Michael Durstewitz
Bernhard Lange *Eds.*

Sea – Wind – Power

Research at the first German offshore wind farm Alpha Ventus

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RAVE
RESEARCH AT ALPHA VENTUS

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Foreword by the German Federal Minister for Economic Affairs and Energy

The use of both onshore and offshore wind energy is a key element in Germany's energy transition. Today, onshore wind energy is already the primary source of renewable energy in electricity generation in Germany. The increased expansion of offshore wind turbines still offers a great deal of potential. However, it also requires a lot of innovative solutions to be developed in the areas of construction and operation.

The research undertaken at the first German offshore wind farm Alpha Ventus has played a crucial part in helping to build up knowledge and expertise in what is still a very young sector in energy generation in Germany. It is particularly pleasing that the various research projects could be coordinated with one another so well, and that it has been possible to combine the different interests of researchers, facility operators, and plant manufacturers, whilst also ensuring that expansion work is environmentally sound. The Alpha Ventus wind farm is a pioneering venture which – together with the research initiative 'Research at Alpha Ventus – RAVE' – has laid the foundations for German projects in the area of offshore wind energy. The results of the research are outstanding – something which is also reflected in the level of international interest that has been attracted.

There is, of course, still a great deal of research yet to be carried out on developing the use of wind energy in Germany. We will only be able to use the potential that exists in this field if we continue to reduce the costs of electricity from wind energy and continue to raise grid security. Doing so will enable Germany's wind sector to stay competitive in the long term.

Given this background, the primary aim of the research funding provided by the Federal Ministry for Economic Affairs and Energy is to reduce both the investment and the operating costs for wind-powered installations. The state-of-the-art in German wind-power technology is impressive – with German industry setting international standards based on high-capability wind-powered installations 'Made in Germany'.

When it comes to the expansion of wind power into the future, it will be crucial to ensure that the electricity generated by wind turbines can be reliably integrated into the public grids. Indeed this is one of the priorities that the Federal Ministry for Economic Affairs and Energy has set in the area of energy research. Further research is needed in areas such as optimising the grid connection of offshore wind farms, load and generation management, wind-energy-specific aspects of storage, and improvements in wind forecasts.

German companies, universities, and research establishments are among world leaders in wind energy thanks to the innovations that are being generated in this field. Research activities are being supported by German manufacturers and service providers, who are developing solutions designed to meet the specific requirements of foreign markets. The Federal Ministry for Economic Affairs and Energy is providing funding for these activities with the aim of ensuring the highest possible value generation in wind energy in Germany and, through this, of making the German wind industry internationally competitive.

I am delighted that an essential overview of the many different research projects being funded by the Federal Government as part of the Energy Research Programme now appears in book form. I wish you interesting reading and hope that this publication will serve as a source of inspiration to you.

Sincerely yours,

Sigmar Gabriel
Federal Minister for Economic Affairs and Energy

Foreword by the Chair of the Offshore Wind Energy Foundation

The construction of the Alpha Ventus test field played a significant role in the development of offshore wind energy in Germany. Within five years of it being commissioned in April 2010 there were wind farms in the German North and Baltic Seas with an output of 3,294 megawatts connected to the grid. And based on the investment decisions and business planning already made, the output will have more than doubled by 2020 – while optimistic predictions reckon that the government-set upper limit of 7.7 gigawatts will be fully utilised. This breakthrough of this new technology, which had no easy task in overcoming many teething troubles, would not have been possible without the extensive research projects and their findings that were part of the RAVE research initiative.

Over 50 universities, research institutions and businesses have been involved in numerous individual projects dealing with the solution of problems that would improve offshore wind turbine technology, making it safer and more profitable while also optimising its compatibility with the marine environment. The entire German offshore wind industry has profited from this.

The foundation would therefore like to thank all the scientists who have been involved in this national offshore wind research project and who have thus helped a new technology to make its breakthrough.

On behalf of this research community the foundation would especially like to thank Project Management Jülich (PtJ) and the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES), who supported and coordinated the individual scientific works, and aggregated all the results.

The RAVE research network has made a great contribution to the development of offshore wind energy in Germany.

Jörg Kuhbier
Chairman, Offshore Wind Energy Foundation

CSI Test Field, CSI Offshore

Publisher's Foreword

RAVE: 1) a frolicking crowd, a dancing mass of people, a swarm 2) abbreviation of Research at Alpha Ventus. So ambiguous and yet so applicable, because the installation and investigation of Germany's first offshore wind farm, Alpha Ventus, also proved to be a ride over the North Sea, for everyone involved.

The start signal for RAVE was given just eight years ago and it is already hard to visualise what it was like back then. Nobody had ever had any experience of erecting wind turbines so far out at sea, over 40 kilometres from the nearest piece of dry land. Nor did anyone have any experience of building wind turbine foundations in water 30 metres deep. The foreseen five-megawatt wind turbine generation was also new and had never been tested out at sea. But we are in a very different position today; nobody asks the question "Is that at all possible?" any more. Five-megawatt turbines are now old hat. Today around 800 offshore wind turbines are operating in German waters, and over 3,200 in Europe. That is also thanks to Alpha Ventus and RAVE.

Both of them are success stories. With around 4,500 full load hours of wind power a year, Alpha Ventus is very impressive. This is especially so compared with other European offshore wind farms – even though Alpha Ventus is a test field. The experiences made and the operating results of Alpha Ventus have significantly contributed to building trust in the technology, which is a prerequisite for further expansion. And this indeed came to pass; in 2015 there was a record 2,282 megawatts of new offshore installations in Germany. There are now offshore wind farms with a total of around 3,300 megawatts on grid. The government goal of achieving its short-range target of 6,500 megawatts of offshore wind power by 2020 appears feasible. Based on current information, around 80 % of the projects planned to date have the financing in place.

RAVE is also a success story. Never in the history of wind power has there been such a large coordinated research initiative, in which the industry and research institutions have acted so in concert. And with success, because within just a few years not only have the manufacturers involved been able to develop their wind turbines further, but based on the research findings they have also been able to develop new guidelines that are now applied across the entire industry. Last but not least, the project has also provided new fundamental knowledge, ranging from the behaviour of porpoises to loads caused by breaking waves. Within just a few years, German offshore wind energy research has made it to the top of the international league – as proven by the many publications and conference contributions.

RAVE has been a joint effort. Despite, or perhaps because of, all the obstacles that had to be overcome. "We were all bitten by the offshore bug." Us, all the researchers involved in Alpha Ventus, Germany's first North Sea wind farm. We are proud that this test field came to fruition – and that we scientists were able to research in the field. Also very important was the financial support that first enabled this research work, for which we must thank the Project Management Jülich PtJ and the Federal Ministry of Economics and Energy. Over 50 universities, research institutes and businesses have been involved in the RAVE research. Their results help to further develop offshore wind energy use.

An incredible amount has been achieved in the past ten years. Our knowledge has increased enormously. But as we all know, miracles take a bit longer, and that is something we should bear in mind when all that is discussed nowadays is how quickly we can expand offshore wind power and how quickly the costs can be reduced. Despite the massive advances made, the offshore wind industry is still a very young industry, which still needs a long time – which it must also be allowed – in order to complete its knowledge, optimise its technology and gather operational experience. Offshore wind farms are built for an operational life of at least 20 years and even the first German offshore wind farm, Alpha Ventus, is not even half way there yet.

Research can make a contribution, and wants to. The long-term behaviour of materials and components in the harsh offshore conditions has to be investigated and understood. Deeper knowledge enables innovations that can reduce the cost of power generated offshore. New approaches in planning, production, construction and operation of offshore wind farms have to be conceived, developed and tested. In ten years' time wind farms will look very different, and also cost less than today.

One last question remains to be asked. Who is this book really aimed at? Everyone interested in offshore wind power, and everyone who wants to understand what research issues had and have to be solved if they are to become reality. In other words, it is for everyone who wants to know more about the work and (interim) results from Germany's first offshore test field. And it is for those who do not want to first study engineering or physics if they are to understand it. This book is an attempt to express the scientific findings of RAVE in a way that is generally understandable. If anyone wishes to have more detailed information we recommend that they read the final reports of the respective research projects, look at the Internet presentations or speak to those involved in the projects.

Offshore wind power in Germany is only just getting started. Research into it continues, and hopefully the success story will also. We researchers want to make our contribution and look forward to doing so.

Foreword to the English edition

After more than half a decade of research involving over 50 universities, research institutes and businesses, Alpha Ventus is the world's most thoroughly investigated offshore wind farm. This translation of the German book "Meer – Wind – Strom" will also give a wider international readership the opportunity to share in the results of the RAVE research project.

Michael Durstewitz

Dr. Bernhard Lange

Credits

We would like to thank

- All the authors for their effort and involvement, for their patience in explaining everything, their work in correcting, for their courage and willingness to tread new paths with this book.
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- The Federal Ministry for Economic Affairs and Energy and Project Management Jülich, who made the realisation of this work possible.
- And the many other helpers who supported us during the production and who contributed to the publication of “Sea – Wind – Power”.

Michael Durstewitz, Bernhard Lange, Björn Johnsen
Kassel, Bremerhaven, Hannover in February 2016

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Construction, Operation, Measurement, Coordination

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Björn Johnsen

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Kai Herklotz, Thomas Neumann, Wilhelm Heckmann, Hans-Peter Link, Copy edited by Björn Johnson

Metamorphoses of an Offshore Wind Farm

Planning, Construction and Operation of Germany's First Offshore Wind Farm and Test Field Alpha Ventus

Björn Johnsen

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1

Project information: Planning, construction and operation of a 60 MW offshore wind farm 45 kilometres off the island of Borkum for test and research purposes
Project management:
DOTI – Deutsche Offshore-Testfeld- und Infrastruktur-GmbH & Co. KG
Wilfried Hube

1.1 In the Beginning Was the Sea

No experience of offshore wind turbines, not much chance of a profit, uncertain territory, and then off out onto the high seas. The first time anywhere in the world at such a great distance from land, in water depths of 30 metres, and a service life of 20 years. Faced with such an investment prospect any business would usually say "Thanks, but no thanks". Luckily the discussions during the planning, construction and operation of Germany's first offshore test field went much better – and finally the Alpha Ventus wind farm actually became reality under the leadership of Deutsche Offshore-Testfeld und Infrastruktur GmbH & Co. KG. Generally known as DOTI, this is a joint venture by energy suppliers EWE, E.ON and Vattenfall which realised Germany's first offshore project in the North Sea and has been operating it ever since (Fig. 1.1). With 4,500 and more full load hours, Alpha Ventus is unparalleled anywhere in Europe. But first things first.

Peripheral Anecdote (I): Legal commuting between Hamburg, the capital and East Frisia

The start was made in East Frisia. In the autumn of 1999, the owner of a wind farm planning and design office, Ingo de Buhr, visited the Federal Maritime and Hydrographic Agency (BSH) in Hamburg to present his plans for the erection of the "Borkum West" wind farm. It was Germany's first offshore wind farm project. There was not yet a legislative framework for offshore wind farms, nor were there any proper wind measurements. EU-wide the use of an exclusive economic zone beyond the 12-sea-mile limit had only been in force for a few years. BSH lawyer Christian Dahlke created the legal framework for offshore wind farms quite quickly, for example with the "Standards for Environmental Impact Assessments", introduced in 2002. There was resistance from residents of the island of Borkum, but backing and great plans from Berlin. In 2002 the federal government set a target of installing 500 megawatts of offshore wind power by the end of 2006, and "at least two to three thousand megawatts more by 2010". At least three German wind turbine managers considered getting involved in offshore wind power. By the start of the new millennium planning was moving ahead at a pace, but the costs of construction were outstripping the budget. The banks were unwilling to risk the financing, insurers were unwilling to insure, manufacturers still had no offshore experience and, putting it diplomatically, there was a great deal of room for improvement as far as the grid operators' inclination to provide the connection to the grid was concerned. For many of the players it was quite clear that the billion-euro offshore business was too expensive for conventional planning and design offices. Offshore, the standard wind farm size of 40 to 50 turbines quickly exceeded the billion-euro mark. Without the involvement of the major energy suppliers there was no way offshore could succeed – it needed an "icebreaker" to prove that offshore wind energy use does work.
So the planned Borkum West wind farm went through a metamorphosis. The planning and design rights were transferred to a specially established foundation, the "Stiftung der deutschen Wirtschaft zur Nutzung und Erforschung der Windenergie auf See" (Offshore Wind Energy Foundation). In autumn 2005, just before the general election, the federal ministry provided its five million euros of starting capital. The Alpha Ventus test field with twelve turbines built by Adwen (then Areva) and Senvion (then REpower) went into planning.

Fig. 1.1 A bird's eye view of Alpha Ventus during construction. © DOTI/Alpha Ventus (Photographer: Mathias Ibeler)

And the DOTI "grid consortium" of power companies EWE, E.ON and Vattenfall also experienced a metamorphosis. It was originally established in 2006 for the sole purpose of building the cable connection from Alpha Ventus to the mainland. But at the end of a long multilayer design process and an "energy summit" with federal government in Berlin the three energy suppliers took the joint risk of transforming the cable planners into a "large suprastructure corporation". Deutsche Offshore-Testfeld und Infrastruktur GmbH & Co. KG leased the offshore site from the Offshore Wind Energy Foundation to become builder and operator of the first German offshore wind farm.
Björn Johnsen

1.2 Prerequisites and Previous Experience

Forty-five kilometres from the nearest piece of dry land – nobody had ever been that far out. Before Alpha Ventus there was no experience with offshore wind farms in water depths of around 30 metres and 45 kilometres from the coast. Previous projects in Denmark and Sweden, mostly in the Baltic Sea, are in much shallower water, a maximum of 15 metres, and less than 20 kilometres from the coast. Building Alpha Ventus thus represented a far greater risk and a myriad of unknowns, in that the offshore wind farm was, technically speaking, a real pioneer project.

The turbine manufacturers had never erected a wind turbine out at sea until 2006, and in fact nowhere in the world had a wind farm ever been erected under the wind and wave conditions that prevail on the open North Sea. It was a similar story with the new turbine size; if possible each machine should have a rated capacity of over 4.5 MW. Up to then the standard offshore wind turbines had a rated capacity of just 2.3 MW, though a few were 3.6 MW – but never had there been a turbine with five megawatt rated capacity. The bottom line was that the erection of Alpha Ventus was the first time in Germany that the offshore industry, turbine manufacturers and energy suppliers worked together on one project.

1.3 Foundation Concepts: Something New on the Sea Bed

Before Alpha Ventus most of the few offshore wind farms in Europe used only monopiles, but these were not suitable for the site conditions of the great five-megawatt deep-water machines. The decision was made to try out two new foundation designs,

1

Fig. 1.2 July 2009: Transporting the first offshore wind turbine to the Alpha Ventus construction site. © DOTI/Alpha Ventus (Photographer: Mathias Ibeler)

tripod tube constructions on the seabed that then joined as one big main tube, and jackets, which are four-legged lattice constructions. Both foundation concepts have a greater load-bearing capacity than monopiles. The installation of the tripods began in April 2009 using a pontoon crane and a jack-up platform, from which the piling, grouting and cementing of the joints was carried out. It soon became clear that foundation construction using a floating crane was subject to extreme weather restrictions. It only makes sense to use one for a small number of foundations, because it led to massive time risks and significant delays. There were no comparable delays with the erection of the jacket foundations because the company chartered the world's biggest installation ship from the very start.

Peripheral Anecdote (II): First wind

"Lessons learned and projects planned" – the German language is full of Anglicisms, sometimes giving rise to a sort of d-english. This was not the case when it came to naming the first German offshore wind farm. Here the owners drew on the languages of classical antiquity. The Greek alpha was not just the symbol for the mathematical angle, but also stands for the first. And ventus is Latin for wind, so this gives you literally first wind. And until the last German offshore wind farm is built, which could possibly be called Alpha Omega Offshore, it will take a few decades – if ever.

Björn Johnsen

1.4 Delayed Completion

When it was established in 2005, the Offshore Wind Energy Foundation still assumed that the Borkum West test field would be going online two years later. Far from it. First of all they would have to effect an agreement between what were in the meantime seven offshore wind farm planners about a common cable route via the island of Norderney. And then the wind farm erection phase developed a life of its own: sudden weather changes, lack of floating crane availability, logistics that could be improved and a lengthy wind turbine tuning process. So after the first turbine was completed in July 2009 (Fig. 1.2), and the first electricity was fed into the grid in August 2009, setting up all 12 turbines took until they were officially commissioned in April 2010. Additional work, such as the cabling within the wind farm, ran on into the following year. Or as general construction manager Wilfried Hube wittily, and slightly overstatedly, put it: "We don't really know how it should be done, but we have learned everything you can do wrong."

Fig. 1.3 The pontoon crane Thialf installs a jacket foundation in the Alpha Ventus construction site. © DOTI/Alpha Ventus (Photographer: Mathias Ibeler)

1.5 Installation, Logistics and Cabling

Here too the maxim was: gain experience! One had to make do with what was available – and unfortunately not everything was available. Were there planning errors, have the machines used done what they were meant to? Was the weather "unplannable"? A particular problem in the North Sea was the subsequent groundswell. While the wave height wanes and is not really all that strong, the lengths of the waves increase. The swell only ebbs away very gradually and continues in areas where there is no wind and the sea is supposed to be quite calm.

The connection of the short cable sections of about 800 metres in length between the individual wind turbines also proved to be difficult. There are tried-and-tested methods for longer sections of cable, such as the cabling between the mainland and the island. At Alpha Ventus it turned out that the laying and injection of the inner-farm cables was one of the most demanding and weather-sensitive jobs in the construction of the wind farm. The challenge was in laying a cable between two foundations very close to one another without any loops or kinks and then drawing it into the turbines' cable protection system.

This work required long "time and weather windows". The "installer ships" on the German market at that time were usually not big enough and the international ships of suitable design and appropriate certification (Fig. 1.3) could only be chartered temporarily as they passed through the German Bight from one job to the next. This led to long delays that were difficult to make up for during the further Alpha Ventus scheduling. Nevertheless: the experience gained and the increasing demand resulted in the development of new ships.

1.6 Operation, Maintenance and Farm Control System

Strict safety precautions apply for carrying out maintenance and repair work. There were no incidents during the erection and cabling of Alpha Ventus – and that with over 5,000 transfers from ships to turbines and their subsections. DOTI set up a control centre for the management of the offshore wind farm in Norden – the nearest port (alongside Norddeich) on the mainland opposite Norderney. The office gathered and evaluated all the wind farm data. There were still challenges in allocating means of transport to Alpha Ventus. Unnecessary capacity stockpiling causes unnecessary costs; waves and swell do not always permit transfer from ship to wind turbine, resulting in unnecessary empty runs. Here there is still massive optimisation potential if one is aiming for high technical availability – as well as meteorological weather forecasts that really are correct. Wind

Fig. 1.4 Helicopter in landing approach to the helideck of the substation at the Alpha Ventus offshore wind farm. © DOTI/Alpha Ventus (Photographer: Mathias Ibeler)

Force 1 was specially developed for the offshore service sector, and was used for Alpha Ventus. It is a catamaran with space for 25 persons, has a large loading deck for loads up to ten tons and its own 1.5-ton crane. The scheduled maintenance of the wind farm takes place from spring to late summer. In acute cases and where there are heavy seas the last resort remains to use a helicopter (Fig. 1.4).

Including the initial months prior to the official commissioning in April 2010, Alpha Ventus had generated a total of 1.35 terawatt hours by 30 June 2015. In the four full operating years between 2011 and 2014 Alpha Ventus had notched up 16,582 full load hours and produced 994.9 gigawatt hours (GWh) of wind power. The average annual yield is 248.73 GWh and thus exceeds the forecasts by around 7 % a year. In 2014 the yield dropped a bit to 235.6 GWh, but was still 1.5 % over the forecast of around 230 GWh (with 3,900 full load hours) per annum. The decrease was mainly due to the replacement of individual components in the course of the year. In 2015 the amount of power produced was 242.1 GWh, once again 3.1 % above forecast, with a technical availability of 93.1 %. In February 2016 Alpha Ventus is expected to hit the 1.5 terawatt hours mark.

Due to the positive experience made with Alpha Ventus, the DOTI partners have now erected more offshore wind farms in the German Bight, though this time each as individual operators: Riffgat (EWE), Amrumbank (E.ON) and DanTysk (Vattenfall).

1.7 Money and Its Usages

All in all the total investment of around 250 million euros was significantly greater than the originally planned 180 million euros. This additional expenditure for the first German offshore wind farm was mainly due to the additional costs for logistics and assembly, increased steel prices and also the higher price of the wind turbines themselves. And despite this there is an immense benefit – in particular for subsequent and future offshore projects. The experience gained from the erection of the turbines, foundation structures and from the cable laying also benefits other projects, making for simpler and more efficient work processes. It has also expedited the development of new installation vessels and enhanced knowledge-building for planning authorities and other specialist authorities. It has enabled the setting of new standards for approval and construction procedures for offshore wind farms. But first and foremost Alpha Ventus has been a joint effort between manufacturers, suppliers, politicians (of successive governments), administration, logistics providers, researchers and developers, and in particular DOTI as investor and operator, and the Offshore Wind Energy Foundation as companion and intermediary (Fig. 1.5).

Fig. 1.5 Panorama of the Alpha Ventus wind farm. © DOTI/Alpha Ventus (Photographer: Mathias Ibeler)

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Who, What, When, Why and Above All – Whereto?

The Coordination of the Offshore Text Field Research

Björn Johnsen

2.1 Sources – 13

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Project information: Coordination of the RAVE research initiative – Research at Alpha Ventus

Project management:
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Biologists, geologists, ornithologists, material testers, psychologists, economists, mechanical engineers, and not forgetting electrical engineers, engineers, structural engineers, logisticians and many other professions. What for some observers might at first glance appear to be a "research supermarket" with a massive range of products, in fact reflects the diversity of those involved in the RAVE research initiative. The Alpha Ventus test field provided the start signal for the development of offshore wind energy in Germany – and also for a large number of research projects. While Project Management Jülich (PtJ) was entrusted with the administrative management of the project, the responsibility for the coordination of the research activities lies with Fraunhofer IWES.

The research coordination involves a great deal more than just organising a few boat trips out to the wind farm for the research organisations. It also includes the planning and coordination of the measurement operations; Alpha Ventus has been fitted out with extensive measurement technology in order to be able to supply all the research projects involved with the detailed data they need. Whether it be verification and modelling of turbines and components, grid integration, further development of lidar wind measuring methods, recording the loads on foundation structures, measurement of the wind farm construction and operation noise or the accompanying ecological research, the job has been to avoid duplication of measurements or that other measurements are omitted. In other words what is called for is coordination of the implementation and shared data management. The most important job for the coordination project was initially to create the structure of a joint programme for all research sections and organisations, and to make it available to them all. The tasks also included the preparation, organisation and staging of workshops and specialist conferences (Fig. 2.1).

The official launch of the enterprise was on 8 May 2008, when the Federal Environment Ministry (BMU) invited over 200 experts from the fields of research, science, government and wind industry to meet in Berlin for the kick-off event for RAVE – Research at Alpha Ventus. This gathering gave all those involved a broad overview of the planned research activities and more. "The Alpha Ventus research project and its findings will in the long term contribute to reducing the costs of offshore wind energy", summed up Professor Jürgen Schmid, then president of the European Academy of Wind Energy EAWE and chair of the Institute for Solar Energy Supply Technology (ISET) in Kassel.

At the time of the RAVE launch event, onshore wind turbines produced 22,000 megawatts, slightly more than six per cent of total power production. Government plans envisaged another, more far-reaching target, which was to incorporate the massive wind energy potential in the North and Baltic Seas into the future energy supply structures and achieve 15 % of the total power consumption from offshore wind by 2030. Alpha ventus was to be the high-profile "door opener" for the use of offshore wind energy; the Federal Environment Ministry provided around 50 million euros for the accompanying research in the test field over a period of five years. In 2007, immediately prior to the main event, 14 projects had already been approved with a total funding volume of over 16 million euros. Around 20 more projects were to follow (Fig. 2.2).

In order to be able to make use of synergies in the research projects and thus increase the quality of the results, Fraunhofer IWES developed a concept for the cooperation between the various projects in the test field which was then coordinated at the regular meetings of the organisations involved. The main work packages in the coordination project involved the organisational and scientific networking of the individual projects; nobody should be "completely detached and researching alone". This meant regular meetings for reporting on partial results and difficulties in implementing projects. Interest and conflict mediation was naturally also in demand, because not everybody could go out to sea at the

Fig. 2.1 Research results from Alpha Ventus, presented at the International Offshore Wind R&D Conference 2015 in Bremerhaven. © Fraunhofer IWES

same time and at any time. The coordination project eventually involved over 30 projects, as well as over 50 research organisations, institutes and facilities. National and international networking was also part of the job, because offshore wind is not just a German domestic issue.

The coordination project has also involved the planning and realisation of specialist workshops and major scientific conferences like the RAVE Conferences in 2012 and 2015 (Offshore Wind R&D Conference). And it is responsible for all the PR work; not just answering questions about the test field, but also informing the industry, government, project sponsors, the scientific community and other interested parties about the research in the test field and about the latest trends and tendencies to do with offshore wind energy use. A job it continues to do to this day.

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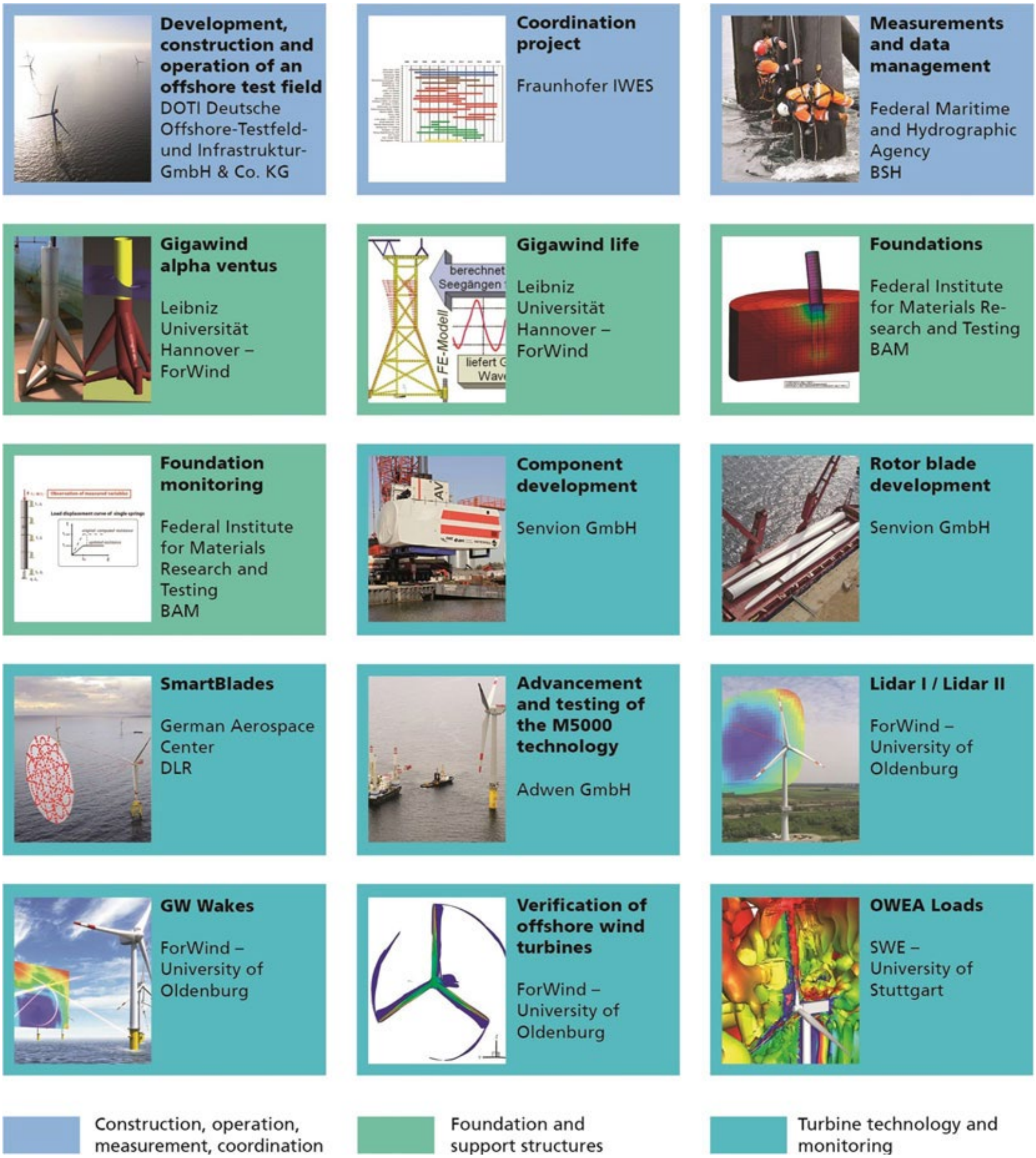

Fig. 2.2 Overview of the RAVE projects – the 27 research projects listed correspond to the chapter sequence in this book. © Fraunhofer IWES

Fig. 2.2 (*continued*)

A Thousand Sensors, from the Blade Tip to the Bottom of the Sea

Between Measurement Technology, Logistics, Scour Holes and the Ocean: The Central Measurement Service Project

Kai Herklotz, Thomas Neumann, Wilhelm Heckmann, Hans-Peter Link, Copy edited by Björn Johnson

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3

Project information: Central realization of measurements within the framework of RAVE research projects

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DNV GL
UL International GmbH (DEWI)

3.1 Measurement Service: One for All

The central measurement service project of Alpha Ventus involves more than just carrying out measurements and providing measuring technology for others. Long before the start of construction of the first offshore wind farm out at sea it involved coordinating and implementing the various measuring requirements and – after installation – making the measurement data available for evaluation. It is a project that is still ongoing and which carries out basic oceanographic and geological research – in the truest sense, because there is a lot going on down on the seabed around the turbines. And this basic data is relevant for virtually all the investigations. There are regular maintenance trips into the test field to maintain all the measuring equipment during plant operation – a work assignment that continues to this day. The measurement service project thus provides all the institutes, agencies and firms involved in the overall RAVE research project with the necessary service facilities.

3.2 Coordination, Organisation, Exploitation

The key component of the test field research is the measurements made on the wind turbines themselves. While the scientists aim to detect the condition of the offshore wind turbines as completely as possible, for financial reasons the turbine operators are more interested in having an as much uninterrupted production as possible, without any production downtime. Two contradictory interests that need to be reconciled.

For this reason it was decided to concentrate the main measurements for the research on one turbine per manufacturer. The two wind turbines selected – AV4 and AV7 – are situated on the western edge of Alpha Ventus, in the direct vicinity of the Fino 1 research platform. Due to the predominantly prevailing westerly wind direction there it would also be possible to analyse a wind field that was to a wide extent uninterrupted, and not in the shadow of wind turbines upwind. It would also be possible to correlate the data measured on both turbines with the measurements from the Fino 1 platform. To be on the safe side, and in case important research instruments on the main turbines broke down, two neighbouring turbines – AV5 and AV8 – were also fitted with sensors at the same time, though with considerably fewer.

The requirements for number, type and positioning of the measuring sensors to be installed that the RAVE coordination committee had drawn up was available well before the construction of Alpha Ventus began. Five hundred different sensors were attached to the chosen turbine AV7 and over 400 to AV4. On top of that came more measuring sensors on the substation, on and in the sea, on the seabed and at the next substation on dry land, at Hagermarsch on the North Sea coast of Lower Saxony. The sensors were spread out from the seabed up to the tips of the blades. Over a thousand sensors were installed in total.

The installed sensors are documented in one central register of measuring points. The data is checked, its plausibility is tested, and once it is released it is made available in the RAVE research archive. The data is exclusively available to the RAVE research projects.

Peripheral Anecdote (I): Not much room for research

Measuring equipment (Fig. 3.1) needs space, and even more measuring equipment means control boxes (Fig. 3.2). One problem that transpired was that the connections of the mea-

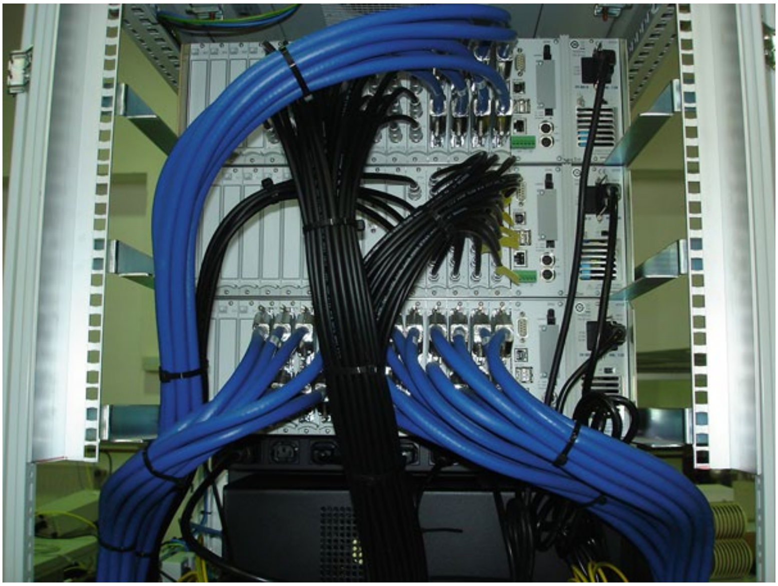


Fig. 3.1 Measurement amplifier with cable routing for the tripod measurements on AV7. © UL International (DEWI)

suring technology – in this case the sensors on the foundation – should with good reason be as far as possible unconnected with the normal power electronics of the offshore wind turbine. But where do you put the additional control box? The tower of a wind turbine is not a convenient warehouse or open-plan office. But finally a place was found in the tower of platform 9 of the wind turbine which, while climatically unfavourable (with the highest humidity and the possible formation of condensation on the floor), was the only place where there was sufficient space for the additional research measuring equipment. And that has worked perfectly ever since.
Björn Johnsen

3.3 Tripod Is Also Hard to Access on Land

The first research sensors were installed far away from Alpha Ventus, in a shipyard near Verdal in Norway, 50 kilometres northeast of Trondheim. This was where the tripod foundations for the Adwen AD 5-116 were welded together, and thus also for the chosen research turbine. The measuring technology was to be attached there in Norway. But a basic problem was the accessibility of the designated measuring points on the foundations, which when set upright were about 45 metres high. It was only possible to attach sensors to the west leg of the tripod as planned before assembly on the ground. The tripod manufacturing process caused increasingly longer pauses during the installation of the sensors and cabling. All this work was carried out in June to August 2008 during a vital six-week deployment in Norway. The integration of the measuring equipment and fitting these previously unscheduled work processes into the tightly scheduled tripod production process was also new territory for the Norwegian yard.

The tower segments were on the other hand comparatively close by at the manufacturer's works site in Bremen, where they were fitted with strain gauges, acceleration sensors and a variety of other sensors (Fig. 3.3). The power electronics were accommodated in the third tower segment. Once in the water, the tripod foundation was also fitted with special collars at three different heights around the main column, and their water pressure sensors supplied precise high-resolution (50 Hz) data about the hydrostatic water pressure around the tripod structure of AV7 for about two years after commissioning.

3

Fig. 3.2 Control box for research measuring equipment in an offshore wind turbine. © UL International (DEWI)

Peripheral Anecdote (II): Swapped

With the autumn storms approaching, the installation of the turbines in October and November 2009 was pretty hectic. During the erection of a tower out at sea, two of the prepared segments were switched, and as fate would have it, it was the tower of one of the turbines to be used for measurements. The result was that because the tower segments were mixed up it was not possible to use the pre-installed measuring equipment. Numerous additional measuring installations had to be installed out at sea. The wind turbine manufacturer bore the additional costs incurred.
Björn Johnsen

3.4 An Obstacle Course Before and out at Sea

Some 120 measuring points were defined on turbine AV4 in the wind farm, a Senvion 5M, another 157 on its foundation structure and 37 measuring points on the neighbouring turbine AV5 of the same type. Here too there were plenty of lessons to be learned in this pioneer project. Contrary to planning, due to contractual arrangements between supplier and wind turbine manufacturer it was not possible to equip the tower segments with structural dynamic sensors at the supplier's works. It was therefore necessary to carry out this work subsequently out at sea in the offshore test field, which took significantly longer than it would have onshore and consequently resulted in much later commissioning of the measuring equipment. The sensors inside the nacelles were installed on schedule. The attachment of sensors in the rotor blades was unproblematic in the area of the blade root (Fig. 3.4), but not so at greater distance from the blade root. This was incompatible with the blade manufacturer's lightning protection concept and therefore not approved.

Where there is movement, there is also wear. Measuring equipment can also break, particularly when subjected to sea waves. The repair of such defective sensors was closely coordinated with the project partner, the test field operator and the manufacturer of the wind turbine in question. Due to a long chain of communication and the fact that research activities cannot of course always be afforded such priority as operating issues, these extended reaction times for necessary installation and maintenance work out at sea obviously affect matters. Are any boats available, and are they ready to use? Is there enough transport capacity for personnel and material? What is the state of the sea and the tidal currents, and what about ice drift? A lot of questions, many of which can only be finally clarified on the quayside just before the service ships leave.

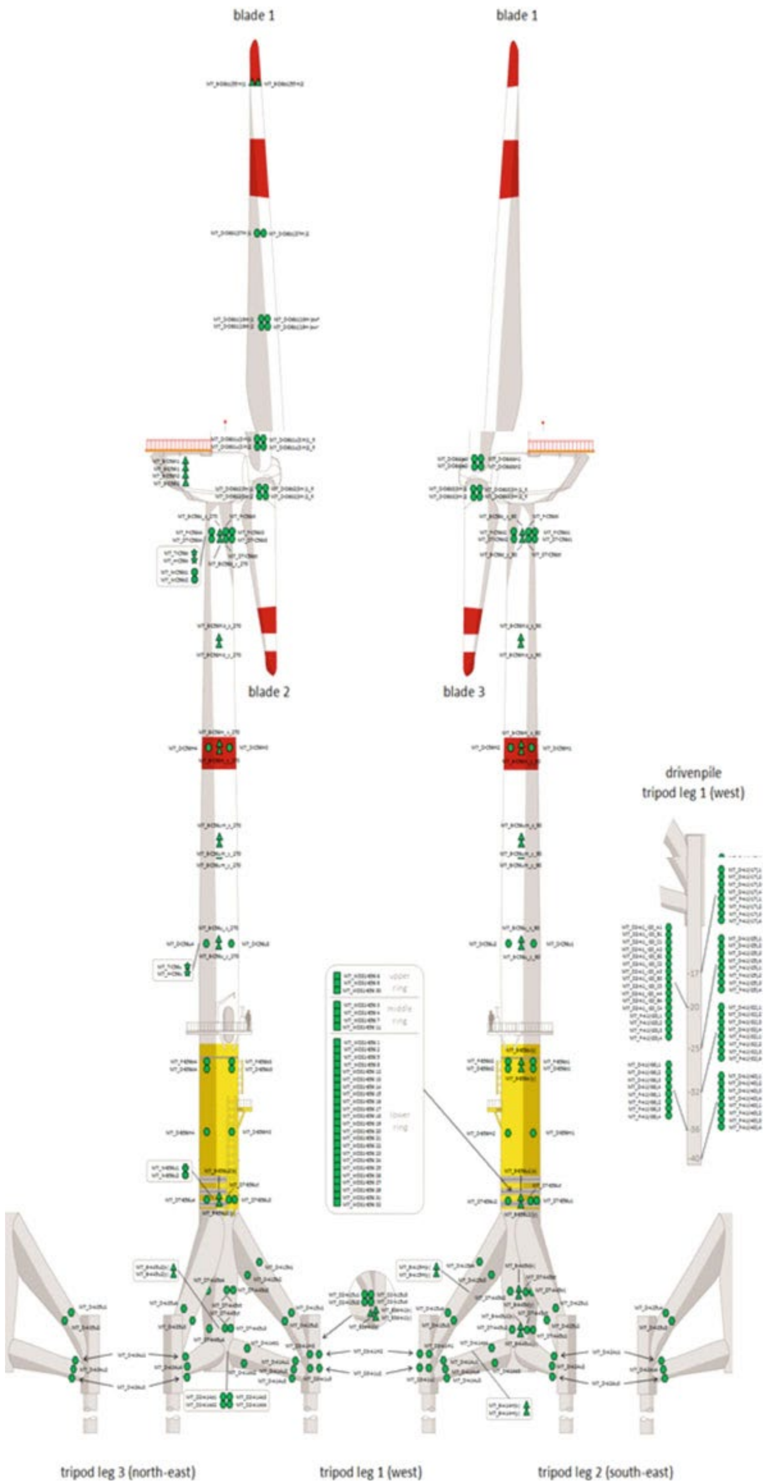


Fig. 3.3 Layout of the measuring point positions on AV7. © UL International (DEWI); Graphic: DOTI, adapted by UL International (DEWI)

Fig. 3.4 Measuring equipment mounted in the root of a rotor blade. © UL International (DEWI)

The project included grid measurements at transmission level. Here it was necessary to install three current sensors (current converters) and three voltage sensors (voltage converters) per measuring point – with measuring points on the substation out at sea (AV0) and in the next substation on land in Hagermarsch (Fig. 3.5). The measuring cables in the substation were pre-laid onshore in the substation in August 2008. The current converter could only be installed at the points required in the 110-kilovolt voltage level out at sea, because the cables were not yet available on land. As far as the installation was concerned, there were no critical systems or measurement points because from a measurement point of view it involved four identical standard grid measurements.

3.5 The Tides and Maltreated Measuring Buoys

The strong tidal impacts shape the ocean circulation in the German Bight. The marked tidal currents caused by ebb and flow cause greater exchange and better mixing of the water in the North Sea at all depths than in the Baltic Sea – and thus also greater harmonisation of temperatures, regardless of how deep the water is. Sea state, temperature and current were measured over several years at Alpha Ventus. This was all necessary for example for planning maintenance trips and the logistics for supplying the wind farms in order to save on costs and resources, or in order to assess any ice drift in the North Sea. In addition to sea state buoys and wave radar, other sensors were deployed at depths between five and 28 metres, for example for measuring the temperature of the water in the North Sea. The "vertical temperature profile" measured at Alpha Ventus was

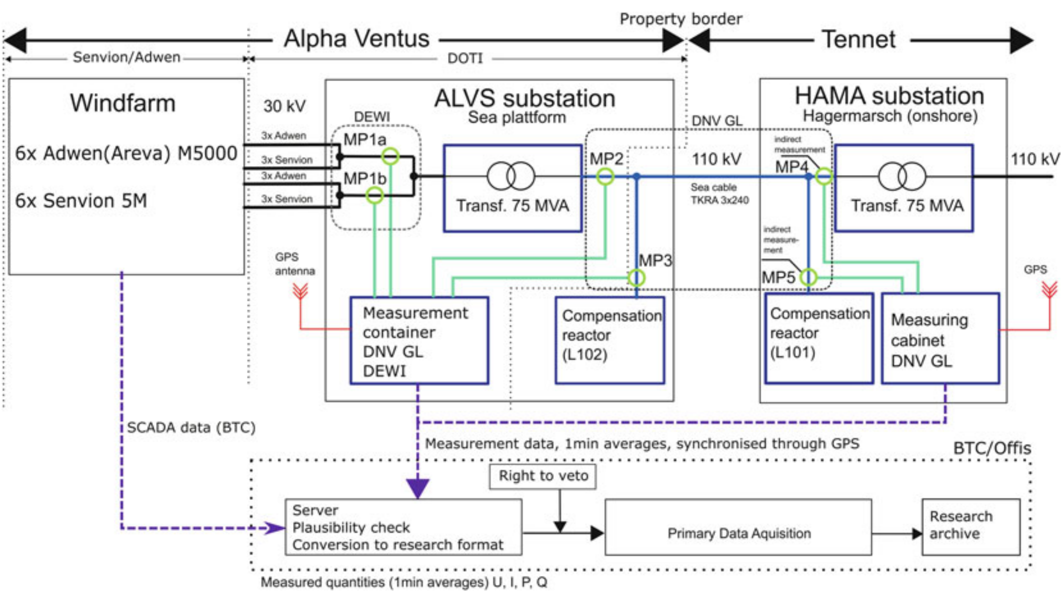


Fig. 3.5 General overview of the electrical measurements onshore and offshore. © DNV GL

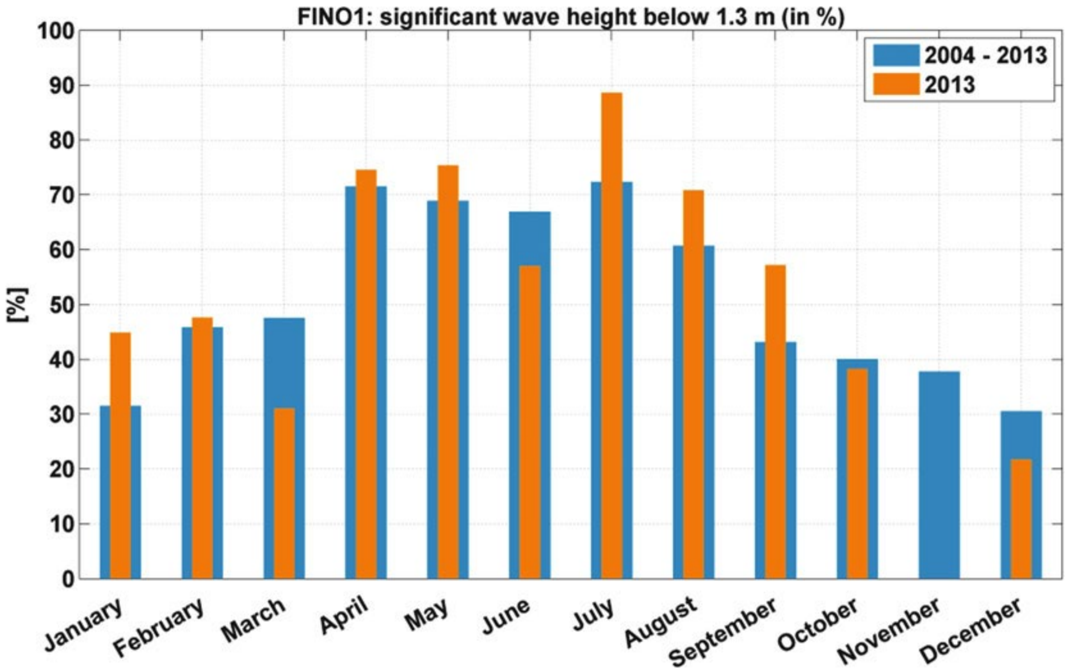


Fig. 3.6 Significant wave height H_s < 1.3 m in per cent per month, measuring period 2004 to 2013. © BSH

around four degrees Celsius in March 2011 at all depths between five and 25 metres. Nor were there any noticeable temperature differences in the water between the turbines.

