities and wind developers can use to improve their interaction with other players, for example the local community. We also monitor what’s happening abroad – for example in Scotland and Norway – which propose other solutions than we have here in Denmark,” says Laura Tolnov Clausen.

Important solutions in a green transition should preferably be rea-

PHOTO: BAX LINDHARDT

LAURA TOLNOV CLAUSEN

Laura Tolnov Clausen graduated as an ethnologist from the University of Copenhagen in 2001, and she also holds a PhD in Environmental Planning from Roskilde University (RUC).

For several years, she has conducted research in citizen participation in nature and environmental management, including subjects such as nature restoration, national parks, and wildlife management.

Protesters against deforestation in the test centre area in Østerild Dune Plantation show their dissatisfaction. July 2011.

PHOTO: AJS NIELSEN

> **We're a success when we can point out possible solutions to the challenges we know; when we're able to identify improvements in planning and development of wind turbine projects, and when these are implemented in practice**
>
> Laura Tolnov Clausen, Researcher

lized as part of ordinary people's lives and within the existing local social, economic, and landscape framework.

Therefore, a broad approach to understanding the citizens' views on the technological development has turned out to be crucial. The opposition is not only about citizens not wanting wind turbines in their own backyard, the so-called NIMBY argument.

"It's much more complex. Citizens often react against the way in which the planning process is approached, including with a feeling of not being heard," explains Laura Tolnov Clausen.

After many years of focusing on onshore wind turbines, the researchers have increasingly begun to tune in to offshore wind turbine planning. This is done based on the recognition that wind turbines are increasingly being placed at sea.

"We hope to get to work more with offshore planning. Placing turbines in offshore sites is often mentioned as the solution to local conflicts, but the sea is also a landscape involving a large number of players. Offshore wind farms therefore don't automatically solve the conflicts," explains Laura Tolnov Clausen.

PHOTO: MATTIAS ANDERSSON

SØREN JUHL ANDERSEN

37

Assistant Professor, Ph.D.
from DTU 2014
Msc. Eng from DTU 2007

Expert on how and why the wind blows as it does

My field of research is aerodynamics, i.e. how and why the wind blows, and the implications it has on the performance and operation of wind turbines.

More specifically, I focus on the wake, which is the region behind a wind turbine with decreased wind speed and increased turbulence, just like behind a ship.

The wake effects are paramount for wind turbines operating in large wind farms as the reduced wind speed leads to lower production and the increased turbulence leads to higher loads on the turbines.

The overall aim is therefore to understand the wake dynamics and how to reduce these adverse effects in order to improve the overall efficiency of wind farms.

The wake flow inside large wind farms is highly turbulent and complex as it constantly changes in both time and space.

As researchers, we intend to model this complexity, and there are various models aimed at capturing different aspects. I employ state-of-the-art Large Eddy Simulations (LES), which capture the complex flow and interaction between the atmosphere and turbines in great detail, but at a high cost in terms of computational resources.

Such wind farm simulation is performed on supercomputers, where hundreds of computers are connected and will calculate for weeks or months to provide results.

We use the detailed information to elucidate the governing physics to increase our knowledge on the dynamic interaction between the wind and turbines, where simpler models fail, and measurements can be difficult to interpret due to large uncertainty and variations. We also use the high-fidelity simulations to test new concepts and ideas on both design and operation.

> **We must keep asking the right and important questions**
>
> Søren Juhl Andersen

Common history and joint interests

Asbjørn Bjerre long held the position as Director of the Danish Wind Turbine Owners' Association and is now an independent consultant. He praises the collaboration between the wind turbine owners and researchers at DTU Wind Energy, which he finds is characterized by high professionalism and openness.

PHOTO: MORTEN STRICKER

DTU Wind Energy

PHOTO: DTU WIND ENERGY

By Asbjørn Bjerre, former Director of the Danish Wind Turbine Owners' Association

The Test Station for Small-Scale Wind Turbines at Risø, DTU Wind Energy, was of essential importance to the development of reliable and efficient wind turbines throughout the 1980s and 1990s.

Seen in the clear light of experience and history, it was an unusually lucky and wise move that the Test Station for Small-Scale Wind Turbines was decided and established precisely when the very first electricity generating wind turbines came onto the market and were connected to the grid. A really good example of a political decision which turned out to be the essence of due diligence.

Joint problems

The Danish Wind Turbine Owners' Association (formerly known as the Association of Danish Wind Power Stations) was founded on 4 May 1978, one reason being that the very first wind turbine owners faced a number of joint problems.

Many of these initial problems were of a technical nature. The wind turbines had not been tested before being erected at the new wind turbine owners. Testing, trials, and gathering of experience took place in practice in the landscape at the new wind turbine owners.

The manufacturer could rarely be of help. Most went into liquidation when a large part of the sold wind turbines quickly broke down. At the same time, the test station was established and the industry began to test the wind turbines to find solutions to previously unsolved technical problems. Right from the outset, there was close collaboration between the test station and the owners of the new wind turbines and their association.

The turbine owners had a great interest in sharing their experiences with the test station. This was, in fact, the place where they could get help in finding solutions.

Some of the new manufacturers were initially less interested in telling the test station and the Wind Turbine Owners' Association – and thus the general public – about their experiences and unsolved problems. They had wind turbines to sell, so they had an admittedly short-term commercial interest in trying to hide the problems.

However, the latter soon proved impossible. The Wind Turbine Owners' Association initiated a systematic collection of operational experiences, including production figures and technical problems.

> **"The Danish Wind Turbine Owners' Association finds that DTU Wind Energy should today receive much larger research funds**
>
> Asbjørn Bjerre, Consultant

Everything was made public, and a close collaboration between the Wind Power Owners' Association and the test station was established right from the start. When the manufacturers later formed their own association, they also became a big part of the collaboration. Firstly, this was in their own long-term interest, and, secondly, the technical problems could not be kept secret in any case.

For a while, there was disagreement between the Wind Turbine Owners' Association and the manufacturers' association on whether the test station's solutions to the technical problems of the individual makes should be made available to the public, including the competitors in the new wind turbine industry.

Full transparency and openness

On the turbine owners' behalf, the Danish Wind Turbine Owners' Association was obviously interested in full transparency and openness. In addition, many of the problems were common to several or all makes. A number of meetings were held on the matter, politicians were involved, and the outcome was a decision on openness about the test station's work and results.From around the turn of the Millennium, there have been quite reliable wind turbines on the market from the major producers. The factories have their own large development departments. The international competition is fierce, and the wind turbine manufacturers prefer to flaunt their new improvements rather than problems. However, this does not mean that there is no need for DTU Wind Energy.

Exploitation of wind energy has now become a central part of our future energy supply and an important part of climate policy decisions. It is therefore no less important today than in the previous 40 years to conduct research and continue to develop better wind turbines. It is a common misconception that there is no potential or need for further development of wind turbines from their current level. There is also a need for research into smarter utilization of the fluctuating production generated by the turbines.