From winter 2010/2011 to the start of summer at the end of June 2011 the water temperature rose from four to 18 degrees. It must be said that the winter had been very cold and had lasted into March 2011. This does not of course say anything about the danger of ice in the North Sea, poor accessibility of the wind farm by boat, or even damage of the supporting structures of the offshore turbines. Because there are few comparable existing "time series" it is not possible to make any definitive statements about the possible temperature fluctuations and changes in the test field and the German Bight; this requires that the measurements are continued and evaluated over a longer period of time.

3.6 Only 30 % Accessible by Ship in Winter

Sea state buoys proved indispensable for gathering data about sea wave states, in that these had in the meantime been fitted with integrated acoustic Doppler current profilers (ADCP) and could therefore also measure the currents. Radar from the Fino 1 research platform can take more exact complementary measurements and is not as easily damaged as the sea state buoys on the sea surface, but does not provide any information about the swell direction.

An example of the importance of wave measurements is that for Alpha Ventus there was a fixed threshold value for safe transfer of persons from ship to offshore wind turbine, a "significant wave height (H_s)" of less than 1.3 metres. Seen over the course of the whole year, wave height and wind speed frequently correspond. In the autumn and winter months with typically high wind speeds, the frequency of significant wave heights below 1.3 metres is only 30 to 40 %; in the spring and summer months on the other hand there is a frequency of up to 70 % (Fig. 3.6).

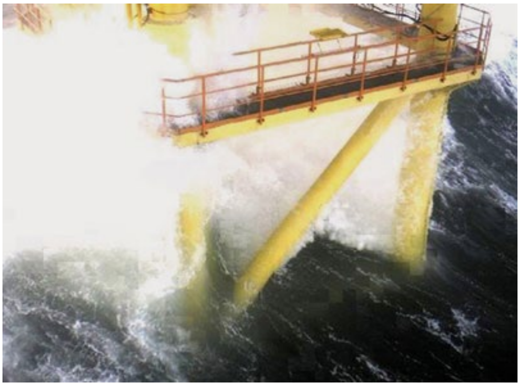


Fig. 3.7 A 12-metre-high wave hits the Fino 1 research platform. Extreme sea state events have an impact on the logistics and plant management of offshore wind farms. © DNV GL

To improve logistical deployment planning the sea state data was made available to the wind farm operator's operations centre in real time. Extreme weather situations that can result in loads on and damage to offshore structures are of course also recorded and evaluated. The measurement data and results are directly integrated into the planning and operation of future wind farm projects. And indeed, the sensors in the wind farm are not just subjected to stress by extreme events but also strongly subjected to corrosion and the state of the sea during continuous operation, and their maintenance is made more difficult due to the rough weather conditions out at sea (Fig. 3.7). In the follow-up project, more instruments for measuring the sea state were installed and the oceanographic measurements were continued.

3.7 Firmly Entrenched in the Ground, even with Scour Holes

There's a lot going on down on the seabed, and not just as far as the fauna is concerned. Enormous motional processes are taking place on the seabed around the turbine structures.

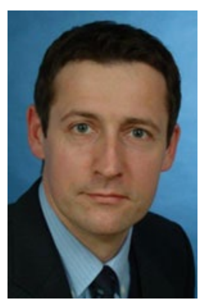
A particular process is the development of scour or scour holes, in the area around the piles that effectively "nail" the turbine's legs (with a tripod foundation) or the framework foundation (jacket foundation) to the sea floor. Scouring occurs when objects such as the supporting structures of offshore wind turbines are put in an environment that is subjected to currents. The course of the current changes, resulting in increased erosion of the seabed.

In order to measure the currents and scour that occur, five echo sounders were attached to each of the bracing elements of the tripod foundation or jacket structure, and additional echo sounders were attached to the central tube of the tripod. These echo sounders permanently installed on the foundation structures (Fig. 3.8) have continuously measured the development of the scour holes on one jacket and one tripod since 2009, and a continuous increase in scour holes has been observed since then. The increase in the depth of scour holes is very rapid in the first three to six months after erection of the offshore wind turbine, after which the process slows down – but after a five-year measuring campaign still persists. After strong storms there is often a big increase in scour depths within a short time.

» The tendency towards global scouring

We have observed scouring, the deep potholes in the seabed around the foundations, for years. The greatest scouring dynamics occur in the beginning, before slowly ebbing away. There is however still a tendency towards global scouring – potholes around the whole foundation.

Kai Herklotz, Federal Maritime and Hydrographic Agency BSH



In the case of the tripod, scour depths of between three and four metres were found around the offshore piles after five years of measurements. The

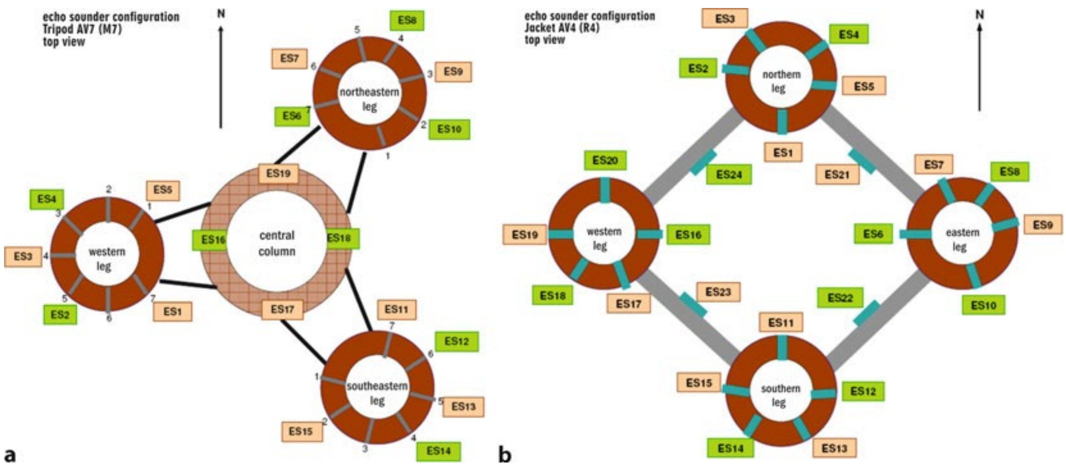


Fig. 3.8 Schematic representation of the arrangement of the echo sounders on the tripod of AV7 (**a**) and on the jacket of AV4 (**b**). The designation "ES" stands for echo sounder. © BSH

echo soundings showed that the scour depth had stabilised at about seven metres in the central area of this supporting structure. These unexpectedly large scour depths around the tripods appear to be due to constructional effects. The massive structural elements close to the seabed cause a reduction of the flowed-through area and thus an increase in current speeds close to the seabed, leading to erosion under the foundation. The erosion effect is intensified by the open central element, which allows fluctuating water levels in the central tube. These fluctuations result in a pumping motion whereby the water flowing out causes the bottom sediment to move and be carried away.

In the case of the jacket foundation, after a (slightly shorter) four-year measuring campaign the scour depths were not quite as deep, measuring 2–2.5 metres. In order to not just measure selective depth development with the installed sensors, both turbine types were also surveyed at regular intervals from on board ship using a spatially high-resolution, large-scale multibeam echo sounder – which verified the results of the fixed-point measurements (Fig. 3.9). The results showed that both types of foundation had developed "global" scour of different types and degrees, the central scour hole below the central tower and the local scour holes around the piles. This tendency towards "global scouring" exists with both types of foundation.

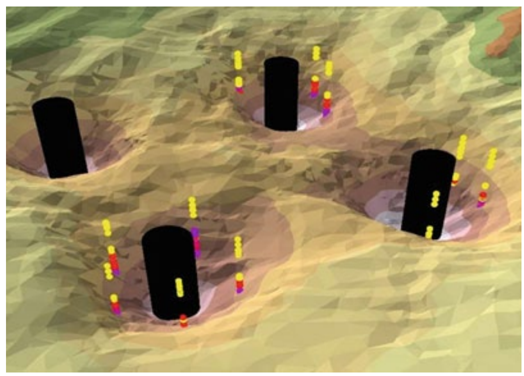


Fig. 3.9 Bathymetry around a jacket foundation from measurements made with a multibeam echo sounder. The *circular markings* each represent one measurement. © BSH

The tripod design was modified as a result of these findings with the aim of avoiding scour development on tripod foundations in future. Current research is investigating which hydrodynamic processes are responsible for the various scour depths. There is a suggestion that it is the impact of local currents that could be responsible for erosion phenomena like submarine landslides, but this has to be more closely monitored. The plan is to broaden the investigations in order to be able to better understand the dominant scouring processes.

To determine the firmness of the sediment on the seabed measurements were also made with a so-

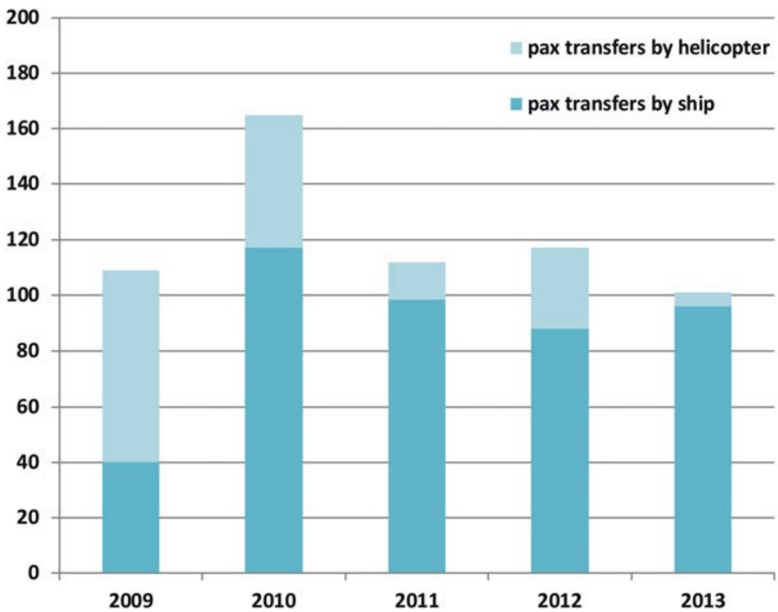


Fig. 3.10 Passenger numbers (PAX) with helicopter and ship for transporting research personnel to work assignments in Alpha Ventus. © BSH

called "dynamic penetrometer", which measures the penetration resistance of the ground. Apart from the scour holes, no substantial changes in the composition of the seabed sediment have been observed to date after the turbines were erected. Nor have any noticeable seasonal changes been observed.

3.8 Logistics: (No) Ship will Come

Organising and providing logistics and transport for carrying out measurements offshore is also one of the jobs of the measurement service project. This includes the transport of personnel and material for the installation and maintenance of the measuring system, whereby the offshore deployments are carried out using a variety of logistical means. These include ship transfer with special service boats, which involves stepping over onto the turbine, helicopter transfer, which involves people being winched down onto the roof of the nacelle, and direct boat operations, where the personnel remain on board the ship and do the work from there, for example when replacing oceanographic instruments. Ships are the preferred mode of transport for maintenance jobs because of the lower transport capacity and higher deployment costs of helicopters. Yet unlike ships, helicopters can be deployed in virtually any weather (Fig. 3.10).

Peripheral Anecdote (III): Flat-sharing out at sea

The original idea was that the measurement service project should itself charter the ships needed for deployments, but the idea was soon dropped. A cooperation was arranged with manufacturer Adwen and wind farm operator Doti whereby the project could share their logistics for any installations offshore. This was simply to be able to more quickly use any small time windows that might arise, which is how the researchers came to occasionally share the Adwen accommodation ship. A small flat-share out on the open sea. When it came down to it, fewer ship days were required than planned (120 days with 33 journeys).

Björn Johnsen

Research work carried out around the turbines (e. g. diving work or attaching measuring instruments) is covered by using the Federal Maritime and Hydrographic Agency's ships. The extensive underwater work involves additional diving operations over several days and weeks, so where possible use is made of hotel ships in order to avoid time-consuming personnel transports to the mainland. The total number of person transfers is about 100 per year. This was only significantly higher in 2010, with 150 transfers, due to the time-consuming installation and commissioning of the measurement technology needed for the research (Fig. 3.10).

3.9 Just Keep on Going

It is not just a question of a one-time installation of the measuring equipment on the wind turbines. Everything has to be maintained and where necessary repaired or exchanged, as was the case with several echo sounders on the foundations that were used for scour measurements. Above all, the measurement data has to be evaluated. The dynamics of the scouring around the foundations is still far from being conclusively assessed, and the same goes for sea state, marine currents and long-term oceanographic measurements.

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- RAVE-Messserviceprojekt: Zentrale Durchführung der Messungen im Rahmen der RAVE-Forschungsprojekte und ozeanographische und geologische Untersuchungen. Bundesamt für Seeschifffahrt und Hydrographie (BSH), Hamburg. Word-Dokument, 6 Seiten. O. D. (2.10.14)

Foundation and Support Structures

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A Firm Hold in Rough Seas

Gigawind Alpha Ventus – Holistic Design Concept for the Support Structures of Offshore Wind Turbines

Raimund Rolfes, Moritz Häckell, Tanja Grießmann,
Text written by Björn Johnson

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power,* DOI 10.1007/978-3-662-53179-2_4

Project information: Holistic design concept for OWEC support structures on the base of measurements at the offshore test field Alpha Ventus (GIGAWIND alpha ventus)
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- Institute of Building Materials Science.
- Institute of Soil Mechanics, Foundation Engineering and Waterpower Engineering.
- Institute of Steel Construction.

Senvion GmbH

4.1 Introduction

Offshore wind turbines are mounted on large supporting structures in the sea. The conditions of the open sea really put these support structures to the test: salt in the air and water, ultraviolet rays and above all immense loads from wind and waves impact on them and therefore have to be taken into consideration in the design and construction, operation and maintenance of the wind turbines. The aim of one of the biggest research projects relating to Alpha Ventus was to optimise the design of the steel constructions based on these measurement results so that it would be possible to reduce the costs of development, material, production and maintenance, and also achieve a longer life for the support structures. These diverse subjects from different scientific disciplines were dealt with in eight different work packages or sub-projects, and analysed so that the results could be brought together to create one holistic concept.

4.2 The Tripod as Wave Breaker

The supporting structures of offshore wind turbines do not just have to take the effects of the wind into account, but also those of the waves. These loads are incorporated in computer-aided modelling. The more accurate the models, the more economically long-life wind turbines and supporting structures can be designed and constructed.

The "Load Models" sub-project investigated how loads caused by breaking waves impact on a tripod foundation. In a model experiment at the large wave flume at the Franzius Institute in Hannover several tests were carried out using an approximately five-metre-tall "miniature" tripod with a scale of 1:12 in water with a depth of 2.5 metres. For these tests the tripod was fitted with 30 pressure sensors positioned at several positions on the model – both below and above the "at-rest water level" (Fig. 4.1). In the wave channel it is possible to exactly define and set the wave characteristics, such as wave heights and lengths as well as whether and in which position the waves break.

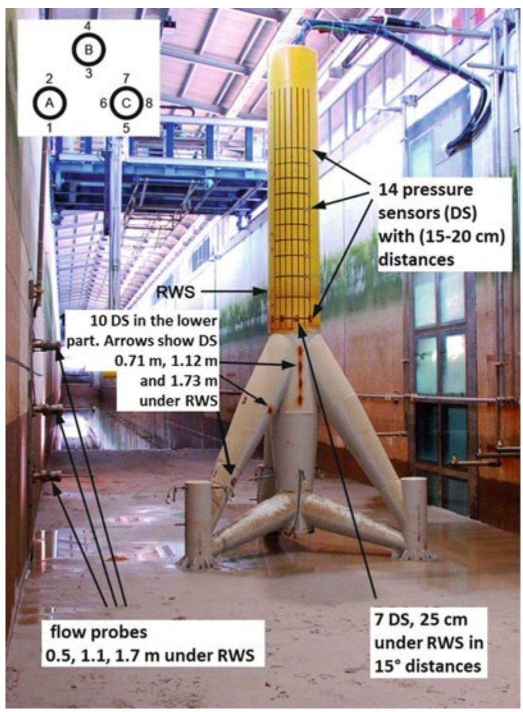

Fig. 4.1 The five-metre-tall model tripod (scale 1:12) in the wave flume. © LUH

In their series of tests, Hildebrandt & Schlurmann (2012) measured the spatial and temporal pressure load on the structure and created a three-dimensional numerical flow model. In addition to the load analysis this also provided additional findings about the movement of waves and the flow around the tripod structure.

Measurements were also made of non-breaking waves on a tripod directly in the Alpha Ventus test field. To achieve this, three measuring cuffs with 30 pressure sensors were attached to the central cylinder of the foundation in order to measure the pressure distribution around the cylinder and water-level changes during a wave period. Using this measurement data it was possible to investigate methods for the theoretical calculation of the wave loads in the lab and in the test field. The projected and measured loads exhibited good congruence. Since the loads of real, irregular waves are, as is to be expected, well spread out compared with waves produced in the lab, there is a need for further research here.

4.3 Steel Structure with an Ideal Figure

As well as the tripod foundations, Alpha Ventus also uses jacket constructions as foundations in deep water. Jackets are lattice-style foundation structures whose struts are joined by weld nodes. The fatigue strength of their structure and nodes were investigated, i. e. examined for cracks caused by constantly recurring, cyclic loads. One cause of material fatigue can be strongly influenced by imperfections – undesired manufacturing deviations of the structural components from their ideal form. These geometric imperfections influence the load-bearing behaviour and thus also the structural durability of the structural components. In the search for suitable measuring systems able to identify such imperfections during the production of the jackets, the choice fell on laser scanners and tachymeters. Laser scanners can quickly scan the surfaces of objects at a number of points without touching them. The result is a 3D scatter plot that can be used to calculate the form and shape of the surface. Automatic self-tracking tachymeters measure the directions automatically in accordance with the set target, whereby the distances are ascertained electronically. Two measuring groups were created for testing the two types of technology, which examined the surface of the imperfect structure on the one hand, and on the other the accuracy of fit of the connections.

The first group undertook the scanner measurements on a jacket manufactured for Alpha Ventus in a Scottish shipyard. The scanner that was used recorded up to 500,000 points per second and had a measuring range of up to 80 metres. For the complete survey, measurements were taken from various angles and combined to create an overall model. This was followed by a comparison of how the structure is and how it should be. The ideal reference geometry was calculated, from which it is possible to determine the deviations of the manufactured structure from the planned geometry. With the aid of laser scanners it was thus possible to determine deviations with an acceptable degree of cost and effort and to optimise manufacturing processes with regard to service life.

The second group took tachymeter measurements on a jacket frame – also made in Scotland. The geometries of unprocessed tubes were also measured. The tachymeter recorded measuring points by using manual targeting by means of a telescopic sight. As with the laser scanner the measuring device converted the measured angles and distances in a Cartesian coordinate system. It showed that the tachymeter was also very suitable for measurements during production.

4.4 Cavity and Grout

In addition the project came up with what is currently the only method capable of measuring the movements of the “grouted joints” – the joints between supporting structure and transition piece, the piles and the structure. These are tube-in-tube connections where the cavities between tubes at sea are filled with grout or mortar.

This joint is problematical because the supporting structures are subjected to very great loads and damage cases have already occurred in practice. A prototype of a measuring concept for determining the relative displacement (◘ Fig. 4.2) was devel-

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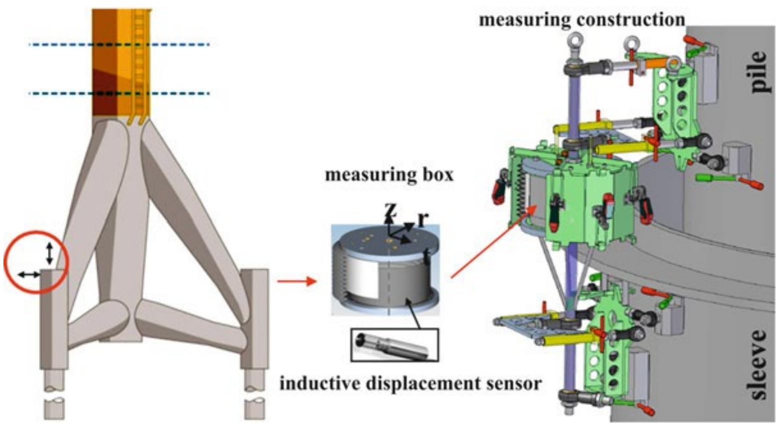

Fig. 4.2 Measuring concept: measurement of relative displacement of grouted joints between pile and sleeve on a tripod. © LUH

oped, which was attached to a tripod in the test field so that it could measure horizontal and vertical displacement with the aid of displacement transducers.

Although the prototype could only record the relative displacements on the horizontal measuring level and broke down after several months it was still possible to demonstrate the basic functionality. It is conceivable that this measuring method could already be applied during the process of installation out at sea in order to monitor the critical period of time between filling and hardening of the grout and to register any displacement of the connecting tubes. Its use for long-term monitoring of the offshore wind turbine is also conceivable.

Peripheral Anecdote: Fino completed – the soft wave bends the steel

That really was something quite amazing: long before Alpha Ventus and the start of the RAVE project, the wind measuring station and research platform Fino 1 was erected in the immediate proximity of what would later be the Alpha Ventus test field. Shortly after its completion, two severe storms, Britta and Tilo, moved across the North Sea on 1 November 2006 and 9 November 2007 respectively. Waves reached a height of up to 16.5 metres above mean sea level – reaching the steel work platform around Fino 1, and washing over it up to a height of 1.5 metres. When the storm had passed, it was found that the handrails of the work platform had been bent – such was the force that the "soft water" at the crests of the waves exerted on the steel. Just 3.5 metres higher and it would have hit the main deck with all the measuring equipment.

Björn Johnsen

4.5 Rust on the Tube

Wind, waves and ultraviolet rays create a great deal of stress on steel structures. Corrosion caused by saltwater attacks construction elements like tubes and connecting nodes, and this can significantly reduce the lifetime of the supporting structures. In the "Corrosion Protection Systems" sub-project researchers therefore tested several coatings and additional sensor systems for corrosion measurement to investigate their suitability for offshore use. These sensors were affixed to the steel foundation structures to help to non-destructively examine the condition of the corrosion protection and detect any damage in good time.

The corrosion protection systems used were primarily organic finishes and varnishes, which in principle guarantee good protection. However, production defects and damage to the coatings incur significant costs for structures out on the open sea in that offshore maintenance operations are both time-consuming and expensive. Damage can occur when errors are made during production on the surface preparation, workmanship, application, drying and hardening. About 80 % of all critical areas arise due to faults during processing. Coatings can also

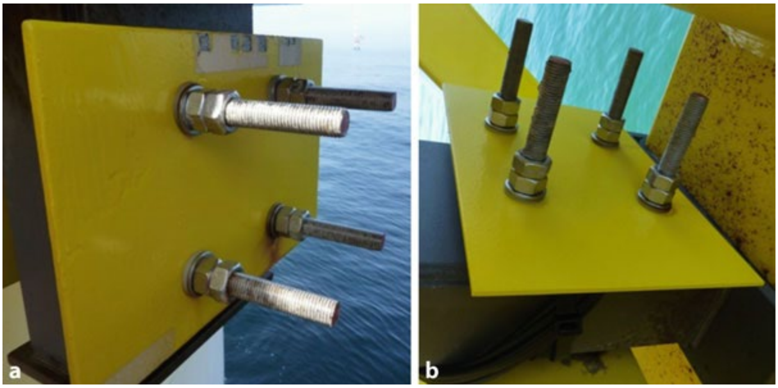

Fig. 4.3 Test plates after two years' exposure: splash zone (**a**), intermittently immersed zone (**b**). © LUH

be damaged during the transport and storage of the supporting structures, and also during installation.

The research project also tested several organic protection systems (varnishes) and developed one mineral protection concept based on the use of high-performance grout. Up to now there has not been a concept that offers lasting protection, and especially in what is known as the splash zone – the area in which the water level regularly changes due to the tides and which the waves break against. Since this zone is greatly stressed it can quickly result in damage to the coating.

4.6 Immersion Bath for the "Problem" Plates

In order to test the suitability of the different protection systems, the researchers coated so-called test coupons or test plates with selected varnishes and mortar compositions and exposed them to authentic environmental conditions in the test field. The plates were installed both on a jacket and a tripod in the permanently immersed zone and the splash zone (Fig. 4.3). The material degradation was then subsequently examined in the lab.

It turned out that the best corrosion protection method is the application of multiple layers of protection. The samples set out in the test field did not display any signs of degradation, which is partly due to the short two-year period of exposure, but they also supported the lab findings that the coatings proved to be very durable.

During the project a grouting system was developed that consisted of a 1 cm thick coat, and which when hard exhibited such a degree of impermeability that it can permanently protect the steel structure against the ravages of the sea. This coating is the basis for the development of an alternative corrosion protection system that can be used on the splash zone of offshore wind turbines. In order to apply the mineral corrosion protection layer, formwork is built to create a cavity around the steel tower to be protected and is then filled with high-performance grout. Various coated test plates fitted with different sensor systems and the associated electronics are attached in three zones (splash, intermittently immersed and permanently immersed zones) on a tripod and a jacket foundation. This showed that electrochemical methods are suitable for use as corrosion sensors and can register damage such as cracks, underlying rust, adhesion loss and blistering. However, during the measuring campaign many sensors that were under water in the test field or in the intermittently immersed zone broke down. This means that in order for the sensors to be used for permanent structure condition monitoring it will be necessary to develop suitable protection mechanisms.

4.7 Monitoring Is Everything

Offshore wind turbines are difficult to access – yet the high dynamic loads on the turbine require condition-dependent maintenance. The focus of the "Global and Local Monitoring" sub-project was on methods that can be reliably used to detect faults. The sub-project also worked on a monitoring concept that enables remote monitoring of an offshore

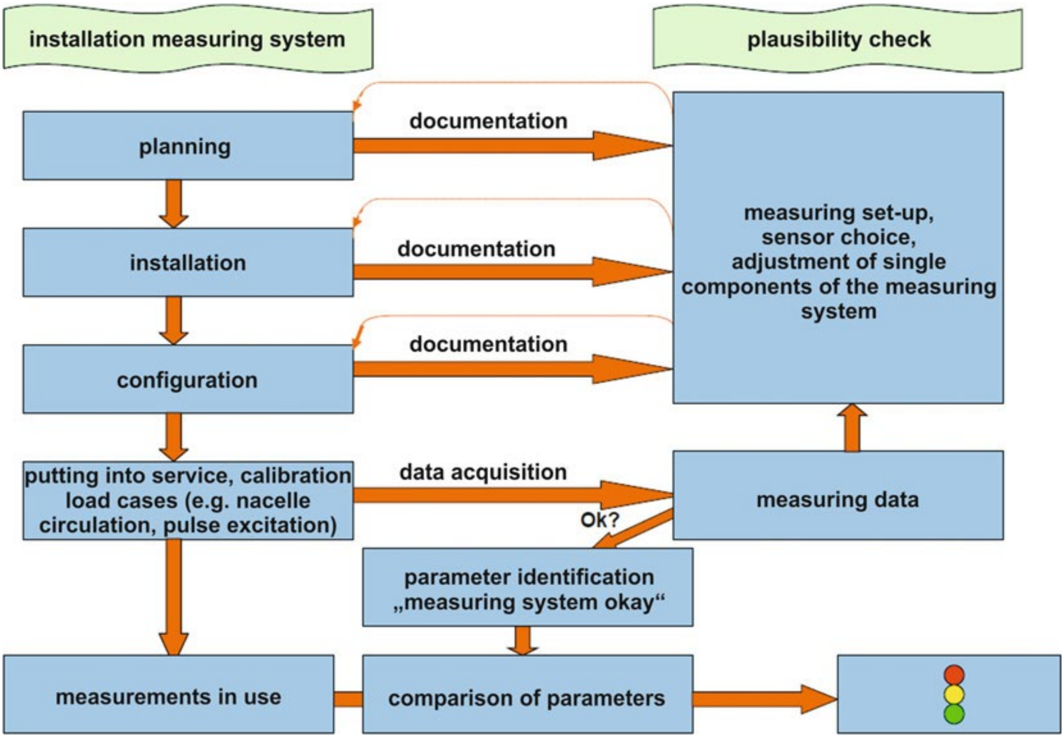

Fig. 4.4 Installation and plausibility check of a measuring system. © LUH

wind turbine. This makes it possible to plan maintenance assignments better, and reduce the costs.

Prerequisite for effective control and monitoring is of course a large amount of measurement data – collected by around 1,200 sensors in the test field. These sensors include strain gauges or fibre-optic sensors that were attached to the supporting structures to determine the stress distribution resulting from the strains. In order to stay in control of such large amounts of data it is first necessary to develop data plausibility methods (Fig. 4.4). This checks whether a value or result is verifiable or not. This method is based on having comprehensive information about the wind turbine, the measuring system and the defined load cases, such as flow around the nacelle, turbine braking manoeuvres or measurements taken at constant wind speeds and directions. On the basis of these load cases, where the behaviour of the turbine is easily predictable, the measuring signals can be compared with the expected values and calibrated for the spreads.

Since sensor defects can occur with time and not all measuring levels can be fitted with sensors, the researchers developed an assessment model in order to avoid misinterpretations and a component damage prognosis model. Investigations were carried out to see if the partial damage at one sensor position can be carried over from one time period to another or can be applied to a similar position on a neighbouring turbine. This should lead to the development of approaches and methods for estimating the residual life of the structures. With the aid of algorithms it is then possible to create a forecast for time periods with similar conditions. These models can then be used as tools for condition-based maintenance of offshore wind turbines and their supporting structures.

A monitoring concept needed for this has to consist of four stages: damage detection, damage localisation, determining the extent of the damage, and the residual life prognosis. A concept was worked out that takes into account the different states of the turbine. To this end, a database was fed with raw measuring data as well as information about the environmental and operating conditions (EOCs) (Fig. 4.5).

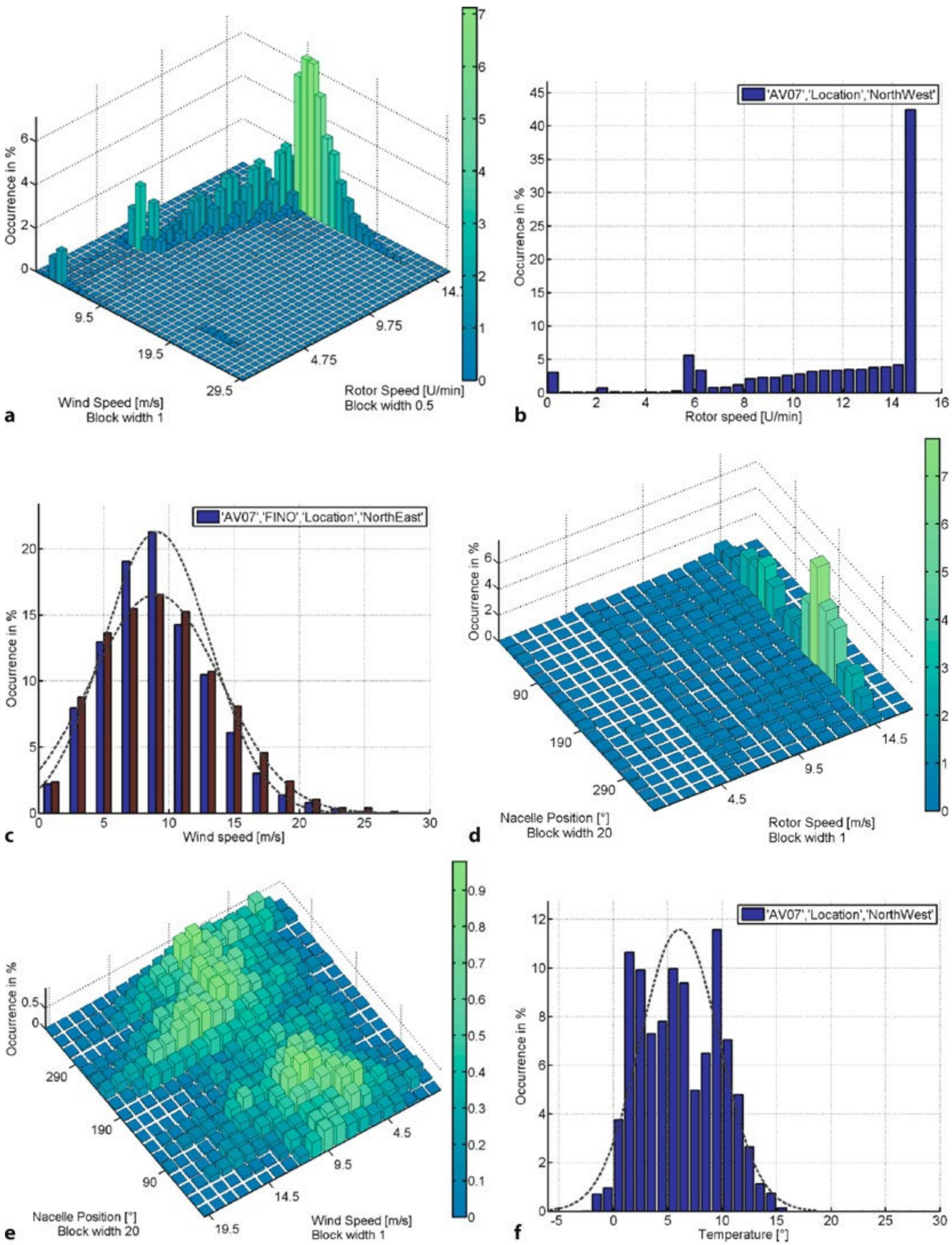

Fig. 4.5 Incidence and dependency of crucial operating and environmental conditions on AV7. **a** Wind speed vs. rotor speed, **b** Frequency distribution of rotor speed, **c** Wind speed distribution (measurements from Fino 1 *red* AV7 *blue*), **d** Nacelle position vs. rotor speed, **e** Nacelle position vs. wind speed, **f** Temperature distribution, **g** Temperature vs. rotor speed, **h** Temperature vs. wind speed, **i** Nacelle position vs. temperature. © LUH

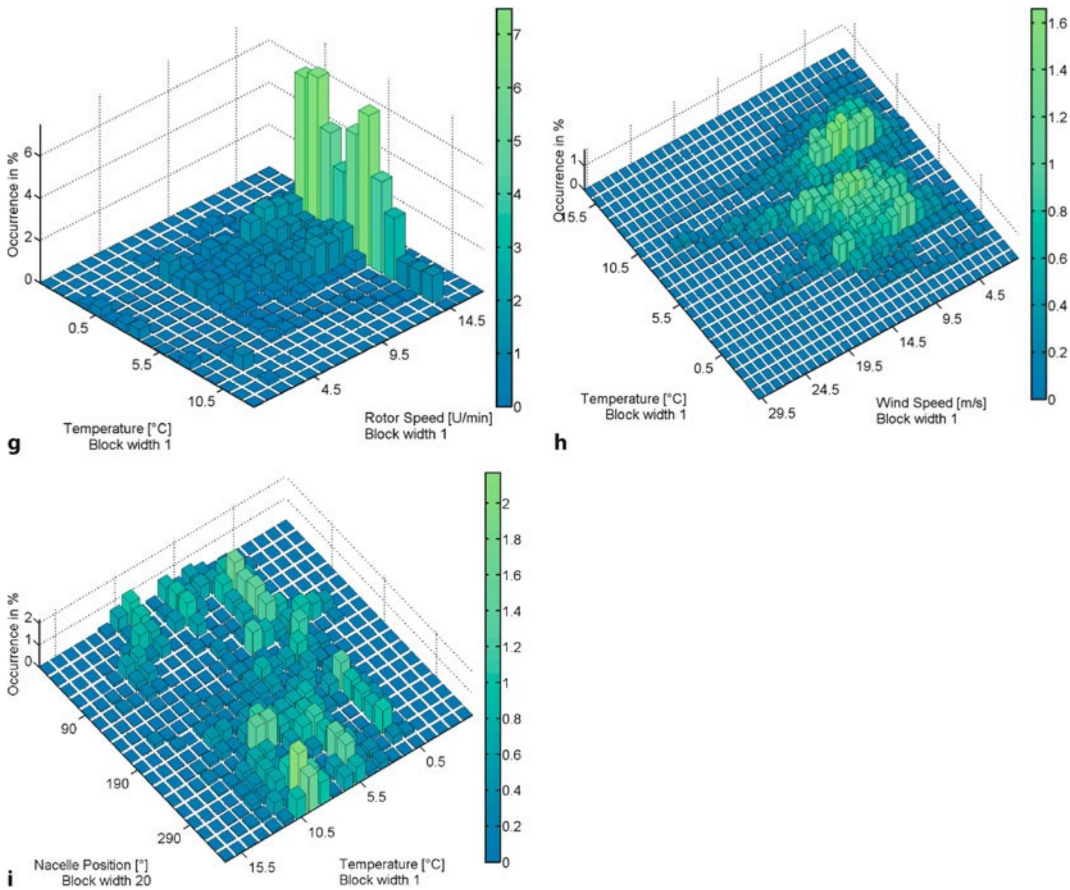

Fig. 4.5 (*continued*)

All in all, the database comprises 48,000 data sets with a volume of about 1,000 gigabytes. The data on the EOCs can be classified and then analysed, and serves to ascertain the expected values for future series of measurements. During the course of the project it was possible to lay the foundations for a comprehensive structure monitoring by developing a fast, automated analysis of time series.

4.8 Scouring, the (Un)Known Entity

The sea, the seabed and the offshore wind turbines are constantly moving. As time goes by, wave and tidal currents can scour potholes in the seabed around the supporting structure. In extreme cases such scour-induced potholes can endanger the stability of the wind turbines if the seabed that gives them their footing is washed away over time. Scientists from the Franzius Institute in Hannover therefore investigated scour phenomena in the "Scour Protection and Local Scour Monitoring" sub-project using a model tripod. The analysis was based on measurement data from physical measurement trials in wave flumes (Fig. 4.6), numerical simulation and real measurement data about scouring development in the Alpha Ventus test field. This showed that the development of scouring is strongly dependent on sea state and tidal currents, the orientation of the structure and the structure parameters, in other words the geometry of the offshore structures. Scouring does not only occur immediately next to the piles that connect the supporting structure to the seabed, but also in the closer vicinity or under the structure.

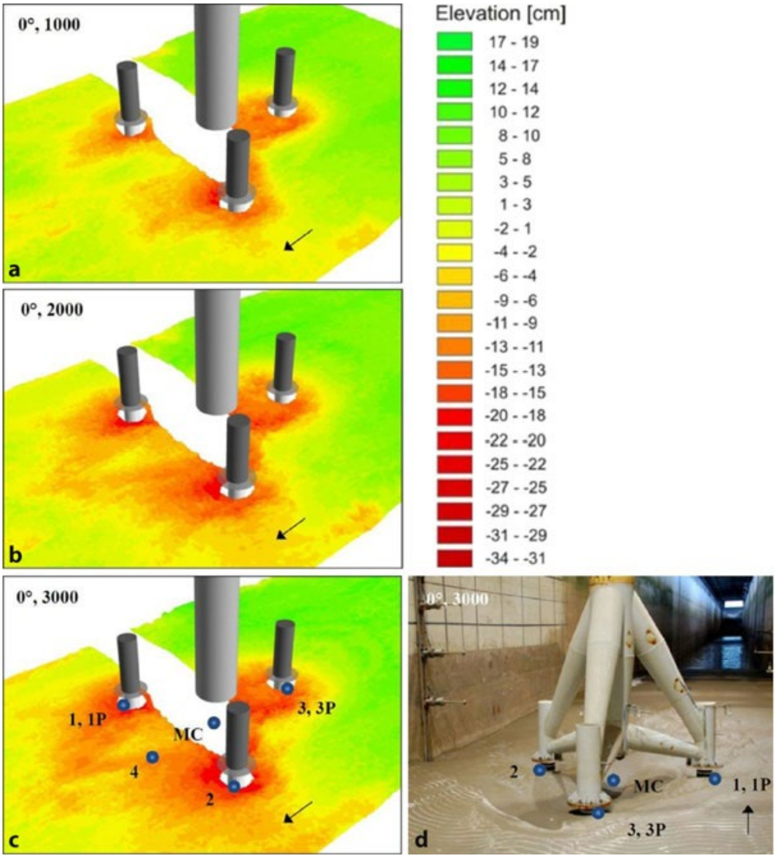

Fig. 4.6 Scour development for a 1:12 trial series in the wave flume. Measurements with multibeam sonar after 1000 (**a**), 2000 (**b**) and 3000 (**c**) wave trains; measuring set-up (**d**). © LUH

4.9 Scour Protection Using Concrete Chains

An innovative scour protection system was developed in the course of the project, one which cannot be eroded or destroyed. With scour protection methods used to date, such as stone deposits or geotextile sand containers, it was found that individual pieces of such protection can be dissolved out or washed away, so that the protection gradually becomes useless. The new scour protection system consists of concrete-filled elements that are linked together to create a long chain. To this end, the elements were inserted into a textile hose. The hose was tied after each chain link, resulting in a flexible and uniform chain that can be laid in various formats (Fig. 4.7).

The elements can be lifted by the current but not carried away. Tests with the model showed that the chains reduce the depth of the scour potholes at the foundation piles and under the central tube of the tripod, but they also showed that the flow conditions around a tripod are very complex and that this form of protection cannot be used without further research. In the case of jacket and monopole foundations the use of this new system is quite conceivable.

4.10 How Much Can a Pile Bear?

Supporting structures like jackets and tripods are anchored in the seabed with steel piles. The piles join the feet of the structure with the sandy ground and are therefore just as responsible for the stability of an offshore wind turbine as the structure itself. This is why research also focussed on modelling the load-bearing behaviour of these driven piles, so that in future it would be possible to identify influencing variables and inaccuracies in existing

Fig. 4.7 Installation variants for concrete scour protection chains before load. © LUH

calculation approaches. To this end, the static and cyclic load-bearing behaviours were analysed using numerical modelling. Part of the research involved investigations with the cyclic triaxial device and in model test rigs. The triaxial device is a test machine used to determine the shear parameters (cohesion and angle of friction) of the cylindrical soil samples. A drill core sample is inserted into the device and then subjected to pressure from the sides and from above until it breaks. Typical for the break is that the sample shears or slips from above onto one or more inclined planes. The shear parameter can be calculated from the stress ratio at the moment of break.

In the test field, the driven piles were open steel tubes with diameters of 1.8 to 3 metres, which were then used to secure the tripods and jackets. These piles must be able to bear extreme loads and thus they must exhibit sufficient load capacity. Pile head deformation and the rigidity of the pile also influence the behaviour of the overall structure, and it is also necessary to clarify what effect the axial (along a single axis) and lateral loads have on the pile and the structure.

To do this, a programme was developed which makes a systematic comparison of existing calculation approaches for any pile geometries and foundation conditions possible. To this end, a numerical simulation model was optimised to clarify possible loss of load-bearing capacity as a result of cyclic loads. The ground behaviour was investigated and clarified with the aid of the triaxial test. A calculation model was validated by model tests with monopiles and, using additional measurement results, was further developed until ready for practical use. It has already been used in a variety of wind farms. All in all, the project enabled a better understanding and better modelling of the load-bearing behaviour of offshore driven piles.

» **The quadrature of steel**

The foundation and supporting structure take up a large percentage of the investment in an offshore wind turbine. This is where we want to reduce costs and extend service life. Two apparently contradictory goals, but an exciting task for researchers.

Raimund Rolfes, head of the Institute for Statics and Dynamics, Leibniz Universität Hannover, ForWind

4.11 Close to Reality

Offshore wind turbines are designed on computers, with the aid of simulations based on numerical models. With their tall and slender towers, and their large head masses, wind turbines display a marked dynamic behaviour. When reproducing dynamic quantities in the model however, large deviations often occur through the implementation of masses, rigidities and damping. This is why the researchers in the "Validated Total Structure Model" sub-project concentrated on the task of reproducing the dynamic structural behaviour as true to nature as possible. The parameters, i. e. natural frequencies and forms, were determined for this automatically. The extracted parameters were then used in the automated model validations.

Various validation algorithms were then investigated. By defining variables, the user can specifically adjust and test characteristics, such as the resonating water mass, with an easy-to-manage user interface.

This saves an enormous amount of time compared with the manual variation of free parameters. The knowledge gained can be used for the creation of future models in order to already achieve greater closeness to reality at an early stage. The adapted model provides the basis for a variety of essential applications, such as load calculations and simulations for structure optimisation.

The basis of the model validation was the measurement data from an Adwen AD 5-116 (in the test field, turbine AV7) with a tripod foundation structure. Structure models of the turbine (Fig. 4.8) were implemented in Ansys – finite element (FE) software with which linear and non-linear problems can be solved.

With its interface, the developed environment of the model validation allows the integration of other FE programmes and the implementation of additional validation algorithms. In addition to numerical models, a more complex, parameterised model of test field turbine AV7 was also created, which reproduced the structure from shell elements. The model has the advantage of being closer to the real structure than simplified rod models and can better reproduce both flange and tube joints and their complex behaviour.

4.12 A Software Puzzle Gets Put Together

Commercial software tools are used in the design and optimisation of wind turbines, as are in-house developments from a variety of research institutions. In the "Holistic Dimensioning" sub-project, scientists developed a simulation and sizing package

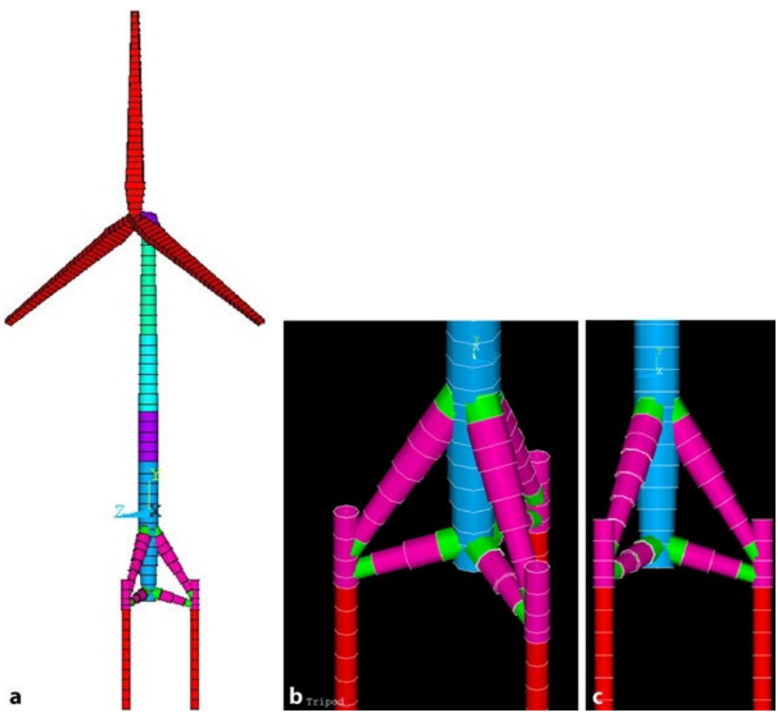

Fig. 4.8 Improved structure model of AV7 with known wall strengths (*a*). In the detail view (*b*, *c*) the nodes, as variable parameters, are marked *green*. © LUH

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that realises a modular integration of the different software tools for the simulation of offshore wind turbines, and which significantly accelerates the process of economic dimensioning. Under the title DeSiO (Design and Simulation Framework for Offshore Wind Turbines) it enables an aero-servo-hydro-elastic overall simulation (◘ Fig. 4.9) – on the one hand with the finite element method, and on the other with the multiple-body simulation.