Based on DTU Wind Energy's many years of experience and its employees' great expert knowledge, DTU Wind Energy has a strong position in this increasingly important work. Also internationally, DTU Wind Energy holds a uniquely strong position.

The Danish Wind Turbine Owners' Association finds that DTU Wind Energy should today receive much larger research funds. The extent of the tasks is continually growing and becoming more urgent from a climate policy perspective.

PHOTO: VESTAS WIND SYSTEMS A/S

CHAPTER 4 | **THE BUSINESS**

"DTU Wind Energy has produced new knowledge to the benefit of the industry"

Working commercially with wind power is a profitable business.

DTU Wind Energy today has detailed and commercial collaboration with the wind turbine industry players. As a knowledge centre, DTU Wind Energy is fiercely committed to international research, development of new technology, tests, and new unexplored areas of research.

New challenges mean that DTU Wind Energy must adapt to the industry's problems and preferably contribute to solving them, while also conducting research and producing competent graduates.

Anders Vedel, CTO, Vestas

After the energy crisis of the early 1970s, there was a declared political desire to create an alternative to the known forms of energy.

"We were granted research funds for tests and analyses, because we were to help the fledgling Danish industry get started," says Head of Department Peter Hauge Madsen, one of the pioneers at the test station.

"We were thus born into a well-functioning collaboration with the wind turbine owners and the industry with all the ensuing advantages."

Due to the success of the overall sector, Risø's research, testing, approval work, and work with Danish and international standards have been useful to the industry and authorities.

"Here, it's worth noting that the whole academic part with teaching etc. only came much later in the process. It's only in the last 10 to 15 years that education has come to play a key role," notes Peter Hauge Madsen. He explains that it was initially all about helping create an industry in Denmark.

It started with practice-oriented tests and technologies, followed by research into methods and modelling, which led to the actual formation of the Danish industry. The subsequent years have seen innovation and close collaboration between DTU Wind Energy's competent researchers and the rapidly growing Danish industrial wind power enterprises.

The essential characteristic feature of DTU Wind Energy has been a specific mission from the outset.

"We had to make a difference and help the industry and the Danish authorities. We had a joint mission, a main objective," explains Peter Hauge Madsen.

EVP & CTO Anders Vedel from Vestas stresses that DTU Wind Energy has been a crucial factor in the development of the Danish wind energy sector. The department has been of great importance with its independent organization and research activities.

"DTU Wind Energy has performed some of the important tasks we have worked with in the industry, and their work has meant that we can today characterize Denmark as a global competence centre for wind energy. Risø has continuously been at the cutting edge and seized the opportunities they had, and I have to say that we would not be where we are today in Denmark without DTU Wind Energy. The department has been particularly strong in value creation, and it has helped the industry differentiate itself from competing industries worldwide," notes Anders Vedel.

DTU has managed to develop and understand the technology

Bo Juul Pedersen is Deputy General Manager of the Chinese energy group Goldwind's branch in Denmark.

He believes that DTU Wind Energy was good at technology development, testing, approval criteria, and procedures for the wind turbines from the start, one reason for these competences being the close collaboration with the small master smiths that constituted the core in the first years.

He points out that DTU Wind Energy has since then managed to develop and understand the technology and exploit it for better and more competitive design. He also notes that one of the clear characteristics has been a marked ability to establish new knowledge to the benefit of the industry.

"There has been an almost symbiotic relationship between the industry and DTU Wind Energy, one reason being that the industry had very little theoretical and experimental knowledge from the outset and was therefore totally dependent on a collaboration," says Bo Juul Pedersen. He highlights a series of analysis tools resulting from highly professional development work at Risø.

"One of the best examples is probably the Wind Atlas Analysis Application Program (WAsP). This work has generally been characterized by a dedicated focus on commercialization of the research, and the researchers have played an important role as trouble shooters. This was also the case for the so-called stall-induced edgewise vibrations – a so-called aeroelastic stability problem – ascertained in our simulation models, but also found to occur in real life. Here, the researchers at DTU Wind Energy were good at gradually consolidating the theoretical understanding of the problem, which gave the industry a good platform for developing and successfully implementing practical solutions," says Bo Juul Pedersen.

Reasons for DTU Wind Energy's close collaboration with the industry

Head of Department Peter Hauge Madsen explains that DTU Wind Energy was one of a number of research centres in the first years. The largest competitors were the USA and the Netherlands, but he believes that Denmark won the battle because Risø joined the other players in the sector with an international aim from the start.

Denmark was also favoured by the first major market being the USA, so that "we went international from early on. From the start, we operated with this order: Proof of concept, documentation, development, and recruitment of qualified candidates. It worked for us."

Peter Hauge Madsen believes that Risø has won its share of the

PHOTO: GOLDWIND

BO JUUL PEDERSEN

Goldwind. Deputy General Manager and Chief Engineer in Goldwind Denmark.

Qualified engineer from Aalborg University.

Previously independent consultant in Windaps, Senior Consultant in the consulting firm Rambøll and R&D Director in LAC Engineering.

VESTAS

Vestas has 35 years of experience with wind turbines and 24,400 employees worldwide.

Vestas has established a total of more than 66,000 wind turbines. In 2019, the company rounded a total capacity of 100 GW.

The wind turbines are erected in 79 countries spread across six continents.

Vestas generated revenue of EUR 2,811 billion in the third quarter of 2018.

business because the players in the overall Danish sector had a joint mission in relation to the other countries.

"Many of the elements we worked with were obvious choices for funding by the industry, and there were no serious skirmishes because we were fighting together for a joint mission."

Bo Juul Pedersen from Goldwind points out that DTU Wind Energy has put together a strong team of researchers in aerodynamic design.

The team has developed a number of new blade profile series, Risø P, Risø B, and Risø C, which are today all used in the industry.

"DTU Wind Energy has largely focused on modern requirements for lower loads and maximum power production. However, I would also highlight one field in which the industry was unable to draw on DTU Wind Energy's competences in solving a highly critical technical problem. In the late 1990s and early 2000s, we had problems in the industry with a number of gearbox breakdowns, and I have to say that Risø didn't have the necessary competences to deal with this problem."

However, Bo Juul Pedersen wishes to credit DTU Wind Energy for the great openness in its communication, which he finds has always characterized the department.

He explains that he has personally learnt a lot from the many Risø reports over the years, and that the publications have been of decisive importance to many players in the industry. This openness also applied when DTU Wind Energy was contacted from the outside.

Chinese top executive spent three months at Risø

"I could name many persons who have been my lifelines in the

> **"DTU Wind Energy has managed to establish new knowledge to the benefit of the industry**
>
> Bo Juul Pedersen, Deputy General Manager, Goldwind Denmark

various jobs I have had. I have always received good, open, constructive, and professional sparring, and this openness has also had a direct influence on my current employer's presence in Denmark."

Nearly 30 years ago, Wu gang, one of the founders of Goldwind, stayed for three months at DTU Wind Energy in Roskilde, where, in his own words, he learnt all about wind power and Danish wind turbine technology with access to all the essential literature in this field.

"I'm sure it has played a role in Denmark being recognized in China as both the cradle of modern wind energy and as a modern academic and industrial centre of knowledge. It has also been a factor in Goldwind's presence in Denmark today and its close collaboration with DTU Wind Energy," says Bo Juul Pedersen.

Anders Vedel, EVP & CTO at Vestas, highlights a common challenge against which Vestas battled in a partnership with DTU Wind Energy in the years from 2009 to 2012.

"As key players in the industry, we were under tremendous pressure quickly to deliver results and new advances to the benefit of the market. There was consequently much focus on lower costs in those years. We were therefore engaged in a number of discussions with the researchers at Risø about the need for research in the long term, medium term, and short term. Both parties clearly had a need for this debate, and I must say that the outcome was good. We had to deliver quick results on the market, and it required a lot of meetings to agree also to focus on the short term," explains Anders Vedel. He adds that the many discussions led to a good and fruitful collaboration on several projects.

Goldwind and DTU Wind Energy have worked closely together on the important processes behind the location of wind turbines in the terrain.

Bo Juul Pedersen states that the collaboration has worked well with good results.

He is confident that Goldwind will continue the collaboration based on the good set-up, and he can easily imagine other poten-

Goldwind wind turbine project in Dabancheng, Xinjiang, China.

PHOTO: GOLDWIND

GOLDWIND

Goldwind has 20 years' experience in the wind turbine industry and has erected more than 28,500 wind turbines globally with a total capacity of more than 44 GW.

In 2017, Goldwind was the world's third largest wind turbine manufacturer after Vestas and Siemens Gamesa. Goldwind operates on six continents and today has more than 8,000 employees, including 30 in Denmark.

The Chinese wind turbine manufacturer Goldwind established a Development Department in Denmark in 2016.

tial collaboration areas, for example offshore technology, including aeroelastic modelling, stability analysis, and aerodynamic design.

"Overall, I must acknowledge DTU Wind Energy as a world leader in these fields," says Bo Juul Pedersen.

Peter Hauge Madsen points out that it is important to maintain close collaboration with the industry.

"We need to focus on what the industry does not or cannot do. We still need to conduct research, and we must have the best of both worlds. We must adapt to the industry's problems and preferably contribute to solving them, while also conducting research and producing competent graduates. We must contribute to the work to develop even more competitive wind turbine technologies in the coming years. In addition, we must develop brand-new energy systems, which can lead the green transition forward and implement new aspects to the benefit of consumers and society as a whole. We are going to see an overall massive social change in the energy area, and we must be in on this. We have the qualifications and competences for it," Peter Hauge Madsen points out.

Bo Juul Pedersen agrees that there are both challenges and threats to a department like DTU Wind Energy. He would prefer not to be too negative, but he points out that some of the Department's strong points are perhaps threatened by the question of additional innovation potential.

"DTU Wind Energy must assess whether it's actually possible to achieve further improvements in selected research areas in terms of contributing to a further reduction of the levelized cost of energy, LCOE. For us in the industry, it is important to reduce costs, and I'm curious to see how current and new research at DTU Wind Energy can reduce the LCOE further in the future," says Bo Juul Pedersen. Anders Vedel from Vestas points out that all parties need to continue their collaboration and ensure joint interests in the long-term future research.

"In the industry, we're getting better and better at formulating challenges and requirements for research in the long term. The challenge will be to keep focused and ensure understanding in society for all aspects of renewable energy in the coming years. The possibilities will be huge, and I'm sure that we can maintain a strong international position in the future in collaboration with DTU Wind Energy."

New business with measurements and advanced measuring technology

DTU Wind Energy is recognized worldwide for its measurements and ability to develop advanced measuring technology. Senior Researcher Rozenn Wagner explains about the future of the work to advise the industry:

"DTU Wind Energy has long experience in wind measurement techniques from classic anemometry to ground based and satellite based remote sensing. We contribute at all levels of development of measurement techniques. DTU Wind Energy develops new measurement technologies itself, but also collaborates with several independent measurement technology manufacturers to bring the most promising up to the required level of accuracy. DTU Wind Energy has a deep understanding of end user needs. It has achieved this through close collaboration with the wind energy industry, including Danish and international wind turbine manufacturers and wind farm developers," says Rozenn Wagner.

The spinner anemometer is a patent from DTU Wind Energy, which enables optimization of power production from a single turbine at a very large scale. The WindScanner system, combining multiple scanning lidars, has resulted from the close collaboration with independent lidars manufacturers and DTU Photonics.

According to Rozenn Wagner, new measurement techniques are

DTU Wind Energy

> **We have built leading expertise in the lidar technology through collaboration with lidars OEM from the very early stage of development 15 years ago**
>
> Rozenn Wagner, Senior Researcher

central to making the development of new wind farm projects more efficient.

"WindScanners make it possible to measure the flow around full-scale wind turbines and full-scale terrain features influencing the wind flow like mountains, forests, and trees. Those features are challenging for numerical modelling, and detailed measurements will help improve the models that are used to estimate wind resources anywhere on the globe."

Rozenn Wagner has been a part of DTU Wind Energy for 12 years. According to her, DTU Wind Energy are in the forefront when it comes to methodologies:

"DTU Wind Energy looks for a deep understanding of the measurement techniques and aims at extracting the most relevant information out of the measurements. We have a strong focus on development and publication of methodologies and best practices.

Once new measurement techniques have reached a maturity level adapted to industrial needs, DTU Wind Energy plays the role of measurement provider and consultant. It also provides services to industrial users, which need pilots or demo-projects to convince themselves of the new technology and to learn how to use it. For example, nacelle mounted lidars have shown to be a reliable and agile technique that meets the needs for wind turbine power performance testing.

The first demonstrations were done in research and development projects in collaboration between DTU Wind Energy and lidars OEM, turbine OEM, and wind farm developers. Those projects enabled us to publish several technical reports and journal publications with recommendations on how to use this instrument for power and loads testing of wind turbines."

The challenge is to get new measurement technology accepted by the certification bodies and introduced in international standards. "DTU Wind Energy has had a leading role in the creation of a task specific to wind lidars in the International Energy Agency Wind Technology Collaboration Programme (IEA Wind Task 32) and in the introduction of lidars in the International Electrotechnical Commission standard (IEC 61400-12-1 Ed.2)," says Rozenn Wagner. He continues:

"DTU Wind Energy is the link between the new measurement technologies and the wind energy industry end users. Through project collaboration, consultancy and executive education, we teach the industry about the capabilities of the new measurement technologies. We also provide the industry with information about their limitations, and the right way to use them for their needs. Our objective is to get the wind industry to perform better using leading edge measurement techniques properly and with confidence. While we are working on getting a deep understanding of the lidar technology, we are also looking for the next measurement techniques that will make a difference for the wind industry. A milestone will be reached when lidars are actually used instead of met masts in all sensible applications."