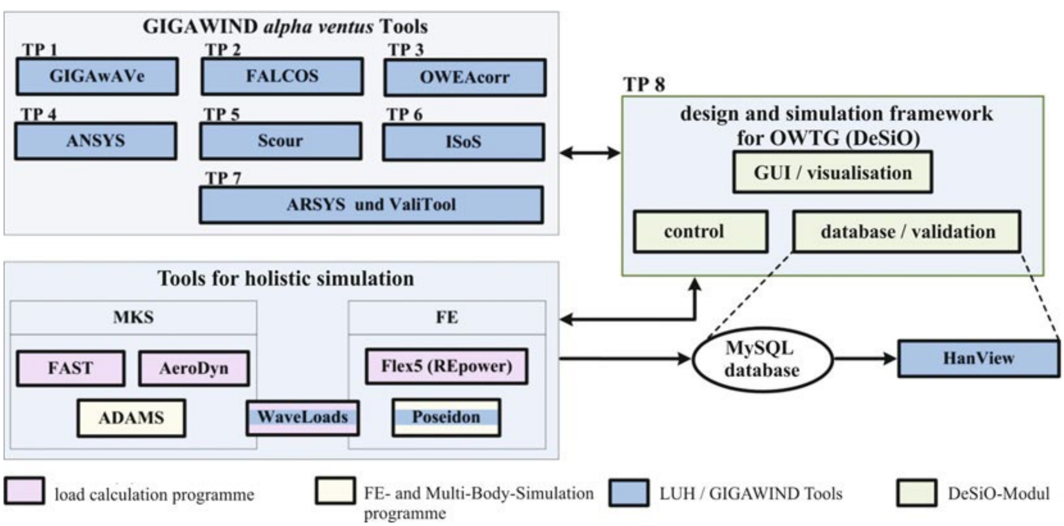
The application of both of these simulation approaches functions using the same database without the user having to regenerate the model.

DeSiO combines the objects from the Gigawind sub-projects to lay the foundation for embedding the latest research findings into the overall simulation. Using interfaces it is possible to integrate additional, new tools. The research results should be made better usable for the overall simulation, and particularly with regard to wave load and scour simulation, as well as ground–structure interaction. The plan is also to embed a freely available equation solver (FE Solver) with shell and volume elements, which enables the optimised design of supporting structures.

DeSiO centres on the three modules GUI/visualisation, controlling and database/validation. Other features are the individual interface modules, which build bridges to the individual programmes and tools. Sensors from the test field and the Fino 1 met mast provided the data – for example about water level, air pressure, current direction, wave direction or wind direction. The database and validation model was developed because of the foreseeable large volume of data and the large amount of time needed for downloading. It enables the centralisation of the measurement data so that it is reliably available for processing. The GUI/Visualisation module contains all the functions needed for representing the model and simulation results, and gives the user the interface needed for controlling. The controlling model enables communication between the interface modules, the GUI/Visualisation and the database module. This means the user can carry out simulations more easily because DeSiO controls the connected software tools.

The software tools include WaveLoads for the simulation of wave loads, and GIGAwAVE for the transferring of loads from breaking waves into DeSiO. Falcos calculates the fatigue strength of dynamically stressed offshore node connections. With a preprogrammed interface it is possible to model the node connections of a resolved offshore wind turbine support structure automatically.

OWEAcorr, a tool that reproduces and calculates the problem of rusting and the mass increase caused by marine growth, is also to be integrated in the numerical overall structure model. Also incorporated is ISoS, which determines the horizontal



◘ **Fig. 4.9** Overview of the modules and software tools integrated in DeSiO. © LUH and vertical initial rigidity of the pile bedding of the offshore wind turbine foundations. With ValiTool it is possible to validate models on the basis of natural frequencies and mode shapes, and HanView is used to call up, read in and visualise stored raw measurement data and simulation results.

One application example is the FE analysis of the structural dynamics of a Senvion 5M five-megawatt wind turbine (Turbine AV4 in the test field), where a modal analysis (numerical characterisation of the dynamic behaviour of vibratory systems) is carried out for the overall structure. A pile foundation was also modelled.

Indicative multiple-body models were also created and prototypical analyses carried out. An example of this is an Adwen AD 5-116 with tripod (Turbine AV7 in the test field), for whose modal analysis the Fast, Aerodyn, Adams and WaveLoads programmes were used (Fig. 4.10).

The overall simulation enables the consideration of the interactions between wind, waves, turbine, supporting structure, foundation and ground. The latest research findings can also be integrated via standardised interfaces, tested for the overall simulation and then made available for industrial application. The software tools tested can be used both in DeSiO as well as in other FE or multiple-body simulation programmes for industrial simulation.

The objective of Gigawind Alpha Ventus is to improve the supporting structures of the offshore wind turbines using a holistic dimensioning concept – despite all the loads from wind, waves, sun, rust and scouring. The end of this development will see solidly standing supporting structures which are also an economical product for the series production of offshore wind turbines.

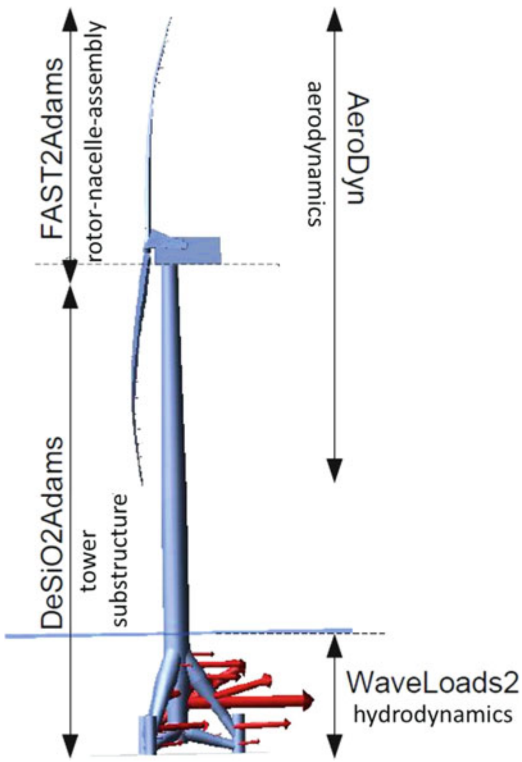


Fig. 4.10 Schematic representation of the sample calculation for Turbine AV7 using Fast, Aerodyn, Adams and WaveLoads in DeSiO. © LUH

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Life Goes on

Services Life Research Starts with the Complete Supporting Structure

Raimund Rolfes, Tanja Grießmann, Text written by Björn Johnson

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power,* DOI 10.1007/978-3-662-53179-2_5

5

Project information: Life time – Research on Support Structures in the Offshore Test Site Alpha Ventus (GIGAWIND life)

Project management:

Leibniz-Universität-Hannover, Institute of Structural Analysis

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Project partners:

- Adwen GmbH
- Fraunhofer IFAM
- Fraunhofer IWES
- Fraunhofer LBF
- Leibniz Universität Hannover
  - Franzius-Institute of Hydraulic, Estuarine and Coastal Engineering
  - Institute of Building Materials Science
  - Institute of Concrete Construction
  - Institute of Geotechnical Engineering
  - Institute of Steel Construction
- Senvion GmbH

5.1 The Journey Is the Reward

Gigawind continues. The follow-on project "Gigawind Life" is dedicated to aspects that first come to light after an offshore turbine has been in operation for several years, i. e. the degradation mechanisms of its supporting structures such as material damage, defective rust protection systems, scouring or degradation of the pile load-bearing behaviour – but also the ascertainment of external loads from waves or marine growth on the supporting structures. So "Gigawind Life" means an immense collection of data from the ongoing operation of Alpha Ventus over many years – and its evaluation right into 2016. The worldwide unique long-term measurements taken on the wind turbines out at sea are then combined with individual investigations and model developments to be created.

So the motto is not necessarily "service life above all else". Solutions like increasing the service life of supporting structures beyond the current 20 years are one possibility – and their optimised, more cost-effective design another. The focus of the ongoing research project is on condition assessment and prognosis for the supporting structures – in other words, for everything below the nacelle – based on measured data. The plan is also to develop verifiable methods and structure models for an integrated and economical design of supporting structures for offshore wind turbines. The tripod foundation is the subject of a special sub-project where the focus is on automated service life determination of the tripod support structures – taking their real loads into account.

5.2 Efficient Data Management

As far as monitoring the supporting structures, monitoring tasks to date have mainly been planned as stand-alone solutions for one wind turbine or for one wind farm. This is associated with a massive amount of effort, frequently accompanied by insufficient reproducibility of the data and a lack of data security, which is why a sub-project of "Gigawind Life" will develop a universally applicable system that eliminates these weak spots and that is easy to use.

In view of the foreseeable great flood of data from the Alpha Ventus sensors, the development of a data management system is an important sub-project (Fig. 5.1). It supports the other sub-projects by providing tools that make data from different systems accessible in a uniform way – in other words, by bringing together monitoring, simulation and lab test data in one standardised user database. The various component research projects can then also implement the intended evaluation with these tools. For the evaluation of this great amount of data ways are being investigated as to how the data can be filed in blocks on a computer cluster, and then processed as part of several sub-projects.

Peripheral Anecdote (I): The future of offshore begins – in the test centre

It might not exactly have been a bargain, but it sets standards – the Hannover-Marienwerder Testcenter for Support Structures, opened in September 2014, cost 26 million euros. Most of the far-sighted investment came from Federal Government, the EU and the State of Lower Saxony, though Leibniz Universität and the local Institute of Statics and Dynamics at Leibniz Universität Hannover also contributed to the funding. The testing hall is 20 metres high and

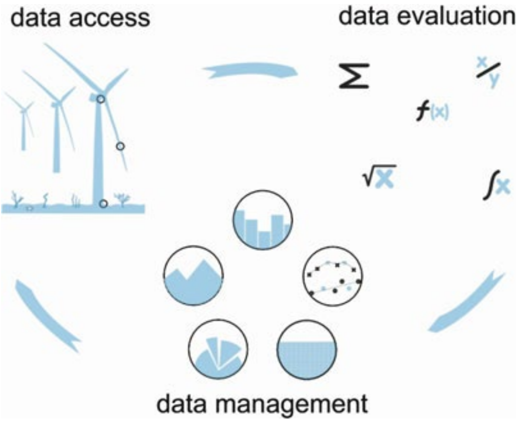

Fig. 5.1 Systems were developed in Sub-project 1 that enable the access, evaluation and management of data in compliance with the special Alpha Ventus requirements. © LUH

20 metres wide. The various different areas can be used for such experiments as testing the tensile forces on the piles of an offshore wind turbine on a concrete wall, or for investigating foundation anchoring concepts and scouring in a ten-metre-deep sandpit, while a resonance test machine observes the tension-compression stresses on bolted or welded connections. There is also a climate chamber with various temperatures and humidities, and there's even (sea) salt spray as well. The test centre for supporting structures – alongside the new turbulence wind tunnel in Oldenburg – is the centrepiece of the ForWind research partnership.
Björn Johnsen

5.3 Research Put into Practice

Methods are to be developed on the basis of long-term measurements which identify the condition parameters, damage and loads, and which can analyse their temporal evolvement. For this you need model tests, for example to test if methods or continuous structure monitoring (SHM, Structural Health Monitoring methods) are suitable to do this based on specific damage scenarios. The findings from improved model approaches and methods for early diagnosis of damage are not under any circumstances meant to stay in the lab, but increasingly put into practical application: thus making an important contribution to the optimisation of existing inspection concepts, and to the determination of the residual life of the supporting structures.

Also important here is the possible displacement of the grouted joints. Down on the seabed these are the most important connections between the foundation pile and the supporting structures. These connections are usually filled with high-performance concrete or grout. The special concrete can already achieve very great pressure resistances. Yet these grouted joints are in danger of material fatigue and deformation resulting from the high number of load cycles experienced by an offshore wind turbine. This is why strain gauges were also attached to a turbine here to measure any possible deformations or displacements of the grouted joints that might occur.

An example of this transfer of supporting structure research into practice is where the existing acceleration measurements taken on the tower of a wind turbine were used to automatically calculate the natural frequency modes of the tower. The changes in the dynamic behaviour are now being monitored further and used to assess the condition of the turbine (Fig. 5.2). This also includes the prognosis for the accumulated pile deformations and the quantification of the system stiffness under operating loads.

Another important role is played by marine growth at various water depths right down to the seabed – and this is much more than just a few algae and clumps of mussels (Fig. 5.3). The growth can affect the impact of waves on the wind turbine and result in an increase in mass. This in turn means more loads on the turbine. The marine environment – sea/wave state, scouring, marine growth – therefore has a direct impact on the fatigue loads of the supporting structures.

5.4 Despite Rust and All that: Is There Anything After the End of Service Life?

With the degradation models, work is being done on the base in order to be able to make statements about the service life of the supporting structures and to be able to estimate residual useful lives of existing supporting structures. For it is possible that

Fig. 5.2 Monitoring the condition of the turbine with modal parameters from the long-term measurements. © Senvion GmbH 2015

"we could get a bit more out of it", once we come to the end of the 20-year operating life it was designed and built for. To do this however, it is necessary to redevelop the existing degradation models or even develop completely new ones taking spatial stress conditions and reductions in rigidity into account. Afterwards these models can be transferred into automated calculation programmes where their validity can be tested using measurement data from Alpha Ventus and other model tests in the test centre. The knowledge learned from this will then enable a holistic consideration of the different limit conditions of the supporting structures, with regard to their load-bearing capacity, fatigue and fitness for purpose.

For example, a model is currently being created which describes the consequences of material loss resulting from corrosion where there are coating defects. The changing water level on the supporting structures – sometimes ebb, sometimes flow, sometimes particularly high waves – represents a massive mechanical strain on the corrosion protection at this point; it is being constantly degraded. In several long-term tests models were developed for estimating the service life of mineral and conventional corrosion protection systems – based on the findings of corrosion tests and "field tests", for example in Alpha Ventus in the North Sea (Fig. 5.4).

» **We want to really boost reliability**

Research is becoming especially important with the increasing size of wind turbines. With the investigations and test series in our testing halls and laboratories we can significantly shorten processes that would take up to 20 years in the sea; in just a few weeks or months we can age the objects we are investigating by years. Our goal is to boost the level of reliability of the wind turbines.

Raimund Rolfes, director of the Institute of Statics and Dynamics, Leibniz Universität Hannover, ForWind

5.5 Model Tests Are Good, but Are Calculation Models Better?

Or is it the other way round? With the measurement data from Alpha Ventus it is possible to develop framework conditions for lab tests, and in turn use their results to optimise the calculation models specifically for conditions in the North Sea. Pre-damaged test specimens from Alpha Ventus were examined in the laboratory – which, combined

Fig. 5.3 Marine growth at different depths on the foundations of turbine AV6 and on the seabed. **a** –1.9 m, **b** –8.6 m, **c** –15.8 m, **d** –33.0 m (seabed). © IfAÖ

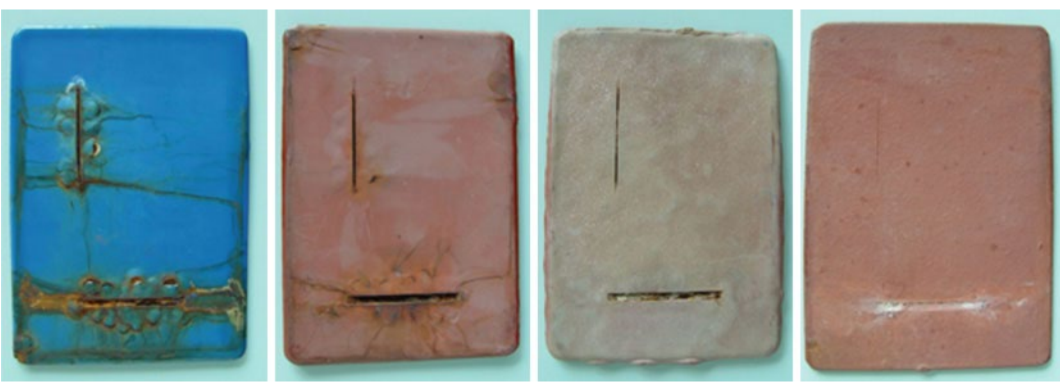

Fig. 5.4 Corrosion on differently coated steel test specimens with damaged corrosion protection. © Fraunhofer IFAM

with the measurement data, gives a more exact reproduction of, for example, the real stresses on the corrosion protection grout that might be expected in a model. Virtual tests can, among other things, serve as a basis for the targeted design and planning of large-scale trials.

Fig. 5.5 3D Wave Basin at the Franzius Institute. © LUH

A key task in offshore research is undertaken at the 3D Wave Basin at the Franzius Institute in Hannover-Marienwerder, which has been extensively enlarged following major construction work (Fig. 5.5). Here it is possible to recreate and analyse wave and current flows. Tests will start in the near future with realistic loads from a multidirectional sea state with superimposed flow, in order to thus recreate a realistic load on the offshore wind turbine.

Peripheral Anecdote (II): Researchers build mini sea

Unique in the German research sector is the 3D Wave Basin at the Franzius Institute in Hannover-Marienwerder (Fig. 5.5). With a length of 40 metres and a breadth of 24 metres it can generate a proper sea state with waves of up to 40 cm height. The 3D wave machine has 72 individual wave blades and enables investigations such as the revetment stability of wave breaker heads and experiments with wave attacks at an oblique angle. There is also a deeper section of the wave pool that is used for the simulation and analysis of the changes in the seabed, especially the transport of sediment as seen in scouring. Opened in 2014, the 3D Wave Basin was extended to include numerous additional functions just a year later.
Björn Johnsen

5.6 The Gordian Tube Knot

When carrying out an integrated overall simulation of offshore wind turbines, the innovative inclusion of design-relevant degradation processes can for the first time reproduce in detail the real development of the dynamic supporting structure behaviour over the complete service life of the turbine. The work that has already begun is showing how it could still be even better – especially where the measurement of fatigue is concerned, as this is crucial for the design of the supporting structure. It may well be that, for example as a result of identifying possible system reserves, this offshore wind turbine can be operated for longer than the service life it was designed for. The numerical tools that have been developed for the fully coupled simulations of offshore wind turbines, including a newly developed FE substructuring technology for offshore wind turbines, are being validated by the measurement data from Alpha Ventus.

During these simulations it is particularly the tube joints of supporting structures that pose a great challenge. With beam element models it is only possible to represent their characteristics in a greatly simplified manner. It would be more accurate if a superelement approach with the finite element method (FEM) was used, which describes the component behaviour for sections and takes the connection conditions of these sections into account (Fig. 5.6). Improved numerical representation of the tube joint geometry with the aid of finite shell

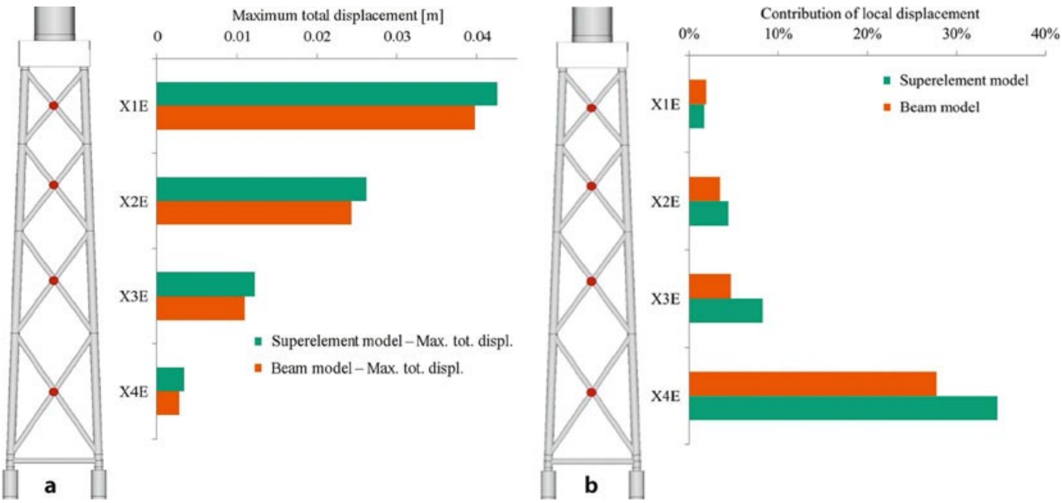

Fig. 5.6 Comparison of beam and superelement model: Maximum total displacement from the level on the X nodes (**a**). Change in the proportion of the local displacement figure on X nodes over the height of the structure (**b**). © Fraunhofer IWES

or volume elements can be integrated in the shape of a superelement approach in the beam element description of a jacket supporting structure. This would make it especially possible to represent the flexibility of these tube joint connections in the supporting structures more precisely.

5.7 Where Will It All End – Automatic Service Life Calculation

We know about it from car construction; if you know the real load data you can predict pretty accurately that a particular engine or gearbox will reach the end of its service life at 200,000 kilometres. In car construction this method is however only used for comparatively few load cycles. Over 100 million cycles occur offshore, yet the method for the automated determination of service life based on real load quantities can, with extensive knowledge and consistent further development, also be used for the supporting structures of offshore wind turbines – and this could in turn lead to reduced costs or longer service lives. This is assuming that we accurately know the loads that occur and the reactions of the materials to these. The plan is for one sub-project to work on the precise, automatic determination of the residual service life of an Adwen tripod foundation.

Unlike with classical methods, which usually provide an early diagnosis of the changes in component behaviour, it is thus possible to provide statements about the length of service life – and long before any changes in component behaviour occur.

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Please Avoid Tilting

Application-Oriented Design and Monitoring Model for Foundation Structures Subjected to Cyclic Loads

Werner Rücker, Pablo Cuéllar, Steven Georgi, Krassimire Karabeliov, Matthias Baeßler, Copy edited by Björn Johnsen

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power,* DOI 10.1007/978-3-662-53179-2_6

Project information: Application-Oriented Design and Monitoring Model for Offshore Foundation Constructions under cyclic loading
Project management:
BAM – Federal Institute for Materials Research and Testing
Prof. Werner Rücker
Dr. Matthias Baeßler
Project partners:
- Adwen GmbH
- TUB – Technische Universität Berlin

A great deal is possible, even on the seabed. Together, wind and waves shake the foundations of the offshore wind turbines. There is also the "normal" current and ebb and flow of the tides that are so distinctive in the North Sea. Pore water pressure can also occur on the seabed, loosening it. Where monopiles are involved, the worst case is that the stability of the whole turbine can be altered – even if such a monopile rammed into the seabed has a diameter of up to eight metres. Over half the planned offshore wind turbines in the North and Baltic Seas are to have monopile foundations, and over 40 % are to have multi-pile foundations, designed for example as a tripod. This is why pile foundations and their loads deserve special attention. For one thing above all is to be avoided in plant operations, and that is the risk of turbine tilt.

6.1 Everything Rests on the Pile

The charm of the monopile is in its simplicity. It can be driven into the seabed relatively easily and without any extensive preparatory work – provided that there are no obstructions in the way and the water is not really that deep. Due to the great depth of the water in Alpha Ventus, around 30 metres, more elaborate tripod and jacket foundations were used. In the case of the tripod the central tower shaft is reinforced with a three-legged bracing on the side and horizontal reinforcements, creating what is like a small pile pyramid above the seabed. Rammed piles are also used here, which are driven through sleeves into the seabed. The jacket foundation is a kind of framework structure with circular hollow sections and is also anchored in the bed with piles, and the stresses on their pile elements are comparable with those on tripods. Also similar to a standard tripod is the BARD Tripile, only that its three steel tube legs are connected to one another with a square transition piece above the waterline. Gravity foundations (only for shallower water) or floating constructions have only been used for offshore wind turbines relatively rarely.

The foundation research projects for Alpha Ventus have been about investigating the scientific background for safe foundations, carrying out laboratory and model experiments, and equipping a pilot wind turbine in Alpha Ventus with an extensive array of sensors and measuring strips on the foundation and the supporting structure, thereby developing a monitoring system for future structural monitoring. The carrying capacity of a foundation depends on the pile characteristics (diameter, length, bonding depth and "soil rigidity"), the type of seabed (sand grain distribution, permeability and density) and of course the external loads. Are these unique or cyclically recurring, do they come from changing load directions or just along one axis, and what strength and number do the load cycles have?

6.2 Pore Water Pressure: Even a Drop Weighs Heavy

One of the loads that occur on the seabed is the pore water pressure. This is the tension in the water-filled pores of the seabed, in the "waterlogged" sea floor. The water is self-supporting, and pore water pressure constantly increases with depth. Excess pore water pressures are created through a reduction in volume resulting from shearing. This excess pressure can be reduced again through flow processes in the sea floor, as with a drainage system (Fig. 6.1). If the drainage is impeded this will result in the deformation of the ground and a further increase of the pore water pressures.

This has a crucial influence on the load-bearing behaviour of the ground. Very large recurring cyclic loads and increasing pore water pressure alter the formerly comparatively elastic fixing conditions of

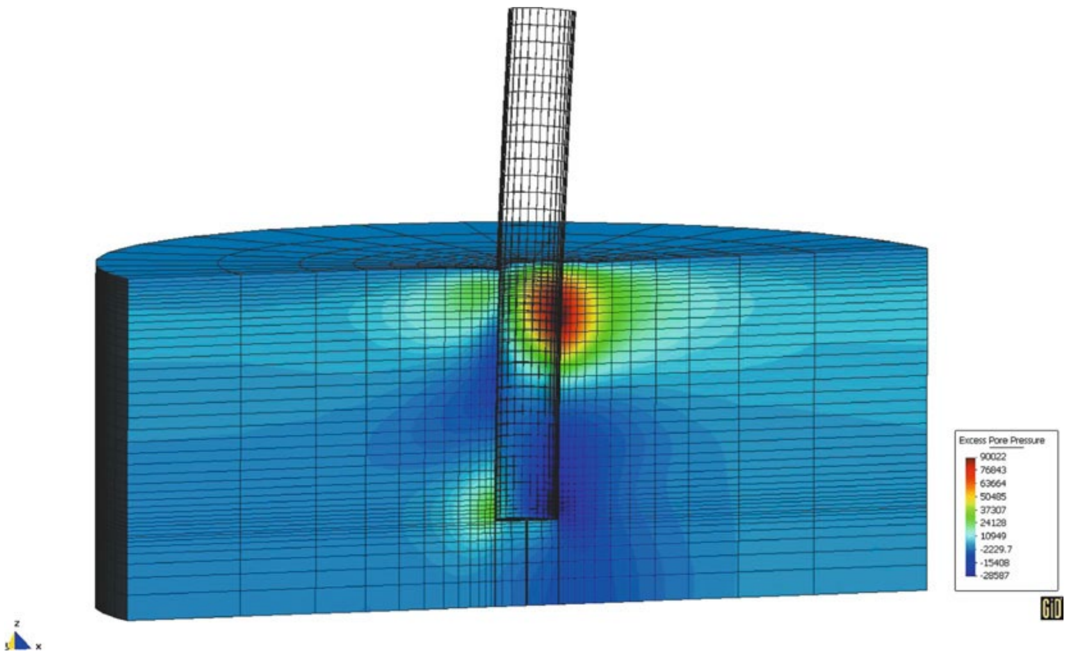

Fig. 6.1 The development of pore water pressure changes on the pile sleeve of a laterally stressed monopile in the calculation model. © BAM

the pile in the ground – and with that, also the entire offshore construction (Fig. 6.2).

6.3 Measuring and Expanding

In the "Foundations" research project at Alpha Ventus the scientists carried out measurements on an Adwen turbine (AV7), especially on one of the three driven piles (Figs. 6.3 and 6.4), and also evaluated the measurements from expansion and acceleration sensors at various heights on the whole wind turbine, and right down to the level of the sea floor.

The results clearly showed that wind speed and expansion on the pile go hand in hand; the greater the wind speed that impacts on the turbine above the surface of the water, the more the pile in the seabed is loaded and stretched – also below the surface of the water. This is because different loads are interacting.

With model tests on smaller-scale piles on land it is possible to quite accurately trace the long-term behaviour of the piles along an axis under recurring, cyclic load. Little by little the researchers turned to larger models and carried out several test series with what is known as "Berlin sand". This sand was completely flooded in the trial box to create a model of "North Sea reality".

Peripheral Anecdote: Far away from the North Sea – Berlin sand

The Berlin glacial valley was originally nothing more than a big swamp until the Ice Age glaciers and the water masses flowing off them brought the sand from Scandinavia. On its long journey from Northern Europe to Berlin the moraine scree and till was ground and washed out under massive pressure. This "Berlin sand" has a grain diameter of almost one millimetre and is thus classed as coarse "medium sand" – and is quite similar to the sand of the North Sea floor. This is why the scientists used it for their foundation trials. The sand that was to simulate the North Sea sand came from the Kraatz sand quarry outside Berlin.
Björn Johnsen

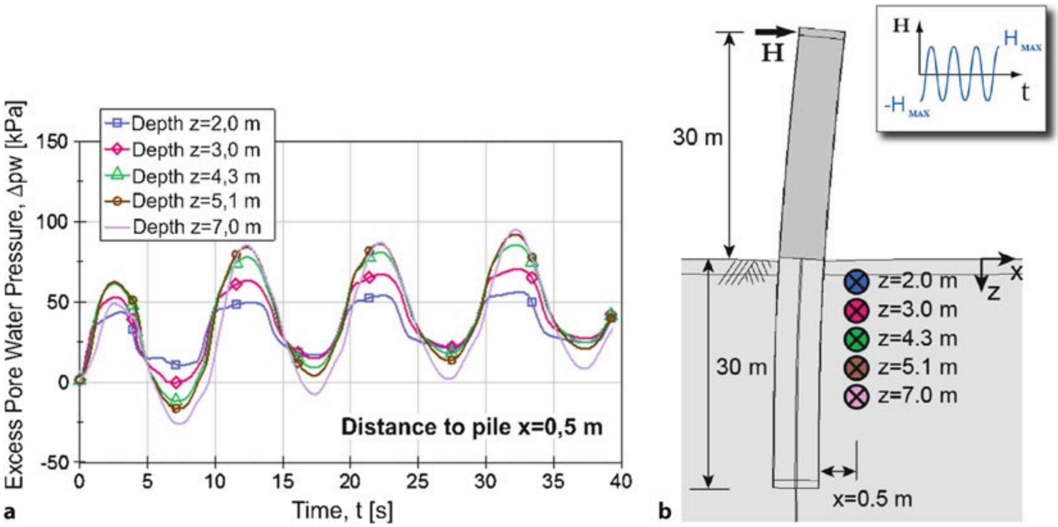

Fig. 6.2 Development of the calculated excess pore water pressures (**a**) in the passive side of the foundation and (**b**) at various selected depths under the top ground surface of the seabed. © BAM

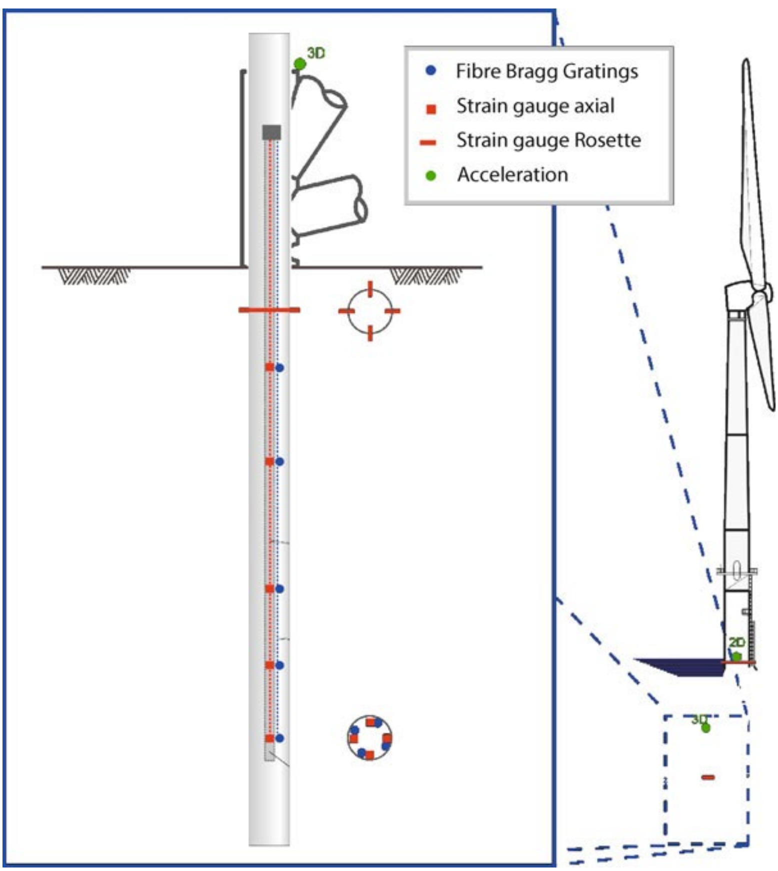

Fig. 6.3 Measurements on the driven pile in relation to the whole turbine. © BAM

Fig. 6.4 Checking the instrumentation on a tripod pile. © BAM

The centrepiece of the trial series consisted of two specially manufactured steel containers with three-metre diameter and a height of two metres – their floors covered with Berlin sand that was permanently under water (Fig. 6.5). The model pile, to which several strain gauges had been fitted, was then driven into the Berlin sand using a hydraulic pump (Fig. 6.6).

The model test showed that there is a rapid compaction of the ground around the pile and consequent stiffening of the lateral pile. This results in a drop in the bending moments at half-height of the pile bedding in the ground (Fig. 6.7).

6.4 Between Ground Subsidence and Pore Water Pressure

The models also show effects that are probably subordinate at full scale. In all test trials carried out under recurring, lateral load there was significant subsidence in the immediate vicinity of the pile. This is caused by the grain location or compression of the sand. Computer-supported numerical models were also developed in order to specifically investigate the basic behaviour of the pile foundation, for example the stress paths of the floor elements around the pile, the course of the pore water pressures along the bonding depth of the pile and the time of the occurrence and extent of the so-called "soil liquefaction". Such aspects are difficult (if at all possible) to measure in model trials – it's easier for the computer to calculate it. The greater the pile diameter, the better the load

Fig. 6.5 Preparation of trial boxes for testing laterally loaded piles. © BAM

transfer and stress distribution in the ground. The consequence of this is less pile head displacement and only minor ground deformation, which in turn results in the excess pore water pressure not reaching quite as high a level as with smaller pile diameters.

The conclusion here is that model trials have supplied a major contribution to the initial assessment of the lateral load-bearing behaviour of the piles. Calculation models were subsequently developed in order to estimate the lateral pile displacement in the event of recurring, cyclic loads when the ground is saturated.

6.5 Extreme Storms Loosen Things up

Extremely strong "storms with a one year return period" (with a wind speed of 32.5 m/s and maximum 12.2 m wave height) in the German Bight also have an impact on the foundation. The storm causes a

Fig. 6.6 Trial boxes with built-in, laterally loaded pile. © BAM

significant compaction effect on the sea floor. This can entail a temporary weakening of the foundation, at least until the excess pore water pressures have completely abated (Fig. 6.8).

Storms of moderate to extreme strength can result in a certain weakening of the offshore pile foundations. A complete liquefaction of the ground and consequent risk to the whole foundation is not however to be expected, because the pore water pressure does not rise to an arbitrary height. The sand in the North Sea is too tightly compacted for this to happen. This means that it does not result in a complete loss of load-bearing capacity because of soil liquefaction, although there is a far greater likelihood of "serviceability problems" that can occur as a result of the weakening of the sea floor during the storm. This could result in restrictions for the operative frequency ranges of the turbine for a while after the storm – the wind turbine then needs a consolidation period, so to speak, until it can withstand a full load once more. This can be briefly summarised by saying that it is most critical in the period after the storm. A good foundation is usually not endangered at the start of the storm, because at that stage the sea floor is still compact. The time that could probably be most dangerous is immediately after the storm, when the strong pore water pressure loosens the ground. It can take a while until the ground stability is then strengthened or normalised once again.

6.6 The Burden with the Load Thereafter

And of course there are still many unanswered questions, such as how does the reinforced concrete and prestressed concrete in the foundation behave when subjected to the particular offshore loads? Or how can these foundation structures be simplified and improved? What could a real load impact scenario for the foundation look like which takes into account the most varied forces and loads, such as constantly changing load directions and combinations of lateral and vertical loads (the tower resonates with it) and the whole thing in the most different time sequences, from the short-term peak to chronic long-term impact? Ultimately this can only be answered by an investigation of whole load ranges with their temporal sequences.

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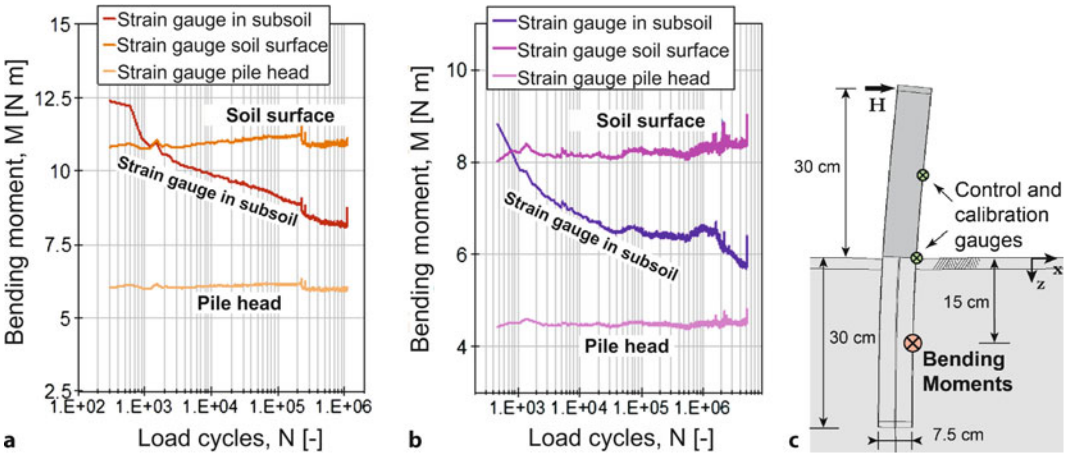

Fig. 6.7 Bending moments, measured with strain gauges at three different levels: **a** measurement data at wave loads of −10 to 40 N, **b** measurement data with alternating loads of 0 to 30 N, **c** Test setup. © BAM

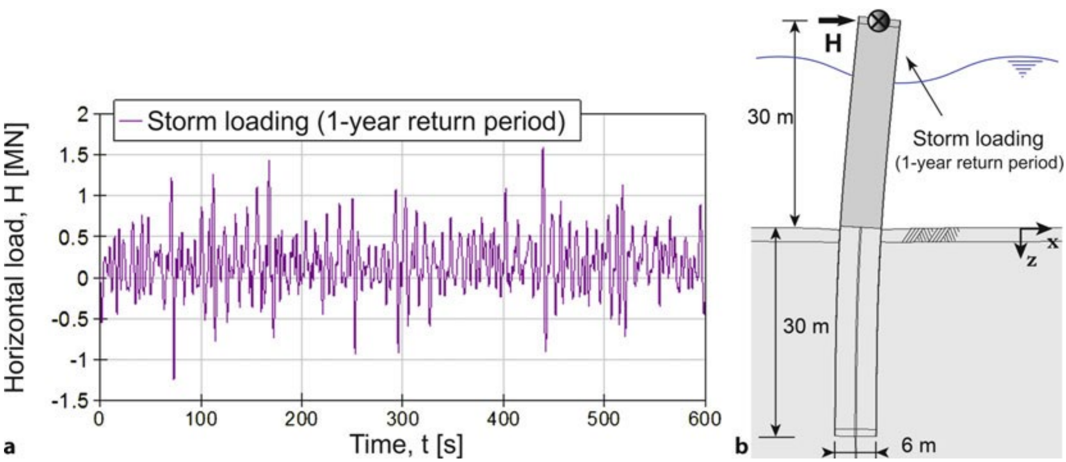

Fig. 6.8 Time signal of horizontal loads (**a**) caused by an extreme storm with one-year return period (**b**). © BAM

Uncharted Territory on the Seabed

Monitoring Procedures and Assessment Model for the Foundations of Offshore Wind Turbines

Matthias Baeßler, Pablo Cuéllar, Steven Georgi, Krassimire Karabeliov, Werner Rücker, Copy edited by Björn Johnsen

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power,* DOI 10.1007/978-3-662-53179-2_7

Project information: Monitoring Procedures and Assessment Model for the Foundations of Offshore Wind Turbines
Project management:
BAM – Federal Institute for Materials Research and Testing
Dr. Matthias Baeßler
Project partners:
- BSH – Federal Maritime and Hydrographic Agency
- BARD Building GmbH

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7.1 Getting the Balance Right

Offshore wind turbines enter unknown territory, especially where the foundations are concerned. This is because offshore wind power can only make use of the experience from the common offshore constructions used by the oil and gas industry to a limited extent. The offshore wind industry has tried to reduce foundation dimensions, especially the pile lengths, as much as possible compared with those of the oil and gas industry. This is because with the large number of wind turbines involved it can provide considerable economic advantages. On the other hand, the stability of the foundations is additionally at risk because due to the much larger number of cyclic loads they are subjected to it is very difficult to predict how they will behave. Since offshore wind farms are manufactured in series, every systematic fault in the foundation acts as a series fault for a large number of turbines. This calls for monitoring – and the right dimensions of pile foundation, the most common type of foundations used for wind turbines.

Where the foundations of onshore wind turbines are concerned, the local ground is explored and it is usually also possible to refer to experiences with comparable locations. Where offshore foundations are concerned there has not been any such comparable experience in the German North Sea to date. This has resulted in a degree of uncertainty about what pile diameters and lengths are necessary. The pile designs could be undersized or oversized. If the foundation is undersized the stability of the structure is endangered and – as a result of series production – so is the whole wind power plant. If the foundation is oversized it will drive up the costs unnecessarily. The foundations of offshore wind farms thus represent a great structural challenge. This situation is aggravated for wind turbines out at sea because of the high number of load cycles, the unfavourable relationship between impacting horizontal forces and the comparatively low weight of the wind turbine (= great torque to be expected), the high cost pressure, the consequences of "series faults", the effective lack of offshore wind knowledge at German project locations until Alpha Ventus, and the high cost of inspection and maintenance.

7.2 Observing and Monitoring

The use of structure monitoring systems is an elementary component of project requirements. They can close the gaps in structural experience and guarantee the stability of foundations in operation. In the geotechnical field the "lack of experience" and especially any defects discovered during the verification of the stability can lead to compulsory measuring and monitoring being prescribed, whereby it is possible that not just monitoring will be compulsory, but also the provision of active countermeasures. The so-called observational method then replaces the verification of stability or represents this verification of stability. The observational method includes measurements, the representation of meaningful indicators and intervention thresholds, the representation of the structural model involved and its degradation, and the representation of possible countermeasures.

The RAVE research project "Monitoring Procedures and Assessment Model for the Foundations of Offshore Wind Turbines" was a joint project carried out in association with wind turbine manufacturer BARD, whose five-megawatt machines have been erected in close proximity to Alpha Ventus, at the BARD Offshore 1 wind farm (80 × 5 MW). A new type of foundation was used here, the Tripile.

Peripheral Anecdote (I): Slimness has its price
Like the tripod, the tripile is a three-legged foundation. In this case, three steel piles of about 40 or 50 metres in length are driven into

Fig. 7.1 Offshore wind turbines with tripile foundations. © Ocean Breeze Energy GmbH & Co. KG

the seabed but, unlike the tripod, they extend several metres above the surface of the water, where they are connected with one another by means of a square transition piece (Fig. 7.1). The basic idea behind the tripile patented by BARD, which has in the meantime been declared insolvent, is that the tensile forces on the foundation in the sea act particularly on the grouted section, the point of contact between pile and load-bearing structure. If something goes wrong there it can only be fixed using divers with a great deal of effort, if at all.
This is why the BARD idea was to" do everything of significance above water". The transition piece and the grout sections for the piles are above the waterline, which means that virtually all repair work can be done by ship, without the need to deploy divers. The steel piles can also be designed to be slimmer, the piledriving is quicker and the slim steel piles can reduce costs. The patented piles really are slimmer than those used on the tripods. But whether this actually saves cost depends on the current steel price, because this slimness also has its price. Inside, the walls have to be substantially reinforced and instead of one thick tube there are now three slim tubes sticking up out of the water. Just these three steel elements and the transition piece of the tripile weigh 500 tons.
On top of this you have the steel for the wind turbine and its tower. According to the manufacturers, 120,000 tons of steel was used in the construction of the BARD Offshore 1 wind farm and its 80 turbines plus transformer station.
Björn Johnsen

7.3 All Beginnings: The PC and a System Identification Procedure

The research project investigated the difference between indirect procedures for monitoring structures, where straightforward load monitoring is used as the basis of assessing the load-bearing capacity of the foundation, and direct procedures. In the latter case the load-bearing capacity itself is directly determined by analysing the actual course of load displacement of the piles.

Based on this, a new system identification method was introduced that can be used to determine the load displacement curves for the pile using the operating data of the offshore wind turbine. This basis creates a simple finite element model for the pile with a freely selectable approach for the tangential and axial bedding in the seabed, the so-called "t-z curves" or "t-z springs" – the derivation of non-linear axial spring characteristics. Vertical counterforces work bottom to top on the foundation

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Fig. 7.2 Horstwalde test field. **a** Driving a pile, **b** View of the test field with ten piles (length 20 m, diameter 0.7 m). © BAM

or steel pile from the seabed, almost like springs. Or, as Isaac Newton put it, for every action there is an equal and opposite action.

This project also initially focused on developing a computer model where identifiable loads, forces and data were entered and further developed in order to identify the "system offshore foundation/ pile supporting structure" as precisely as possible. Here the forces do not in any way act linearly; if for example a pile is pulled out of the foundation soil, this results in a non-linear displacement curve. The computer model and procedure were theoretically tested and the performance limits for the pile foundations determined. This was followed by a subsequent reference test at the Federal Institute for Material Testing (BAM) test field in Horstwalde near Berlin (Fig. 7.2).

7.4 Field Trials at the Bottom of the Berlin Glacial Valley

The load facility in Horstwalde (Fig. 7.3) allows half-scale offshore piles, around 20 metres in length, to be driven into the ground. The Berlin sand is densely bedded and has a comparable grain size to that in the floor of the North Sea. Like the sea, the high water table – it is located in the former Berlin glacial valley – provides complete saturation of the ground. The load tests on the sandy Berlin-Brandenburg ground confirmed the opportunities offered by the method and model that were developed. The load-bearing capacity can be determined from incomplete force and deformation recordings. The great challenge for an offshore foundation consists of two important questions: what quality does it have and how accurate is the structural model for the piles? And how accurately can the structure be measured and monitored?

7.5 The Early Piles: Still Not Very Resilient

An important finding of the field tests with the driven piles relates to the increase of load-bearing capacity with time. During the piledriving the ground material is disturbed around the pile sleeve. The load-bearing capacity of the pile is therefore rather poor after installation. With time the ground tenses up again around the pile sleeve, and the load-bearing capacity can increase sharply. The load-bearing capacity on the pile sleeve is determined by the dilatancy. Dilatancy is the volume change observed in a compacted granular material when it is sheared (Fig. 7.4).

It is also a fact that when a pile is repeatedly subjected to load its load-bearing capacity is altered.

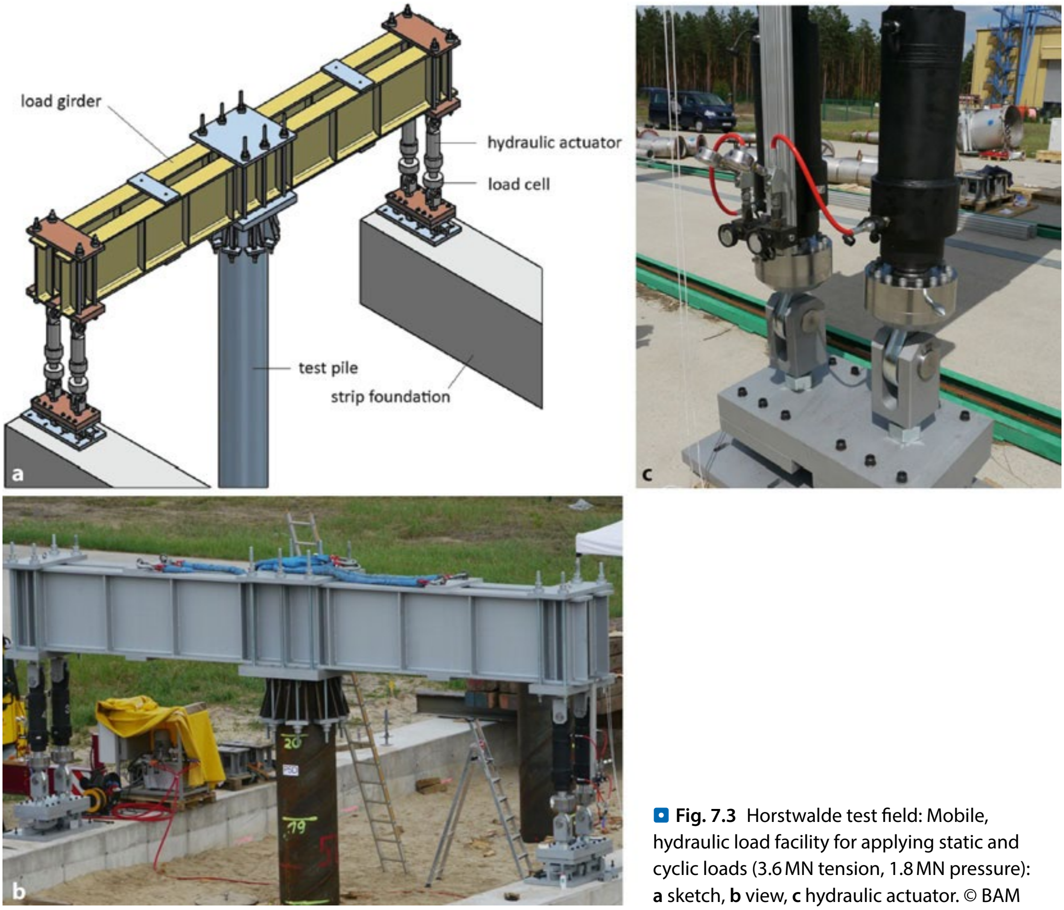

Fig. 7.3 Horstwalde test field: Mobile, hydraulic load facility for applying static and cyclic loads (3.6 MN tension, 1.8 MN pressure): **a** sketch, **b** view, **c** hydraulic actuator. © BAM

The difficulty is estimating this accurately over its service life, because the load-bearing capacity does not decrease in a linear manner over the 20-year service life of an offshore wind turbine, and the loads caused by wind and waves, and their yearly trends, are too diverse. The impact and the evaluation of extreme events, such as severe storms, are also important.

On balance it is clear that large driven offshore steel piles, and especially so-called young piles, exhibit a significant increase in load-bearing capacity when the turbine first goes into operation.

7.6 No Signal in Normal Operation

As with many system identification methods, and similar to dynamic pile load tests, the procedure developed in the project only delivers good results when it is sufficiently near to the load. Since no continuous extreme loads are to be expected in offshore operation, but rather underlying cyclic loads, the prerequisite for model identification is seldom found. In "normal operation" the measurement signal is simply too small. It only displays signals when there is a major storm, when for example 50 % of the possible bearing load of the offshore foundation has been reached.

This does not however represent a weakness of the method developed, because this method can and should only display results for very large load amplitudes with plastic changes on the pile. This meant

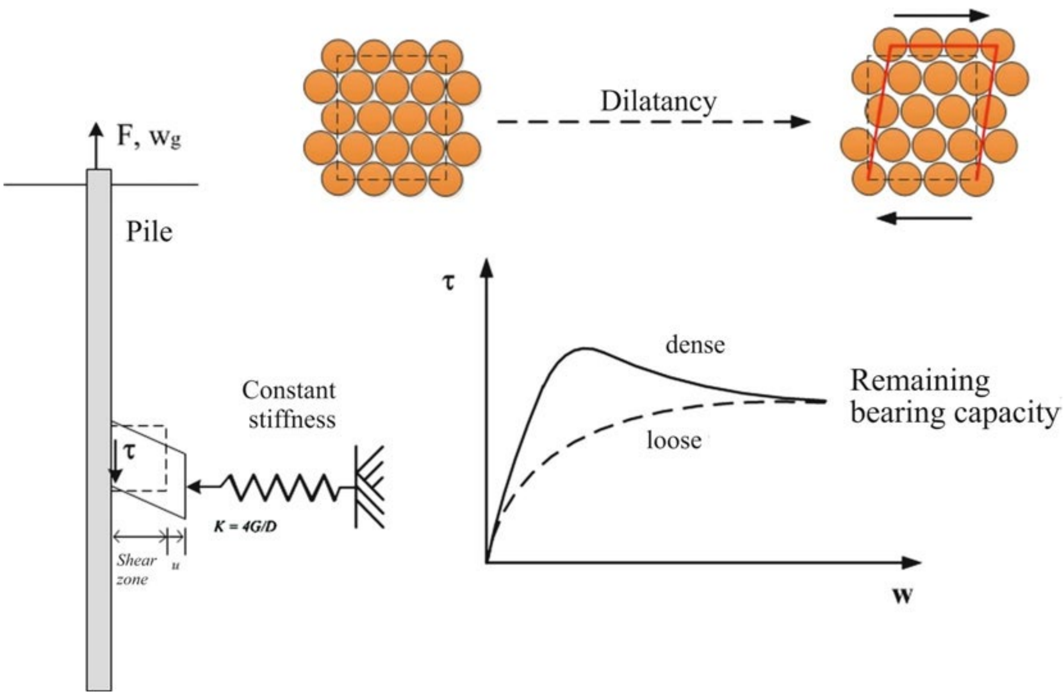

Fig. 7.4 Driven pile dilatancy model: shear load on a compact aggregate grain material causes an increase in volume that results in a pronounced maximum load-bearing capacity. © BAM

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that it was primarily the quality of the measurement installation that was tested.

Peripheral Anecdote (II): We are not measuring for tsunamis, but for the North Sea

This is most certainly a case of pile degradation: a volcano erupts in Iceland, triggering a tsunami that surges across the German Bight and, among other repercussions, snaps a pile in a wind farm. But such a tsunami is not really very likely. It is far more likely that pile degradation will occur as a result of weaker extreme events, such as an extreme event that occurs once a year. Then you would certainly find material fatigue. But you would also find that the pile can recover after a few days' rest – without storm or wind turbine operation. So there is a cure.
Björn Johnsen

7.7 Testing out at Sea Still Not Completed

As well as developing models and carrying out field tests on land, the research project also included trials of the new structure monitoring method on a wind turbine out at sea. In this case it was on a wind turbine belonging to our project partner in the BARD Offshore 1 wind farm in the direct vicinity of Alpha Ventus. The wind turbine manufacturer's structure monitoring system was positioned on one side. The manufacturer had installed this measurement technology at the beginning of 2014, towards the end of the research project. The measurement technology was implemented in the manufacturer's data system.

The centrepiece of the measurement technology concept turned out to be the choice of the right acceleration sensor. The difficulty was in getting a low-noise measuring signal for the relatively small and low-frequency vertical acceleration vibration in the pile. Only then is it possible to calculate the displacement amplitudes of the pile with sufficient accuracy. To achieve this, the acceleration sensors that take the accurate measurements have to point in the three spatial directions (height, width, depth). Several months of experiments and tests in the laboratory of the Federal Institute for Material Testing showed that a special seismic sensor model was most suitable. So many laboratory tests were necessary because the data provided by the manufacturer was often insufficient and its use for offshore applications turned out to be not possible. A false initial selection on land would have had effects offshore that could only be remedied with difficulty. The system has to be simple and robust, but still be able to measure the slightest vibrations very accurately – and last for many years out at sea.

Project partner BARD had also previously attached strain gauges as a rosette around the outside of the pile.

Because the measuring equipment was only installed in 2014, the tests and any subsequent monitoring programme on the BARD test system could not be completed. The measurements are to be continued.

» Monitoring procedures for offshore structures are important. The main problem is when in future it displays damage or just unscheduled degradation on the pile. What measures can and must the wind farm operator take? Here there is still a significant need for research and above all development.
Matthias Baeßler, Department 7.2. Civil Engineering, Federal Institute for Material Testing

7.8 Outlook: Please Continue to Develop Countermeasures

An accurate forecast of the load-bearing capacity of typical offshore piles and also the measuring of the condition of their load-bearing capacity in a monitoring concept is a difficult task. Unless absolutely uneconomically dimensioned, cases will therefore inevitably occur where the sufficient load-bearing capacity cannot be verified upon installation and where a definite identification of the load-bearing capacity cannot be made during operation.

The more uncertain this starting position appears to be, the more important the applicability of countermeasures needed to counteract any progressively failing foundation. With this in mind the project analysed the main possibilities of countermeasures. It is however urgently recommended that practical countermeasures should be developed to maturity for application.

The findings of the research project and the practical experience brought in by the project partner for the trials, planning and implementation of the measurement and evaluation concept, as well as the knowledge gained about procedural possibilities and limits, represent great added and utilisable value. The new VDI Guideline 4551 "Structure Monitoring and Evaluation of Wind Turbines and Platforms" currently being drawn up takes experience from this project into consideration and places the corresponding possibilities for action offshore at the disposal of planners.

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Long-Lived Despite Harsh Winds

The Further Development of Components in Offshore wind Turbines

Jan Kruse, Copy edited by Björn Johnsen

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Project information: Further Development of Offshore Wind Turbine Components with Respect to Cost, Longevity and Servicing Convenience
Project management:
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How long do the components installed in offshore wind turbines last in tough conditions at sea? How can the monitoring inspections be improved and if possible the maintenance intervals be extended? And if they need to be serviced, repaired or just tested, how can these operations be simplified for more service friendliness? These are important issues for the operation of offshore turbines, and are a component of several research projects at Alpha Ventus, where data about structural dynamics, meteorology, hydrology or ecology is measured and evaluated. This data is factored into the further development of the turbines. The main focus of one of the projects was to develop the components of the Senvion 5M wind turbine to give it a longer service life, reduce costs and improve service friendliness at sea.

The prototype of this five-megawatt machine with its 126-metre rotor diameter was erected on land in 2004. This was followed in 2006 by two offshore turbines for a demonstration project off the Scottish coast (Beatrice Wind Farm). For logistical reasons, a part of the research tasks for Alpha Ventus was not carried out at the offshore wind farm itself, but was processes onshore on a prototype in Ellhöft, Schleswig-Holstein.

In 2009 Senvion erected a new prototype turbine type with a rated capacity of 6.15 MW. Forty-eight of these machines were recently erected as Senvion 6.2M126 in the Nordsee Ost wind farm, about 30 kilometres north of Helgoland at water depths of around 25 metres. The 6.XM series has already profited from the findings of the research on the 5 MW turbine from the Alpha Ventus project.

Unlike the competition's five-megawatt turbines in Alpha Ventus, the Senvion turbine has a modular drive train (Fig. 8.1). The hub is attached to the gearbox via a double bearing rotor shaft. The "5M", as the turbine is called by the engineers and technicians, has a three-stage planetary/spur gearbox with a system for filtering and cooling the oil. Due to this design the generator has less weight. The double rotor shaft bearing means that all loads are fed directly into the main frame via the bearing, so that the gearbox is only loaded with torques. In the event of a gearbox replacement it is no longer necessary to dismantle the whole rotor, including the shaft – it can now remain fitted to the mainframe.

8.1 The Gearbox – Highly Stressed

The gearbox is one of the most heavily stressed components in a multi-megawatt turbine. Replacing a complete gearbox is also very costly. Out at sea this requires a jack-up vessel with a large crane. The manufacturers are obviously working on designs that will specifically extend the service life of the gearbox, allow early detection of any damage, and allow for any repairs to be carried out simply and economically. Reducing the mass of large gears like those used in an offshore wind turbine should be one way of lowering unit costs. It is also hoped that by being able to dismantle the gearbox components separately as far as possible it will minimise repair and service costs. Cost reductions are also expected as a result of reducing complex maintenance operations out at sea and introducing anticipatory maintenance planning.

8.1.1 A Small Crane on Board Instead of a Big Jack-up Rig out at Sea

Until Alpha Ventus went into operation there had never been anything like it: a gearbox in an offshore wind turbine that could be dismantled into its component parts out at sea. With conventional designs, if there is any damage, the whole gearbox has to be removed and transported off for repair. Senvion had to develop and test a new concept for the new gearbox that can be semi-dismantled. An important part of this concept is a small on-board crane. It is a fixed part of the nacelle and has a maximum load capacity of 3.5 tons. This saves the use of a large external crane which otherwise has to be chartered and shipped in.

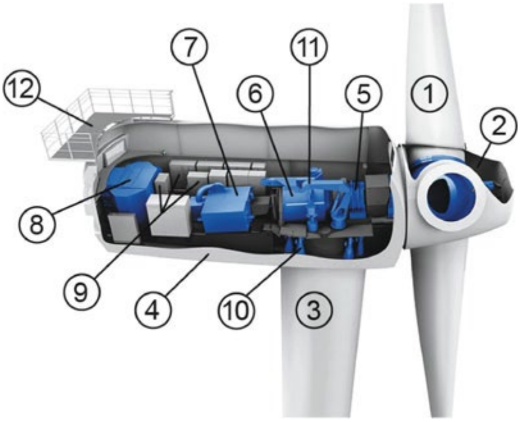

Fig. 8.1 Schematic representation of the main components of a Senvion 6.XM wind turbine. *1* Rotor blade, *2* Rotor hub, *3* Tower, *4* Nacelle, *5* Rotor bearing, *6* Gearbox, *7* Generator, *8* Transformer, *9* Control system, *10* Yaw system, *11* Deck crane, *12* Helideck. © Senvion GmbH 2015, edited by Fraunhofer IWES

Peripheral Anecdote: The second and third prototypes are already standing in the water

After the prototype of the five-megawatt machine was erected in Brunsbüttel in November 2004, more of these turbines were to be erected on land in order to gather more operational experience. However, the sudden offer from Scotland gave Senvion the opportunity to test the turbines under realistic conditions out at sea earlier than planned. Two wind turbines were to be installed offshore in the British Beatrice offshore oil field. Senvion grasped the opportunity, and erected the second and third prototypes of the five-megawatt machine out at sea in 2006. Both machines celebrate their tenth anniversary in 2016.
Björn Johnsen

8.1.2 Sufficient Capacity for a Long Service Life

As with so many pieces of technical equipment, the shaft, gearbox, brake and generator in standard types of drive train in a classical wind turbine have been conservatively dimensioned and with greater safety margins than for the minimum necessary design. Without these margins there is an increased risk that unexpectedly strong loads can result in component failure before the end of the planned service life (usually 20 years). This capacity buffer is therefore calculated to ensure that the wind turbines can be operated without risk, and possibly for a longer time, even if it initially involves greater investment costs. A good understanding of the interaction of the components in the drive train and the loads that occur helps the developers to avoid unnecessarily conservative designs and to find a compromise with regard to added safety margin and cost.

The more detailed knowledge being sought also includes the correlation between grid instability, also in millisecond range, and the overall drive train, in other words the chain of effects of rotor, blade-pitch system (Fig. 8.2), shaft, gearbox and generator. A reliable investigation using a model requires an exact mathematical calculation of the entire drive train with all flexibilities, rigidities and inertias of the individual components. The calculations must also factor in the development of the generator torque and the influence of the tower vibrations on the drive train. This model-based description represents the so-called multiple-body simulation (MBS).

While this multiple-body simulation for wind turbines was widely discussed in the industry at the time when Alpha Ventus was being planned, it had not yet been established as a “standard tool” in the development phase. For the new design of the main gearbox for the 5M the engineers involved in Alpha Ventus were able to simulate the load behaviour of the entire drive train, with rotor, shaft, main bearing, coupling, brake and generator. MBS verifications of the drive train dynamics are now part of the usual steps between design and certification of wind turbines.

In the course of the gearbox analyses the Senvion developers also investigated three different gearbox designs with regard to their ability to be easily disassembled. As general proof of the feasibility, one version was tested in a practical trial on land. Here a planet carrier bearing was dismantled in installed condition and the corresponding bearing maintenance work was “pretested” on an off-

Fig. 8.2 Installation of the pitch mechanisms in the hub of a Senvion offshore wind turbine. © Senvion GmbH 2015

shore wind turbine without the use of an external crane – with success.

The future overall turbine simulation with special monitoring of the drive train should enable a holistic view in order to achieve optimised parameterisation of the entire turbine and an analysis of deviations in the operational behaviour of the wind turbine out at sea. This would make it possible to identify components needing repair earlier in future, to reduce downtimes or even larger repairs, such as by postponing component replacements to the weak-winded summer months and generally extend the service life of the drive train components.

8.1.3 Online Oil Tests to Combat Salt in the Gears

Salt on metal causes rust. For offshore wind turbines another problem would be a negative influence of the salty air on the service life of the gearbox oil. In suboptimal lubrication conditions gear damage can also occur on land due to water in the oil. This is especially true when it is salt water – which cannot be absolutely ruled out if the wind turbines are close to the coast. Salt water can lead to increased corrosion (rust), increased wear and sludge formation in the bearings and the detachment of particles from the oil and gears. Increased water content in the oil reduces its lubricating capacity, and this can result in the thickness of the lubricating film becoming too thin. Up to now the rolling bearing manufacturers have only stated a global threshold value for water content in oils, which are however just an average value determined in the lab. And this does not satisfy the special conditions caused by salt water content.

Despite the air conditioning of the 5M nacelle, salty air could impact on the service life of the gear oil that the developers did not want to eliminate from the outset. Here it was about extending the oil service life until the next scheduled oil change under salty environmental influences. The aim of the project was to undertake a regular, computer-aided online measurement of the water and salt content of the oil that also included all the other usual investigations, from metal particle counting to infrared spectroscopy.

Combined with aggregate tests, oil analyses can extend the oil change intervals. Aggregate tests are also more effective than classical lab tests. These involved taking oil samples from the wind turbine every six months and sending them to the lab to be analysed. Only then is it possible to draw any conclusions as to what extent wear, contact load, fatigue or even corrosion prevail. It is possible that this loses valuable time for an oil change – other than with a reliable online maintenance system.

Aggregate tests can determine the combination of oil, water, salt, temperature and shear in tooth flank and rolling bearing contact better than a lab test. An early diagnosis therefore represents an important opportunity to avoid costs – be this through early detection of damage, or quite the opposite, through extension of the oil change intervals. The research work on practical offshore suitability of an oil particle counter in the research project was successful, and that result will in future be used as part of a condition monitoring system (CMS) for early fault detection and service scheduling. The experimental setup for investigating the sensor system in the gear oil takes high-resolution measurements, and records pressure and vibrations. Different operating situations and special operating conditions like low outside temperatures in the winter months can be identified and taken into account as an influence on the counting of particles in the oil.

Since the research on Alpha Ventus this oil particle counter is now series standard for this type of wind turbine. Recording of measurement data was also introduced in order to make it possible to set up a long-term evaluation of the measured oil condition variables like purity classes and oil moisture combined with operating data like turbine output and gearbox speed. In collaboration with the gearbox manufacturer, Senvion developed and carried out a dynamic bench test for the 6-MW main gearbox: with a test duration of four months it ran parallel to a conventional field test lasting one year in a working wind turbine.

8.2 SCADA, Interfaces and the Like

8.2.1 Standard Communication Interface

Automation and interface systems (SCADA) of wind turbines and the wind farm periphery are based on a variety of hardware platforms and software concepts that in turn use a broad-based range of interfaces, both at the protocol documentation level and on the hardware level. So while Alpha Ventus was being planned it was not possible to have any uniform data transmission and exchange between the various types of wind turbines. Two different types of wind turbine within an offshore wind farm being controlled by a common farm controller was not possible at that time, nor was data exchange between them.

There are now several manufacturers who have erected wind turbines with a rated capacity of five megawatts or more out at sea; as well as Senvion and Adwen, these include Siemens, Vestas, Alstom and others. The need for a common interface connecting them with one another in one or more wind farms was thus all the more urgent. This objective was achieved in the research project and was then implemented in Senvion's subsequent offshore projects in Thornton Bank (Belgium) and Ormonde (United Kingdom). The engineers also developed an additional common interface according to IEC standard for the monitoring, visualisation and controlling of components for power distribution with the aid of protection devices: their PC application software (IEC61850-Proxy) enables farm visualisation, switching operations and display of protection device reports.

8.2.2 Closely Linked: Data Flow and Communication Technology

In the offshore sector the demands on the engineering are increasing as much as the demand for a greater degree of automation in order to increase the expensive maintenance and repair intervals. There are also other increased requirements, such as constant monitoring of the functionality of the telephones (for the safety of people at sea), the installation of additional voice and image communication, and a constantly increasing number of systems integrated into the overall wind turbine monitoring system. The classic transmission methods are often insufficient for recording the increasing data volumes and achieving sufficient redundancy at the same time. This meant that it was necessary to equip the data connection with broadband, in other words with greater transmission capacity. Only then is it possible to make full use of a standardised communication interface and the Ethernet technology generally used today. Satellite communication with improved communication characteristics was also developed and tested for the turbine components, so that the maintenance of these components can optionally be carried out via a satellite path. Simultaneously the research project also realised a redundancy concept for the wind turbine type, which ensures further problem-free operation in the event of impairments and damage to individual communication paths.

8.3 Grid Integration of the 5M

8

Prerequisite for the expansion of wind power are reliable, substantiated statements about the interactions of wind turbines and the power grid. Here there is now a diametric exchange of requirements, particularly for the operators of offshore wind farms. The earlier requirement demanded by grid operators that "in the event of a grid fault wind turbines are to be immediately disconnected from the grid" no longer applies. Now the grid requirements are in quite the opposite direction; wind turbines should if possible be treated the same as conventional power plants, at least as far as their own reactive power capability and the maintenance of voltage and frequency is concerned. This sets special requirements for the management of wind farms with a planned rated capacity of 400 megawatts and more.

8.3.1 Power Plant Characteristics

When the project began in 2007 there were no suitable simulation models of the mechanical and electrical systems that could reproduce the symmetrical and asymmetrical voltage dips in the grid for the verification of power plant characteristics for wind turbines with doubly fed asynchronous generators like the Senvion 5M. The old conventional simulation models were too slow and inaccurate for this. The grid operators in particular saw that there was a considerable need for research in this area. In addition to specific models for the Senvion 5M/6M platform, it was possible to develop generic models and a cross-platform format that includes standardised model descriptions for multi-manufacturer use. As a rule, all users of the simulation software can select the corresponding model in a model library. This generic grid simulation model now includes the doubly fed asynchronous generator used by Senvion. A working group of the standardisation panel achieved such a harmonised reference implementation for generic models at the end of 2011. This reference implementation is closely based on a Senvion wind turbine.

8.3.2 System Services – the Wind Turbine on Grid

The ride-through of short voltage drops in the grid (Low Voltage Ride Through/LVRT) and the simultaneous supporting of the voltage (reactive current support) has already been tested in a 2-MW Senvion wind turbine and built into the 5/6.15-MW turbine. It is also part of the new control strategy for reducing the mechanical loads on the drive train in the event of voltage drops in the grid. The supply of reactive power – depending on the grid operator's requirements either a fixed or temporally variable quantity – is also implemented in the Senvion wind farm control strategy.

A concept for providing active power from the centrifugal mass of the system (inertia control) was also drawn up. This makes it possible for the wind turbine to feed even more energy into the grid, for a short time, than it actually generates from the wind. This is particularly relevant if active power is needed to stabilise the grid frequency.

8.3.3 Successful Simulation: The Grid Simulator

Because a wind turbine is also an integral component of a power grid, it is not always possible to try out new functions in the turbine controller as part of an extensive field test from the outset and whenever desired. As an alternative solution the research project procured a grid simulator. This grid simulator complemented the existing test bench and enabled “real-time lab tests”. This was used on the test bench to test the grid code compliance features “voltage control, active power reduction in the case of over-frequency, active power increase in the case of under-frequency” and the “provision of active power” (inertia control) for the 5M/6M wind turbine types, and was verified by an independent measuring institute.

8.4 Intelligent Control

8.4.1 Recently in the Tower: No Wobble

Up to now wind turbines were controlled just on the basis of speed and performance indicators. Structural and tower vibrations, which particularly occur with increased load out at sea, were not taken into consideration as important system control factors. The structural vibrations – from the nacelle, down the tower and into the foundation – have a direct influence on the fatigue loads and consequently also on the size of the foundation structure. Offshore, high and strong waves in particular can cause the tower to vibrate strongly, causing significant fatigue. This can inevitably lead to altered tower design loads. This is comparable with the wind that can hit an offshore structure with a blade tip height of around 200 metres.

The development of an active, load-specific controller is therefore an important part of the research in order to reduce the tower vibrations and prevent strongly increasing tower loads both during operation and when the turbine is standing still. The research project was able to create the basis for testing modern control processes. The fundamental idea of active tower vibration control (TVC) is to reduce the natural vibrations by controlled generation of aerodynamic counterforces with the aid of the individual blade pitch mechanisms.

Vibration sensors in the tower and the return of the signal to the turbine controller provided the basic data for this. Algorithms for active tower vibration control were thus introduced into the controller of the wind turbine and initially tested on a hardware-in-the-loop (HitL) test bench. For financial reasons the field test was carried out on a two-megawatt turbine on land, and this was fully verified by the simulation results. The control procedure for the tower vibration control applied to the characteristics of the six-megawatt machine (◘ Fig. 8.3) and tested on the onshore prototype in Schleswig-Holstein. The control algorithm also worked here. It became evident that active tower vibration control can significantly reduce structural loads, which means that turbines of this kind can in future be designed much slimmer, with the corresponding potential for material and cost savings.

◘ **Fig. 8.3** Thornton Bank offshore wind farm with Senvion turbines. © Senvion GmbH 2015

8.4.2 The End of "Manual Control"

And finally, the introduction of the active vibration control into the Senvion 5M reached the practical limit up to which the control algorithms can be manually translated into control code, which means that automatic conversion is essential for efficient controller development. Here the challenge is to validate this conversion.

» **Helping to keep costs down**
With active tower vibration control it is possible to drastically reduce design-relevant loads. This can enable a slimmer design of the foundation structures and a significant reduction of investment costs. Onshore wind turbines also profit from this control process: we were now able to use a tower variant formerly only suitable for IEC Class 3 low wind locations for IEC Class 2a medium wind speed locations.
Dr. Jan Kruse, Senvion GmbH

In order to gauge the controller's possibilities and to identify optimised parameter sets, many different versions of the control algorithm have to be translated into specific control codes. Here the engineers implemented the realisation of an automatic code generation and compared this new code with conventionally generated control codes. The conclusion was that the control process for active tower vibration control is successful. It is possible to upgrade other wind turbines with this control software update. All in all, many research results – such as the gearbox that can be dismantled, the on-board crane, SCADA interfaces for different wind turbine types or active tower vibration control – from this project have already been factored in for the next offshore wind farms to be built with Senvion turbines (Thornton Bank, Nordsee Ost). Nonetheless, reducing the costs of offshore wind turbines and the development of more service and maintenance friendliness will remain a constant challenge.

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Wind in the Blades

The Development of a New, Yield-Optimised and Cost-Effective Rotor Blade

Jan Kruse, Copy edited by Björn Johnson

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Project information: Development of an Innovative, Yield-Optimised and Cost-Effective Rotor Blade for Offshore Wind Turbines

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Project partners:
- Hottinger Baldwin Messtechnik GmbH
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- RWTH Aachen, Institute of Plastics Processing

9.1 What Is Required of Rotor Blades

As far as the rotor blades of offshore wind turbines are concerned, noise, sound emission or shadowing are not a priority. More important for rotor blades used offshore are their aerodynamic characteristics, their durability under high stress caused by strong winds, gale-force gusts and salty sea air – and especially and despite all this: cost reduction in the production of the rotor blades, despite them being subject to significantly higher loads. Achieving more at less cost – offshore rotor blades should do no more and no less.

One of the two wind turbine manufacturers in Alpha Ventus is Senvion. The company took the lead for the research project, working together with scientists from the Institute of Structural Analysis at the Leibniz Universität in Hannover, Hottinger Baldwin Messtechnik GmbH and the Institute of Plastics Processing at RWTH Aachen. The main aims of the Alpha Ventus rotor blade project were to improve the aerodynamics and reduce production costs. The aim was to achieve this with a newly developed "profile family" of rotor blades, by developing a production concept for the process engineering to increase the efficiency of the manufacturing and possibly by the use of so-called "double blades", extra trailing edges integrated into the rotor blades like a kind of spoiler. The new blade was to be made entirely of glass-fibre-reinforced plastic (GRP) instead of partly carbon-fibre-reinforced plastic. The plan was to also develop an innovative condition monitoring system.

Like many wind turbine manufacturers, for the 5M Senvion also used blades made by the Danish blade manufacturer LM, the world's biggest independent rotor blade manufacturer. The six Senvion turbines in Alpha Ventus are fitted with LM blades. The rotor consists of three rotor blades, each 61.5 m in length, that are connected to the cast iron hub with double-row four-point bearings so that they can be individually pitched about their longitudinal axis by means of the co-rotating pitch drives – the so-called pitch control. The rotor is operated in a speed range between 6.9 and 12.1 rpm. In partial-load operation, below the rated capacity, the turbine works with a constant blade angle and variable rotary speed. To ensure continued operation of the pitch system in the event of a grid power cut or plant malfunction, each rotor blade (▣ Fig. 9.1) has its own, independent, co-rotating electrical energy storage device.

The rotor blades manufactured by LM at the time that Alpha Ventus was being planned included components made from carbon-fibre-reinforced material. The blades used back then did not have any wing fences, so that turbulences (radial currents) occurred, which reduced the aerodynamic efficiency on the suction side of the blades. The use of "wing fences" on the blades was to be tested as part of the project and thus required fundamental research. And the so-called "double blades" had up to then only been installed on smaller wind turbines where their aerodynamic characteristics were investigated. The corresponding investigations had not yet considered their possible application on blades over 60 m long.

9.2 The Work Packages for the New Blade

9.2.1 In Abundance

The new blade structure was to be robust, reliable and economical. To this end the developers used GRP and PET foams, which enabled them to keep

Fig. 9.1 Rotor blades being loaded for installation in an offshore wind farm. © Senvion GmbH 2015

the blade weight down to the desired maximum of around 21 tons despite doing without carbon-fibre parts. The use of PET foam in blade production is far more environmentally friendly because it can be thermally recycled without leaving any residue. PET foam is also cheaper than the PVC foam used previously. A modified groove construction for the resin infusion process also reduced the amount of waste. The statistical analysis of rotor blades has also been improved across the industry at the same time. This applies to the FE modelling of the blade and more refined load calculation, and also to the strength analysis. While for years previously just the pure fibre strength was investigated, an inter-fibre failure analysis is now standard. This is an essential prerequisite for the use of fibre composite rotor blades. Before this research project at Alpha Ventus all rotor blades of this size, with a length of 60 metres and more, used carbon fibres.

In the model for the new blade design, the developers repositioned shear webs inside the blade in order to distribute the loads more evenly. In their opinion the wing fences on the surface of the rotor blades that were to be investigated did nothing to improve the aerodynamics, the more so as the production and maintenance costs and effort were greater. The same opinion was formed of the so-called "double blade" during the course of the investigations. The aerodynamic advantages that had been hoped for could be achieved just as well with a cut-off trailing edge on the blade profile. Due to its use of GRP and PET foam, the new rotor blade is thicker around the root – which thus increases the overall aerodynamic performance and safety. The new blade geometry, with a flattened trailing edge, is now a hallmark of all of Senvion's longer rotor blades (Fig. 9.2).

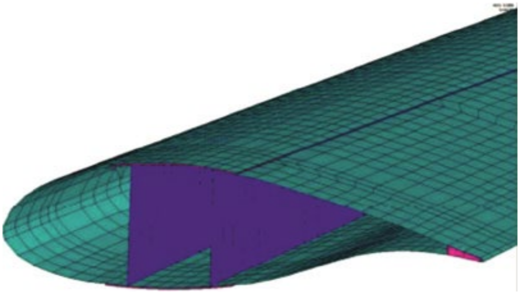

Fig. 9.2 Computer model: section through the newly developed rotor blade. © Senvion GmbH 2015

9.2.2 Process Development and Mould-Making

The choice of material also played a major role in the implementation in the production process. In drawing up the concept for series production, special attention was paid to the adhesion work, particularly in the sensitive blade root area. The new, thicker rotor blade, with a cut-off on the trailing

Fig. 9.3 The prototype of the rotor blade is prepared for installation. © Senvion GmbH 2015

edge, obviously required a new production mould. In the end, as always, two large blade halves were manufactured and glued together. But with the new blade, structurally important components on the inside of the blade did not have to be made within the main form. They were made separately earlier and then inserted. The complete set of moulds thus consists of individual forms to manufacture the girders, shear webs and shells of the two blade halves. This enables greater quality control in the preliminary stages while at the same time reducing the amount of work needed on the main mould. Since this had always been the bottleneck during the production of every blade, the new method achieved a significant increase in efficiency.

9.2.3 Stackable Transport Racks and a Set of Prototype Blades

The 61.5-metre blades are produced manually at Senvion. New transport racks were also developed parallel to this. These new racks make it possible to stack several blades, which provides logistical benefits as less storage area is required. This is especially true for transporting the blades out at sea. The glass and sandwich kits for the blades are now pre-assembled in a separate station so that there is less waste and the time needed for insertion in the main mould is also reduced. During the later production process, cooperation with the gluers improved the fitting precision of the cut pieces and increased the insertion speed. The web-setting mechanism for the individual components was extensively measured, tested and compared with the CAD model. As well as manufacturing the prototype set, refinements were also made to the production process.

9.2.4 Blade Test and Measurement "in the Field"

The new rotor blade was tested on the test stand to gain precise knowledge of the blade behaviour. The tests included blade behaviour under static and oscillating loads, the analysis of natural frequencies, blade bearing, durability and quality. These tests were successfully concluded, and in spring 2011 measurements began on a real wind turbine onshore (Fig. 9.3). And incidentally, for the first time the complete rotor star was not dismantled; the blades were replaced one by one. This only requires cranes with a smaller load-bearing capacity, so not only are such cranes more easily available, but they are also cheaper. Senvion used this erection technique – individual attachment of the blades to the hub – for the first time offshore in the 295-megawatt Nordsee Ost wind farm around 30 kilometres north of Helgoland.

Once the rotor blades had been swapped on the onshore prototype in Schleswig-Holstein for the Alpha Ventus research project, they were fitted with strain gauges and the hardware and software necessary for the measurements. The integrated condition monitoring system (CMS) was developed externally and also tested and validated in this field trial.

As far as loads are concerned, measurements were made of the blade root bending moment, the tower torsion and the rotor shaft bending under heavy load. Together with the rigidities of the individual components (generator, brake, etc.) this provides a comprehensive picture of the load situation of the whole wind turbine.

Peripheral Anecdote: Too much wind = not enough grid = no research!

The best strain gauges and measurement software in the world are no use at all if the wind farm management switch the wind turbine off beforehand! It is well known that there is often grid congestion at the strong wind location for the measurement prototypes in Schleswig-Holstein – especially when there are high wind speeds that result in "too much" energy being generated. So as far as the measurements of the new rotor blades was concerned there were several what appeared at first glance to be paradoxical situations where the wind turbine had to be switched off – not because the turbine and the new blade were subjected to too much load as a result of the high wind speed, but because the grid was simply unable to carry off the six megawatts of electrical power output. So at exactly the right moment, when the wind is blowing strongly into the rotor and the great forces and loads that are of interest to the scientists and developers are working on the wind turbine, the grid control centre can order temporary shutdowns. When it is not possible to make continuous measurements at such times the whole research project gets behind schedule.

Björn Johnsen

9.3 Advances Made by the Others

Even if it is not part of the Alpha Ventus project, we should not fail to mention the advances made by others during the project duration 2007–2012. Siemens manufactured a 52-metre blade in one casting and without adhesives. Adwen announced a 66-metre blade, LM Glasfiber, a 73.5-metre blade for the Alstom prototype Haliade 150, and Siemens a 75-metre blade for a six-megawatt turbine. The prototypes mentioned here have in the meantime – after the end of the project – been erected. And Senvion has also extended the rotor diameter of its 6.15-MW machine to 152 metres with the addition of a new 74.4-metre blade.

9.4 Outlook: What Have We Got from It, and What Can We Still Get from It?

The project achieved successful blade certification and push-started the construction of a rotor blade production plant in Bremerhaven. The blade production by PowerBlades, a one hundred per cent subsidiary of Senvion, creates jobs and strengthens Germany's position as a business base. The blade's improved aerodynamic properties have resulted in increased yield compared to the conventional blades used to date. Senvion will also use the new rotor blade developed in the Alpha Ventus project for its 6M series. The knowledge and experience gained from the project make it possible to develop new, larger rotor diameters with greater energy yield.

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The Wiser Blade Knows When to Yield

Searches and Trials with Intelligent Rotor Blades – an Outlook

Björn Johnsen

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power,* DOI 10.1007/978-3-662-53179-2_10

Project information: Smart Blades – Development and Design of Intelligent Rotor Blades
Project management:
German Aerospace Center (DLR)
Dr. Jan Teßmer
Project partners:
- ForWind – Carl von Ossietzky University of Oldenburg
- ForWind – Leibniz Universität Hannover
- Fraunhofer Institute for Wind Energy and Energy System Technology IWES

10.1 Withstanding – and Exploiting – 100 Million Gusts of Wind

A larger rotor diameter enables a significantly higher energy yield, which is why the trend is towards increasingly bigger rotor blades, both onshore and offshore. With a swept area the size of two football pitches and more, the blades turn increasingly slower in the wind. They become heavier and more sluggish. But the number of gusts they are subjected to, and the increasingly greater loads – due to the greater size – does not decrease. The gusts still "slam" onto the rotor blade – and the pitch drive that changes the blade angle only reacts to this relatively slowly. This is why it appears to make sense to develop a blade actuating system that goes beyond the conventional pitch drive.

If rotor blades are to have a length of 100 metres and more in the future, they would weigh over 100 tons using conventional designs. The usual fibreglass construction would then not only be too heavy, but the blades would also no longer be rigid and stable enough to cope with the deformations caused by the enormous wind loads and they would then be at risk of flapping, could no longer maintain the minimum distance to the tower and in extreme cases would even beat against the tower. This means it is also necessary to investigate another method of construction using other materials, for example using more carbon fibres, which are five times stronger and stiffer than glass fibres (◘ Fig. 10.1).

Problem: rotor loads are continuously increasing with greater blade size, and their own weight is also increasingly greater. At the same time the inhomogeneous wind field in front and behind the turbines causes large aerodynamic vibratory loads. With a wind field that is so varying, there are very different loads on the blade tips than on the blade roots.

One solution could be the development of "intelligent" rotor blades with new control approaches for reducing load. The SmartBlades research project funded by Germany's Federal Ministry of Economic Affairs and Energy is developing various innovative models with a look to the future. Within the project, one work package is investigating the turbulent wind flow in the immediate rotor field.

10.2 Turbulences from the Front

The turbulent inflow of the wind is what significantly determines the load on the rotor blades and the wind turbine as a whole. During its 20-year operating life it can be expected to experience up to 100 million gusts of wind and the corresponding number of load changes. The investigation of this turbulent wind field in the rotor near field in front of the turbine – both temporally and spatially – has only been possible to a limited extent to date: measuring methods are currently often limited to point measurements, with for example anemometers or pulsed lidar laser devices that have only a relatively slow scanning rate in the range of up to about 5 hertz. The SmartBlades research project acquired a so-called "short-range wind scanner", which is planned to be mounted on top of a wind turbine nacelle as part of the RAVE project. The device can measure up to 400 points per second in the wind field, at a distance of up to 200 metres in front of or behind the turbine. While the spatial resolution is – depending on the focal distance – considerably smaller than in conventional devices, the temporal resolution is much faster than in the devices used up to now. In short, approaching turbulences can be measured much more accurately.

This nacelle-based measurement of the inflowing air should as it were "scan" the whole of the approaching turbulent wind field. This means it is pos-

Fig. 10.1 Rotor blades are becoming increasingly longer – as are the test benches. This is the rotor blade testing centre at Fraunhofer IWES in Bremerhaven, where the operational stability of blades with a length of up to 90 metres can be tested both structurally and dynamically. © Fraunhofer IWES

sible to measure and evaluate averaged, or effective, wind speed across the whole of the rotor surface as well as four more wind field parameters: the vertical and horizontal wind shear, and the vertical and horizontal flow inclination.

The measuring campaign in the "Turbulent Inflow in the Rotor Near Field" work package aims to use the short-range wind scanner to find answers to the following questions: which local turbulence structures are to be expected in the rotor near field? What effects do these have in turn on the rotor, and on the rotor blades in particular? And what feedback effects does the rotor have on the turbulent wind structure?

10.3 Act Early rather than too Late

From the measurement results the scientists are able to create or derive "turbulence and wind field characteristics" in front of a wind turbine. The linking of the data about the turbulent wind flow with the local rotor loads makes it possible to derive aero-elastic models and then verify them in the real world. In the end, this reference data serves one great goal: the design of straightforward, robust, laser-controlled systems for anticipatory control procedures. The new kind of control should work immediately prior to the wind, and therefore the load, reaching the rotor blades, and not first afterwards as is the present situation.

10.4 Twisting Instead of Pitching?

Why is the whole rotor blade laboriously turned out of the wind with a great deal of physical effort by the pitch motors, which with the "giant blades" of the future will be subjected to massive strain and still not be able to react to localised gusts? Is it possible to develop a supple blade that yields in strong wind, thereby changing its shape – but without breaking or hitting the tower? The passive technology component project is about seeing if the rotor blades of the future can bend with massive aerodynamic load changes and even if they can turn or twist around their own axes. As they twist, they change the inflow angle of the wind and thus counter the threat of massive load changes (Fig. 10.2).

The investigation of passive SmartBlades with bending and torsion coupling is about two different approaches. One is a "structural" bending and torsion coupling, where the laminates mounted along the longitudinal axis of the rotor blade create a corresponding effect due to their direction-dependent arrangement. The other is a so-called geometrical

Fig. 10.2 Active rotor blades adapt to the wind strength. © DLR; Lizenz CC-BY 3.0

bending and torsion coupling, where the curvature of the rotor blade out of the rotor plane automatically and passively adjusts the rotor blade for the wind flow.

10.5 By Bend or by Twist

"Passively intelligent" rotor blades with a structurally induced bending and torsion coupling of the rotor blade require a special layer structure of the fibre-plastic laminate inside the blade. This is because the desired effect of twisting the blade a few degrees should not be equally distributed in all directions, but specifically only along the longitudinal axis of the rotor blade. To this end and in addition to altering the layer structure along the longitudinal axis, manufacturing also requires improved components. So in the automated rotor blade production using vacuum infusion of the resin into the blade a special binding agent is required so that the resin dries faster and the glued components bond better. During the research project numerous tension and compression tests were carried out with a variety of binding mixtures for the desired bending and torsion, and it was possible to achieve material pairing with varying suitable degrees of strength and rigidity. Depending on which rotor blade manufacturing method the manufacturer chooses – such as the vacuum synthetic resin infusion methods or the so-called prepreg method where the inside of the blade is lined with fibre mats already impregnated with synthetic resin – the results of the trials should enable a selection of optimised binding systems.

The project also involved component tests for checking the desired coupling characteristics of bending and twisting, and absolutely necessary reduction of the rotor blade mass and the development of fatigue models for these multi-axial loaded "twisting laminates" for this new type of rotor blade. So much for the theory. In order to test and validate the theoretically designed models in reality a subsequent project should involve the building of rotor blades up to 20 metres in length and then test them on a real wind turbine. Knowledge gained from 80-metre rotor blades is already being incorporated for the "demonstration blades". A reference turbine model was used within the scope of the SmartBlades project that was designed in accordance with the specifications for IEC strong wind class 1A – in other words, for offshore wind locations (Table 10.1). This gearless reference turbine model with individual blade pitch has a rated output of 7.5 MW. The rotor diameter is 164 metres, which corresponds to the 80-metre rotor blades mentioned.

10.6 The Bigger the Flap, the Easier the Influence

"Active intelligent rotor blades" have elastically or rigidly adjustable flaps on the trailing edge of the rotor blades. The latter resemble the starting and landing flaps on aircraft wings. The variable trailing edge flap on the end of an aircraft wing alters the angle of attack there and thus enables the aircraft to take off. The rotor blade of a wind turbine is not of course meant to take off as such, but the adjustable trailing edge flaps can be positioned in different places along the blade

Table 10.1 Technical data of the reference turbine. © Fraunhofer IWES

Turbine data	Unit	Value
Rated capacity	MW	7.5
Power density	W/m^2	355
Wind class		IEC 1A
Cut-in wind speed	m/s	3
Rated wind speed	m/s	11
Cut-out wind speed	m/s	25
Drive design		Direct drive
Control concept		Variable-speed, individual blade pitch
Min. rotational speed	rpm	5
Rated speed	rpm	10
Hub height	m	120
Tower's natural frequency	Hz	0.23
Drivetrain angle of inclination	°	5
Cone angle	°	2
Hub diameter	m	4
Rotor blade length	m	80
Max. blade tip speed	m/s	87
Nominal tip speed ratio		8.4

so that they react differently to the most varied loads. Because where the rotor blade has a length of 60, 80 or 100 metres these loads are, as is well known, very different between blade root and blade tip. And the trailing edge flaps can therefore also counteract these very differently. Investigations in the project to date confirm the assumption that the bigger the flap the greater the influence on the rotor blade. The project will also demonstrate the advantages and disadvantages of rigid or flexible trailing edges.