PHOTO: BAX LINDHARDT

ROZENN WAGNER

Senior Researcher.

MSc applied mathematics and mecha-nical engineer from Bordeaux, France.

PhD from DTU.

Rozenn has been working at DTU Wind Energy for 12 years and is now leader of research projects and standardizati-on on lidars for wind energy.

FACTS MULTI-ROTOR

A conceptual wind turbine built and erected in 2016 in collaboration with Vestas at DTU Risø Campus.

The conceptual wind turbine has a height of 74 metres.

Output: 900 kW.

Dismantled in December 2018.

PHOTO: DTU WIND ENERGY

DTU Wind Energy

ÁSTA HANNESDÓTTIR

Ásta graduated as an atmospheric physicist from the University of Copenhagen.

Her Master's thesis dealt with determination of the height of the atmospheric boundary layer. Ásta has just started as a postdoc at DTU Wind Energy, where one of her research assignments will be to participate in the development of a global atlas of siting parameters for wind turbine standards.

Ásta Hannesdóttir is 36 years old, married to a high school teacher in mathematics and physics, and they live on Frederiksberg with their three children of ten, seven, and two years.

PHOTO: BAX LINDHARDT

Ásta has studied many years of wind speed measurements

Ásta Hannesdóttir has just completed her PhD thesis on extreme weather conditions, especially strong gusts of wind, and how they affect wind turbines. In her thesis, she has studied wind speed fluctuations on different scales. From Small-Scale turbulence to large so-called coherent fluctuations.

In connection with her PhD, Ásta has studied many years of wind speed measurements from different measuring stations, identifying fluctuations using different detection methods.

Ásta has developed a method for identification and characterization of sudden wind speed increases. This method provides estimates of amplitude and rate of increase, which are then described statistically.

Simulations of different wind conditions have been made to determine the effect of wind conditions on wind turbines. These simulations are then used in combination with aeroelastic software used to calculate wind turbine loads.

These loads are compared with load models specified in the leading standard for wind turbine safety. However, this standard was prepared based on very general considerations about extreme wind conditions and how they affect the various parts of the wind turbine.

The results from Ásta's thesis can therefore be used to identify differences between the models of the standard and the actual measured wind conditions.

The thesis gives a better understanding of extreme wind conditions and how they affect wind turbines, enabling us to improve safety standards, so that production costs do not become too high as a result of excessive cautiousness or unforeseen weather conditions.

In this way, wind energy can maintain its role as a well-suited source for contributing to the world's energy supply.

> **"My thesis gives a better understanding of extreme wind conditions**
>
> Ásta Hannesdóttir

PHOTO: BAX LINDHARDT

CHAPTER 5 | **PEOPLE**

“I have worked with wind all my life, enjoying every moment”

Some people have made a special difference at DTU Wind Energy.

Many researchers at DTU Wind Energy have been involved from the first days at the test station at Risø, spurred on and retained by a good working environment, professional challenges, and a burning desire to make a difference.

Helge Aagaard Madsen and his son Mads Holst Aagaard Madsen have both chosen to conduct research at Risø. Politicians and business executives have vigilantly followed developments from the sidelines.

> **My father works with rapid calculation models which may be 95 per cent correct and precise for what we're doing out here, and I work with the last five per cent**
>
> Mads Holst Aagaard Madsen, PhD student

Professor and Senior Scientist Helge Aagaard Madsen and his son Mads Holst Aagaard Madsen share a passion for wind power.

Mads is sometimes asked how it feels to work with his father, and his reply is: "Well, I like him." However, several days can go by without them seeing each other.

Helge Aagaard Madsen is among those who have worked at DTU Wind Energy for many years without having had a spell in the industry. In fact, he has worked at DTU Wind Energy since 1984.

He currently works with engineering models, simulating aerodynamics and aeroelasticity, all essential elements in industrial design programs.

"My father works with rapid calculation models which may be 95 per cent correct and precise for what we're doing out here, and I work with the last five per cent," says Mads with a big, teasing smile. Father and son work in the same department, and they have done so since Mads arrived at Risø two years ago.

Father Helge first graduated as a BSc in Engineering in 1977, then as an MSc Eng., followed by a PhD in aerodesign from Aalborg University.

"I have worked with wind all my life, enjoying every moment. Very early in my career, I had a short spell with the Jutland Technological Institute, where I tested joints in district heating pipes. There, I realized that I had to work with wind power, and I have not looked back since," says Helge Aagaard Madsen. He later had a short spell with the consulting firm Cowi.

"However, it was only three months, and, no, the prospect of a significantly higher salary did not entice me sufficiently. I wanted to return to DTU Wind Energy quickly," says Helge Aagaard Madsen.

His interest in wind began with a couple of inspiring teachers who opened his eyes to wind. Later during his studies, he visited Tvind, and he remembers thinking: "If they can, we can also get far with the technology."

Both Helge Aagaard Madsen's final projects were about wind.

DTU Wind Energy

PHOTO: DTU WIND ENERGY

"I can simply say that my life with wind has been incredibly exciting. There has been a huge development from the period in which we were at the very first test station out here on a ploughed field and until today. I had not in any way imagined the extent of wind power that we are seeing today. I have been allowed to work with many crazy and experimental projects, and I have never considered changing fields," says Helge Aagaard Madsen.

A perfect match

His son Mads Holst Aagaard Madsen holds a degree in physics from the University of Copenhagen.

"Once I wanted to work with hospital physics, and I have also looked into many other specializations. However, I think I have always known that I would end up working with fluid dynamics," says Mads, who has now worked in the same workplace as his father for two years. He graduated in the summer of 2016 and was immediately employed at DTU Wind Energy.

"The key point for me has definitely been my Master's thesis, where I simulated the transition to turbulence. It was then clear that I would continue to work with fluid dynamics, but preferably in a more industrially relevant context. DTU Wind Energy was therefore a perfect match for me."

Helge and Mads agree that the core of the work at DTU Wind Energy is basically about collaboration with the industry.

"It's fantastic working with heavy, important research which lead to something," they both say, and point out that the walls are still filled with the spirit of the time of the very first test station.

"At DTU Wind Energy, we're still influenced by the pioneers from back then. Several of them are still working out here, and seeing them makes a big impression on a young researcher. People are here because they want to be, and they have built strong collaborations across different specializations over time," says Mads Holst Aagaard Madsen. He stresses that it is a great place to be as a young scientist.

PHOTO: : BAX LINDHARDT

HELGE AAGAARD MADSEN

Professor and Senior Scientist at DTU Wind Energy.