In addition to influencing the loads in individual operating conditions using flap deflection, the plan is to also develop a complete system that combines the wind turbine controller, the usual pitch drives for individual blade pitching and the active trailing edges with one another. A blade segment demonstrator for investigating the active trailing edge is currently being constructed and tested.

The active trailing edge flaps should reduce the various blade loads. To this end the standard controller of the Wind Energy Research Association's 7.5-MW reference turbine was enlarged in order to reduce the blade root impact moments. Forces that have an impact on the blade root in the transitional area between rotor blade and rotor hub were measured and integrated into the controller. With the newly developed controller it should be possible to especially reduce the loads that occur as a result of inclined inflow, wind shear (changes in wind speed or direction with height) and the most varied degrees of turbulence, whereby the main focus is on the reduction of blade fatigue loads depending on the position of the trailing edge flaps, flap span and adjustment speed. The interim conclusion of the research to date: flap positioning near the blade tip causes the greatest load reduction. The increase in flap position is not proportional to the reduction of the blade root impact moment. Initial estimates show that a flap length of 1/8 of the rotor blade length, i. e. with the given 7.5-MW 164 reference turbine model a moveable flap part that is a good ten metres in length, is very effective. The aim of this sub-project is to identify the potential of a rotor blade with an active trailing edge and to demonstrate the functional capability of the mechanism.

10.7 Don't Just Work Backwards, Also Work Forwards for a Change

The most innovative technology is that of active slats (Fig. 10.3). The work on illustrating the turbulence that occurs and the assessment of the dynamic response of the slats with regard to the influencing forces such as lift, torque and resistance is still at an early stage, meaning that here it will "only" get as far as research in the wind tunnel.

As far as the slats are concerned, there are two different research approaches: a so-called integrated slat and a superimposed slat, with a correspondingly large gap between it and the rotor blade. What both concepts have in common is the endeavour to cause a delayed separation of the flow on the profile.

Where the slats are concerned it is also necessary to specify and test various construction details geometrically: for example the profile depth of the slat, and in the case of the superimposed slat how big the gap between slat and main rotor blade profile has to be, or what angle the trailing edge of the slat should have.

According to the intermediate results achieved so far, the superimposed slats generate higher maximum lift values – probably due to the longer profile depths compared with the integrated slats. On the other hand, with the integrated approach the efficiency, especially in the mid angle of attack range, and the power is significantly better. The integrated slat is thus currently favoured to further design and upcoming experimental investigations.

The rotor blades and the new control approaches – whether passive or active – play a key role for the wind turbines of the future. This is not just because they should be more efficient and deliver greater yield, but because these wind turbines have to be more reliable, easier to manufacture and easier to maintain – despite all the new dimensions.

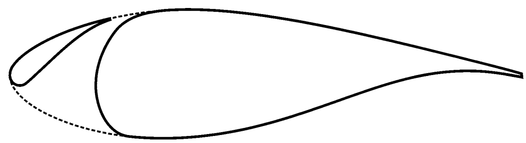

Fig. 10.3 Rotor blade profile with slat. © DLR/Manso Jaume; Lizenz: CC-BY 3.0

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The "Exclusively Offshore" Wind Turbine

Advancement and Testing of the Adwen M5000 Technology Under Severe Conditions at Sea

Gerrit Haake, Annette Hofmann, Copy edited by Björn Johnsen

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Project information: Innovative further development, construction and testing of the offshore wind turbine AREVA Wind M5000 under severe offshore condition in the offshore test field Borkum West
Project management:
Adwen GmbH
Joachim Arndt

11.1 Objectives

One of the two wind turbine types in the Alpha Ventus offshore test field is the Adwen AD 5-116 (previously: Multibrid M5000) with a power output of 5 megawatts (Fig. 11.1). Its prototype was initially also erected four times on land. But it is the first wind turbine developed exclusively for use in deep sea water.

The questions raised in connection with the research project on this wind turbine were therefore of great importance: how can the weight of the rotor blade be reduced to save costs? How can an even greater rotor diameter for even higher energy yields be developed in the future? This would require a larger crane and an appropriately dimensioned jack-up vessel.

And what about the components inside the turbine? Are converter and transformer correctly dimensioned? Are the established cooling systems adequate? What special protection systems are needed during deep-water operation to prevent salt accumulating inside the nacelle and damaging the components? What kind of electronic interfaces need to be developed to enable an exchange of data between wind turbines from different manufacturers within one wind farm? How can a helihoist platform be integrated into the structure to provide access to service technicians or for emergency responses by helicopter? And above all: what is the degree of wear to the compact drivetrain during deep-water operation? Do generators, gearboxes, bearings and rolling elements hold up to the promises of their manufacturers? Interim results were provided when, after four years of operation for testing purposes, the entire drivetrain of an Adwen wind turbine was removed, almost entirely taken apart and then comprehensively examined and analysed. The results confirmed the assumptions made up to now that aim for a service life of 20 years and longer.

Another special aspect of this project is that Adwen (formerly Multibrid GmbH) – unlike Senvion (formerly REpower) – also supplied and installed the foundation structures for their wind turbines in Alpha Ventus so that the wind turbines erected were handed over to the wind farm operator DOTI (Deutsche Offshore-Testfeld und Infrastruktur GmbH & Co. KG) in a "turnkey" condition.

11.2 Forward Sweep Instead of Bending Moments

The rotor blades played a key role in the research project "M5000 Advancement" (Figs. 11.2 and 11.3). The aim here was to develop a load-reduced rotor blade – which is what the subsidiary Adwen Blades did. Two development consultancies specialising in aeroelastic calculations for wind turbines were also involved. The conclusion reached: a greater forward sweep in the new blade design ensures greater aeroelastic stability. At the same time a change was made in the material used for the load-bearing elements of the rotor blade: glass-fibre-reinforced plastics (GRP) instead of the carbon fibres used up to then – which leads to considerable cost savings. The altered geometry of the rotor blade, its increased forward sweep, combined with the new GRP material means that the rotor blade can now be larger without significantly increasing the loads on the drivetrain and nacelle. Thanks to stringent development efforts it has therefore been possible to maintain the existing nacelle and drivetrain structures without significant changes in spite of the marked increase in the size of the rotor.

The increased size of the rotor diameter means that the wind turbine is activated even at lower wind speeds, gets up to its rated power more quickly and can therefore supply a lot more offshore wind power. A prototype with 135 metres rotor diameter was constructed on land in Bremerhaven-Lehe in 2013 and has been certified as AD 5-135.

Fig. 11.1 Nacelle AD 5-116 with rotor star and the Alpha Ventus wind farm in the background. The red structures on the nacelles are the winching platforms that enable personnel and material to be transported to and from the turbine. © Adwen/Jan Oelker

Fig. 11.2 Nacelle and rotor star of an Adwen AD 5-116 on an installation vessel ready for assembly. © Adwen/Jan Oelker

11.3 Learning Objective: Ruggedness

Before the wind power generated by the wind turbines could be transported to the consumers on land the generator voltage must be adjusted by the converter to 50 Hz and by the transformer to 33 kV. Prior to Alpha Ventus the state of technology was that the converter and transformer in some offshore wind turbine types are located in or below the nacelle in a special container (as in the 3.6 MW wind turbines in Arklow Bank in the Irish Sea) or down in the foot of the tower on a platform (as in the 1.5 W wind turbines in Utgrunden in the coastal waters of the Swedish Baltic). All these construction types were unsuitable for the M5000 technology because they are subject to different loads and methods of construction. Something new was needed. For the AD 5-116 in the North Sea there was the further stipulation that 90 % of the heat loss be discharged outside the tower to avoid overheating the components in the tower. The second major stipulation was that no fresh air should enter the tower for cooling purposes in order to avoid harmful deposits of salt and dust.

Fig. 11.3 A tower segment being raised from the installation vessel and onto the segment already in place where the service technicians are ready and waiting. Part of the 56.5-metre-long rotor blade can be seen in the foreground. © Adwen/Jan Oelker

Definition

- **Converter:** The converter's job is to adjust the variable frequency generator current of the wind turbine to the grid frequency.
- **Transformer:** The transformer is used to transform the voltage of a wind turbine generator to the voltage level of the internal wind farm cabling, e. g. from 1,000 to 33,000 volts (33 kV). At the offshore substation another transformer adjusts the voltage level to that of the high-voltage grid (110 kV) for the approximately 75-kilometre connecting cable from Alpha Ventus through the North Sea, over Norderney and through the Wattenmeer to the mainland.

These two stipulations and the dimensions of the tower made it necessary to develop a new and complex method of construction with liquid-cooled converters and transformers with integrated cooling plants. There was nothing like that on the market. In order to develop the converter for offshore operation the engineers changed the cooling pipework and enlarged the expansion tank to make the overall cooling system in itself more robust. Objective: greater ruggedness against the harsh environmental conditions at sea such as air pressure, temperature, humidity and salt.

The developers additionally doubled the chopper resistance to fulfil the grid connection requirements in case of power failure – plus an additional reserve of 80 % and implementation of corresponding control programmes in the wind turbine. For operation of the transformer at sea they reduced the size of the oil–air heat exchanger and changed the design accordingly.

» **Alpha Ventus has been an important milestone for us!**
Using the knowledge gained through Alpha Ventus the company has been able to move on to commercial offshore projects. This has resulted in 120 of our wind turbines in commercial operation in the North Sea today. We will continue this burgeoning development from 2015 onwards in the Adwen Joint Venture.
Luis Álvarez, CEO of Adwen GmbH in August 2015

They similarly established long-term monitoring of the converter and transformer with error–root cause analysis. Example: in the course of a failure of a semiconductor in the Alpha Ventus wind farm the error–root cause analysis showed that a connecting cable had been incorrectly fitted. As a result of this the assembly process was reviewed so that this error could not happen again. This systematic quality assurance enables errors to be identified at a very early stage and their cause to be swiftly remedied. These learning experiences led to the development of a full load test stand. The test stand went into service in 2011.

11.4 Before We Take to the High Seas: Testing

Adwen built a test stand in Bremerhaven for quality assurance and optimisation and additionally for the further development of converters and transformers (Fig. 11.4). All wind turbines can be completely tested here with 5 MW full load or part load and, in particular, with all functions. Troubleshooting on the high seas is both time-consuming and expensive. The effects on the 20 kV grid and compliance with mains supply criteria are the key elements of the Adwen test stand. The full load test stand has been in full serial operation since 2012. In the course of the project another comparable test stand for wind turbines was built at the University of Hanover for 1–2 MW output. Adwen was able to share their knowledge in the planning and realisation of this test stand.

The full load test stand uses the “back-to-back” procedure (B2B). For this two wind turbines of the same type are mechanically and electrically connected (Fig. 11.5). The Adwen test stand in Bremerhaven is additionally used for various tests and measurements outside the serial tests, for example for the verification of a generator cooling system, the exact measurement of all currents, voltages and outputs of the B2B test stand and also to check a condition monitoring system (CMS) that has been developed. Before it is erected at sea every completed wind turbine is subjected to a 27-hour endurance test, 12 hours of which is nonstop under full load.

11.5 Not Quite Like Your Living Room Yet: Climate Control in the Inner Tower

There were endless demands on the cooling systems for climate control in the interior of the tower – but nothing on the market at that time. Some solutions for a few individual demands were already available though.

Example: an air/water heat exchanger did not have to be invented – these systems are not new.

Fig. 11.4 Bird’s-eye view of the Adwen test stand in Bremerhaven. © Adwen/Jan Oelker

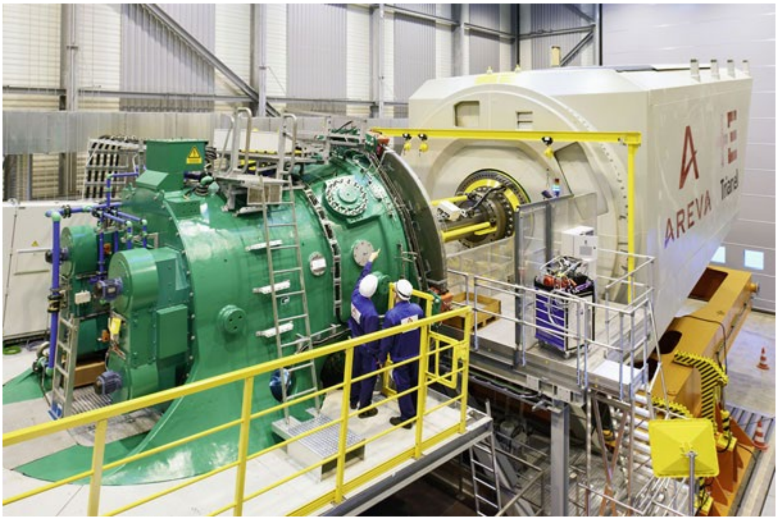

Fig. 11.5 Inside view of the Adwen test stand. © Adwen/Jan Oelker

However, a heat exchanger installed "outside" next to the tower had to be constructed in such a way as to ensure that it always had the same cooling characteristics. However strongly the wind howls outside or the outdoor temperatures rise or fall, the air/water heat exchanger must ensure that the temperature inside the tower is always the same. It must also be protected from corrosion by salt water and function for at least two years without maintenance. After all you can't send the service team out to sea every few weeks or months just because the climate control in the inner tower is not up to living room standards.

Similar applications on large oil rigs were only of limited assistance in designing this system: because there is more room on a rig than in a tower, the components are more easily accessible and the climate control expenditure much higher. And 24-hour monitoring by personnel is guaranteed on an offshore oil rig.

Conclusion: the cooling concept is known but needs new development before it can be used in an offshore wind turbine. What is more, the wind turbines stand on different foundations depending on the specific conditions of their location – and the cooling concepts therefore must be suitable for tower substructures both of steel and concrete. The decision was made to fit three or four air/water heat exchangers directly onto the tower to the right and left above the entrance door. An oil/air heat exchanger is also located in the tower: the cooling air is drawn in through vents in the tower door, led through ducts to the heat exchanger and then taken back through ducts to the tower door where it is released into the atmosphere.

The higher the altitude the lower the salt content of the air. By moving the air intake point of the tower from 15 metres to a height of 90 metres it is possible to reduce the salt content by 27 %. This leads to: a lower salt content, a lower filter load and therefore longer run times for the systems without servicing. A multistage filtration system was additionally installed at the intake point at the top of the tower to reduce the filter load and enhance the separation needed for the innovative cooling system.

The high degree of technical plant availability in the Alpha Ventus test field proves that the cooling systems for converters and transformers (Fig. 11.6) are thermally correct and functioning. The required provision of active and idle current is likewise maintained. Nevertheless, there is still room for operational improvement such as better installation devices for fast connection of the power cables, use of a smaller transformer cooler or the construction of even more compact medium-voltage switchgear. This has been achieved in the following offshore wind turbines of type AD 5-116 and in the prototype of AD 5-135. But it was the test operation in Alpha Ventus that opened our eyes to this.

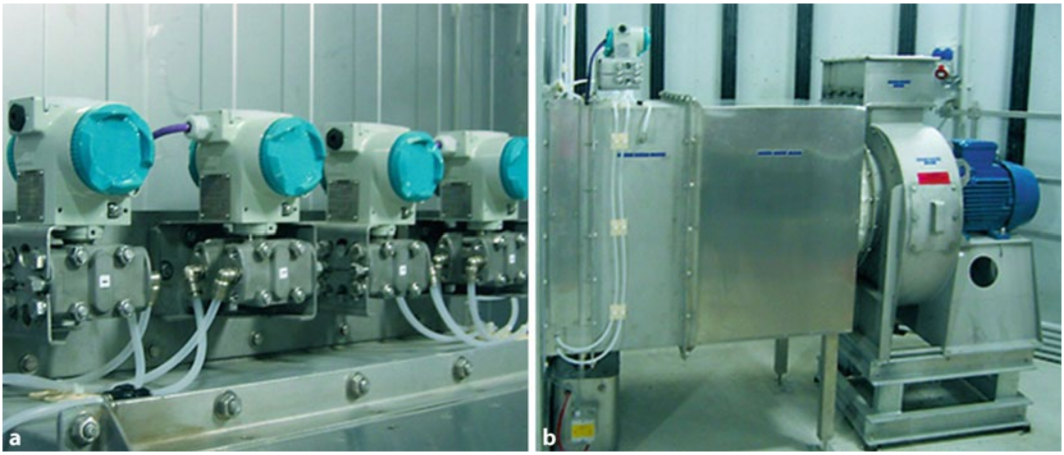

Fig. 11.6 Internal cooling (**a**,**b**) Adwen AD 5-116. © Adwen

11.6 Maintaining Maintenance

Maintenance concepts and condition monitoring systems for constant surveillance play a vital role in the operation of wind turbines at sea. There was not much experience available in the offshore business when the Alpha Ventus project began. The wind farms that had already been built at this time were in the Baltic and there were initial pioneering projects in the Danish and British North Sea but these were close to the coast and in shallower waters and therefore not to be compared with Alpha Ventus.

There was hardly any useful "literature" available on offshore maintenance and monitoring concepts either. What remained was an exchange of information by word of mouth: Adwen held talks with the operators of offshore wind farms. Onshore operation of the prototypes of the AD 5-116 in Bremerhaven over a period of several years provided a framework of data and experience in maintenance and monitoring. These data and statistics contributed to the development of a monitoring system for the offshore wind turbines in Alpha Ventus which in turn was adapted and successfully implemented to simplify inspection of the offshore plants. The potential has not yet been exhausted, particularly in the case of structural measurement data to measure the vibration of the tower and rotor blades. Data analysis to establish the actual strain on the mechanical components is therefore an area of constant development.

Various types of vessels for use in construction and maintenance were also tested. These included accommodation vessels for the technicians who can, if necessary, remain at sea for up to three weeks.

11.7 Keeping in Touch …

The times when only the manufacturer was in possession of a special electronic interface to "their" wind turbines are long past. In wind farms the turbines of different manufacturers must be combinable and compatible across the system in terms of SCADA (Supervisory Control and Data Acquisition) – this was one of the specifications in the Alpha Ventus research project. And it was fulfilled. The server that was developed is completely compatible with the SCADA systems of other manufacturers. The new standard interface enables the AD 5-116 to be used in mixed wind parks with several different types of wind turbine. This also means that the additional expenditure in the development of SCADA systems is kept to a minimum. The new interface is also used in the neighbouring wind farm Trianel Windpark Borkum (40x AD 5-116), which was built in 2014.

11.8 Keep Turning in High Wind …

Wind turbines usually switch off in high wind. They change into the so-called idling mode to keep the enormous strain on the foundation to a permissible limit. In the case of AD 5-116 this occurs at wind force 10 and can result in a loss of power yield, particularly in high-wind offshore locations.

The engineers have devised a solution for this that enables the continued operation of the offshore wind turbine at reduced power during high wind. The newly developed control strategy pitches the blades to a position away from the wind to reduce the pressure on the rotor and therefore the strain on the foundation. A new type of sensor system additionally recognises peak loads and uneven stress on the rotor before the situation becomes critical. The plant reacts automatically with individual pitch control (IPC) for each blade and can therefore avoid short-term extreme loads. This regulation strategy results in an increase of the annual power yield but not of the load level.

Peripheral Anecdote (I): One plant with many fathers!

Ingo de Buhr (then Prokon-Nord) was the first and only planner of a wind farm project to take on the challenge and become a manufacturer of wind turbines. He took over the Multibrid development corporation of the Bavarian wind turbine manufacturer Pfleiderer and thereby "inherited" the plans for a multi-megawatt machine together with a patent licensing agreement with the plant developer Aerodyn. After the prototype had been built on land, the exclusively offshore machine with Multibrid M5000 technology was first implemented in Alpha Ventus. The French energy concern AREVA joined Multibrid at the end of 2007 and took over 100 % of the shares in 2010. The joint venture Adwen Offshore was established in 2015 between the Spanish manufacturer Gamesa and AREVA who have brought their M5000 wind turbine types AD 5-116/AD 5-135 and their offshore projects entirely into the new enterprise.

Björn Johnsen

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11.9 Helicopter Air-Drop Platform: Abseil!

To avoid any misunderstanding: air-drop here means abseiling. But this has nothing in common with a safe descent on firm ground! Helicopter air-drop platforms are needed for emergencies or perhaps essential quick maintenance work when a vessel cannot approach the wind turbine because of high wind and waves. Here again there were at first no DIN standards at all in respect of offshore wind energy. At the beginning of the project the only advice came from international regulations which was more or less "Heli-decks on offshore (oil) platforms, please be kind enough to comply". After the construction of the German offshore wind energy test field, the minimum requirements for helicopter air-drop platforms on offshore wind turbines were legally established in Germany. The "Principles of the Federal Republic of Germany for Service Areas on Wind Turbines" have applied since 2012 (Federal Gazette of 27.01.12). The helicopter platform (◘ Fig. 11.7) built for the AD 5-116 was accepted and approved by the Federal Maritime and Hydrographic Agency (BSH) and the Federal Ministry of Transport, Building and Town Development; certification was by Germanischer Lloyd (DNV GL). A patent is pending, and the economic potential is high: these helicopter decks were subsequently also installed on the 40 wind turbines in the neighbouring wind farm Trianel Windpark Borkum in 2014 and the 80 wind turbines in the offshore wind farm Global Tech I.

11.10 Drivetrain in Long-Term Test

Trust is great, control is better. For everyone concerned. In order to find out exactly what loads the main components in the drivetrain are subjected to, the drivetrain of an AD 5-116 was completely taken apart and examined. After four years of service and production of 38 gigawatt hours of power. In particular, the suppliers of the components were invited to take part in the assessment because they also profit from the findings obtained. Interim result after four years: the encapsulation of the wind turbine works and lives up to expectations, all screw connections

Fig. 11.7 A technician is lowered onto the winch platform for a service assignment. © Adwen/Jan Oelker

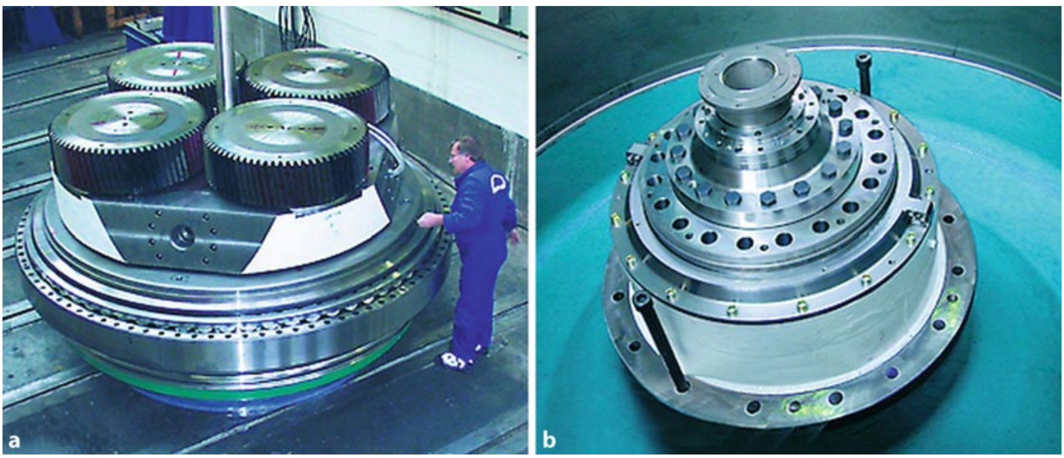

Fig. 11.8 Planetary gear (**a**), detailed view (**b**). © Adwen/Jan Oelker

were free from corrosion and easily loosened. According to the assessment of independent experts, the rotor blades are in a normal condition in consideration of their operational service.

The blade bearings with raceways, cage, rolling elements, gear teeth and sealing were flawless according to the manufacturer present during the examination. They could well reach their expected service life of 20 years. The main bearing with raceways, cage and rolling elements was also in a good condition, said the component manufacturer. As expected, close attention was paid to the gearbox, which was removed and then examined by independent experts. They pronounced that there was no reason to change the design of the gearbox (Fig. 11.8). The large slide bearing C (near the oil pocket) is free from significant deformation and can continue to be used. There was no indication of overheating or false oil circulation. The gearbox is therefore in a good condition. Nor were there any complaints when the generator was inspected.

Overall conclusion of the experts about the "used" drivetrain: the technical concept of the offshore wind turbine AD 5-116 was confirmed together with the materials used and the design of the components. All findings are important because

Fig. 11.9 A view inside the assembly shed. © Adwen/ Heike Winkler

they may on occasion lead to improvements and, in particular, lead to more exact data concerning the service life of the components. The significant results of a technical examination are important for the financial feasibility of future offshore wind farms. By the way, the drivetrain was reassembled and returned to service (Fig. 11.9).

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11.11 Sources

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Shooting into the Wind with Laser Beams

Lidar Wind Measurements in the Offshore Test Field open up New Horizons

Björn Johnsen

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power,* DOI 10.1007/978-3-662-53179-2_12

Project information: Development of LiDAR measurement techniques for the German offshore test site (LIDAR I)

Project management:
University of Stuttgart, SWE – Stuttgart Wind Energy
Andreas Rettenmeier

Project partners:
- ForWind – Center for Wind Energy Research, University of Oldenburg
- FGW – Federation of German Windpower
- German Aerospace Center (DLR)

Project information: Development of nacelle-based lidar technology for the measurement of power performance and the control of wind turbines (LIDAR II)

Project management:
ForWind – Center for Wind Energy Research, University of Oldenburg
Prof. Martin Kühn

Project partners:
- Adwen GmbH
- University of Stuttgart, SWE – Stuttgart Wind Energy
- FGW – Federation of German Windpower

Wind turbines are getting taller and taller, with hub heights of 120 to 150 metres and more now quite common. The taller the turbine, the greater the work involved in the erection of met masts that can measure the wind conditions so that wind turbines can be operated efficiently. At the same time, turbulent airflow determines the wind conditions at such heights. On land the wind turbines are also often situated in complex terrain: hills, valleys, mountains or even buildings in the wider surroundings also ensure complicated wind flow patterns. New measuring methods are needed in order to be able to make more reliable statements about such wind conditions at blade tip heights of 50 to 300 metres. One of the most promising procedures to date is shooting laser beams into the wind!

While this might initially sound like something out of "Star Wars", not only can it be used to measure the wind speed directly in front of the rotor, but also to capture complete wind fields along with their currents and the resulting loads on the wind turbines, thereby enabling better micro-siting when planning a wind farm. This applies both offshore and onshore. It is thus no wonder that the lidar research is one of the RAVE Initiative's largest projects. On completion of the four-year Lidar I project the scientists continued their research in the follow-up project Lidar II.

12.1 How It Works

Lidar (light detection and ranging) devices shoot laser beams into the air at the speed of light. There they can hit even the smallest particulate material, such as dust particles, that are almost always to be found in the air: the so-called aerosols. The most frequently occurring aerosols above the sea are salt crystals. These particles always move in the current wind direction, and when hit by a laser beam they reflect a fraction of the laser light back towards the lidar device, which then evaluates the signal. If pulsed laser beams are used, it is possible to measure the wind at different distances and heights above the ground or surface of the sea simultaneously, just as radar is used to measure the distance to an object. This thus gives not just one wind speed at one position, but a complete "wind field" in the surrounding air. In other words, it can do a lot more than the conventional wind meters usually found in meteorological stations, which can only capture and measure at one single point.

12.2 Not Just Research for Research's Sake

So we have an abundance of topics, with an abundance of institutes involved. Lead partners in the research project "Lidar Wind Measurements for the Offshore Test Field" were Stuttgart Wind Energy (SWE) at the University of Stuttgart and the ForWind Center for Wind Energy Research at the University of Oldenburg. The German Wind Energy Institute (DEWI) was called in for power curve measurements, while the German Aerospace Center (DLR) supported the project both with its knowledge of lidar and with its own long-range lidar. While cooperation between the wind industry and the aerospace industry might otherwise offer room for improvement, on the lidar project it was conspicuous.

The Federation of German Wind Power (FGW) played a lead role in passing on the research findings to the German industry and in the guidelines resulting therefrom. All in all, this was not just research for the sake of it, but research that has direct consequences for the wind industry and for the further development of wind energy technology. Sometimes it is only possible to see the real value of the work in hindsight, which is why independent research is so important.

12.3 Lidar Technology

12.3.1 Snowfall Test in Swabia

Almost 1,000 kilometres south of Alpha Ventus; not on the high seas, but in truly complex terrain: the first test for the research project with a lidar instrument took place in 2008 on the roof of Stuttgart Wind Energy (SWE), not far from the Swabian Jura. The test used a French-made instrument that can measure winds of up to 30 m/s at heights of 50 to 200 metres (Fig. 12.1), hence far above the normal cut-out wind speed for wind turbines. It can also capture several measuring heights simultaneously. The reference instrument used later for comparison and to investigate the wind in the wake flow of wind turbines was a pulsed Doppler wind lidar with 2 µm wavelength from DLR in Bremerhaven.

The French lidar works on the ground, so it's not attached to the nacelle of a wind turbine. The first test on the roof of the institute in Stuttgart was carried out in wintry conditions (Fig. 12.2). There was snow and ice all around, but the instrument worked. The lidar was modified by SWE and fitted with a more flexible scanner unit.

The lidar emits up to 10,000 laser impulses or shots in the four main wind directions (north, south, east, west) and at up to ten predefined heights. Each measurement cycle takes half a second. A further half-second is needed to calculate the readings received, to turn another 90 degrees to the next compass point and then to shoot the next laser beam.

Fig. 12.1 Measurement principle of the lidar system. © Leosphere

Fig. 12.2 Initial test on the roof of Stuttgart University. © SWE University of Stuttgart

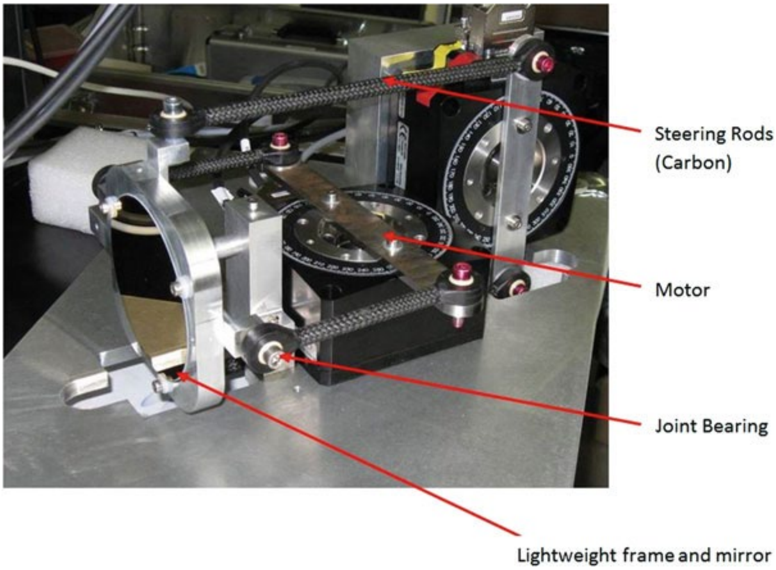

Fig. 12.3 View of the SWE scanner system. © SWE University of Stuttgart

The course of the scan describes the volume of a cone. The whole measuring period for six different measuring heights is just 1.5 seconds. Two things are important for a precise measurement: first a particular minimum concentration of aerosols in the air needed to reflect the beams, and secondly a high laser power in order to get a clear signal from the backscattered light beams.

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12.3.2 Scanner System and Specification Offshore

Scanner and reflector are the crucial factors for developing a simple lidar to reach new heights – for use on the nacelle of a wind turbine. A scanner system with a control unit was developed for nacelle-based lidar measurements (Fig. 12.3). The reflector is used to steer the laser beam in any desired direction.

The scanner and control unit were integrated in a second casing that can be connected to the lidar. This way – depending on the assembly – you can capture the wind field in front of or behind the wind turbine – and in each case with a range of several hundred metres. Furthermore, the wind field is now captured three-dimensionally, resulting in a complete flow pattern. Thanks to the scanner and reflector it is possible to direct the laser beam in the desired, predefined positions. With several thousand laser shots within half a second it only looks like continuous blind shooting – but the points have in fact been clearly defined beforehand. The scanner in the lidar follows the predefined times and points. By measuring at five points along the laser beam you can measure the so-called "radial velocity". Parallel to this the researchers developed the necessary simulation software.

The initial test of the new nacelle-based lidar scanner system was not carried out on a rooftop in Swabia. The trial was done in 2009 near Alpha Ventus, but still on land: on the prototype of the Adwen AD 5-116 outside Bremerhaven, where the system was mounted on the roof of the nacelle. This was done quite traditionally, using scaffolding clamps and poles. With this experimental scanner it was now possible to use the lidar for measuring the power curve and the load measurements.

12.3.3 Wind Measurement Buoy on the Crest of a Wave?

The ground-based lidar also shows what it can do offshore: it was installed on the Fino 1 platform, but still ground based. There it also demonstrated a good correlation with the anemometer measurements from the met mast. It was also possible to achieve good availability of the instrument at all heights off-

Fig. 12.4 First measured prototype in Bremerhaven and the met mast. The lidar (not visible in the photo) is located about 10 m from the met mast. © SWE University of Stuttgart

shore as well. This is down to the high concentration of aerosols over the North Sea, which enables a better reflection of the laser beams. Incidentally, lidar instruments are also suitable for "offshore spin-off inventions" and lead to other developments. One example is a buoy the so-called "Floating lidar". These float on the waves and make it possible to carry out wind potential measurements offshore without the need for massive, stationary ground foundations.

12.4 The Burden of the Power Curve

12.4.1 From Wmo to Demo

A look back at the days before lidar: up to now the power curve for a wind turbine (▶ Sect. 20.5) was measured with a point measurement of the wind speed and wind direction, ideally with a distance from the met mast to the turbine of 2.5 times the rotor diameter – according to an International Electrotechnical Commission (IEC) guideline. The "power curve measured in accordance with IEC" is the central benchmark for the wind turbine and the basis of the yield calculations. Measuring a power curve with these parameters at locations with weaker wind strengths can require several up to nine months until enough data for all occurring wind speeds can be gathered.

In the case of the Adwen AD 5-116 prototype in Bremerhaven the lidar was initially installed directly adjacent to the met mast (Fig. 12.4) – and the comparative values were very good. So the lidar does also work without met mast onshore (wmo).

For the offshore test it was once again back to the roof. The ground-based lidar system was erected on the roof of a container on the Fino 1 research platform in the North Sea, ten metres from the met mast (Fig. 12.5). Here it was easily possible to compare the data with that from the "conventional" cup and ultrasonic anemometers and wind vanes. In the case of the cup anemometer the availability at all heights was just short of 100 %, and with the ultrasonic anemometer it was 97.5 %. At all measuring heights on Fino 1 the availability of the lidar was 98 %. At the new windy height of 200 metres without met mast the availability dropped to 91 %. This is due to the fact that the signal-to-noise ratio decreases with increasing height – so here we need further development, especially powerful laser devices.

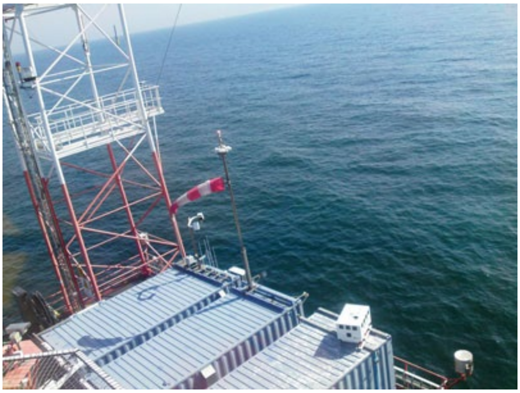

Fig. 12.5 Position of the lidar on the container (*right*) on the Fino 1 offshore research platform. © UL International (DEWI)

Peripheral Anecdote (I): A bit too hot
The sun and the north both have their own laws. When used on the Adwen AD 5-116 prototype in Bremerhaven the new lidar scanner worked for ten months without any problems. Well, almost without any problems. On hot summer days the temperature inside the casing reached 40 degrees Celsius, with the result that the software thought it had "a bit of a temperature" and so switched the whole system off automatically. To avoid this happening out at sea the lidar used on Alpha Ventus had a sunshade fitted.
Björn Johnsen

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At met mast height the lidar achieved similarly good results as the conventional devices, not just regarding availability but also with the actual measurements. The offshore lidar trial on Fino 1 lasted one year. The ten-minute average readings showed over 99 % conformity with the anemometers. The discrepancies between lidar and anemometer are thus smaller than the measurement uncertainty of the met mast.

The wind profiles and turbulence intensities at sea are different from those on land. In this respect it may prove beneficial to differentiate between a power curve with unrestricted wind inflow and turbulence intensities of 5 to 10 %, and a power curve within a wind farm with significantly greater turbulence intensities. This could enable an easier measurement method using lidar within an offshore wind farm – and make a major contribution in ensuring that planners, operators and turbine manufacturers have a fast instrument for verifying wind power yields at their disposal.

The influence of the vertical wind profile and the turbulence intensity on the dynamic performance characteristics was also investigated. To this end, the lidar wind measurement was carried out at five different measuring heights within the rotor diameter of the Adwen AD 5-116. The capturing of the whole swept rotor area can improve the accuracy of the dynamic performance characteristic. This not only applies to the vertical wind profile – the course of wind speed and wind direction with the height – but also for measuring the turbulence characteristics across the whole swept rotor area.

12.4.2 Lidar on the Nacelle

Can you also get reliable power and load curves from nacelle-based lidar measurements? Here the lidar is not on the ground, but on the nacelle or directly on or in the spinner, e. g. on the roof of the nacelle as with the tests using the Adwen AD 5-116 near Bremerhaven. In the practical test the nacelle-based lidar system with scanner apparatus also achieved results highly comparable with those of conventional anemometers in this area of application. And that is not all: due to the lidar being on the nacelle it is possible to measure the whole wind field in front of a wind turbine for the first time; and not just the vertical wind inflow conditions "above and below", but the whole wind field across the gigantic swept area including the inclined flow (Fig. 12.6).

This not only provides a lot of new data about the movement of the wind, but possibly also a better understanding of the "interaction of wind and wind turbine". And with the inclined flow it identifies a cause for a weaker power yield or stronger, temporarily occurring loads on a wind turbine. It shows that with nacelle-based lidar wind measurement there is a good correlation between wind speed and power output of a wind turbine.

Nacelle-based lidar measurements can in any event measure the transient performance charac-

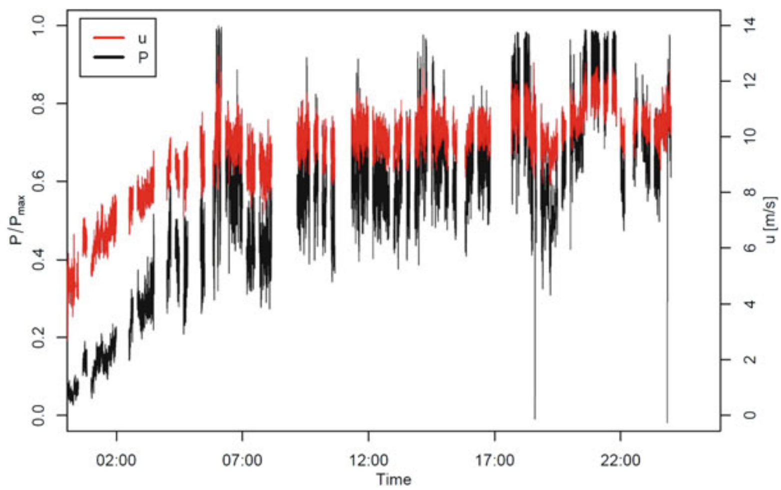

Fig. 12.6 Measured data for wind speed (*red*) at a distance of 116 m and the turbine output. © ForWind – University of Oldenburg

teristics as well as the power curve of a wind turbine significantly faster and in more detail than a ground-based measurement, because the measuring system turns with the wind direction – and thus also with the nacelle of the wind turbine. Provided of course that the lidar instrument in/on the nacelle is robust and powerful.

12.5 Turbulent Wind Fields in Front and Behind

12.5.1 Inflow from the Front, Initial Investigations into System Control

Gusts of wind, inhomogeneity of the incoming wind field (vertical and horizontal wind gradients, when the wind decreases near ground level, partial gusts) are currently the main load factors affecting wind turbines. This is expressed in terms of high load peaks and frequent alternating loads, with up to 100 million alternating loads in the lifetime of a wind turbine. At present, load reductions can only be actively achieved with control measures by changing the rotor speed or through collective pitch adjustment, after the wind impulse – i. e. the load impact – reaches the turbine. But at that stage the load has already hit the turbine or is already past! A fast wind field forecasting system within the short-term range of 5 to 30 seconds could help remedy the situation, an anticipatory and proactive system that relays the relevant information to the turbine control system before the wind reaches the wind turbine. Such systems have already been simulated – what is lacking is the practical implementation …

Peripheral Anecdote (II): Open the flap!
In the wind tunnel at the University of Oldenburg they are following new paths "in the search for turbulences". Here they place a heavy grating in the tunnel, which consists of 126 individually moveable panels and flaps. The flaps can be moved in a variety of directions by means of 16 axes, also against one another. This way the researchers try to generate air vortices and reproduce the turbulences that prevail in front of a wind turbine. In conventional wind tunnels there is just an even flow of wind in one direction, which then flows over a rotor blade, for example. This is rather an unrealistic model – reality and nature are wilder.
Björn Johnsen

12.5.2 Simulation Is Part of Testing

The Witlis (wind turbine lidar simulator, Fig. 12.7) was developed as the preliminary step to creating such a system. The lidar system to be developed

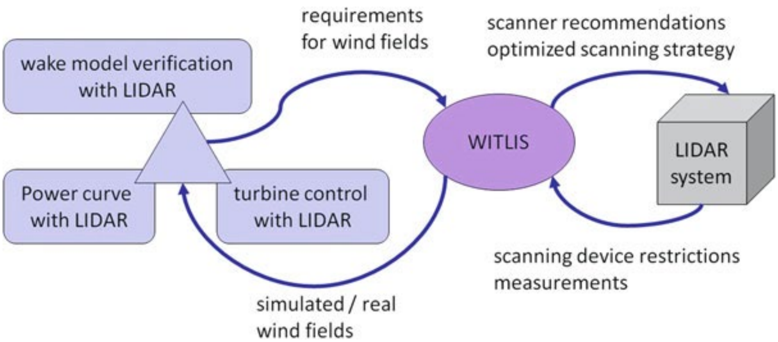

Fig. 12.7 Scanner development concept with Witlis. © SWE University of Stuttgart

should provide wind fields for wake verification, for power curve measurement and for controlling a wind turbine. In other words, very different tasks with rather different requirement profiles: for measuring the wind vortex – the air turbulence behind a wind turbine – you need high-resolution spatial measurements, but for controlling you require rather more high-resolution temporal measurements. And this in turn means the scanning system has to be more flexible.

There is a lot of development potential in the system controller, and there has been a lot of experimentation and trials. For example, a lidar-based controller was compared with a standard controller and checked in ten-minute wind fields. In a second step, Witlis was paired with a commercial aeroelastic simulation tool. In the first trials, virtual tests were made of identified options with considerable (up to 30 %) load reductions of the tower bending moment.

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12.5.3 Like a Smoke Trail – the Wind Loads Behind the Turbine

The wind flow field behind a wind turbine has a considerable impact on the wake – before it reaches the next turbine in the second or third row in the wind farm. Even where the distances between the turbines are greater, only on statistical average does it appear to be like the "even" shadow impact of a building structure. In reality this wind in the wake moves slowly to and fro to the stream – and as "wave meandering" it resembles more the billows of smoke from a tall chimney or the vapour trail behind a large passenger plane! And this "wake" additionally creates an irregular load on the main components of the wind turbine behind.

While an accurate determination of the wake flows of multi-megawatt turbines is desirable, this can only be achieved with elaborate scientific simulation techniques (CFD), which require a lot of computing time. This means that broader industrial use is hardly practical at present.

» We still don't know enough
In recent years there have been huge advances in all areas of wind technology. And yet we still don't know enough. At best, we can only describe the incoming wind flow on to the rotor blades in broad terms. But new knowledge also opens up new possibilities.
Dr. Matthias Wächter, ForWind, Institute of Physics, University of Oldenburg

A simulation model for the dynamics of the wake of multi-megawatt wind turbines was developed during the research project. This Disc Particle Model (DPM) now makes it possible to generate synthetic time series of wakes for the most different atmospheric situations. Great turbulences in the atmosphere that can alter the wind direction shift

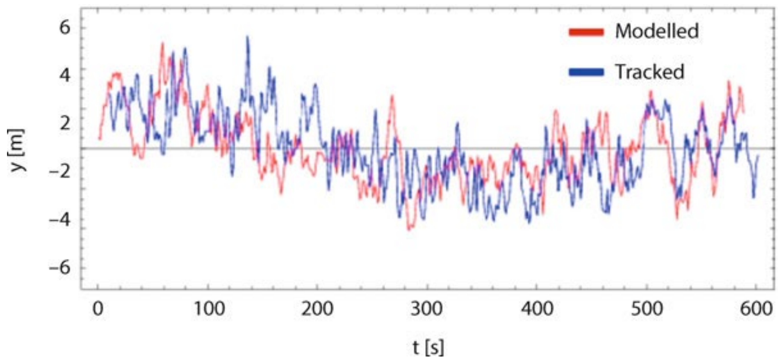

Fig. 12.8 Comparison of modelled (*red*) and measured (*blue*) time series of the wake position. © John Wiley & Sons

the wind wake in lateral and vertical direction – almost like a body. In contrast, smaller turbulences do not alter the wind direction, but do cause a mixing-up of the wake. In science, similar models are used for modelling the distribution of contaminants and toxic gases in the atmosphere. The whole trail of smoke is reconstructed using a large number of particles. The models make it possible to observe the behaviour of the particles and thus also the smoke trails for different atmospheric stratifications.

The wake simulation model that was developed was compared with the real lidar measurements. This showed a large degree of congruence between simulation model and lidar measurements (Fig. 12.8). It also turned out that the lidar instrument measures with higher temporal resolution – in millisecond range – and spatial resolution than conventional anemometers.

These simulation models for wind turbine wake loads need to be developed further. By taking better account of the wind wake behind the first row of turbines it would be possible to develop recommendations for improved positioning of the turbines in the second or third rows of a wind farm.

12.6 Quo Vadis? New Offshore Measuring Method and FGW Guidelines

The results with the new ground-based lidar measurements mean that it is possible to use the ground-based lidar system along with a reference mast to measure the power curve. This has been included in the IEC norm and the corresponding Federation of German Wind Power (FGW) directive. As far as the nacelle-based results are concerned, they also have some influence on the FGW guideline activities, and the same goes for the non-stationary power curve measurements. The experiences gathered from the lidar research will be made available to the entire wind industry.

12.7 When the Nacelles Have Lidar

A start has been made with the Lidar I research project, but lidar work continues. In the near future we can expect to see multi-megawatt turbines with output capacities of 10 MW and more. Ten-megawatt wind turbines will have rotor diameters of around 250 m, with a swept area the size of five football pitches. Such power plant scale turbines require new, adapted control and monitoring strategies. Here it will be crucial to reduce the enormous wind loads effectively and under minimum use of control systems. The goal is to feed their generated electricity into the grid with an already optimised yield while thereby being able to identify small deviations from intended normal operation early on.

12.7.1 Modern Control Systems First React upon Wind Impact

Despite many advances in all areas of wind energy technology, this vision faces one fundamental obstacle: there are too many uncertainties and too little knowledge about what can at best be described as statistical inflow onto the swept rotor area. And the current control concepts for wind turbines can only react to changes in the incoming wind field which have already provoked rotor speed or load changes.

In assessing the average or momentary output it is unclear which wind conditions on the special site in the wind farm have caused them. A precise variance analysis is therefore impossible.

The follow-up research project Lidar II "Development of nacelle-based lidar technology for the measurement of power performance and the control of wind turbines" should develop several technological components.

12.7.2 Robust and Suitable for Industrial Use

One of the main goals of the project is to continue to develop a lidar system for nacelle-based use on wind turbines that is "robust, cost-effective and suitable for industrial use". The series price of the new instrument must be competitive with the ultrasound anemometer technology used to date. Ideally it would be best to integrate the lidar in the spinner of the wind turbine, but if necessary it could also be mounted on the roof of the nacelle. Here it would be necessary to use modern, reliable components to guarantee low-maintenance automated operation all-year round. A prototype could be tried out in Alpha Ventus within the scope of the project. The "commercialisation" of the new device starts now, straight after the completion of the project in 2015 – in other words: marketing and preparations for series production.

Based on the nacelle-mounted lidar wind measurement, other methods were also developed during the project, which meet the requirements for power curve measurement in accordance with the international IEC guideline (IEC 61400-12) and at the same time determine the dynamic performance characteristics in the fast 1-Hz range. Result: the direct measurement of the incoming wind using a nacelle-based lidar leads to a shortening of the measuring time necessary for determining the power curve and to a significant reduction of uncertainties about the incoming wind field. Lidar instruments are not of course to be seen as a total substitute for the nacelle-mounted anemometers normally used today, because in a very few weather conditions – such as snowfall – lidar measurements are not possible and it is necessary to fall back on conventional sensors. Lidar devices can however measure and process important information about the incoming wind field faster and more accurately – before the wind field has reached the wind turbine. Because, as opposed to permanent, continuous laser beams, pulsed laser "points" enable multiple measuring distances simultaneously as well as a constant measurement volume, the project decided to use the pulsed lidar method.

For examining the stationary performance and yield potential the lidar scanner that was developed was tested offshore on the nacelle of a Senvion wind turbine in Alpha Ventus – on turbine AV4 on the north-western edge of the wind farm. The location had the advantage of being a distance of 400 metres (corresponding to 3.2 times the rotor diameter) to the Fino 1 research platform and its wind measurement data could be used immediately for comparison. Due to the device not being watertight and the resulting water penetration there were several hardware breakdowns during the four measurement campaigns. The measuring period was therefore extended into the spring of 2015 so that the planned measurement campaigns could be successfully completed.

12.7.3 Collective "Blade Feed Forward Control" Before the Wind Hits?

In the continued lidar project a monitoring method was developed that enabled continuous monitoring of the performance behaviour. A more precise, early regulation of a wind turbine with a nacelle-mounted lidar system can also increase the energy yield – by means of a more exact wind realignment and improved speed control. But first and foremost the lidar system should significantly reduce the extreme and fatigue loads of wind turbines. Trials and experiments were carried out here as well in order to develop and test the most suitable control strategies.

The favourite by far is a control concept for collective blade angle feed forward control that, thanks to lidar measurements, receives the necessary information about the incoming wind field and can thus proactively intervene as the situation demands. In a complex process a lidar feed forward control was successfully developed and simulated for an Adwen wind turbine (Turbine AV7 in the wind farm). This demonstrated that with the collective blade angle feed forward control there could for example be a load reduction of up to 20 % on the tower. Whether the feed forward control is largely used for load reduction, for positioning activity or speed variability, depends mainly on the decision of the wind turbine manufacturer when designing "his" turbine. A more complex individual blade feed forward control was also developed during the project, which however only offers minor advantages over the collective blade feed forward control.

At the end we have here a technology transfer of research results from Alpha Ventus to the entire German wind industry, especially to the technical committee conference of the Federation of German Wind Power (FGW) – and significantly beyond. As a result we now have "Wind Task 32" of the International Energy Agency concerned with "wind lidar systems for wind energy development", which in the meantime deals with eleven lidar topics, ranging from wind field reconstruction to nacelle-based power curve measurement. The know-how transfer is in full swing.

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"Get Out of My Wind"

About Wind Farm Shadowing, Wakes and Turbulences

Björn Johnsen

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power,* DOI 10.1007/978-3-662-53179-2_13

Project information: Analysis of shadowing effects and wake turbulence characteristics of large offshore wind farms by comparison of "Alpha Ventus" and "Riffgat" (GW Wakes)
Project management:
ForWind – Center for Wind Energy Research, University of Oldenburg, Institute of Physics
Prof. Martin Kühn
Project partners:
- Fraunhofer Institute for Wind Energy and Energy System Technology IWES

Even if it initially sounds like a somewhat unpleasant concept: every time a wind turbine turns, it brakes the incoming wind and then churns it around as it passes through the rotor blades. This creates a wake, a vortex of increased turbulence that has a shadow effect on the turbines behind. This results in reduced yield and increased alternating loads on the wind turbines in the rear rows, which can shorten their service life. The behaviour, especially the dynamics, of these wakes and their interaction in wind farms is complex and difficult to gauge. Up to now, the planning and simulation models contain uncertainties and inaccuracies in the assessment of shadowing and follow-on effects under different meteorological conditions. This leads to risk premiums when planning offshore wind farms or can cause a reduction in electricity supply. This inhibits the economic efficiency of projects. And these shadowing effects do not just occur within a wind farm, but even whole wind farms can be shadowed by one another. It is possible for the wake vortex of a wind farm to extend tens of kilometres.

The shadowing losses and characteristics of the wake turbulences within offshore wind farms were analysed in a large-scale joint research project consisting of two large sub-projects: the measurements in the German offshore test field Alpha Ventus, which are part of the RAVE research initiative, and the measurements in a second, much larger offshore wind farm for comparing and verifying the investigations carried out so far. This was originally intended to be the Bard Offshore 1 wind farm with 80 turbines, each with 122 m rotor diameter. As a result of the insolvency of the Bard Group it was necessary to find a new location for the measurements. A good replacement location was found in the shape of the Riffgat offshore wind farm. The wind farm has 30 turbines with 120 m rotor diameter and measurements began in summer 2015.

13.1 Measure More with Multi-Lidar

The first time a multi-lidar system was ever used offshore was in the GW Wakes research project at the Alpha Ventus wind farm. This remote sensing method uses laser beams to determine the wind flow (see ▶ Chap. 12 "Lidar – Shooting into the wind with laser beams"). The GW Wakes project used three so-called "long-range lidar wind scanners" for the measurements in Alpha Ventus as a multi-lidar with a range of several kilometres. For the approximately eight months of the measuring campaign, two of these wind scanners were set up on the Fino 1 research platform west of Alpha Ventus, with the third scanner on the AV0 transformer platform to the southeast (◘ Fig. 13.1). By setting up the scanners at two physically separate locations (◘ Fig. 13.2) it was possible to carry out a variety of measuring scenarios. With this configuration, the intersecting and overlapping lidar measurements make it possible to calculate the horizontal, two-dimensional wind vector in large areas of an offshore wind farm, which is why the MuLiWEA (multiple lidar wind field evaluation) algorithm was developed in this research project. Taking into account a two-dimensional continuity equation, this calculation process generates the so-called 2D wind field, with wind direction and intensity, using the data from several lidar devices.

A specially developed measuring buoy was anchored near Fino 1 (◘ Fig. 13.3), which also records the water surface temperature, the air pressure and the air temperature. These measurements contribute to a better understanding of the dynamics and turbulences above the sea (see ▶ Chap. 17 "Sometimes it almost bubbles like a witches' cauldron"). The measurement profiles of air temperature, atmospheric pressure and humidity have proven to be a source of important information for describing the wakes. This becomes particularly clear with the example of the thermal: onshore, when the sun

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Fig. 13.1 Long-range lidar on the Alpha Ventus transformer platform. © ForWind – University of Oldenburg

shines onto a dry sand hill, the air there heats up faster than over a marsh and then rises. Offshore, the sea is still comparatively warm in autumn, even though the wind is already cold – and this creates an unstable stratification of the atmosphere over the water. These atmospheric stratifications significantly influence the behaviour of the wakes. This influence could be metrologically measured more accurately.

13.2 A Deficit Is Obvious – Where the Wind Is Concerned

In the GW Wakes research project the wakes are measured with lidar in up to 240 measuring points with a range up to 6.5 kilometres behind the wind farm.

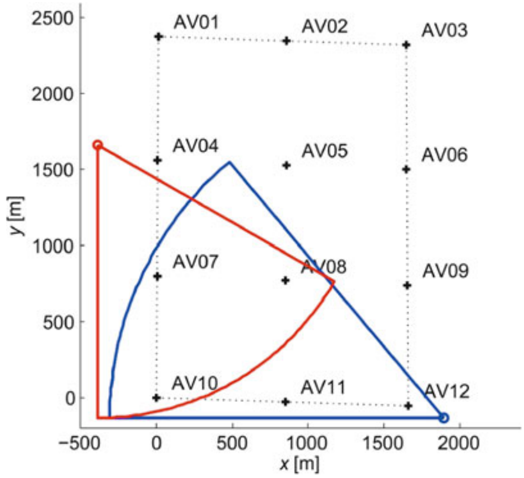

Fig. 13.2 Schematic representation of the measurement scenario in the Alpha Ventus offshore test field. One lidar on Fino 1 (*red*) and one on the transformer platform (*blue*) measure the wake vortex of turbine AV10. The *areas* captured by the instruments are *outlined in red and blue*. © ForWind – University of Oldenburg

Thanks to the high temporal resolution of the measurements it was possible to detect and investigate the dynamics of the wakes in detail. The evaluations of the measurements clearly show the meandering wake behind the wind turbines, with this example showing it with a southeast wind (Fig. 13.4).

The wake flow behind the wind turbines very much depends on the incoming wind direction in front of the turbines. The graphic (Fig. 13.5) shows how the wind velocity deficit behind the wind turbines depends on the inflow direction on the basis of numerical computer simulations.

13.3 Satellites, Lidars and a Source Code

Measurements made with long-range lidars were also compared and combined with those taken using satellite radar. The radar technology covers a very large area, making backscatter images of the sea surface and thereby using the intensity of the backscatter to measure the roughness of the sea surface. This can be used to derive the wind speed. This method can capture significantly larger areas than lidar, though the satellite can only measure

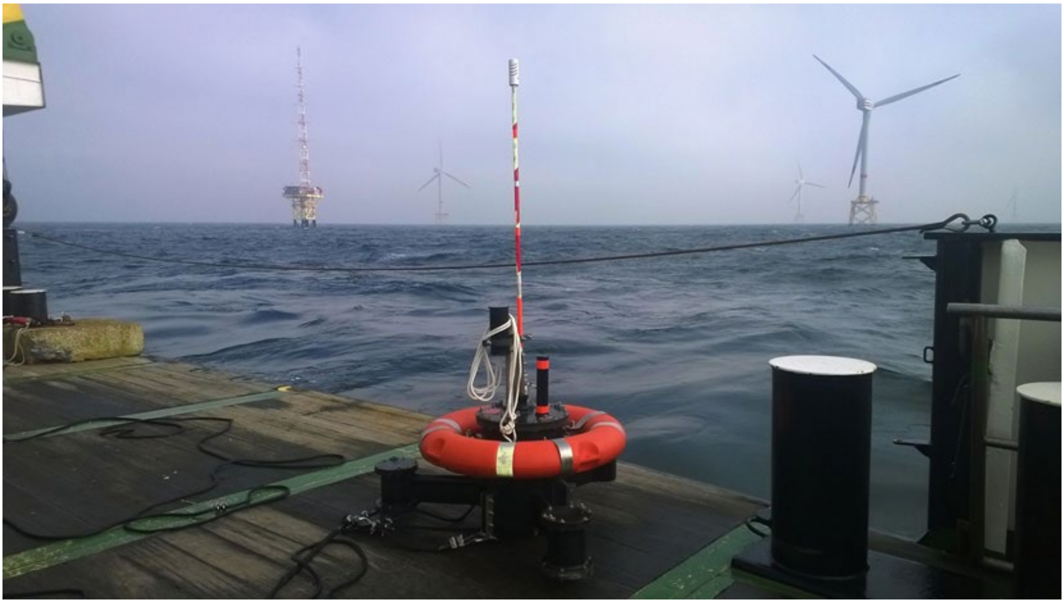

Fig. 13.3 The measuring buoy used in the GW Wakes project before it was positioned near the Fino 1 research platform. © BSH

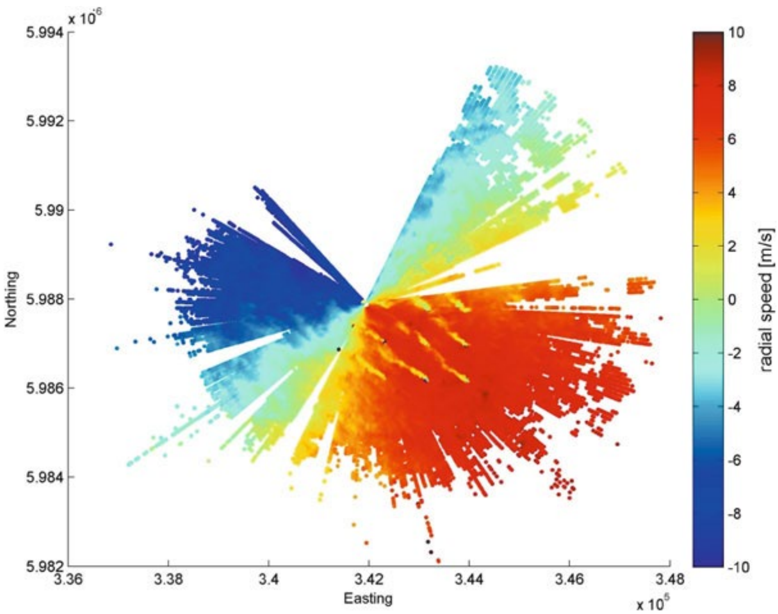

Fig. 13.4 Measurement of the wind flow in Alpha Ventus with a lidar mounted on Fino 1. The speed component is shown in *different colours* looking towards the lidar (radial speed or line of sight speed). The prevailing wind direction is southeast (*red fields*). The wakes of the wind turbines of the southernmost three rows of turbines can be seen clearly (*below right*). The *white sectors* show where the view of the lidar is blocked by objects on Fino 1. © ForWind – University of Oldenburg

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the same position every two or three days. A lidar on the other hand can take measurements in the same region continuously, with higher spatial resolution than the radar satellite and at various heights. But when both were combined – lidar and satellite technology – the initial comparison proved to be a promising instrument for detecting the characteristics of the wakes, and should be used to do this in future measuring campaigns to make the most of the respective advantages of the individual systems.

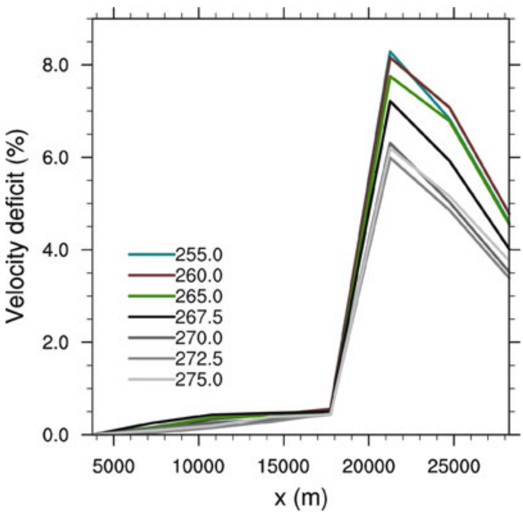

Fig. 13.5 Average velocity deficit from numerical calculations by averaging over grid elements sized 3.5 × 3.5 km^2 for inflows at the Alpha Ventus wind farm from directions between 255 and 275 degrees. The farm's turbines stand in an area 19,500 to 23,000 m behind the inflow margin, and here a marked increase of the deficit is clearly visible. In the area behind the wind farm it slowly decreases again. © ForWind – University of Oldenburg

The GW Wakes project partner Fraunhofer IWES used the findings and approximation models from the GW Wakes research project to augment the "Flap-FOAM" wind farm optimisation software. The programme continues to be developed further within the scope of the ongoing project and validated with real measurements.

13.4 More Accuracy Without a Mainframe Computer

The first measuring campaign in Alpha Ventus has been successfully completed. With northerly or southerly inflowing wind it was only possible to measure fourfold overlapping wakes at most, because the offshore wind farm only consisted of four rows with three wind turbines each. In the summer of 2015 measurements were taken at the Riffgat offshore wind farm for purposes of comparison and for mapping the results onto large offshore wind farms – with lidar and additional measuring systems on four wind turbines. Riffgat, around 15 kilometres northwest of Borkum, is suitable for investigating multiple overlapping wakes, in that there are 30 turbines on the wind farm. While their rated capacity of 3.6 MW is a bit less than the 5 MW wind turbines in Alpha Ventus, what is interesting for the research project is the arrangement of the turbines. In Riffgat the turbines are arranged in three rows of ten machines. So if for example the wind comes from the southwest, this results in tenfold overlapping wake currents behind the wind turbines, which can be measured and investigated.

The overriding objective of the ongoing, overall research project is to gain a better understanding of the wakes that arise behind the wind turbines and their interactions. The next step will be the application of this knowledge and its transfer into industrial practice: the development of efficient, numerical computer models that do not just run on a mainframe computer, but which can be used directly in the planning of wind farms. This will lead to significantly reduced uncertainties in the calculation of wind farm shadows and wake turbulences – and to more precise wind yield estimations, which could in the end contribute to better wind farm planning and operation.

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The First Test for Offshore Turbines

Design Requirements for Offshore Wind Turbines on Trial

Björn Johnsen

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power,* DOI 10.1007/978-3-662-53179-2_14

Project information: Verification of Offshore Wind Turbines (OWEA)
Project management:
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Project partners:
- Adwen GmbH
- Leibniz Universität Hannover, Institute of Steel Construction
- Senvion GmbH
- UL International GmbH (DEWI)
- University of Stuttgart, Institute of Aerodynamics and Gas Dynamics
- University of Stuttgart, SWE – Stuttgart Wind Energy

14.1 Wish, Will and Achievement

When you consider the real substance of the extensive offshore research project "OWEA – Verification of Offshore Wind Turbines", it's about nothing more and nothing less than the "truth" about wind turbines out at sea: what influence does the atmospheric boundary layer have on the power curve of the turbines? What effect does the wind performance have in the supposedly simple "terrain" out at sea? What impacts does the wake have on the turbines in the second and third rows behind a turbine? How and with which simulation models is it possible to determine the performance and loads of an offshore wind turbine more precisely? And what could a simple and stable load monitoring system for system operation look like?

14.2 Air and Power Curve: the Greatest Deviations by Stable Atmospheric Conditions

The direct proximity of Alpha Ventus to the Fino 1 research platform offers numerous benefits – the power curves of the offshore wind turbines can be determined in various ways there at sea. As well as using the conventional measurement of power curves with the data from the Fino 1 wind met mast, it can also be done with the new lidar technology, which uses innovative laser technology. With lidar systems (see ▶ Chap. 12) it is possible to capture the spatial structure of the wind fields both in front and behind a turbine.

The atmospheric boundary layer is characterised by turbulence, and depending on the intensity of the turbulence by a more or less "well-mixed state of the air masses in it". It is however hardly possible to portray these turbulent structures in large-scale simulation models, because these capture structures with an order of magnitude between two and several thousand kilometres, whereas the turbulence elements in the boundary layer are only between a few millimetres and several kilometres in size.

The measurements show how dependent the power curve of a wind turbine is not only on the wind speed but also on the weather-related stability of the atmosphere. The partial load range – in which the output power of the turbines increases the most – is also where the greatest influence is to be detected. Here the difference in output between stable and unstable stratification with free inflow onto a turbine is a good 15 % of the rated capacity of the turbine.

It is similar for the wind turbine in the wake of another wind turbine. Measurements taken over a year show that the greatest power deficit can be observed when the stratification of the atmosphere is stable, because the wake structures are then very persistent and the airflow is only churned up a bit (◘ Fig. 14.1).

14.3 Measuring at Hub Height: The Standard Is Not Enough

The effects on the power curve are mainly a result of the turbulence intensity and the wind profile. To rule out the possibility that this is a type-specific effect, these investigations were made with two different wind turbine types (Adwen AD 5-116 and Senvion 5M) in Alpha Ventus – with a comparable result, whereby the researchers and wind farm planners were able to significantly improve the previous assumptions. Up to now only the wind speed measured at hub height was considered to be representative of the whole rotor area. This only fits in

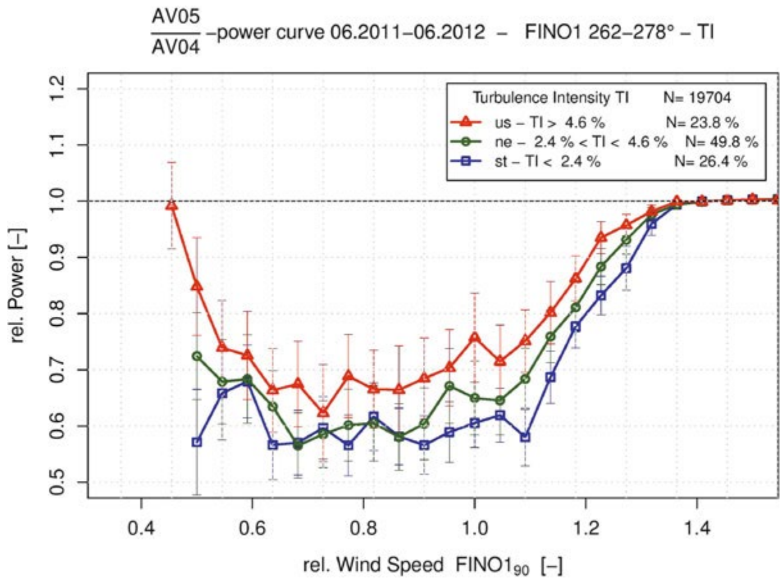

Fig. 14.1 Standardised power curve (AV5/AV4) for a turbine in a single wake, classified according to turbulence intensity, 06.2011–06.2012, 262°–278°. © ForWind – University of Oldenburg

a rough estimate though, because the wind profile, i. e. the change of wind speed with the height, also has a significant influence. Where the stratification is stable, i. e. where there is a particularly marked change in the wind speed with height, using the assumption of the wind speed at hub height as the basis for calculation leads to an overestimation of the wind power of almost 4 %. An improvement is achieved here by using what is known as the "rotor equivalent wind speed", which is calculated based on the wind profile from a weighting of the wind speeds at different heights. If the rotor equivalent wind speed is used as the basis, the power curves of the three stratifications – unstable, neutral, stable – are once again similar and more independent of stability influences (Fig. 14.2).

By using the lidar wind measurement technique on the transformer platform it was possible to measure the wind flowing in to Alpha Ventus from all wind directions without any distortion caused by shadowing. The temporary application of a ground-based lidar on the transformer platform replaced the Fino 1 wind measurements for easterly wind directions, because in these cases Fino 1 was in the shadow of the Alpha Ventus turbines.

The part of the project dealing with the power curves resulted in a far better understanding of the atmospheric influences on the output of individual wind turbines and whole wind farms: the more turbulent the stratification, the higher the specific power at the same speed of inflowing wind. Under stable stratification conditions, combined with greater wind shear and less ambient turbulence, measurements showed significantly lower power outputs at the same speed of inflowing wind. This has quite an influence on Alpha Ventus' wind power production, particularly as this stratification clearly prevailed in some time periods, for example between March and May 2011.

The results of the knowledge thus gained go far beyond just a better understanding of wind flow. The old IEC power curve standard (IEC 61400-12-1 from 2005) did not take into account the wind profile in front of a wind turbine, because only the wind speed at hub height was evaluated. If a turbine produces less than would be expected from the power curve, this does not have to be due to the turbine type or some deviation in turbine behaviour. There are plans that a new IEC guideline will therefore include a wind shear correction based on the rotor equivalent wind speed.

14.4 What Is Really Going on Behind the Turbine?

As the wind passes a wind turbine, this flow behind the turbine is massively altered as a result of the deceleration of the wind speed caused by the

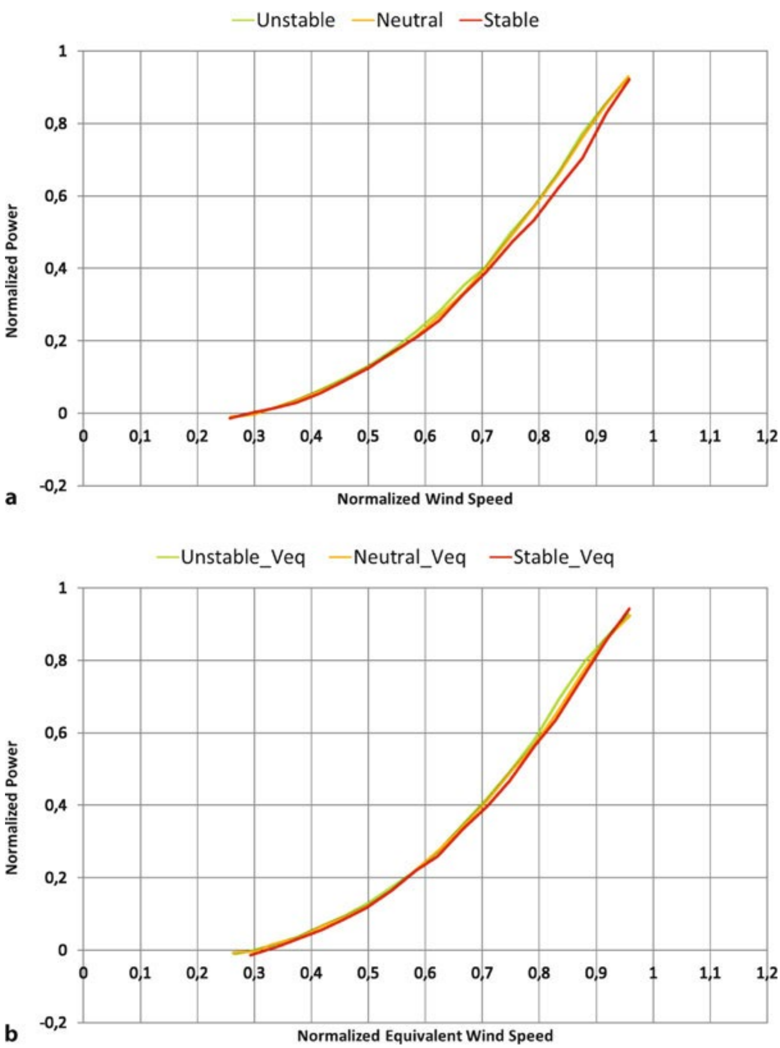

Fig. 14.2 Power curves for each stability class based on the wind speed at hub height (**a**) and the equivalent wind speed (**b**). © UL International GmbH (DEWI)

extraction of energy from the wind and as a result of the turbulence caused by the rotor blades in the near-wake region. Turbines positioned farther back in the wind farm – leeward – are subjected to completely different wind conditions than the wind turbines in the front row of the wind farm that are in free inflow conditions. The issue becomes more complex for a mathematical-physical representation because these altered conditions in the wake are also considerably dependent on the conditions in the undisturbed atmospheric flow far in front of the first row of turbines. It is therefore to be expected that where there is stable stratification of the inflow, the wake dissipation "at the back" is significantly slower than where the stratification is unstable and intensely mixed. Due to the lower ambient turbulence over the sea compared with onshore, and the associated persistence of the wakes, planners must take the "wakes" for offshore wind turbines far more into consideration than for onshore. In addition, and particularly due to the diminished ambient turbulence, neighbouring wind farms probably influence one another to a far greater extent than on land. Satellite images of the Horns Rev wind farm in the Danish North Sea show that the wake turbulences spread over several dozen kilometres.

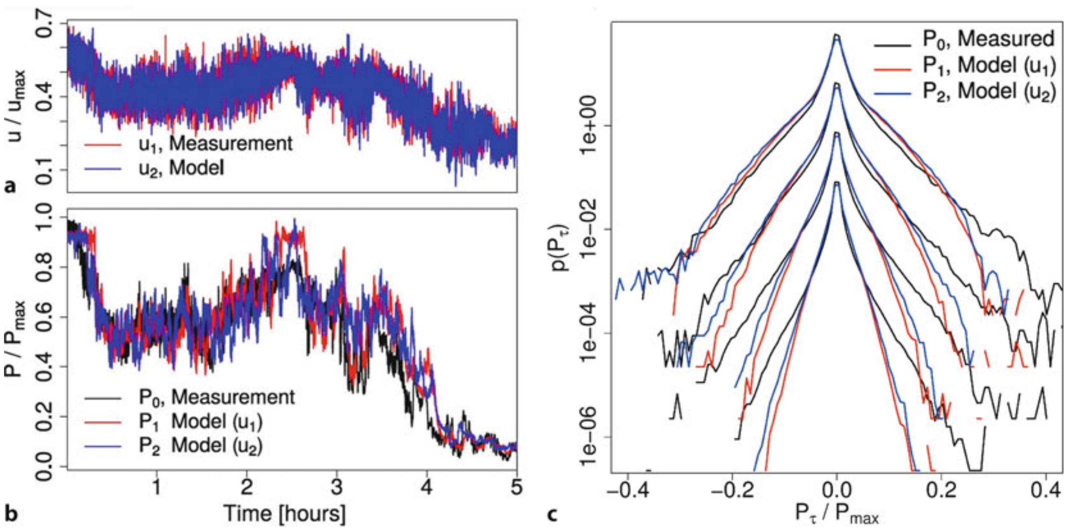

Fig. 14.3 **a** Extract of the wind speed on turbine AV4 (nacelle-mounted anemometer) with a scanning rate of 1 Hz, measured (u1, *red*) and modelled (u2, *blue*), **b** Extract of the power output of turbine AV4, measured (P0, *black*), modelled with u1(t) (P1, *red*) and modelled with u2(t) (P2, *blue*), **c** Probability distribution of the speed increments, measured (P0, *black*) and modelled (P1, *red* and P2, *blue*) for the time scales τ = (8,16,32,64) s (from *bottom* to *top*) for the month of May 2011. © ForWind – University of Oldenburg

14.5 Not Enough Chaos in the Simulation Model

The research project also developed a stochastic model of the fluctuating energy conversion in wind turbines: it is able to replicate the rapid dynamic fluctuations and apparently "random" leaps in the resulting power output depending on wind speed and the atmospheric boundary layer. It had been assumed to date that the power fluctuations followed a normal (Gaussian) distribution. In reality, however, great changes in power within just a few seconds occurred much more frequently than the rather simple mathematical assumptions applied up to now would lead us to expect. The results of the calculation of the partially chaotic fluctuations using the new stochastic model now come very close to the real findings (Fig. 14.3).

However, compared with reality, the model still generates too little intermittency – in other words sometimes not enough "chaotic" jumps in the power. Though while extreme events are statistically underrepresented in this model, they are nevertheless already present. Because fluctuations can also be specified, with this model it is possible to calculate the power output with regard to power fluctuations and stability for days in advance – assuming of course that a viable weather and wind speed forecast exists.

14.6 When Super Computers Begin to Fume – Part I: In the Turbine and Around the Turbines

The flow behaviour in the Alpha Ventus wind farm and the flow around the turbines was reproduced in parallel in a modelling chain from various detailed computer models in order to be able to study the complex interdependencies and the loads on the turbines in more detail.

In one of the first steps of the modelling chain, the atmospheric conditions in the area around Alpha Ventus determined using the met mast were reconstructed in a so-called LES (Large Eddy Simulation) model. With this model, the temporally and spatially variable maritime wind field was simulated with a resolution of fractions of a second and a few metres, whereby the energy-rich larger turbulent structures were resolved and the effect of the smaller

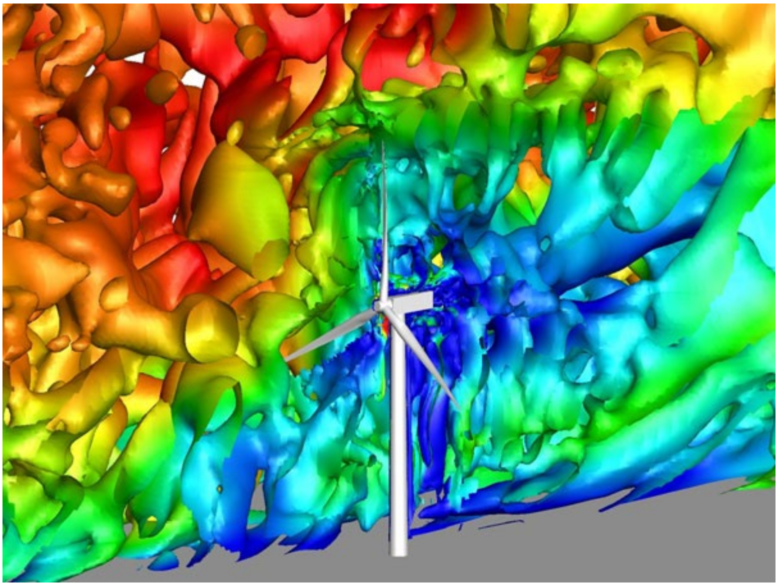

Fig. 14.4 CFD flow simulation of an offshore wind turbine subjected to turbulent, maritime flow using a hybrid RANS–LES procedure. © Konrad Meister

ones on the larger turbulent structures was parameterised. This scale separation is possible in the LES thanks to the Richardson-oriented energy cascade model. In this model, a turbulent flow is supplied with energy on a large scale, the large vortices break up into smaller vortices in accordance with certain physical laws and the energy is then finally transformed into heat on the smallest scales. To achieve as good a match as possible between the measured wind fields and those simulated with the LES model, boundary conditions for the LES model, such as the heat influx in the atmosphere, were derived from detailed analyses of the atmosphere, as are also used to drive weather models.

In the next step of the modelling chain the wind field measured with the LES model was fed into a second numerical model that covers a smaller area. It was thus possible to realise the high spatial and temporal resolution needed for the precise calculation of the flow around the wind turbines. By combining LES with the RANS (Reynolds-Averaged Navier–Stokes) method it was now possible to resolve turbulent structures of the inflow, which are relevant for the aerodynamics and the load fluctuations at the rotor. So as well as the precise calculation of the variable load ranges above the rotor radius it is also possible to make a detailed calculation of the turbine wake and its interaction with the maritime boundary layer (Fig. 14.4). The sophisticated numerical model also takes into account the transient, aero-elastic deformations of the rotor blades. The application of this calculation chain helped the researchers to better understand the development of the turbine wake under offshore conditions as it reaches the neighbouring wind turbines. It was thus possible to investigate the influence of the turbulence intensity and the inflow angle on wake development to a degree of detail that measuring methods such as lidar cannot resolve to date. It must however be pointed out that this kind of simulation of one or two wind turbines is extremely CPU-intensive and requires the use of the fastest high performance computing clusters currently available.

14.7 When Super Computers Begin to Fume – Part II: From Inflow to Distant Wake and to the Wake of the Whole Wind Farm

Unfortunately, even on the most powerful high performance computing clusters available today it is still not possible to calculate the airflow in the whole wind farm with the aid of the RANS–LES approach described above. So instead of this, research in general, and therefore also the OWEA project,

Table 14.1 Electrical power output at AV2 and AV3 in % of the power at AV1 or at AV5 and AV6 in % of the power at AV4 derived from the results of the LES simulations for various wind directions. © ForWind – Universität Oldenburg

Wind direction (°)	AV2 (%)	AV3 (%)	AV5 (%)	AV6 (%)
255	97.2–102.2	101.6–105.4	94.9–103.5	100.5–106.3
260	100.5–108.9	98.6–111.7	97.4–100.1	99.6–104.3
265	87.8–93.6	91.9–95.1	92.0–94.0	92.8–96.9
267.5	65.7–70.7	70.0–72.0	69.8–71.5	68.3–71.1
270	47.4–50.3	53.8–58.4	49.1–51.1	53.7–56.5
272.5	40.7–47.4	41.7–48.2	43.7–44.7	46.1–47.9
275	48.6–51.0	50.3–53.0	51.2–53.8	49.2–54.6
280	88.2–91.4	87.7–82.1	91.0–95.9	88.5–96.5
285	97.5–102.6	99.5–102.5	95.1–102.0	94.1–99.5

uses LES models for which a variety of approaches have been developed in recent years for the consideration of wind turbines. In the OWEA project, the LES model “PALM” was further developed by including parameterisations for wind turbines. The further developed model was then used for simulating the flow conditions in the Alpha Ventus wind farm for different wind directions.

The study showed once again how the wind direction influences the wind farm output. When the inflow to the wind farm came from 280 degrees, the power deficit on turbines AV2 and AV3 was only about 10 %, whereas when the inflow was only 5 degrees less – i. e. from 275 degrees – the deficit was five times as much (Table 14.1). On the other hand, with an inflow from 260 degrees the wind turbines in the second and third row achieved in part a higher output than the turbines in the front row. One reason for this could be increased wind speeds on the edges of the wake area due to the conservation of mass flow, because when the wind direction is 260 degrees to Alpha Ventus the turbines in the second and third rows of the wind farm are directly lateral to this wake area.

Summary: The wake begins to fluctuate significantly directly behind the wind turbine. The researchers have developed a computer-based modelling chain for wind turbine simulations with special inflow conditions that other RAVE projects can also draw on. This means that improved modelling of offshore conditions in complex three-dimensional wind field models is already available for further research, both in the small-scale segment and also as a one-dimensional wind field model. The CFD models that have been developed are fundamentally suitable for the investigation of the near wake, far wake, wind farm flows and the wakes of whole wind farms. They are therefore being further developed in the follow-up project “OWEA Loads” (▶ Chap. 15 “Load, load monitoring, and load reduction”).

Peripheral Anecdote (I): Under false omens

Wherever people are involved, mistakes are made. And when the data sometimes seems very strange the reason is occasionally the human factor. To be able to measure the turbine dynamics, in the “Measurement Service Project” (▶ Chap. 3, “A thousand sensors, from the blade tip to the bottom of the sea”) hundreds of strain gauges were attached to the foundation structures and wind turbine components under tremendous time pressure. The challenge was that the installation of the sensors, which were stuck directly onto the metal and then protected using a complex multilayer process, had to be seamlessly integrated into the production process at the shipyard and production shed. It was only possible to do this during pauses in production so that it did not cause any delays in the very tightly organised production process.

All in all this went very well thanks to the support and understanding of those on site. Final checks could not always be carried out as they normally would be under laboratory conditions. Luckily such inadvertent mistakes, such as "reversed polarity", could be quickly detected and remedied thanks to subsequent plausibility checks and the close collaboration between the "Measurement Service Project" and other research projects. One such example is where four strain gauges each were stuck onto the tower or tower tripod at different heights. It was logically expected that the measuring results for each signal would show a phase displacement of 90 degrees in each case, but this did not happen at all measuring points. The reason for this was simple "sign errors" on these sensors, because the alignment of the strain gauges was reversed when the measuring channels were being installed. By investigating a constant bending moment from various directions with a "nacelle rotation" it was possible to explain these deviating values and mathematically compensate for them.
Björn Johnsen

14.8 Verification of the Turbine Dynamics: First Steps

In order to better understand the behaviour of wind turbines, simulation models were set up for the 5-MW Adwen and Senvion turbines in different simulation environments. The aim was to validate the dynamics of these offshore wind turbine models with the measurement data from Alpha Ventus. Before this could be done it was necessary to calibrate the measuring signals. This was done by analysing nacelle and rotor rotations at very low wind speeds. Load conditions of the turbines under measured site conditions were subsequently replicated with the simulation models. This showed that it was possible to replicate the statistics of the stochastic loads with the simulations. This did not apply to the chronological sequence of the loads measured, because of missing information about the spatial and temporal sequence of the wind and wave field. The validation of the turbine loads was carried out by undisturbed inflow onto the wind turbine in order to rule out the influence of the wake on the turbine loads. Future projects will attempt to achieve a better spatial resolution of the wind field with the aid of lidar measurements, thus enabling a load validation in the time range.

14.9 Integration and Identification

The great majority of all simulation programmes have been developed for onshore wind turbines. But for offshore turbines it is necessary to also consider the hydrodynamic loads on the supporting structure – the impact of waves, tides, marine growth and current on the stress and strain on the foundations, tower and the wind turbine itself. The complexity of the excitations and the flexibility of the wind turbine results in a vibration-friendly structure. It is therefore necessary that the turbine design always takes the complete offshore dynamics into account. It is also necessary to record interactions with the complex foundation structures (e. g. jacket framework or tripod) at great water depths.

» We're still learning

After every research project, the question is always "What did it achieve?" In this case the great project network achieved a great deal: a better understanding of the atmosphere, the airflow conditions in a wind farm, the offshore influences on the power curves and the turbine loads. New computer programmes and methods for plant monitoring were developed and the first verified model calculations could be made available. And yet we still can and must say: we're still learning – with our faces in the wind.
Prof. Martin Kühn

To this end, Flex5 – a specialised, tried and tested programme for turbine simulation – was combined with one of two corresponding special programmes for offshore support structures, either Ansys Asas or Poseidon, as desired, to create an integrated simulation tool. Flex5, developed at the Technical University of Denmark, is a very sophisticated programme for the aero-elastic simulation of wind turbines, which up to now was only able to deal with simple monopile offshore foundations. The Ansys Asas package widely used in the industry and the Poseidon software developed at the Leibniz Universität in Hannover was specially developed for simulations of complex offshore foundation structures. Both programmes draw on the offshore experience of the oil and gas industry and use the finite element method (FEM).

The new combination made integrated load calculations possible, including special effects like aerodynamic and hydrodynamic damping. The example of the jacket foundation showed that additional interactions take place between the rotor-nacelle unit and the slim, vibration-susceptible, braced framework. This can significantly influence the loads (Fig. 14.5). This made it possible to reduce the uncertainties in the calculation of design loads for offshore wind turbines and thus indirectly reduce the cost of energy generation.

The computer models were compared with the real test field measurement data. Verifications were carried out on the basis of tower top displacements in longitudinal and lateral direction or tripod stresses in an extreme wave load scenario without turbine operation, i. e. when the turbine was switched off or not running. The expansions measured on the tower and foundation were and are especially suitable to get an initial overview of the plausibility of models and measurement data.

For validating the methods and models, this integrated approach takes the complete model chain into account (Fig. 14.6), in order to roughly classify the influencing factors and possible uncertainties in the simulation. These include the turbulent wind field and the wave field along with its characteristic parameters such as wind shear, turbulence intensity, wave height and period as well as hydrodynamic force coefficients including marine growth on the substructure, which influence the loads from waves and current.

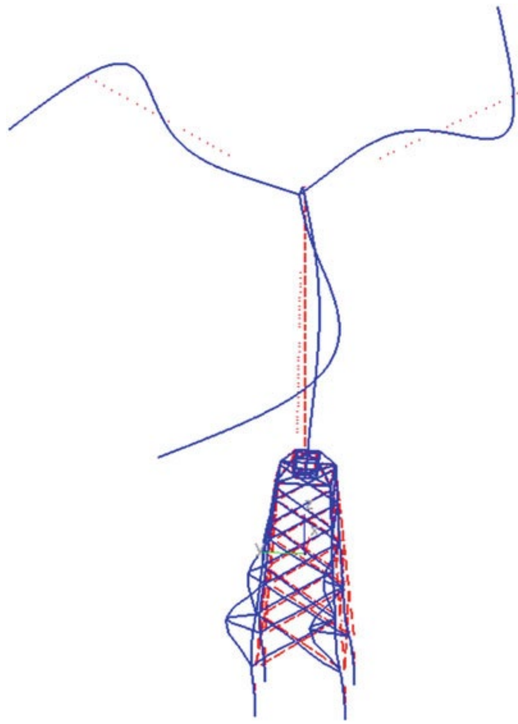

Fig. 14.5 Example of the interaction of vibration modes between the rotor-nacelle unit and the slim, vibration-susceptible braced framework of a jacket foundation. © ForWind – Universität Hannover

The new combined tool for "integrated simulations" is now being used by manufacturer Senvion and the Universities of Stuttgart and Hannover for load calculations for wind turbines and foundation structures.

The extensive evaluations of the multitude of measurement data for the different wind turbines in the test field also made it possible to develop new software tools. The treatment of the extensive measurement data, split by turbine type from Adwen and Senvion, has resulted in a modularly organised, system-neutral toolbox for evaluating operating data. Extensive parameterisation and implemented allocation of rights means that in future different manufacturers will be able to use this for "virtually any measurement campaign". The open interfaces also enable the further development of components.

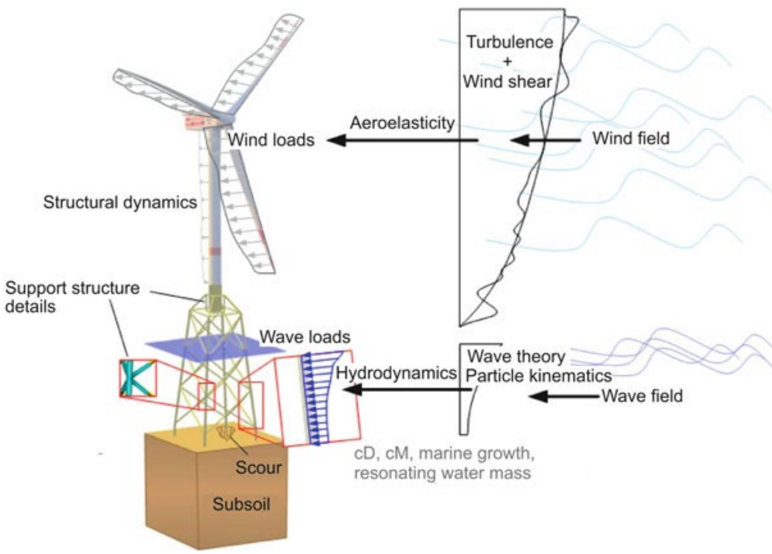

Fig. 14.6 The relevant environmental and simulation parameters of the integrated approach. © ForWind – Universität Hannover

14.10 Despite All the Effort: Still Only Little "Strain Wear"

So much for the use of simulation programmes – but do their results actually match the measured stresses? Strain gauges affixed to the tripod both above and below the water level were made available to researchers for the analysis of the structural loads (Fig. 14.7). The installation conditions offshore meant there was unfortunately an unusually high level of sensor malfunctioning right at the start of the measurements. The built-in redundancy meant it was still possible to carry out the investigations with the remaining sensors. In the following two-and-a-half-year measuring period from December 2009 until June 2012 only two more strain gauges had to be abandoned due to wear. The central tripod main tube in particular provided a good match of the measurement data with the simulation data. So for most of the measuring points it was possible to determine the real impacting forces.