Civil engineer from Aalborg University with a PhD from 1982 in flow modelling of vertical axis wind turbines.

Employed at Risø in 1984 and subsequently at DTU Wind Energy with specialization in aerodynamics, aeroelasticity, and acoustics.

The collaboration with the industry acts as an attractive carrot. All the work done at DTU Wind Energy is relevant to the industry, and thus also to young researchers. He is sure that all the other young researchers at Risø agree with him that it is extremely important that the research will one day leads to something specific, something that really matters.

"I can easily imagine being here for a long time, perhaps for as long as my dad. In fact, my dad has not remained here just for the fun of it. Continuity is important, and as PhD students, we are completely spoiled. Everything is available all the time. We enjoy a lot of freedom, have good supervisors, and direct access to competent professors. We have the leading researchers and specialists in the world around us, we have a good environment, and there is much international interest in the constant 40-45 PhD positions we have here," says Mads Holst Aagaard Madsen.

One of the pioneers involved from the beginning is Deputy Head

> **"There has been a huge development from the period in which we were at the very first test station out here on a ploughed field and until today**
>
> Helge Aagaard Madsen, Professor and Senior Scientist

Peter Hjuler Jensen. He does not hesitate one second when asked to characterize his nearly four decades at DTU Wind Energy.

"Well, it has been an adventure. It has been a privilege to be here, I feel lucky," he says, and rewinds his thoughts to the period of overalls, sweaters, and shoulder-length hair.

He remembers that he was part of a group of students who helped get the iconic Tvind turbine running, and he was also active in OOA, the Organization for Information about Nuclear Power, and in OVE, the Organization for Renewable Energy. Primarily the latter.

"I also worked at Risø, which was one of Denmark's dominant advocates for nuclear power at the time. This meant that we were looked at critically. We had to perform better than everyone else to counter the scepticism attached to us being from Risø." Peter Hjuler Jensen says that DTU Wind Energy has been a deeply fascinating place to work for him personally. He has constantly been challenged since graduating as a BSc in engineering in 1978 and being employed at Risø in January 1979.

"I have thought, breathed, and lived for wind turbines, and I can now confirm that you cannot move mountains without working yourself to the bone. I have truly experienced that commitment creates miracles."

Sublime collaboration

Peter Hjuler Jensen remembers the many wind turbine years filled with conflicts and challenges, but, fortunately, there were more good days, as he puts it.

Among other examples, he emphasizes a sublime collaboration with the wind turbine owners and companies in the industry.

"My friends are today primarily engaged in wind turbines, while my children have chosen completely different paths. My son Simon is studying to become a social worker, and Johanne (with the sur-

> **We – the next generation – are ready for the next phase of DTU Wind Energy, and I can see lots of exciting challenges for us in the coming years**
>
> Nikolay Dimitrov, Senior Researcher

name Schmidt Nielsen) is probably known to most Danes after her many years as a leader of the Danish Unity List party. I have lived 25 years on Christianshavn in Copenhagen, renovated two town houses, and I now live in a detached house in Slangerup with my new wife."

Head of Department Peter Hauge Madsen is another of the pioneers from the period with the first test station. He graduated as a civil engineer in 1979 and immediately started his PhD at Risø the same year. His PhD thesis was about stochastic dynamics and reliability, and the relation to Risø was to study the importance of earthquakes in connection with nuclear power plants.

"After 18 months on that subject, I switched focus to wind power. I could quickly see that I could use my knowledge of building design principles in the work with wind turbines. I satisfied my innate curiosity and met new challenges. This characterized my working life up to 2008, when I again faced new challenges in working with people as an executive."

Peter Hauge Madsen is married and has three boys. Henrik (30) lives in the Philippines and works as an IT consultant. Mikael (27) works as an accountant with Deloitte, and Magnus (23) is studying computer science at the University of Copenhagen. "No, none of them works with wind power, but I remember that they all wrote high school reports on various aspects of green energy."

Peter Hauge Madsen points out that it has been important for him to be able to see a purpose, a mission, with his work. He describes it as a personal satisfaction "that we can now see that the outcome was what we were then dreaming about at the end of the 1970s. We have had a huge impact, and this is important to me. We wanted to influence the world – to save it, if possible – and it is probably not too much to say that we have succeeded. Against this background, I would say that I have had a good and full working life."

Nikolay Dimitrov (37) is among the many young, talented researchers at DTU Wind Energy. Nikolay took his Bachelor's degree in Bulgaria and Master's degree at DTU in 2008. After five years at Siemens, where he did his industrial PhD in reliability and probability theory, he came to DTU Wind Energy in 2013.

"I'm experiencing a wealth of opportunities, great learning, and that the boundaries are constantly being pushed with exciting challenges. I like working with my colleagues and we have a clear purpose. I enjoy the great flexibility and exciting assignments, which is the direct reason I'm at DTU Wind Energy today," says Nikolay Dimitrov. He believes that many of the future challenges for DTU Wind Energy will be external. He is also confident that DTU Wind Energy will retain its close relations with the industry, but that the industry will expand further away from Denmark, thus necessitating a more international and global scope for the researchers at Risø.

"In the future, we will also see a need for research that will attract external funding, and this will entail new challenges for our research. We will come under pressure from the political system and the industry to focus on short-term and very result-oriented research. It

PHOTO: BAX LINDHARDT

NIKOLAY DIMITROV

Senior Researcher at DTU Wind Energy Nikolay graduated as an MSc Eng from DTU in 2008 with a Master's thesis in wind energy.

In 2013, he completed his industrial PhD in structural reliability of wind turbine blades.

Today, he primarily conducts research into applied wind energy statistics, including subjects such as machine learning, reliability, and risk analysis.

> **No one would have believed the development we've seen merely 25 years ago, and I experience all the time that it takes people by surprise**
>
> Ida Auken, MP, Danish Social Liberal Party

needs to be fast, better, and cheaper, but conversely, we also need long-term and more in-depth research. This balancing act will be a challenge, not just to us here at DTU Wind Energy, but for the research environment in general," says Nikolay Dimitrov. He says that DTU Wind Energy must continue to deliver unique and useful results to the benefit of all parts of the industry, "we simply need to keep up the good work."

"We will be capable of this. We are the next generation of researchers, and we are ready for the next phase of DTU Wind Energy. I can see lots of exciting challenges for us in the coming years," he says. Nikolay expects to remain in Denmark and work at Risø. "I live in Virum close to Copenhagen, I'm married, yes, she is also an engineer, and we have three children aged one, five, and seven."

Great climate miracle

If there is a Danish politician who puts the environment at the top of the agenda, it must be Ida Auken from the Danish Social Liberal Party. She calls the story of the Danish wind energy adventure a great climate miracle.

"I can't praise it enough that we can today deliver the lowest energy prices with sustainable energy relative to all other energy sources. No one would have believed the development we have seen merely 25 years ago, and I experience all the time that it takes people by surprise. At a conference in Delaware in the USA, I could proudly tell them about the electricity prices we can look forward to from 2021 from the coming wind farm at Kriegers Flak in the Baltic Sea. The other participants did not believe me before I showed them the documentation. We have a miracle that isn't sufficiently known around the world," she says.

She does not think that the development would have been possible without the tremendous research work done by DTU Wind Energy.

"They must get much of the credit for Denmark's position in wind power, and part of the reason must be found in the short distance between the political decisions, the companies in the wind turbine industry, and the research at DTU Wind Energy. We must all contribute to preventing this three-legged stool from tipping over, all three legs are extremely important for us to maintain and expand the position we hold in Denmark. The stool only works if all three legs function optimally," she says.

Ida Auken would like to praise DTU Wind Energy for leading the way in both hardware and software development.

The main challenges in the coming year are to ensure that consumers are involved in the future development.

"We must all be involved in smart consumption, and here DTU Wind Energy must conduct research and attract the best talent worldwide. It has been a great challenge to go from zero to 50 per cent of the total electricity consumption in Denmark being covered by wind energy. Now that we are to go from 50 to 100 per cent, it will require that both the industry and us consumers take active part in the transition. This requires an advanced and multi-faceted system, the use

PHOTO: STEEN BROGAARD

IDA AUKEN

Ida Auken is a Master of Theology (cand.theol.) and a member of the Danish Parliament for the Danish Social Liberal Party.

Minister for the Environment 2011-2014.

Inaugurated Test Centre Østerild.
She was initially elected as an MP for the Danish Socialist People's Party on 13 November 2007. She switched to the Danish Social Liberal Party in 2014.

> **DTU Wind Energy must be active in the battle to create a unified international world-class knowledge environment**
>
> Anders Eldrup, former CEO of DONG, former Permanent Secretary

of artificial intelligence, and the Internet of Things when we need all digital installations to communicate with each other to utilize electricity optimally at the right times," says Ida Auken.

She is convinced that DTU Wind Energy will succeed in maintaining its current global position.

"The future will be just as much about IT as about technology in the utilization of the large quantities of data at our disposal," she says.

"Therefore, DTU Wind Energy must be ready to collaborate with other parts of DTU which are at the forefront in the area of IT. I believe that they will succeed, as Risø has the relevant and necessary competences."

A valuable midwife

From his positions at the head of Dong Energy and a number of organizations, Anders Eldrup has kept a watchful eye on DTU Wind Energy.

From his chairmanships in Offshorenergy.dk and LORC, he has detailed, up-to-date knowledge of the challenges that characterize the department today and in the coming years.

"DTU Wind Energy has been crucial to the development we have seen in the wind energy industry in Denmark. You must bear in mind that it all began with a number of small master smiths and Gyro Gearloose types. They were only able to act on the market because they could draw on the knowledge centre that was quickly established at Risø. Due to the farsighted researchers, the master smiths could handle the technology, and I'm convinced that we would not have seen the development we have had in the Danish wind turbine industry without Risø," says Anders Eldrup.

He points out that DTU Wind Energy has been a valuable midwife for small start-ups without their own R&D department.

"Risø was a crucial and important helper in ensuring that the small enterprises had more than a transient existence. The researchers at Risø could help with crucial knowledge about all vital parts of a wind turbine," says Anders Eldrup. He also points out that we are currently in a completely different situation.

"Today, the market is characterized by marked consolidations. The enterprises have become fewer, and the remaining players have become massively bigger. Companies like Vestas and Siemens can largely handle their own necessary development, but DTU Wind Energy still has an important role to play. Despite the consolidations we have seen, it is still difficult for the large companies to establish and run a test centre like the one created by DTU Wind Energy in Østerild. A centre of that magnitude would be an impossible task for a single company. The same applies to the impressive wind tunnel just inaugurated at Risø. Here, DTU Wind Energy offers a set-up which even the very biggest companies on the market aren't large enough to provide."

Anders Eldrup says that it is good that DTU Wind Energy today delivers what the industry really needs, based on its test facilities, demonstrations, and, not least, production of new, competent engine-

ANDERS ELDRUP

Anders Eldrup is a former Permanent Secretary in the Ministry of Finance and a former CEO of the oil and natural gas company DONG, later DONG Energy.

He is currently Chairman of the Board in LORC (Lindoe Offshore Renewables Center) and Grøn Energi, Rockwool Foundation, Terma A/S, Experimentarium, and Technical University of Denmark (DTU).

DTU WIND FACTS

Cups for measuring wind speed – so-called cup anemometers – are widely used in most of the world and have been developed at DTU Wind Energy.

PHOTO: MATTIAS ANDERSSON

ering graduates. The food chain with constant production of highly qualified engineering graduates is a reputation that DTU Wind Energy must protect.

"The industry needs the best people and the best educational environment. DTU Wind Energy must be active in the battle to create a unified international world-class knowledge environment," says Anders Eldrup. He points out that the future will entail new challenges for DTU Wind Energy.

"The companies will become even bigger in the future. We have already seen Vestas join forces with its Japanese colleagues, and we have seen Siemens team up with its Spanish competitor. The future will be dominated by few and even bigger players and DTU Wind Energy must find its new role in this constellation. Concurrently, the largest markets for both onshore and offshore wind turbines are moving around the globe, far from Denmark. We are currently seeing developments in, for example, the USA, India, and South East Asia. Previously, there was a knowledge core gathered around Denmark. In the future, DTU Wind Energy will have to fight more to retain its current position. However, I'm sure that DTU Wind Energy will find a new role to play," says Anders Eldrup.

He points out that it will also be a future challenge that DTU Wind Energy is a university department and thus represents all of society's knowledge. The knowledge should thus be made available to everyone.

Must find a new balance

The largest companies, which, as mentioned, will only grow bigger in the years to come, do not have the same interest in openness. They will regard it as highly risky to share new crucial knowledge with any competitors. According to Anders Eldrup, DTU Wind Energy must find a new method and balance in the dilemma that will enable it as a university department to maintain an openness in its collaboration with the industry. "External funding of specific departments increasingly takes place via projects linked to commercial players. In addition, here, the future will entail a new role for a centrally located DTU Wind Energy. I can see that there will be a need for heavy, large innovation projects focusing on what the industry must use the day after tomorrow, and not tomorrow, because it can handle that itself. This change will be a challenge to the way funds are granted today because, here, the focus is unfortunately often on the short term," says Anders Eldrup.

He points out that it will be a general challenge for DTU Wind Energy to develop the projects that the industry cannot cope with itself. For example, the challenge with which the whole industry is currently struggling: foundations for floating offshore wind turbines. According to Eldrup, this could be an obvious assignment for the researchers at DTU. It will be an assignment that will probably last for several years before the necessary solutions have been found and tested. An assignment, which is contrary to the universities' current grant systems.