Conclusion in this part of the project: The extensive measurement data available regarding expansion, bending, torsion and acceleration on the tower, the foundation structures and the rotor were validated, meaning that extensive data sets are available for further research. Above all it was possible to develop and validate calculation tools for designing offshore wind turbines with branched support structures like tripod and jacket foundations. These are now being used in industrial practice. Integrated load calculations are possible using standard and industry-specific software. The computer models were compared with the measurement data from the test field and successfully verified.

Peripheral Anecdote (II): Why fatigue is seldom measured

In practice, fatigue from the tower base bending moment, the drive train torsion etc. are only measured on a very few prototypes, but not on many of the hundreds or thousands of wind turbines of a particular type. While the cost of the installation and maintenance of such a measuring system is far too high, it is primarily because the 20-year operational life of a wind turbine is far longer than that of the simple strain gauge that is meant to monitor the turbine. Despite this, for the future there is still great interest in increased monitoring of fatigue loads, as long as the cost is reduced and the usage of the results becomes easier and more attractive for operations management.
Björn Johnsen

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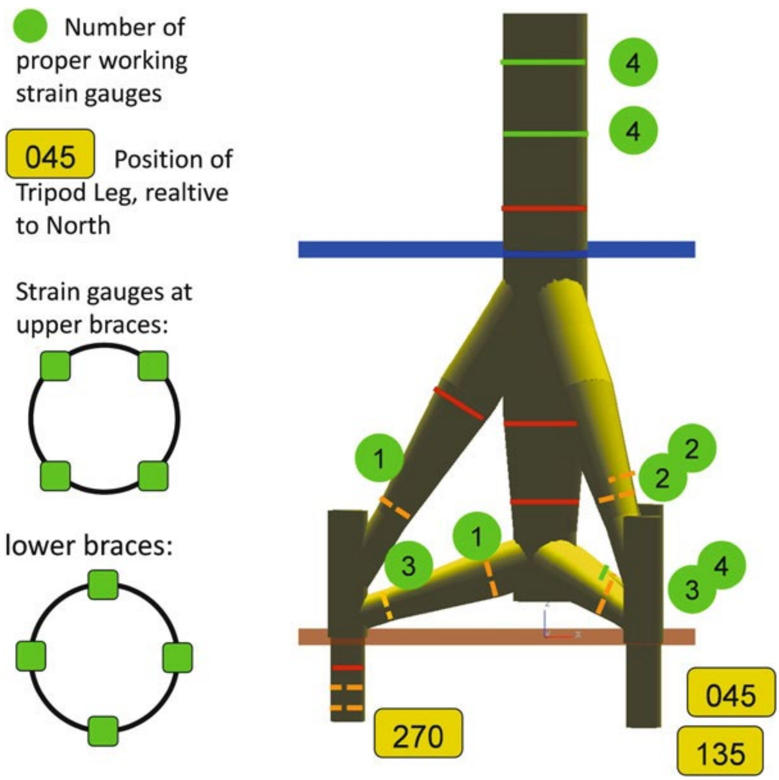

Fig. 14.7 Overview of the strain gauges installed on the tripod. © SWE – University of Stuttgart

14.11 Load Monitoring from Only Standard Data?

The researchers worked on methods of load monitoring for the 10 to 100-million load cycles during the operational life of a wind turbine, with which it is possible to estimate the actual loads on an offshore wind turbine without the need for a complex measuring system. One possibility that was successfully demonstrated is the use of neural networks that work with the standard signals from the operating system, the so-called SCADA (supervisory control and data acquisition) data.

Load estimates with neural networks use the data from the strain gauges affixed to the tower, nacelle and foundation, as well as the turbine status signals and the wind measurement data. The measurement data is used as training data from the neuronal networks and later used as comparison data for judging how good the neural networks are for estimating the loads. Later, the fatigue loads on the main components such as blade root bending moments, drive train torsion and tower base bending moments are not measured exactly, but estimated with the neural networks. Transfer functions are created on the basis of real operating data from a measurement campaign or aero-elastic simulations, and these in turn translate the available information, almost "self-learning", into loads. This method has to be specially tailored for each turbine and its location and can then achieve a satisfactory accuracy of estimation.

Hydrodynamic loads, and particularly waves, are especially important for the fatigue condition of the foundation structure (Fig. 14.8). So for an evaluation of the expansions on the legs of the tripod using this evaluation system based on standard operating data the wave influences also have to be added. Without them an overall evaluation just using the operating data from the rotor-nacelle unit is virtually impossible. The method has to be further developed especially for the optimisation of the maintenance cycles for an offshore wind turbine and for the assessment of its "residual lifespan".

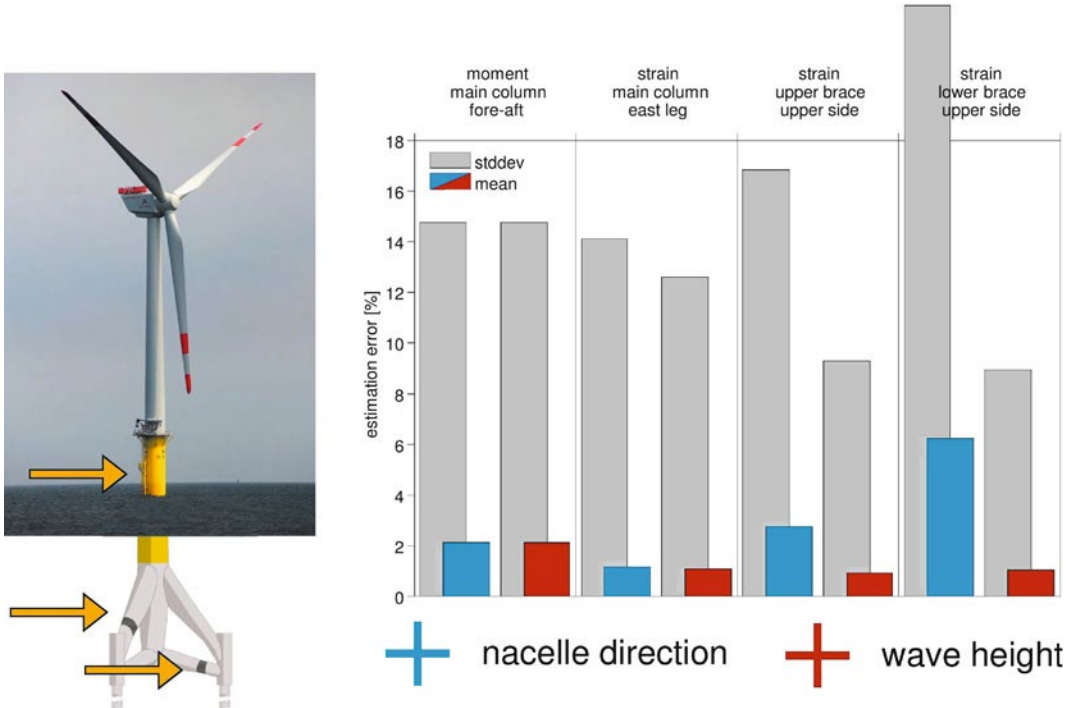

Fig. 14.8 Investigation of the influence of the significant wave height on hydrodynamically dominated loads. © SWE – University of Stuttgart

The follow-on project "OWEA Loads" (▶ Chap. 15, "Load, load monitoring, and load reduction") is investigating the influence of wave loads on the stress on the foundation structure in detail.

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Load, Load Monitoring, and Load Reduction

Requirements for Future Turbine Generations; an Insight into the Ongoing Research Project OWEA Loads

Björn Johnsen

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power,* DOI 10.1007/978-3-662-53179-2_15

Project information: Probabilistic load description, monitoring and reduction of loads of future offshore wind turbines (OWEA Loads)

Project management:
University of Stuttgart, SWE – Stuttgart Wind Energy
Prof. Po Wen Cheng

Project partners:
- Adwen GmbH
- DNV GL
- Eberhard Karls University of Tübingen, Environmental Physics
- ForWind – Center for Wind Energy Research, Leibniz Universität Hannover, Institute of Steel Construction
- ForWind – Center for Wind Energy Research, University of Oldenburg, Institute of Physics
- Senvion GmbH
- University of Stuttgart, Institute of Aerodynamics and Gas Dynamics

The research project "Verification of Offshore Wind Turbines OWEA" (▶ Chap. 14) continues as "OWEA Loads". This is more than just a continuation; the main objective is to understand how offshore wind turbines actually behave in these challenging environmental conditions. The measurements taken in the Alpha Ventus wind farm since 2009 provide comprehensive data that still has to be evaluated – especially with regard to the loads and stresses on offshore turbines. This will provide new knowledge leading to improved offshore wind turbine design. Since the joint research project, carried out in collaboration with manufacturers Adwen and Senvion, will be completed in August 2016, instead of the presentation of specific results there will be a short overview of the planned research objectives of OWEA Loads (◘ Fig. 15.1). The ten work sub-packages should help enable an "optimised load, reliable design and operation of offshore wind turbines" while taking into account the special design requirements in the German Exclusive Economic Zone (EEZ).

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15.1 Corrections Welcome

The first foundation stones for the verification of loads on offshore wind turbines were laid in the previous project "OWEA". These include the first considerations and algorithms for carrying out plausibility checks of measurement data. Due to the large amount of measurement data continuously gathered, this was really a Herculean task. In OWEA Loads the processing of the measurement data was further systematised and developed so that it will be possible to create a consistent and first-class data archive that can serve as a basis for this and further research projects. This also means that, where possible, inaccurate measurement data has to be corrected or discarded. One example that illustrates the difficulties in dealing with measurement data is the correction of strain measurements altered as a result of temperature effects. The influence of sunlight on the installed strain gauges caused greater expansion of the materials, which has to be taken into consideration when calculating the loads. Alternatively it was also possible to only evaluate the data gathered at night (i. e. without exposure to sunlight), though this would massively cut down the amount of data. In addition wind conditions are also often very different by day and by night.

It is therefore important to determine the degree of influence of variables like temperature effects in order to derive a recommended course of action in dealing with the loads already recorded.

The researchers also want to develop a computer-controlled, automated calibration algorithm for the strain sensors installed on the rotor blades. This should enable early detection of possible changes in the accuracy of the sensors installed. Such an algorithm would also be useful for systems that use load measurements on rotor blades for operational management and control. They also want to use the strain gauges installed on the blades and the rotor positions recorded for each individual blade where possible in order to draw conclusions about the wind shear, i. e. changes in wind speed or direction with height. These evaluations should also provide valuable knowledge for use in the design of future wind turbines.

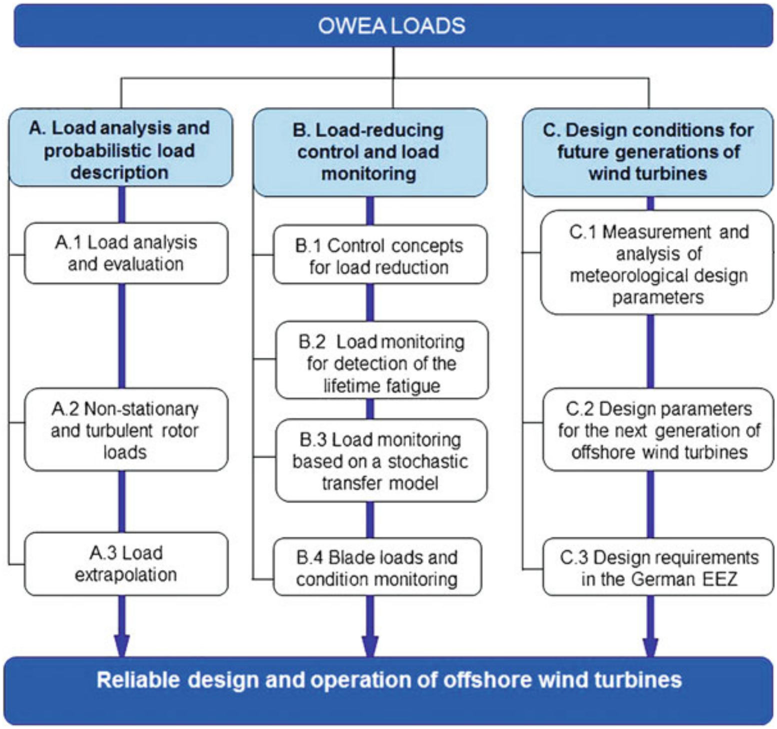

Fig. 15.1 Organisation of the joint project OWEA Loads in work packages and sub-packages. © SWE – University of Stuttgart

15.2 Interaction in a Different Way – the Tower Vibrates as well

The loads on wind turbines are characterised by complex, dynamic interactions between a highly turbulent atmospheric inflow and the airflow around the turbine. This also includes the interaction of the loaded vibrating tower and additional aero-elastic effects. The air that flows in over the rotor disc can be very different in different places and can fluctuate greatly in time, so that this can result in phase shifts between excitation and the resulting loads on the blade. These complex effects can only be represented very inadequately using simplified calculation models – if at all. One sub-package aims to analyse the dynamic loads along the rotor blade subjected to turbulent inflow by further developing a computer-based numerical modelling chain and new structure measurements on the rotor blade.

It will also determine a "likelihood of occurrence" of characteristic extreme and fatigue loads. In contrast to deterministic loads this approach will enable a rational and efficient design of the structural components of the offshore wind turbines. Thanks to their large volume, the data sets recorded in the Alpha Ventus wind farm offer a unique opportunity to verify the assumptions of the design guidelines, which have until now only been based on simulations, with the aid of measurement data.

Peripheral Anecdote: No access to the sea
Lidar measurements taken from the nacelle of a wind turbine in the Alpha Ventus wind farm offer new possibilities. The OWEA project had planned to get a worldwide unique data set from the simultaneous nacelle-based lidar measurements of the incoming wind in front of a turbine and the wake behind it. Unfortunately the installation and commissioning of these two lidar instruments were delayed due to unforeseen problems with both the hardware and the software, and the difficulty of gaining access to the offshore wind turbines before the end of the OWEA proj-

ect in September 2012. This meant that it was no longer possible to do any evaluations during the project lifetime. These measurements will now be performed during the OWEA Loads project so that the inflow air and the wake in the offshore environment can be better understood, and wind flow models can be developed further.
Björn Johnsen

15.3 Load-Reducing Regulation and Load Monitoring

Another OWEA Loads sub-project deals with the development and validation of new operational management concepts for offshore wind turbines in order to reduce the aerodynamic and hydrodynamic loads on the supporting structure and the rotor-nacelle unit. This relies on selective use of the turbine control system, active influencing of the turbine operation and integrated design methods. During these measurements the researchers are especially looking for situations causing particular loads on the supporting structures – and for possibilities of reducing their effects on the overall structure. This includes the application of control concepts for operating states, which is dependent on concrete load cases: for example sea conditions with a misalignment between the direction of the wind and waves and the associated strong lateral tower vibrations, oscillations caused by sea swell when the wind turbine is not in operation as well as various situations in which the turbine is situated in the wake of another turbine. Control methods for foundation concepts not used in Alpha Ventus, such as monopile foundations, are another focus of the project to make their use more economical in terms of material expenditure, greater water depths and larger wind turbines.

Future load monitoring systems could be used for evaluating the load reduction concepts and the determination of the actual residual life, as wind turbines are often subjected to significantly lower loads at their individual locations in the wind farm than originally assumed when they were designed for use at the most unfavourable location within the wind farm. Innovative load monitoring concepts offer the possibility to estimate loads with standard operating data (SCADA) without the need for these to be measured directly with such costly methods as strain gauges. Load monitoring should mean it is possible to make reliable statements about the residual life of a turbine. Two different methods are being further developed in the OWEA Loads project that are based on neural networks and the stochastic transmission behaviour of dynamic load fluctuations.

15.4 Loads Along the Rotor Blades

Previous knowledge of the detailed load distribution along the rotor blades is also comparatively imprecise, and can lead to uncertainties in the calculation of aerodynamic loads. Because of the complex component and material behaviour of the rotor blades it is necessary to develop special measuring and analysis procedures to monitor the loads and condition of the blades. This is important for both the control methods and individual blade pitch control.

15.5 Always Further, Always Higher?

Future wind turbine generations of higher capacity classes will be operated at significantly greater heights than the 5-MW turbines used in Alpha Ventus. It is therefore important to expand previous investigations and analyses to include higher layers of the atmospheric boundary layer, the so-called Ekman layer, and to make a more precise description of the dependency of the speed and turbulence profiles on the atmospheric stability. This is well above the measuring heights of the Fino 1 met mast, reaching heights of up to 100 m. The OWEA Loads project will use new measuring methods to investigate a height range of up to 300 m.

15.6 Small Unmanned Aircraft: To New Heights Without Daedalus …

Besides the wind conditions at great heights, the plan is to also measure atmospheric quantities that influence the wind profile, such as air temperature, humidity, turbulent flows etc. To achieve this, the project uses a small unmanned aircraft (the trade term for which is Unmanned Aerial Vehicle, UAV) owned by the University of Tübingen, which measures the condition of the marine atmospheric boundary layer up to a height of 300 m. Although technically possible in principle, it is not currently possible to obtain a licence to use the UAV autonomously, and therefore the flights can only take place within the view of a pilot. As a result, the exploration of the boundary layer with such a "science drone" can only take place horizontally for a maximum range of one kilometre. In order to still be able to measure conditions out at sea, the flights are launched from the island of Helgoland. The high cost of personnel and maintenance means that the UAV is not available for an unlimited time for the whole of the project. Five intensive measuring campaigns with a total of 200 measuring flights lasting 30 minutes each will be undertaken and evaluated.

15.7 … And with Ice on the Blade Tips

This data will then be used to develop and verify models for describing the wind speed and direction. The risk of ice accretion on future wind turbine generations in the North Sea is also an aspect being focused on. This work should lead to improved forecasts of the expected energy yield and short-term power output. Especially the depiction of the change in wind direction with height should result in an improved estimation of the loads to be expected on the turbine.

15.8 Did the Storm Contravene the Rule Book?

With the aid of the measurement data the researchers want to consider the question as to what extent the loads depend on the combination of wind speed, turbulence class, wave height and wave period. The analysis will also include to what extent any storms occurring within the observation period (such as those in August 2010 and January 2012) match the previous prognoses, and whether the progress of these storms – their maximum wind speeds, duration, wave directions and heights – match previous theoretical depictions in the relevant guidelines.

Another work sub-package should draw up recommendations for a simplified and more effective design process for offshore wind turbines based on the measurement data for the mechanical loads. From the engineer's point of view, the design requirements for wind turbines and supporting structures in the German Exclusive Economic Zone (EEZ) are based on the meteorological, climatic and oceanographic conditions. From a legal point of view the requirements are based on planning rules. Operators or finance providers of wind farms frequently demand certification of a particular wind turbine type, which is usually based on the relevant regulations, in particular the "Guideline for Certification of Offshore Wind Turbines" of Germanischer Lloyd (DNV GL). For a critical and practically oriented interpretation of the results, this work package will consult DNV GL, the publisher of the most used book of rules for wind turbine design in the world. At the end of the research project this could mean the creation of adjusted "design requirements for wind turbines in the German Exclusive Economic Zone".

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coordinator: Stuttgarter Lehrstuhl für Windenergie (SWE) am Institut für Flugzeugbau, Universität Stuttgart

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Different than Previously Assumed

Turbulences in the Atmospheric Boundary Layer and Their Consequences for Wind Field Models

Stefan Emeis, Copy edited by Björn Johnsen

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power,* DOI 10.1007/978-3-662-53179-2_16

Project information: Verification of turbulence parameterisation and description of the vertical structure of the marine atmospheric boundary layer in numerical simulation models for wind analysis and forecast (VERITAS)
Project management:
Institute of Meteorology and Climate Research
Karlsruhe Institute of Technology
Prof. Stefan Emeis

A great deal has been written about wind turbulence, but something that has never been done, at least not over the sea, is to measure and verify the turbulence description in the marine atmospheric boundary layer above the sea. Or more simply put, "the air above the water": This is because such scientific turbulence descriptions to date have only been on land – due to the lack of suitable measurement data on the oceans. It is also questionable as to whether the old "land turbulence descriptions" can be directly applied to the North Sea. The conditions on land and sea are obviously not comparable.

But there is a unique source of data for researching the marine atmospheric boundary layer, out in the North Sea, 45 kilometres off the island of Borkum: the Fino 1 research platform with its 101-metre-high met mast, directly adjacent to Alpha Ventus (◘ Fig. 16.1). Equipped with cup anemometers at eight different measuring heights and with fast ultrasound anemometers at three different heights, the met mast has been delivering wind and turbulence data for years. It also takes temperature, precipitation and radiation measurements, as well as oceanographic wave measurements, and has done for over ten years. That warms the cockles of any scientist's heart if he is interested in collection and evaluation.

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16.1 Nobody Is Perfect – Not Even Fino

Even if the wind and turbulence measurements on Fino 1 provide a unique opportunity to examine the existing turbulence descriptions and adjust them where necessary, there are two weaknesses. One is that there are no measuring points on Fino 1 that provide information for the area between the sea surface and the lowest measuring height of 33 metres, even though there are also turbulent currents of moisture and heat in the atmosphere there. But nothing can be done about this "weak point" – it is not possible to take continuous measurements at Fino 1 from directly above the sea surface up to a maximum wave height of almost 20 metres without the instruments being damaged or even completely broken by high waves.

The other weak point is that up to now there have not been any high-resolution moisture measurements at various heights. Yet the vertical moisture distribution plays a far more dominant role in the marine boundary layer than on land. Because the sea is a permanent moisture source for the air and the temperature difference between near-surface air and water is for the most part very small, it is easier for a moisture flux to occur. And as it turned out, this has a significant influence on the stability of an atmospheric layer – and consequently also on turbulences. In short, the detection of this "research gap" led to high-resolution moisture analysers finally being installed on Fino 1, and the instigation of an additional, independent research project that dealt exclusively with moisture flux in the atmosphere (► Chap. 17).

16.2 Not "Just Air": Boundary Layers in the Atmosphere

The atmospheric "layer of air" above the sea, the so-called marine boundary layer, can be divided into roughly two layers: the lower layer, the up to 80-metre-high "Prandtl layer", and the "Ekman layer" above it. The Prandtl layer can however also be much flatter (10 to 20 m) if the water is much colder than the air and the wind speed is not so high. This layer, in which the wind increases with height but without changing direction, can in turn be subdivided into three sub-layers: the lowest layer, which is directly influenced by the waves, then a transition layer that is not always present, and then above that the real Prandtl layer (◘ Figs. 16.2 and 16.3). In the Ekman layer above 80 metres, the increase in wind speed is less, but the wind direction changes. With

Fig. 16.1 Approaching the Fino 1 research platform. The wind turbines of the Alpha Ventus offshore wind farm can be seen in the background. © Forschungs- und Entwicklungszentrum Fachhochschule Kiel GmbH

increasing height it turns 30 to 45 degrees right in a clockwise direction. These are the values on land, but over the sea this change in direction is only in the order of ten degrees.

Anyone wanting to correctly describe and predict the wind speed at various heights – the vertical profile and wind speed – needs accurate knowledge of the corresponding vertical turbulent "momentum flux". This turbulent momentum flux above a horizontal, almost homogeneous surface, as represented by an ocean, is significantly different from those on land.

16.3 Of Young and Old Waves

Turbulence over the sea displays a number of interesting features. For example, the turbulence intensity increases once again with greater wind speed (over c. 12 m/s) due to the increasing wave height

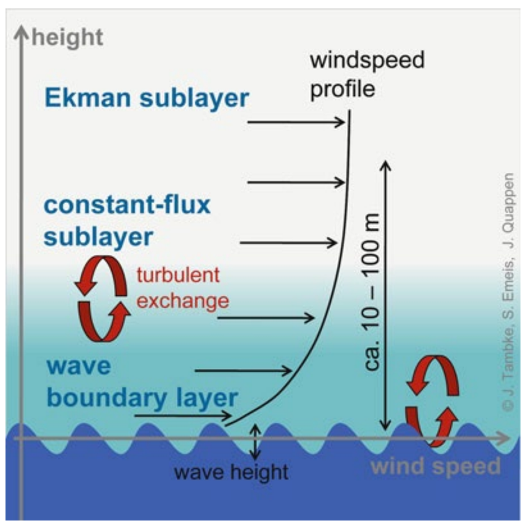

Fig. 16.2 Wind profile in the marine boundary layer and the influencing processes. © ForWind – University of Oldenburg

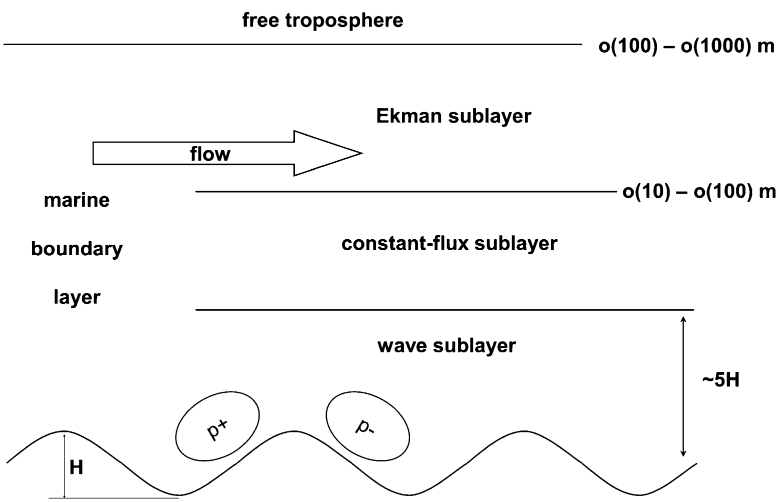

Fig. 16.3 Vertical structure of the marine boundary layer. © KIT Stefan Emeis

– which is not the case above land. Generally speaking, the turbulence intensity out at sea is nevertheless significantly lower than over land.

At low wind speeds the so-called "wave age" also plays a role. Only with "young waves", where the wind speed is greater than the wave speed, can one expect that the description approaches for land can also be applicable to the ocean. For "old" waves however, with their so-called "groundswell" (where the wave speed is greater than the wind speed), this does not apply. Here the sea surface does not act as a "brake" for the wind, but as a surface it actually "powers" the air movement. The old description of wind and turbulence profiles on land is thus no longer sufficient to explain these special characteristics above the sea.

And the "thermal stratification" of the "air", sorry, I mean the atmospheric boundary layer, which helps to decisively influence the turbulence intensity and structure, is subject to very different time histories out at sea than over the land. Dominant at sea is the annual rhythm of the stratification, which is influenced by the temperature difference between water and air. Over land on the other hand, the daily rhythm is dominant. In the case of offshore wind it is necessary to reckon with the formation of internal boundary layers and stronger wind shear on the boundary surfaces. In other words, a sudden change of wind direction or strength. Such vertical wind shears could have a significant influence on the verification of the power curves in Alpha Ventus and other near-coast offshore wind farms. This is because the wind speeds measured at hub height are then possibly no longer even approximately valid for the whole rotor area, where the wind can hit and pass at different speeds. This is particularly so for the foreseeable large rotor diameters of 130 metres and more.

Peripheral Anecdote: NDR transmitter mast is not in the way, but in fact helpful

For the turbulence investigations contact was also established with the Danish Risø research centre at the Danish Technical University (DTU) in Roskilde and the Meteorological Institute of the University of Hamburg. This provided data not only from the Danish research mast at Høvsøre, but also from the NDR transmitter mast in Hamburg-Billwerder, which had the appropriate wind measuring instruments attached to it long ago. The data made it possible to examine if the improvements found in the turbulence description would also make for improvements for onshore application as well. And yes, they do!
Björn Johnsen

At high wind speeds the spray can also influence the impulse and especially the heat and moisture flux from and to the sea surface.

Numerical, computer-supported simulation models for analysing and predicting the wind field in offshore regions like the German Bight therefore need suitably adjusted turbulence descriptions. These must also be able to guarantee a steady transition to the conditions over the land. This is so that the influence of the coast there and the position and height of any wind shears can be calculated reliably.

16.4 Describing the Sea Without Wave Data

Apart from the thermal stratification of the atmosphere, the turbulence intensity in the marine boundary layer also depends to a significant extent on the roughness of the sea surface. When wave data such as wave height or length is available, instead of using the wind speeds to describe the roughness of the sea surface it is of course better to directly use the wave parameters. If however there is no available wave data – and this was a significant finding of the research project – there is another possibility to describe the roughness of the sea surface. This is in turn very important, because it is the “lower” constraint for the calculation of wind turbulence above the water. This sea surface roughness can thus be described empirically with a single resistance coefficient. This is the key finding and innovation of the research project. The new formula states that the quotient of the root of the turbulent kinetic energy and the mean wind speed is proportional to the turbulence intensity, and this has been empirically proven by the measurements. The new description simulates the turbulent kinetic energy of the wind and thus the near-surface turbulence intensity significantly better than the previous approaches. It has been investigated for eleven different weather conditions up to now, and has yielded similar results for all of them. Whereas the earlier wind turbulence description yielded far too low turbulence intensities, the new description fits in with the data really well – as a comparison between Fino 1 and on land (Hamburg) for the 2005 measuring period shows (Fig. 16.4).

In order to check if this process is due to the special properties of the sea surface or if it also applies on land, a comparison was made of the data from a met mast in Hamburg-Billwerder and a mast in Høvsøre on the Jutland coast of the Danish mainland. The result was that the new model simulations have been improved both for over the sea and over land. They are however more pronounced over the sea, meaning that one can expect a significant improvement of the predictions of the turbulent variables for the wind simulations over the sea with immediate effect. On the other hand, the prediction of the mean wind speed with the change in turbulence description is insignificant.

» **More than just any old square root quotient**

The new description is more than just any old root quotient that someone thought up just for the sake of it. The new description shows that, particularly in the lower atmospheric layers, the turbulences are more intensive than previously thought – and especially over the sea. It also shows that they can differ quite significantly from the turbulences measured at hub height at the same time. The consequence is that the long rotor blade of an offshore wind turbine can be subjected to quite different loads than previously assumed. It is therefore all the more important that we learn more about the incoming wind fields in front of an offshore wind turbine and about the atmospheric layers over the sea in which they occur.

Stefan Emeis, Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research, Garmisch-Partenkirchen
(Photo: © Brigitte Gronau)

The greatest improvements are to be found primarily in the lower part of the atmospheric boundary layer. In particular, the “near-surface” turbulence – or to put it another way, the turbulence over the sea surface – is calculated higher. On the upper edge of

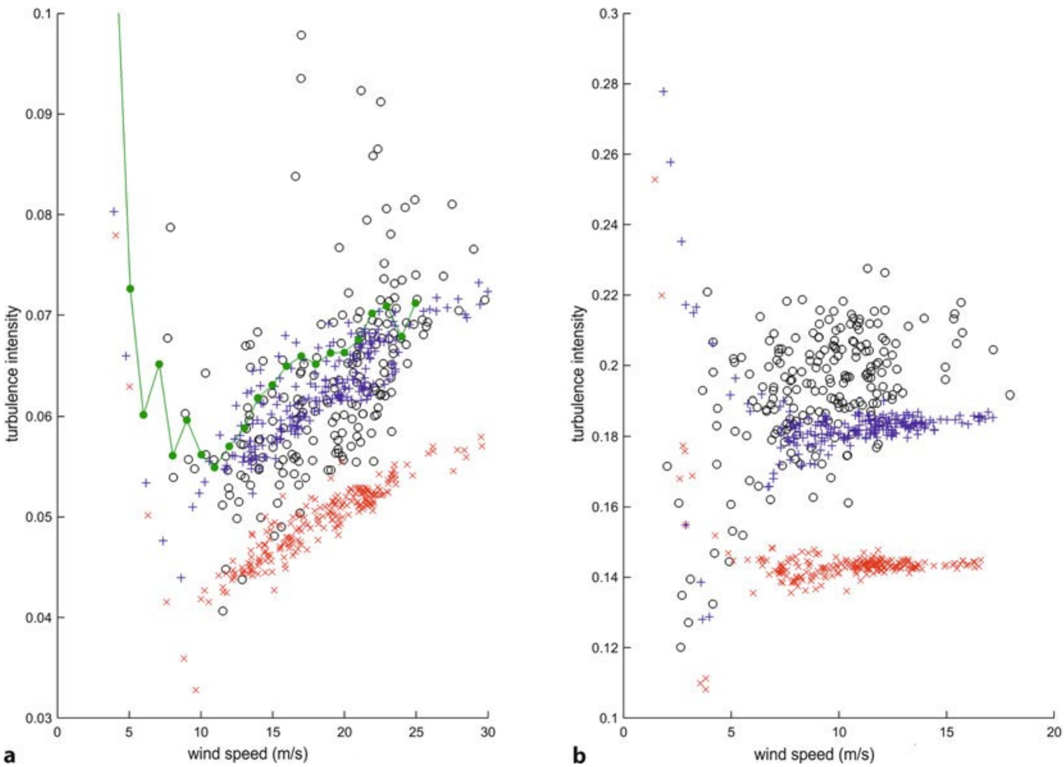

Fig. 16.4 Turbulence intensity (*y-axis*) as a function of wind speed (*x-axis*, in m/s) from measurements for Fino 1 (**a**) and the Hamburg met mast (**b**). *Empty circles* measurements, *red x* previous turbulence parameterisation after Janjic 2001, *blue+* new turbulence parameterisation, *green line* and *full circles* (*only* **a**) averaged data for the whole of 2005 for nearly neutral stratification. © KIT Richard Foreman

the boundary layer on the other hand the old and the new approaches overlap. It then follows that the "improvements in knowledge" achieved here with regard to the turbulence description for wind power usage are essentially relevant for thick boundary layers which can arise at high wind speeds and thermally unstable conditions (Fig. 16.5).

16.5 Outlook

The research project showed that the earlier description of the turbulence in extensive mesoscale wind field models was inadequate. The description of the resistance coefficient of the sea surface should be altered so that it does not continue to increase indefinitely for high wind speeds. This means that lower resistance coefficients apply for very high wind speeds than were previously used. The turbulence is now better described and simulated across the whole vertical extension of the marine boundary layer in the atmosphere. For the lower part of the boundary layer this means a significant increase of the turbulence values accepted up to now. For this reason the loads that impinge on the supporting structures and the rotor blades of the offshore wind turbines are also greater in this range than previously accepted. The new research approach has in the meantime received international attention and been accepted by experts.

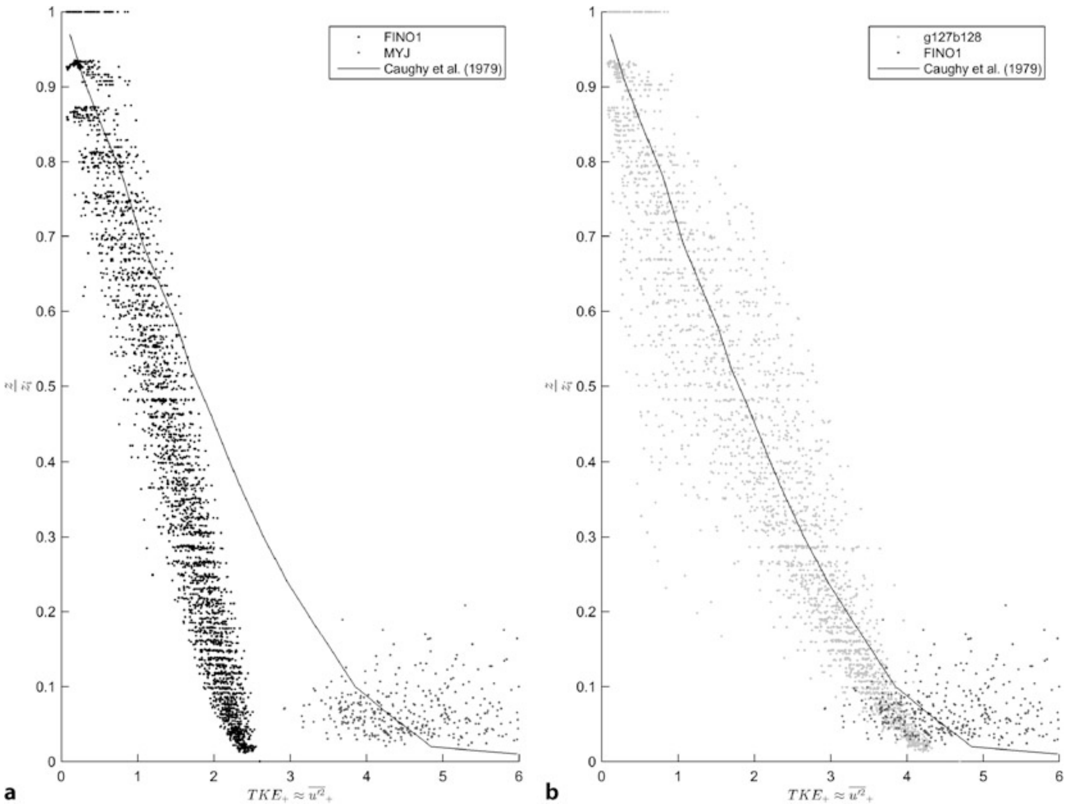

Fig. 16.5 Vertical profile: the *continuous lines* show the theoretical curve after Caughey et al.; **a,b** *dots below* Fino 1 readings, **a** *black dots* Results according to previous approach (Janjic 2001), **b** *grey dots* results of the improvements achieved in the Veritas project. © KIT Richard Foreman

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Sometimes It Almost Bubbles Like a Witches' Cauldron

How the Moisture Fluxes Above the Sea Influence the Turbulences in Offshore Wind Farms

Stefan Emeis, Thomas Neumann, Richard Foreman, Beatriz Cañadillas, Copy edited by Björn Johnsen

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power,* DOI 10.1007/978-3-662-53179-2_17

Project information: Measuring and Evaluating the Influence of Turbulent Humidity Fluxes on the Turbulence in Offshore Wind Farms (TUFFO)

Project management:
Institute of Meteorology and Climate Research
Karlsruhe Institute of Technology
Prof. Stefan Emeis
Project partners:
- UL International GmbH (DEWI)

The air above the sea – like all air in the atmosphere – always contains water vapour. And usually less than it can theoretically absorb, whereby "evaporation" frequently occurs over the sea. The moisture rises up out of the comparatively "warm" North Sea water. The moist air directly above the sea surface is lighter than the dry air above it (when they both have the same temperature) and wants to rise upwards. So the moister air pushes upwards, thereby forcing the heavier, drier air downwards. This causes a rearrangement of the air layers – thus creating turbulences. This is a phenomenon that you can observe in a saucepan of spaghetti. At the bottom, on the hub, the water is hot, and the water above it is still cold. The hot water wants to rise up and starts to bubble like a witches' cauldron.

Of course the "turbulent moisture flux" over the North Sea doesn't actually "boil", but does result in the aforementioned vertical rearrangement of the air layers. And when this very different vertical moisture profile, with its strongly rearranged layers of air, meets a 60 or 80-metre-long rotor blade, the impact is also correspondingly different. The extremely different loads thus also influence the service and operating life of the wind turbines. The investigation of the "turbulent moisture profiles above the sea" was one of the RAVE projects. The meteorological data required was gathered in the direct vicinity of Alpha Ventus, on the Fino 1 measurement platform.

17.1 Installation Takes Precedence over Studying

First discover and describe what is there. What goes for most research also goes for this. There have never been any exact measurements of the moisture flows in the atmosphere over the sea, and certainly not any rapid high-resolution temporal data. The only measurements to date have been at ten-minute intervals – and that is not enough to capture the rapid upheavals in the air.

In order to be able to achieve this goal, two fast moisture analysers with high temporal resolution were installed on the Fino 1 research platform west of Alpha Ventus (Fig. 17.1). These work with a ten-Hertz scanning frequency and thus enable ten measurements a second. The two moisture analysers were attached in 2012 at two different measuring heights, 41.5 and 81.5 m, in order to get data at different heights. So to start with, installation takes precedence over studying.

Peripheral Anecdote (I): Permanently at least wind force 3

Fino 1, the first German offshore measuring station in the North Sea, has now been supplying data about turbulences, wind speeds, wave heights and a good deal more for over a decade. What is particularly encouraging is the extraordinarily high "minimum wind speed" out at sea. There are 8,760 hours in a year, and according to the long-term measurements on Fino 1, one can count on having more than 8,000 hours of at least Force 3 wind (a wind speed of about four metres per second). The rotors of the wind turbines in Alpha Ventus already start to turn with a wind speed of about 3.5 m/s. Provided that there is a high level of technical availability, the rotors of Alpha Ventus are rarely likely to stand still.
Björn Johnsen

17

■ **Fig. 17.1** Measuring arrangement for high-resolution moisture measurement on Fino 1 at a height of 41.5 m. The humidity was measured with the white device in the foreground using optical absorption, and behind it is an ultrasonic anemometer for measuring wind speed fluctuations. © UL International GmbH (DEWI)

17.2 Over the Sea It's Always on the Up and Up

The moisture flux above the sea is basically always there, because there is always evaporation on the sea surface, even with stable air stratification. It has been found that this evaporation – the upward moisture flux in the air – has a significant influence on the stability of the atmospheric boundary layer over the sea. Depending on the prevailing ambient conditions, the marine atmospheric boundary layer ranges from 30 to 40 metres. When the air is very cold above very warm water it rises up to several hundred metres above the surface of the sea. The results of the moisture measurements for both heights on Fino 1 prove that the moisture flux significantly influences the vertical rearrangement of the air layers.

When the air stratification is unstable and becomes turbulent, the moisture flux at both measuring heights contributes up to 30 % of this instability. If on the other hand the stratification in the air remains relatively stable, because warmer air is flowing over colder water, there is less moisture flux. Over warmer water the evaporation is significantly greater than over colder water. So the destabilising influence of the moisture flux in summer and autumn is much greater than in winter and spring, when the water has not warmed up much. As a result, the moisture flow over the seas in the south is far greater than over the seas up in the far north.

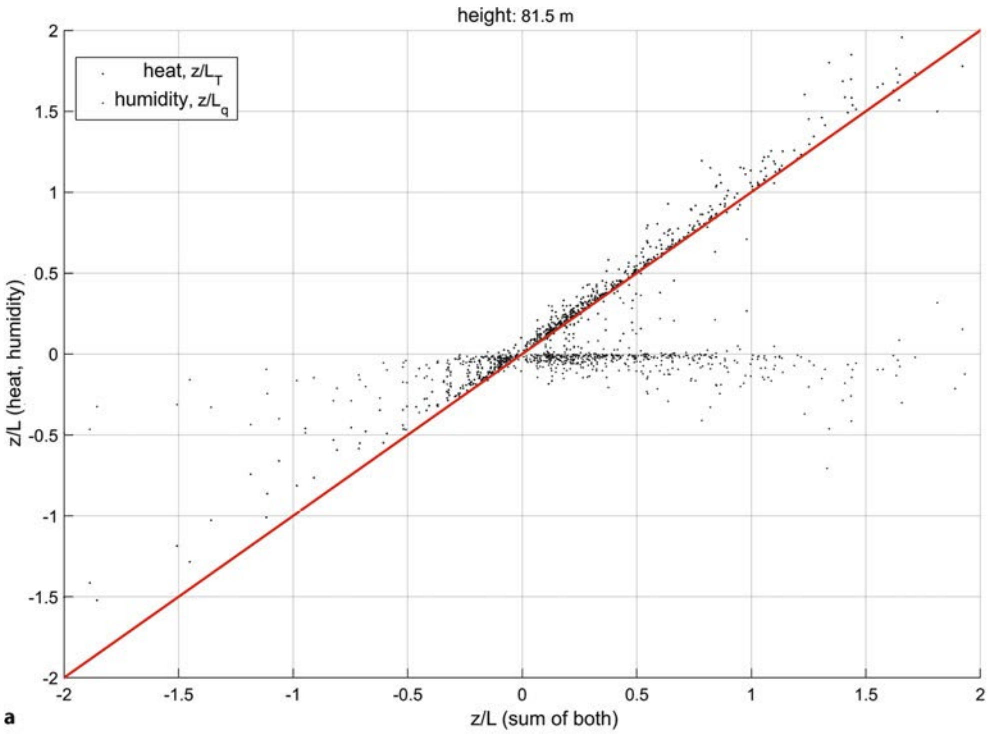
The moisture flux within the atmospheric stratification always has an effect towards "destabilisation" (■ Fig. 17.2). At a measuring height of 81.5 metres the moisture flux has an even greater effect than at a height of 41.5 metres, and consequently different turbulence loads occur in this range.

The measurements taken on Fino 1 confirm a prior basic assumption. The turbulent moisture fluxes over the sea that are always upward ("evaporative effect") alter the static stability of the marine boundary layer towards instability.

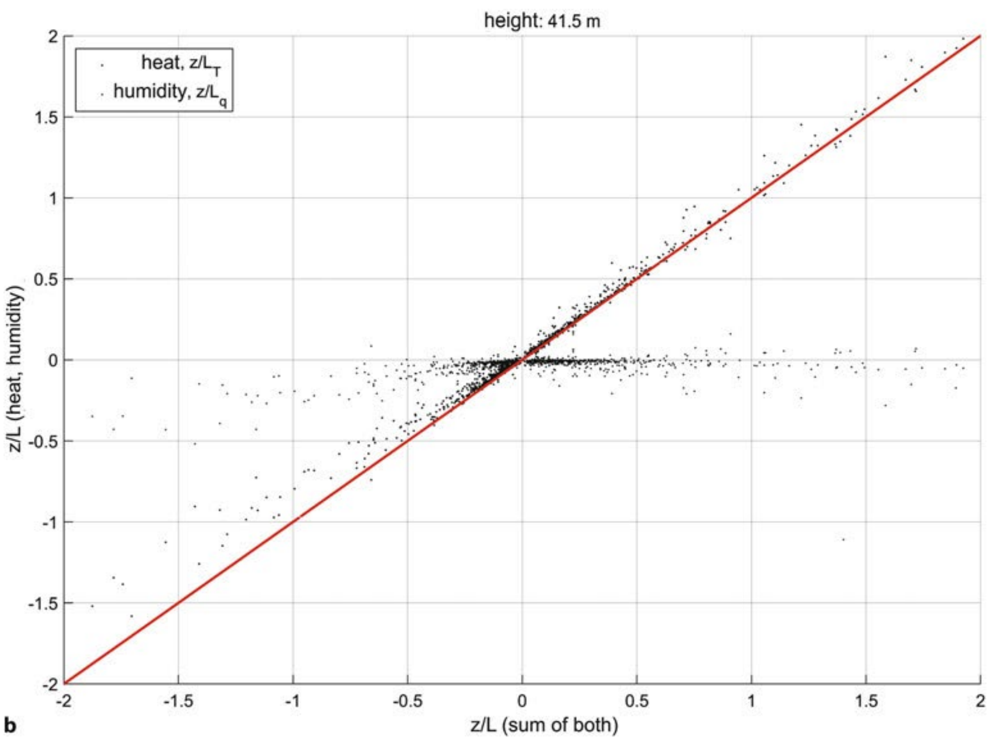
17.3 Like in the Classroom: It Gets More Turbulent Behind the First Row

What influence does the turbulent moisture flux have on the arising wind turbulence? Rather a lot in fact. These exist in the atmosphere, especially when the layers of air are unstable. The turbulence in the incident flow of the "open sea", in other words in front of the wind farm, is always small. The wind turbulences in the wake of Alpha Ventus, in other words "behind" the wind farm, are on the other hand significantly greater, as can be seen in ■ Fig. 17.3. So like in a classical schoolroom with the desks arranged in rows, it's mostly calm in the front row, and it gets more restless the further back you go … Although this image is not entirely true. The cause of the increase in turbulence within a wind farm is the wind turbines themselves (■ Fig. 17.4). When their rotors turn "vortices" increase and thus also turbulence.