"In addition, the researchers at Risø have not focused sufficiently on research into these floating foundations. It is a problem – a dilemma – to which DTU Wind Energy must find a solution. DTU Wind Energy must find a new place in relation to the growing industrial companies and find out what it will supply to the industry in the future."

Need for new course and new dynamics

From her position as Head of R&D, Ørsted Offshore, Christina Aabo has followed DTU Wind Energy for many years.

She highlights a number of fine competences and outstanding results from the researchers at Risø and in Lyngby.

She also canes a slightly dusty, old-fashioned, and somewhat anecdote-oriented department, which must wake up if it is to tackle efficiently the global challenges of the future.

The teaching methods may also need a review, and the management must dare to lay down a new course for the 40-year-old department.

> **Other universities are closing the gap, and DTU Wind Energy must safeguard it's position in key market areas**
>
> Christina Aabo, Head of R&D, Ørsted

Christina Aabo fully acknowledges the historic feats that characterize DTU Wind Energy.

She praises the department's performance and research in the classic key areas in wind energy: the wind turbines, the technology, models for wind turbine output, and the aerodynamic turbine design.

"Here, DTU Wind Energy possesses unique, global competences. They have also built up extensive knowledge about wind farms and are very strong in this field thanks to a large number of competent researchers and many years of work," she says.

Christina Aabo also emphasizes DTU Wind Energy's ability to combine education with research in wind energy.

"They were early in introducing a Master's degree programme which young students worldwide apply for after their Bachelor's degree. A Master's degree programme in which they're the absolute world leader." However, here the praise stops.
Christina Aabo finds that the department is too attached to the results achieved in the past. Today, the place basks in the glory of the good old days and past achievements.

"I have heard the same anecdotes countless times. Many of the employees have been involved right from the first test station at Risø, and they often still focus on the same research areas. They have become a bit stuck, and it's a problem."

A time warp

"How come so few of them have switched to a challenging job in the industry? In addition, have come from the industry after a career of some years there? Many have never worked anywhere else, they have never done anything else."

Christina Aabo feels she occasionally enters a time warp when she visits DTU Wind Energy. The Head of R&D from Ørsted calls for more dynamics and a more modern adaptation to the rapidly growing global industry, which is currently developing by leaps and bounds on all fronts.

"DTU Wind Energy is not using quite the same high gear," she feels.

Christina Aabo points out that DTU Wind Energy may need a change of gears, and she notes that the department often stresses its excellent partnership with the industry.

"I must say that this is particularly based on the past. Today, there is a need for a better understanding of the wind energy market and that the interaction with us and other companies is a significant challenge, which they should meet now. Other universities are closing the gap, and DTU Wind Energy must safeguard its position in key market areas."

College of Advanced Technology

Christina Aabo notes that DTU Wind Energy's teaching form with classic group classes with a lecturer who writes something on a board which diligent students copy seems somewhat antiquated.

There is still a spirit of "the good old days at the College of Advanced Technology", and she points out that it might be an idea to try to develop the teaching forms.

"Academic depth in engineering is good, but students learn a lot by working with projects in groups. Greater project orientation in which the students solve problems together with an external company would also be an option. This produces students and graduates who are unique in how they work and convert their knowledge after university. They will then also know something about finances, business cases, and project management, which are precisely what we're looking for in the industry," she points out.

The Head of R&D praises DTU Wind Energy highly for its new online Master's degree programme, which she finds is in line with the future requirements for modular further and continuing education.

"It's clear that they're highly committed to new digital study programmes, and that's well spotted," says Christina Aabo.

"This can help put DTU Wind Energy on the world map as the place for remote upgrading of engineers from other industries and into the wind power industry. Really good thinking," she adds.

She hopes that this can help show them the way forward and away from the classic and often somewhat manual engineering disciplines. There must be focus on highly specialized knowledge that can be used in practice.

"Today, it's all about mastering in-depth technical knowledge and collaborating across sectors. It's this interdisciplinary knowledge and the ability to see the bigger picture that we're looking for in the industry," says Christina Aabo.

The researchers at DTU Wind Energy must also become better at collaborating with other relevant departments at DTU, because she finds that this cooperation does not function quite well enough today, seen from an industry, which ranges across many disciplines and thus departments.

"It's difficult to get the different departments to talk to each other. Seen from the outside, they are not good at interdisciplinary collaboration. It's a challenge today – and not least in the future – if DTU wants to be a partner in many aspects of wind energy."

Fierce competition on the way

Another massive future challenge will be that DTU Wind Energy will be exposed to fierce international competition in both research and education.

"Already now, we're seeing a heavily increasing interest in wind energy throughout Europe and, not least, on large markets such as Taiwan and the USA. Everyone wants to fly the flag in research and education. When we enter into local contracts today with, for example, an American State on the East Coast, there is pressure on us also to engage in collaboration with local universities there. It is a prerequisite for the commercial partnership, and we help ensure that they build up knowledge and study programmes in wind energy. This means that we will see a number of new emerging centres worldwide in the coming years. They can and will compete with DTU Wind Energy, and it doesn't seem to me as if they have completely taken note of this yet and identified their position."

Global knowledge centre

Christina Aabo states that Ørsted is already strongly linked with other universities such as Oxford University in the UK, which has manifested itself as a global knowledge centre for geotechnics.

"Therefore, we obviously choose them as a collaboration partner when we're engaged in projects in this field."

Ørsted and many other companies in the global industry have grown so large and have so much volume that they themselves create partnerships with specific universities with knowledge about precisely the field and knowhow that they are looking for.

"I could fear that DTU Wind Energy will slip somewhat out of the exclusive group in the future if it neglects to renew itself. At Ørsted, we target the very best partnerships in our key areas, and we are obviously not bound only to cultivate research in Denmark. If I didn't go for the best, I wouldn't be doing my job," says Christina Aabo with a twinkle in her eye.

PHOTO: ØRSTED

CHRISTINA AABO

Head of R&D, Wind Power, Ørsted.

20 years' experience from the wind energy industry.

Board member in Hydratech Industries. Member of InnoBooster, Innovation Fund Denmark.

Qualified engineer from Aalborg University in 1997.

COURTESY OF BRISTOL UNIVERSITY

ANDREW GARRAD

Doctor of Engineering,
Bristol University.

"Risø has been a foundation stone of our industry"

By Andrew Garrad, Doctor of Engineering, Bristol University

Risø test station for small wind turbines has grown up. It is no longer just a test station, and it is certainly no longer for small wind turbines. I have witnessed that metamorphosis as a more commercial, but nevertheless scientifically-driven, foreigner.

DTU Wind Energy

Over the decades, Risø – I shall still call it Risø, whatever its present name – has been my friend, collaborator and, from time to time, my competitor.

It continues to command my respect. In the early days, it did much to form a firm basis for the industry.

When survival was considered success, its 'Design Guidelines for Wind Turbines' helped to keep the wind turbines standing. It has been a staunch supporter of the Danish industry and has played a lively part in the global development of technology.

Its activities covered the whole spectrum from sensors to tensors! To us non-Danes, it was clear that it took its national responsibilities just as seriously as its interest in science, a Danish trait. Fortunately, for me, commercialization of its endeavours has not been its strong suit.

Risø's singular focus on science has been refreshing in a steadily more commercial world. Its brief foray into certification was not sustained perhaps, specifically, because this activity is not leading-edge research but rather application of existing knowledge. My particular interests in aerodynamics, dynamics and aeroelasticity have been a central part of Risø's activities and our joint efforts are visible in a lot of standards and "rules".

Is it a feature of a small country that a single institution can be chosen as the sole national depositary for a particular technology or industry?

Such a pragmatic and sensible approach has allowed Risø to grow and prosper and, thereby, create a place where the world can find expertise. My company played a similar role in Britain, but without the government support enjoyed by Risø, so I have often looked enviously across the North Sea. The grass is always greener on the other side! An important feature of the wider industry is exemplified in Risø: people quickly become addicted to wind energy.

Many of the pioneers of the industry from the early Risø days stayed all their professional lives. A few are even still there today! Such continuity of knowledge is hugely valuable in a rapidly developing industry. Risø has been a foundation stone of our industry and has played an important and Danish role in its growth and success. Long may they continue whatever they are called.

> **"An important feature of the wider industry is exemplified in Risø: people quickly become addicted to wind energy**
>
> Andrew Garrad, Bristol University

MICHAEL MCWILLIAM

Michael McWilliam (37) is a graduate from Victoria, close to Vancouver in Canada.

He came to Risø three years ago after doing his PhD.

Michael started reading about wind energy in 2003 and came across Risø.

PHOTO: MATTIAS ANDERSSON

Canadian wanted to get closer to the wind energy industry

Michael McWilliam wanted to get closer to the industry, and he is very enthusiastic about Risø, which he finds contains all conceivable aspects of wind energy

I work in the field with two names: 'System engineering' and/or 'Multi-disciplinary Design Optimization'.

These fields were primarily developed in Aerospace, where they want maximum performance for a complex machine with many interacting parts.

Accordingly, I have studied under people who were in the aerospace field. The conventional engineering approach is to break the design down into components like 'Aerodynamics', 'Structural Dynamics', etc.

Then have experts focus on just those aspects one at a time. However, in reality, these different parts have strong interactions. Thus, when you focus on just one component at a time, you miss many opportunities in the interactions.

So my research is based on taking a system approach where you integrate all the different parts of a wind turbine into a single workflow. You then apply Multi-disciplinary Design Optimization (MDO) techniques to help develop better wind turbines for the future.

MDO applies numerical algorithms like optimization and uncertainty quantification to these system-engineering workflows. Optimization will help figure out problems like finding the best design that maximizes power without exceeding loads.

My research is involved in the application and development of Multidisciplinary Design Analysis and Optimization (MDAO) techniques to help improve wind turbine blades.

Other results: Applying numerical design optimization to evaluate smart-blade technology. Investigate the co-design of wind turbines with active flaps. Developed multiple rotors with different passive load alleviation.

> **"I definitely expect to remain here with my Danish girlfriend, who's an anthropologist**
>
> Michael McWilliam

The future

A special group of pioneers and innovators have now been researching, teaching, and collaborating with industry and authorities for 40 years.

The future places new demands on DTU Wind Energy.

DTU Wind Energy

By Peter Hjuler Jensen, Deputy Head of DTU Wind Energy

In the past 40 years, the wind energy sector has developed from being a relatively low-tech niche industry to being today a global high-tech industry and a significant driver in technological areas such as wind power meteorology, aerodynamics, and composite materials.

In Europe alone, the sector employs more than 250,000 people and generates revenue of more than EUR 60 billion, and European enterprises supply 40 per cent of the world market.

In 2017, 55 per cent of all new electricity generation capacity in Europe was wind energy. According to the IEA 2018 World Energy Outlook, wind energy will be the EU's largest electricity generation source before 2030. The turbines have become bigger, the integration in the electricity system is better than expected, and new research breakthroughs have made competitive wind energy possible far beyond the industry's expectations just ten years ago. With good wind conditions, wind energy is the cheapest electricity source. In just a few years, there will no longer be a need for subsidizing the industry.

The success is great, but so are the challenges. Electricity is only a minor part – 24 per cent in Europe – of the world's energy consumption, which must be made climate neutral over the next 30 years. The success of wind energy means that other countries are now investing heavily in research, development, and production in the sector, and competition has never been sharper.

There is not only competition in the wind energy sector; the transition to a green energy system means that wind energy forms part of complex interaction and competition with other renewable energy sources. To stay at the very front of the field in the future, we must increasingly utilize our ability to convert research into new products and services in design, production, transport, erection, and operation of wind power stations. A successful wind energy sector must know how to deliver energy system-friendly solutions which can form part of a circular economy focusing on environmentally-friendly production, operation, and recycling.

DTU Wind Energy has been one of the largest and most important global research players, and has every opportunity to remain valuable in the continued development of wind energy technologies and to attract the best researchers in the world through a global outlook and commitment. DTU Wind Energy must continue to be a leading and attractive global player in education through both conventional study programmes and e-learning. In future, wind energy will be of increased research importance in the energy system in a globalized world with accelerated digitization.

This means focusing on knowledge, competences, and technological capabilities in digitization, artificial intelligence, and sensor systems, among other fields. It will also be essential that the department is able to adapt and further improve its ability to develop and implement new knowledge together with the industry.

DTU Wind Energy must continue to be a significant global player in research and development of wind energy. This means that we must speed up the green transition to counter climate change and contribute to meeting the UN's global sustainable development goals. This must be achieved in close collaboration with industry, politicians, and research institutions.

WIND

With this book we wish to tell the story about us and 40 years of wind energy research and development.

We wish to tell our story to document how knowledge is put into play and impacts the development of an industry, worldwide exports, and the importance of our technology to society.

From the modest beginnings in 1978 with the Test Station for Small-Scale Wind Turbines at Risø and up to the department of today, DTU Wind Energy has come of age together with the Danish wind turbine industry and wind turbine pioneers.

The joint venture nature of this development shows how collaboration and community are inherent in the DNA of both the department and the Danish wind energy sector.

Together, we have changed and developed the technology from being a simple one based on research knowledge from other sectors to being a sophisticated technology which today drives the development in other sectors.

We have gone from local low-tech to global high-tech.
We describe how the research in meteorology and materials at Risø as well as the Fluid Dynamics research at the old DTU and the national test centres have now been gathered at the new DTU Wind Energy.

Research and development have been putting knowledge into play for 40 years. A development that our employees and partners have had the privilege of witnessing, while the technology raced ahead.

The visions became reality, and reality surpassed the visions.