Another phenomenon is that although the shadowing caused by the wind turbines in front should mean that the output of the turbines in


height: 81.5 m
heat, z/L_T
humidity, z/L_q
z/L (heat, humidity)
z/L (sum of both)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2

a


height: 41.5 m
heat, z/L_T
humidity, z/L_q
z/L (heat, humidity)
z/L (sum of both)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2

b

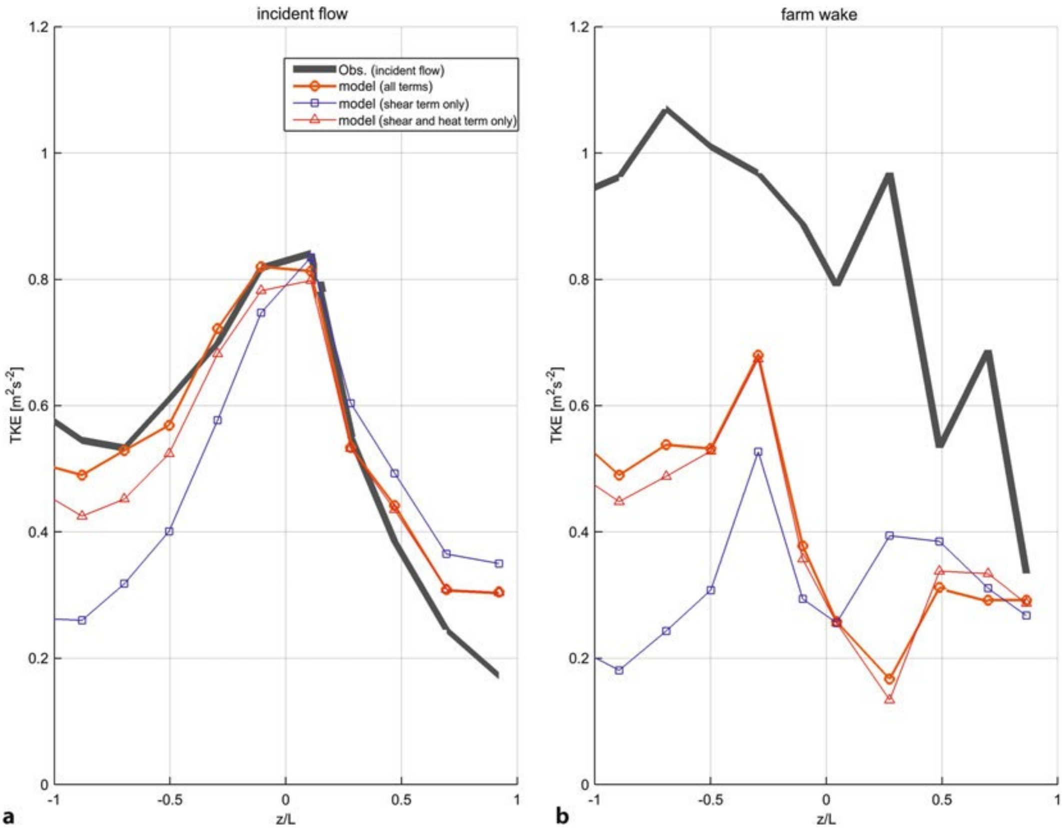
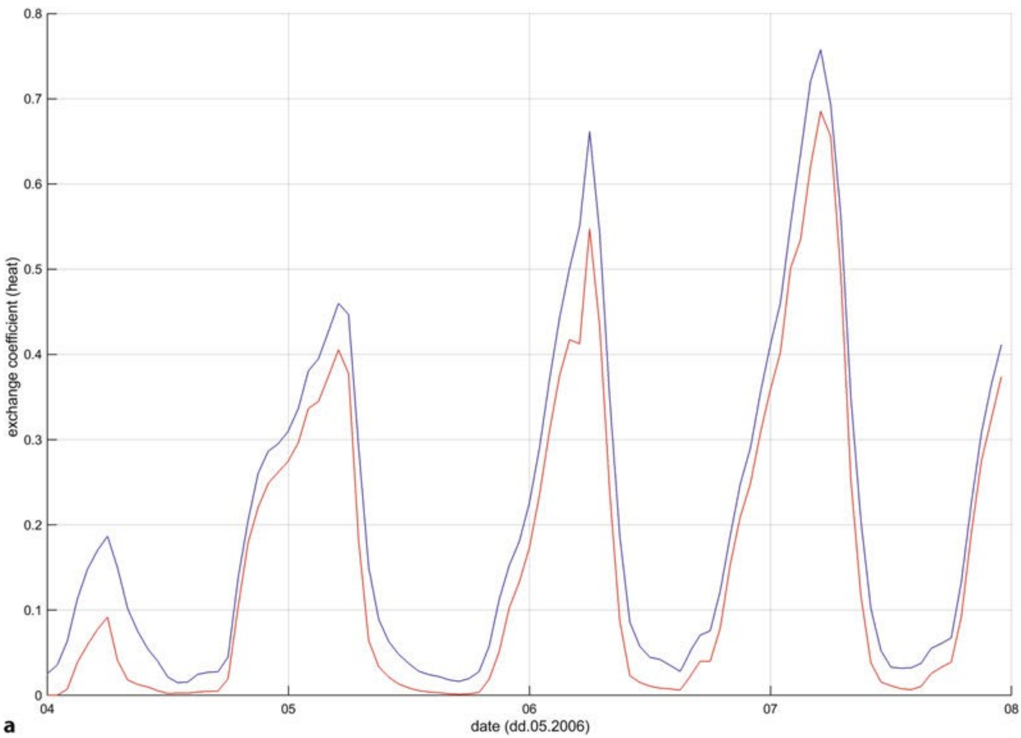
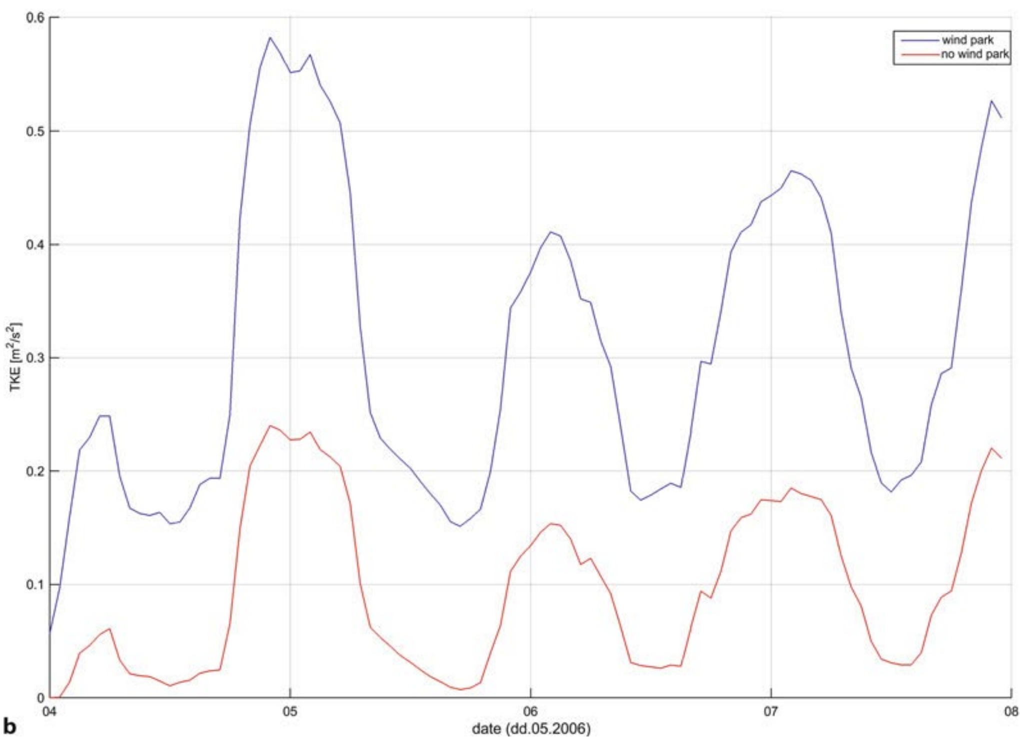


Fig. 17.3 Turbulent kinetic energy as a function of the static stability of the boundary layer (−1 very unstable, 0 neutral, +1 very stable) at a height of 41.5 m on Fino 1 for winds from the western half space (**a**) and in the area of the wake of the Alpha Ventus wind farm (**b**). *Thick grey line* measured turbulent kinetic energy, *blue squares* and *line* measurement data for momentum flux, *red triangles* and *line* measurement data for momentum and heat flux, *orange circles* and *line* measurement data for momentum flux, heat flux and moisture flux. © KIT, Richard Foreman

the fifth, sixth or even tenth row (as in the Danish Horns Rev wind farm) should decrease to zero. But it doesn't. The reason why even the back row can still produce enough wind power is that the atmosphere is able to "top up". Turbulent motions that run from top to bottom across the vertical wind field also provide "wind replenishment from above". So the wind field "recovers". This process works even better on land to the extent that wind turbines in the second and third rows can be sited closer behind one another. Out at sea the "recovery" of the wind field – the "topping up" by turbulence – doesn't work quite as well, which is why the distance between the wind turbines should be much greater. Nevertheless, the wind turbines within an offshore wind farm can be arranged in up to ten or more successive rows (as in Horns Rev 2), because sufficient space is available. The moisture contributes to a certain increase of this turbulence. And where the stratification is unstable anyway, the

Fig. 17.2 Analysis of the two contributions z/L_T (turbulent heat flux) and z/L_q (turbulent moisture flux) to the overall static stability (z/L total) at both heights, 81.5 m (**a**) and 41.5 m (**b**), on the Fino 1 mast. The stability measure has negative values when the stratification is unstable, is zero at neutral stratification, and is positive when the stratification is stable. © KIT, Richard Foreman


exchange coefficient (heat)
date (dd.05.2006)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
04
05
06
07
08
a


TKE [m^2/s^2]
date (dd.05.2006)
wind park
no wind park
0
0.1
0.2
0.3
0.4
0.5
0.6
04
05
06
07
08
b

moisture is why the wind shadows behind the farm are about 10 % shorter.

The improved recuperative for the wind field, the "recharging" of the wind speed, especially in larger wind farms, constitutes as it were the "reward" for the wind turbine – for enduring the stronger turbulence.

Peripheral Anecdote (II): Foreign moisture analysers on Fino 1

Fino 1 is also of interest to its neighbours. And that does not just mean seagulls and porpoises. Even though it is hundreds of sea miles away, the Norwegians are also using the unmanned research platform for a year, until June 2016. The Norwegian offshore centre Norcowe in Bergen is installing two lidars and a microwave radiometer on Fino. The latter will supply data about temperature and moisture profiles up to a height of a thousand metres. Next to Fino 1 the Norwegian offshore researchers are also positioning an autonomous measuring buoy in the sea, which will measure the waves and the atmospheric layers, and their turbulences, above them. Because of the predictably high loads the buoy will be subjected to, the measuring period will be significantly shorter.
Björn Johnsen

17.4 Outlook: Keep on Writing!

The research project might have reached the end, but the evaluations are not yet complete. Results about the parameterisation of the moisture flux in numerical wind field models and the more detailed influence of the moisture flux on the wakes of offshore wind turbines are still awaited. When warm air (which usually comes from land) flows over cold water it reduces the "evaporative process" and results in the formation of internal boundary layers in the atmosphere – and thus to strong influences on the vertical wind profile. Turbulence intensity and vertical wind profiles have a strong influence on the wind power production and the wear and tear of offshore wind turbines. This particularly affects the strength and length of the "wind wake" behind the front turbines on the wind turbines in the second and third rows, and thus for the entire wind farm. This is important for estimating the load on and service life of the wind turbines and for calculating the necessary distance between the turbines within the wind farm and between the wind farms.

The task remains to accurately investigate and describe the turbulence intensity, because without this it will not be possible to develop mesoscale models some day, which could then predict the influence of a whole wind farm on the wind field at an early stage.

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Fig. 17.4 Turbulent kinetic energy at a height of approx. 90 m simulated with WRF without and with an idealised large wind farm in the southern North Sea for a period with very stable stratification in May 2006. The exchange coefficient is shown in subframe (**a**), the turbulent kinetic energy in subframe (**b**). © KIT, Richard Foreman

Artificial Intelligence and Automatic Self-Organisation

Methods and Tools for Proactive Maintenance at Sea

Stephan Oelker, Marco Lewandowski, Klaus-Dieter Thoben, Dirk Reinhold, Ingo Schlalos, Copy edited by Björn Johnsen

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power,* DOI 10.1007/978-3-662-53179-2_18

Project information: Methods and Tools for Proactive Maintenance of Offshore Wind Turbines (preInO)

Project management:
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Stephan Oelker
Marco Lewandowski
Project partners:
- Senvion GmbH
- SWMS Systemtechnik Ingenieurgesellschaft mbH

18.1 Wind Farms Inaccessible for Six Months?

Maintenance and repair out at sea is expensive (Fig. 18.1). The maintenance and replacement of components can make up a good 25 % of the total operating costs (including erection). A significant factor thereby is repairing unexpected damage. Up to now repair and maintenance of offshore wind turbines was carried out in fixed time cycles – or when damage occurred. This involves a high risk of loss of production, because there is a risk of turbine downtime if the components are not quickly available or the wind farm cannot be reached by ship. Maintenance work is only possible to a limited extent when wave heights reach just one and a half metres or – as is often the case – wind speeds exceed 20 m/s. Wind farms in the North Sea are usually only accessible by water on half the days of the year. While some work can be done with the help of a helicopter, that is an expensive and risky business. Rough calculations suggest that "suboptimal" maintenance and repair can cost a 60-megawatt offshore wind farm a good 600,000 euros a year in lost income. Over a service life of 20 years that makes about 12 million euros. At this stage the right maintenance strategy is now an important subject at last, and it would appear that there is great potential for optimisation offshore.

Whether "artificial intelligence" and "automatic self-organisation" will in future be able to optimise maintenance and repair operations out at sea was investigated and further developed in the "Methods and Tools for Proactive Maintenance of Offshore Wind Turbines (preInO)" project. Previous maintenance and repair concepts have always differentiated between breakdown-oriented, periodic and condition-dependent maintenance.

18.2 Inspired by the Good Old Used Car

Everyone who has ever owned an "old banger" of a car knows the principle of breakdown-oriented maintenance; you completely do without preventative care and concentrate on getting it repaired (or not …) when something goes wrong. Type, time and extent of the repairs required are unknown and usually unscheduled.

With periodic maintenance the aim is to replace ageing components at predefined intervals before they break down. Staying with the car: the drive belt is replaced every 60,000 kilometres regardless of the actual load, in other words regardless of whether the driver regularly drives around hairpin bends at 180 kilometres an hour or chugs along through play streets at walking speed … this principle accepts that the service life of a component is usually not fully exploited.

Condition-oriented or condition-dependent maintenance is a strategy that focuses on prevention. Maintenance and repair measures are only taken as required, but before the component breaks down. The necessary knowledge about the condition of the components is often determined via sensors and on-site inspections. This strategy is of course based on the idea that most failures are signalised beforehand by measurable indicators.

18.3 It Takes a Breakdown to Trigger the Maintenance Process

The most frequently used maintenance strategy for wind turbines is still the periodic strategy – the maintenance team comes out once a year, and usually in the summer – or the strategy applied is a strictly curative one. Condition monitoring systems (CMS) are now usually installed in the newer wind turbines, where parts and components are

Fig. 18.1 View from the nacelle of a Senvion 5M in Alpha Ventus. © Senvion

equipped with technological aids, such as sensors, that are used to judge their condition. In the event of previously defined deviations or when thresholds are reached, they transmit an alarm message and service management can then plan and initiate the appropriate maintenance measures. To date however, these technical systems have not been able to provide a complete basis for comprehensive planning and management of the operational maintenance. They only serve to discover faults, so the maintenance process is thus only triggered when a fault occurs.

Is such condition-dependent maintenance then really the "ultimate solution" for offshore wind turbines? Their limited accessibility poses great challenges with regard to the availability of ships and spare parts.

18.4 About the Peaceful Coexistence of Systems

Most offshore wind farms use a mixture of the aforementioned strategies. The scheduled annual maintenance is usually for carrying out checks, servicing and making minor repairs. Such "standard maintenance operations" can take several weeks out at sea. Most of the particularly critical components are monitored with a condition monitoring system – but not all of them. And their sensors can also be faulty or wrong, like strain gauges for example, which can change as a result of environmental factors – without there actually being any impending component damage. And even if there is – and this is exactly where the problem lies – the error report far from guarantees that spare parts and ships are available to carry out the repairs, or that the weather window is long enough to do the job.

The "preInO" research project was thus to extensively investigate methods and tools that could be used for a proactive maintenance strategy, taking into account a variety of data sources. To be able to make the best possible prognosis about the condition of critical components, very different sources of data like sensor values, statistical data, maintenance data from the offshore wind turbine's "life cycle file, questioned and externalised" employee knowledge and expertise, weather data, warehouse stocks and personnel planning were analysed, automated and combined to create, as software developers like to say, a "relevant event" (Fig. 18.2).

18.5 Gathering Data: From Gear Oil to "Concert Pitch" of the Blade Rotation

This must include the setting of priorities for detected faults, a loss of gear oil can be more important than the "concert pitch" of the turning rotor. This

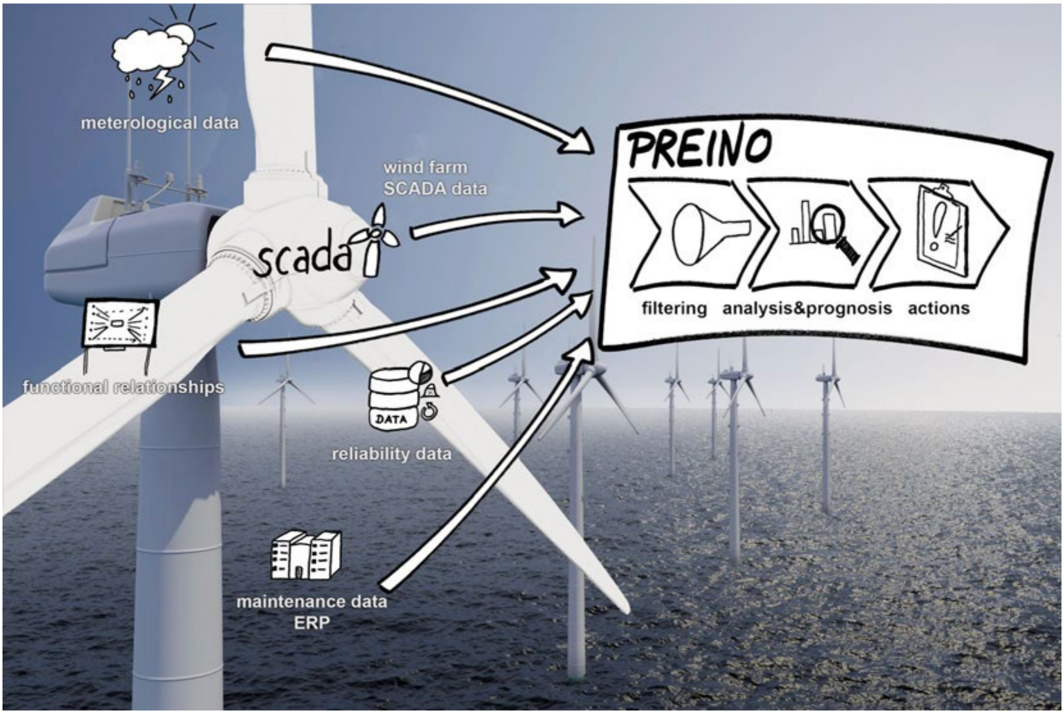

Fig. 18.2 PreInO data concept: a wide range of data and information is passed to the system for filtering, analysis and recommendation for action. © BIBA

also involves the dynamic and non-static planning of the extent of the maintenance required is also part of this, including the planning in of the work processes, the associated logistics and the use of decentralised control systems. The "regular" offshore maintenance processes are also factored in, with data sources being identified for automated decision-making support (Fig. 18.3). All this knowledge was to be used to develop a software module and a demonstrator, which can examine the applicability of the methods and tools developed on the basis of real data.

18.6 The Process Machine Is Running

The project consists of several work packages and runs until 2016. The first work package, "process mapping", depicts the offshore service processes based on a Senvion offshore wind turbine. The subsequent concept and algorithm development is to be simplified with a database specially created for this. The wind turbine's hierarchical and functional relationships are also to be integrated into the system. Building on this, it was possible to develop a concept for a proactive maintenance strategy for determining the condition of the wind turbine and for automated provision of recommended actions, with four sub-items: data concept, framework with algorithms, processing engine (as a pure execution engine) and evaluation.

The concept foresees that data from various sources is combined, either by way of defined interfaces or by aggregating the data, in a "data warehouse" for example. Then the so-called "processing engine" comes into play, as a "pure execution machine", which works through predefined processes bit by bit. It ensures that evaluations are made using a range of calculation procedures from the programme library with the corresponding algorithms and data. The evaluations are then examined in terms of such parameters as urgency, aggregation or postponement with other repair work before being sent as an automated recommended action.

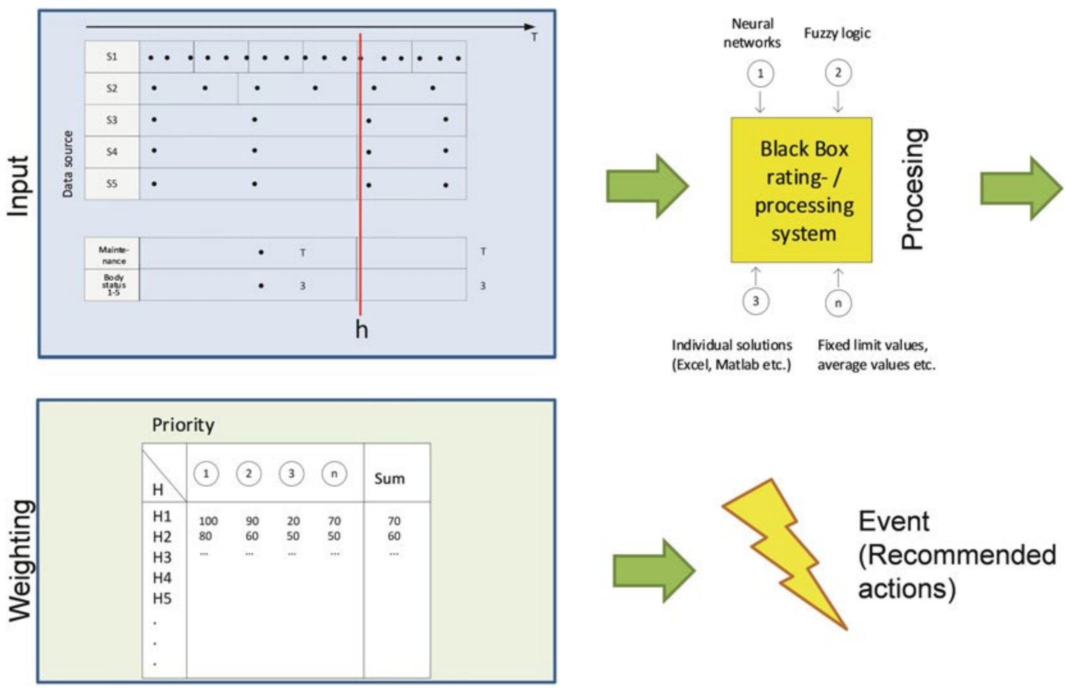

Fig. 18.3 PreInO data flow: from data migration to recommendations for action for maintenance and repair operations. © BIBA

18.7 A Different Selection for Once: Please Present a Wide Range of Faults

The components whose condition characteristics were to be determined by "preInO" were defined in collaboration with wind turbine manufacturer Senvion: the rotor bearing, the main gear as a complete system, the pitch batteries, the inverter, the generator and the yaw/rotor holding brake. These selected components thus present a broad spectrum with which it is possible to extend the principle to the entire wind turbine.

Workshops were held together with the responsible persons for each of the subsystems in order to analyse any possible failure behaviour of the respective components and to talk to experts about possibilities of automated evaluation. The knowledge gained from these is currently being implemented so that in the end the "processing engine" will be ready for use, the "data capture platform" is filled with data, and the algorithm pool is also available. A demonstrator is currently being developed based on this, which will visually illustrate the corresponding options for action like a simulation game and thus enable trials with a greater number of turbines.

Peripheral Anecdote: On both sides of the "Canal Grande"

The research project has a strong practical orientation, which is why there was a regular exchange of ideas and information between researchers and the industry. The Senvion on-site maintenance processes were therefore incorporated at the base in Norden-Norddeich in Lower Saxony and at the production plant and test turbine in Bremerhaven as well as the control centre in Osterrönfeld and the base in Büdelsdorf in Schleswig-Holstein. These two Senvion sites face each other on opposite sides of the Kiel Canal, which might one day become the "Canal Grande" of the Schleswig-Holstein offshore wind energy industry.
Björn Johnsen

18.8 When the Offshore Machines Negotiate About Maintenance with One Another

Proactive maintenance can also contribute to the optimisation of the strategies and processes applied. For example, it would be possible to readjust the fixed preventative maintenance intervals based on the evaluations of the gathered data. It would also be possible to better plan, or even avoid, corrective maintenance measures, for example by providing statistical data about the estimated time needed for the maintenance work or the predicted residual life of the individual components. There need be no necessity to alter the strategies and measures applied at present. Each individual measure can however be organised more efficiently in order to increase the overall efficiency.

In perspective it is quite conceivable that in future, in the sense of self-guidance with an "agent-based" approach in the machine, wind turbines will be able to trigger maintenance measures themselves with regard to resource allocation and available logistics. And then one step further into the future, offshore wind turbines will be able to negotiate with one another about which of them needs a service visit more urgently and which can wait a bit …

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Well, How are They Running?

Monitoring Offshore Wind Turbines in Germany

Berthold Hahn, Stefan Faulstich, Volker Berkhout,
Copy edited by Björn Johnsen

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power,* DOI 10.1007/978-3-662-53179-2_19

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Berthold Hahn
Project partners:
- Engineering Company for Reliability and Process Modelling (IZP)
- FGW – Federation of German Windpower

19.1 Going from Land out to Sea

The inspiration here was on land: the Offshore WMEP – Scientific Monitoring and Evaluation Programme for Offshore Wind Energy Use – effectively carries on where the Scientific Measuring and Evaluation Programme (WMEP) of the 1990s left off, a programme that successfully accompanied the start of wind energy use on land. The WMEP made it possible to compare production and site conditions of over 1,500 wind turbines on land. It was also possible to evaluate a total of over 60,000 maintenance and repair reports for these, which came in over the programme period (usually ten years per turbine).

The still young use of offshore wind energy faces just as great a challenge as wind energy use back then on land with regard to turbine technology, investment, production and insurance costs, logistics, maintenance and repairs. Final evidence is still lacking as to whether wind energy use in water up to 40 or 50 metres deep and over 50 kilometres from the coast can realise the hopes placed in it in the long term.

With higher average wind speeds offshore, the energy yield is significantly greater than on land. The significantly higher, combined load created by waves, wind and turbine operation creates much greater demands for offshore turbine design and maintenance planning, particularly because offshore wind turbines are frequently inaccessible for maintenance work to be carried out.

The determination of reliability parameters and their use in reducing the amount of maintenance work required as well as in increasing availability require several years of prior investigation. Failures and breakdowns under particular operating conditions first have to be systematically recorded over longer periods of time before they can be subjected to analysis.

With the Offshore WMEP as part of a longer-term effort, the Fraunhofer IWES will also contribute to ensuring that operational experience is systematically recorded and evaluated, so that it can be used by the wind industry in further developments.

19.2 More Than Just Counting Kilowatt Hours

A systemic approach is always preferable to hasty rush jobs. The earlier WMEP was a valuable source of information about development on land. The WMEP failure database provides valuable knowledge about the reliability of wind turbines, for example the annual failure rate and downtime for each failure incident. ◻ Fig. 19.1 shows these characteristic values for the average of all the wind turbines recorded in WMEP.

The operating and maintenance data for the new offshore wind farms therefore needs to be systematically collected at component level and in a standardised form by operators and scientists working together with other players, such as component manufacturers and logistics providers. We want to know more about the components: not just determine that the pitch control has broken down for example, but to analyse where exactly the fault is – in the motor, in the gears or on a particular circuit board. It is only possible to recognise the relationships between faults and the respective operating conditions if detailed recordings have been made so that it is possible to detect and even avoid similar faults in the future.

19.3 A Word in Your Ear: Confidentiality and Individual Evaluations

The objective of the Offshore WMEP is to investigate the reliability of offshore wind turbines and their components using a cross-company database,

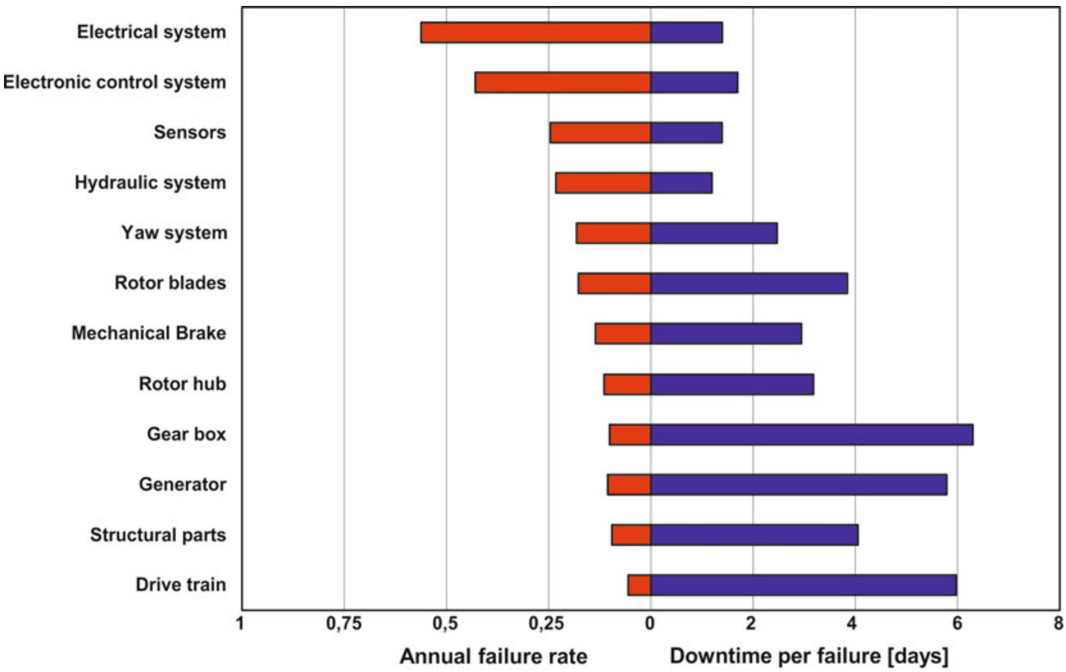

Fig. 19.1 Number of annual failure cases of main components and the associated typical downtime from almost 30,000 maintenance reports. © Fraunhofer IWES, Wind Energy Report Germany

and specifically in the interests of the operators. It should also give a – fully anonymised – higher-level, fundamental look at the situation and allow the general public to derive information about broad technical development tendencies. This is not a contradiction, but a sensible, mutual supplementation.

This requires a sophisticated confidentiality concept (Fig. 19.2) that has to be accepted and strictly adhered to by all the partners. A pioneer wind farm operator might not necessarily want to see any difficulties they had with installation and logistics made widely public. And a turbine manufacturer might not want the teething problems with their new turbine type seen straight off as a typical serial fault. The Offshore WMEP is thus developing a knowledge database that both the actors involved and the interested public can profit from.

The confidentiality concept divides both the data to be collected and the data resulting from the analyses into different confidentiality levels and different recipient groups. This makes it possible to make general trends and wider results available to the general public that are to a great extent derived from non-confidential data. Detailed analyses based on confidential data that makes up the greater part of the data pool are shown as "group results" for a restricted group of participants (Fig. 19.3). These group analyses can include such things as results relating to turbine concept or site features like sea depths, distances from the coast or wind speeds. There is also the possibility to provide individual results solely to the participant in question and no other – such as the evaluation of his wind farm individually tailored to suit his requirements and parameters. This "bespoke suit" remains confidential.

19.4 Involving the Actors: Persuasive Efforts

Wind farm operators are obviously very interested in determining the fault behaviour of wind turbines and their components because for them, a reduction in maintenance work with constant or even improved availability has a direct financial effect. Several German offshore wind farm operators are currently involved in OWMEP and the Federation of German Windpower and other Re-

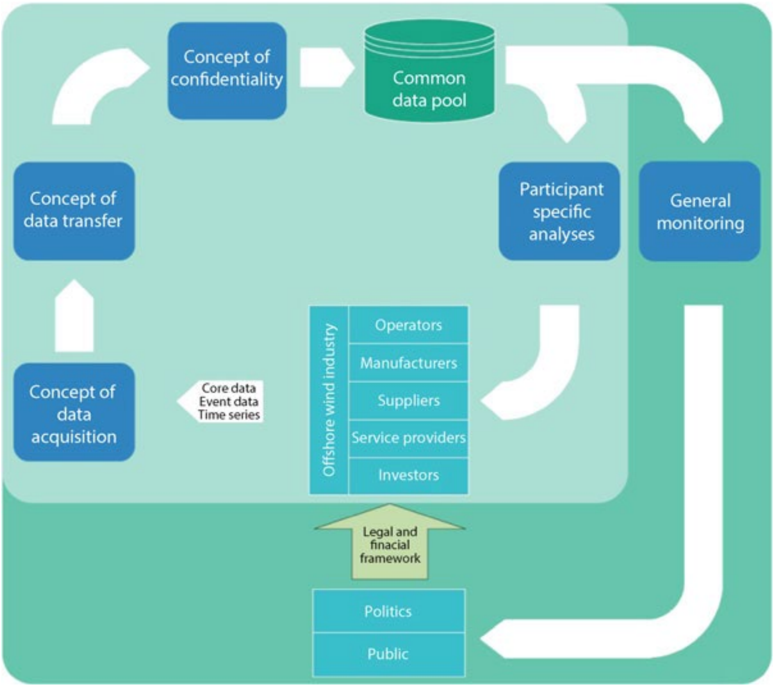

Fig. 19.2 OWMEP confidentiality concept: the offshore wind farm operators maintain ownership of the data they have fed in, and they receive detailed, confidential analysis results. The general public gets previously agreed, anonymised knowledge of a more general nature. © Fraunhofer IWES

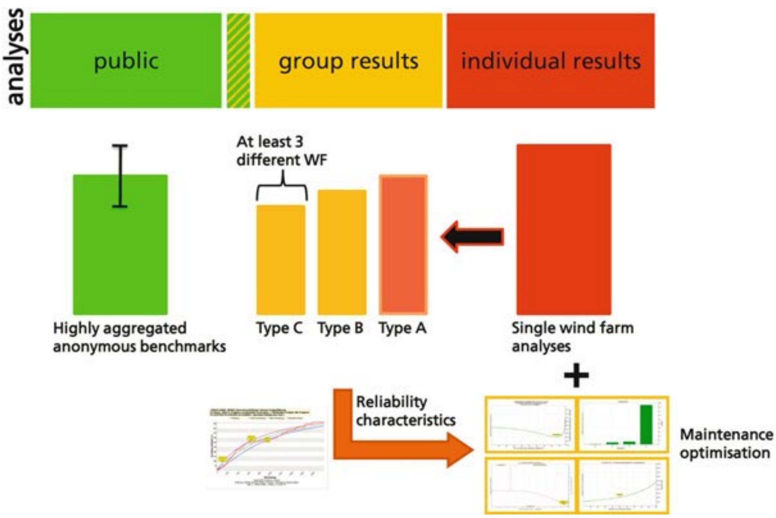

Fig. 19.3 Analyses for the offshore wind farm operators: groups and individual analyses. © Fraunhofer IWES

newable Energies (Fördergesellschaft Windenergie und andere erneuerbare Energien – FGW) and IZP Engineering Company for Reliability and Process Modelling Dresden continue to support the project.

Many actors are involved in the maintenance processes and relevant information is being generated at all locations, and virtually all the companies involved with maintenance must therefore be included in the research.

The database should also generate valuable analyses for manufacturers and component suppliers, so that they can use them to improve the designs of their wind turbines and components. Service pro-

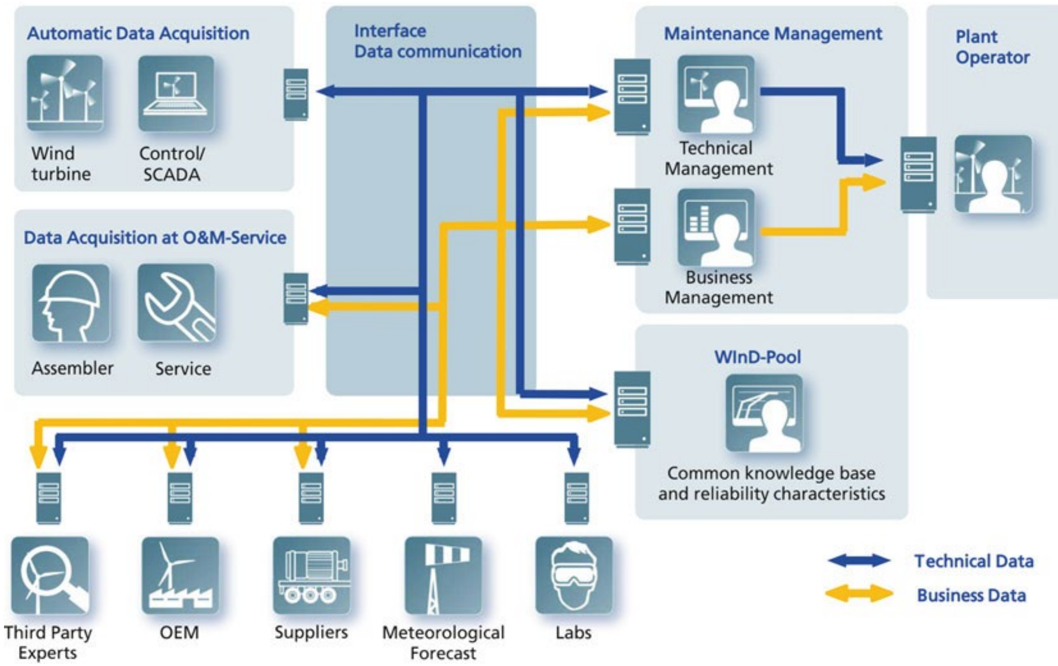

Fig. 19.4 The many communication channels need a uniform language: in other words, standards or guidelines for the naming of components, describing faults and the circumstances under which they occurred, as well as an interface for transferring the information. © Fraunhofer IWES

viders would use reliability analyses to improve their maintenance activities, while insurers and banks can back up their risk calculations with solid data. But first and foremost the wind farm operators and the service providers have to import reliability-relevant data into the cross-company database in a standardised form (Fig. 19.4).

19.5 Events, Results – and a Library!

The mandatory standardised data structure consists of three parts: core data, operating data and result data.

The data survey and structure was developed in unison with the interested parties, including in an early workshop in 2008 involving ten wind farm operators, representing 15 of the 23 offshore wind farms approved in Germany at that time. The data catalogue that was developed consists of the core data from the wind farm, current measurement value time series and special event data. This serves – taking operator expectations and the confidentiality concept into consideration – as the minimum requirement for the offshore operators involved.

The core data contains general information about the wind farm and turbine. In addition to classification characteristics like a unique turbine ID, it includes information about the type of turbine and site information. The core data must contain all the relevant parameters that identify the respective wind turbine and allow a differentiation of the results according to site specifics and turbine technology for use in later analyses.

The second information category is the operating and event data. Uniform and unique identification is also indispensable here. First of all the current operating data, especially wind and power data, is recorded. This also includes technology-related readings like gear temperature or grid parameters. At the start of the project not all operators are in a position to provide all the valuable measured quantities, but as soon as the values started to come in it is possible to make a pretty good estimate of the current operating state of the wind turbine.

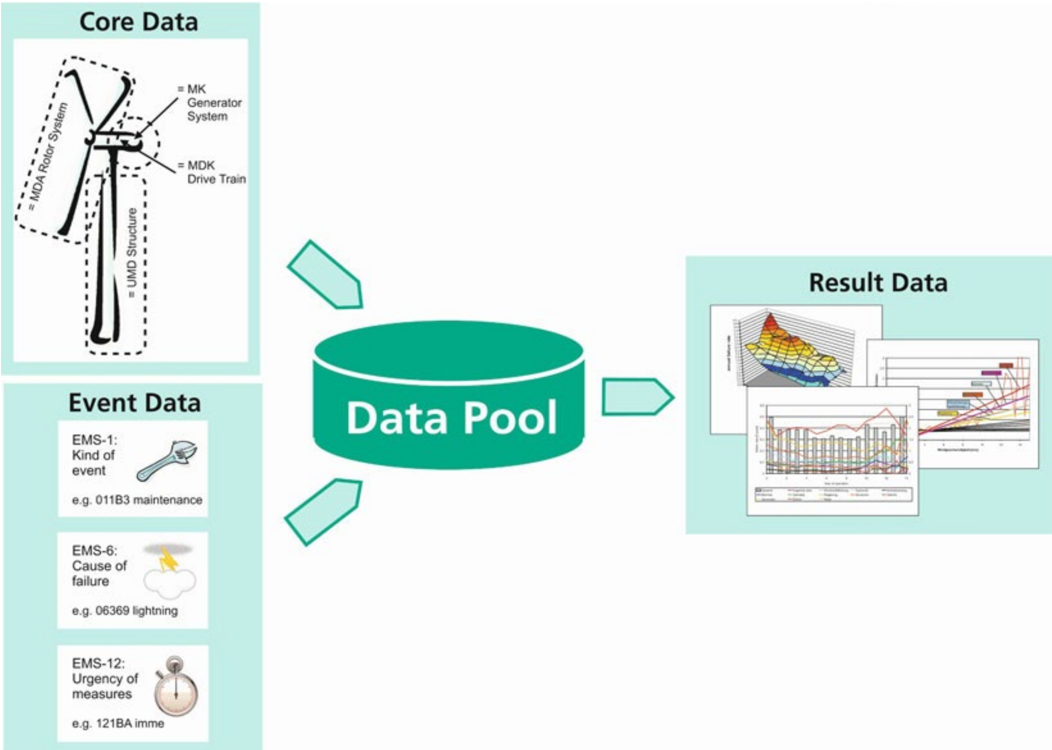

Fig. 19.5 The database subdivided into core, operating and event data. All result data should later make up a parameter library of the reliability parameters and functions. © Fraunhofer IWES

Event data describes all operating conditions that deviate from normal operation, especially maintenance activities. This includes such things as affected components, and their damage or malfunction that triggered the change of the operating condition from normal operation to standstill. And this also includes information about the type and extent of the damage and its cause, etc.

This event data later creates the basis for all reliability investigations. Together with the core and operating data and further maintenance information, such as time of damage and time required for remedy, this data is analysed for every component.

The result data makes up the third part of the extensive data acquisition and is comprised of core, operating and event data. This means reliability parameters like the average time between two failures of the same component or the repair time. As gruesome as such categories might at first sound, they are essential to be able to make sound statements about the reliability or failure probability of specific turbines or components under particular operating conditions. Just as indispensable is a broad database. The wealth of experience of each individual wind farm operator or technical operations manager is not enough to achieve this range. It is therefore quite logical that many operators are coming together to set up a joint "parameter library" (Fig. 19.5).

19.6 Zeus Makes It Possible

The data for this must however first be acquired, transmitted and processed in a uniform manner, because this is the only way to make a wind turbine "readable". Working groups of the Fördergesellschaft Windenergie, the publisher of technical guidelines (for wind energy generating units), and VGB PowerTech (publisher of guidelines for the energy industry) were also significantly supported in cooperation with the joint project "Increasing the Availability of Wind Turbines", also funded by the Federal Ministry of Economic Affairs and Energy. These working groups are dedicated to developing coding systems for the designation of plant components, the description of operating conditions, faults and damage, and a transmission protocol. The resulting new guidelines, RDS-PP® (Reference Designation System for Power Plants), ZEUS (State-Event-Cause Code) and GSP (Global Service Protocol), and here the circle closes, have all been taken into account in the Offshore WMEP database structure.

» **Long-distance running with a magnifying glass and a telescope**

The Offshore WMEP is a long-distance run – and a team sport where there are no losers. Because with the data reporting and the feedback received – some of it confidential, some only for groups, and some of it as a comprehensive trend analysis – every wind farm operator gains knowledge which will make him able to avoid some of the negative experiences that may have been made by his peers. To put it simply, he doesn't have to put his hand on the same part of the hob to find that it can be painful. The Offshore WMEP is a magnifying glass (and not a burning lens) and telescope at the same time. With the magnifying glass we reflect the detailed results back to the wind industry and with the telescope the public can recognise the general trends and perspectives. The maritime long-distance run in Germany may have started late and be somewhat delayed, but it will continue for decades.

Berthold Hahn, head of wind farm planning and operation, Fraunhofer IWES

19.7 "IEA Wind Task" – More than Just a Talk Show

It became clear in the concept phase that the creation of a suitable data structure cannot be completely solved at the national level. To this end, Fraunhofer IWES organised a follow-up expert workshop within the scope of the International Energy Agency (IEA) "Wind Task 11", in which 23 experts from ten countries exchanged ideas and experiences. The unanimous result of this workshop was that an international guideline for standardised acquisition of reliability and operating data that enabled comparability of the data could make a great contribution in improving the operation and maintenance of offshore wind farms. Since then IWES has been running Task 33 "Reliability Data" in the IEA Wind Section. The Task is drawing up an international guideline for the acquisition, processing and analysis of reliability-relevant data. This guideline is due to be published in autumn 2016. The existing and future national guidelines should be integrated as much as possible into the resulting international guidelines with the support of the Offshore WMEP.

19.8 Over 200 Offshore Turbines Are Involved

Now that the preparatory work has been largely completed, the participating operators are starting to feed current and historical data dating back to the commissioning of the wind farm into the Offshore WMEP database. The data from 237 offshore wind turbines from five wind farms are currently being evaluated according to various aspects.

The evaluations are currently focussing on the so-called operator reports, which are only made available to the respective operator. These reports show the wind conditions in the location, the respective power curve (based on the readings of nacelle anemometers), time-based and energetic availability, capacity factors and full load hours, operating conditions and the number of switching operations, standstill durations and frequencies, both as a composite for entire wind farms and also in detail for each wind turbine.

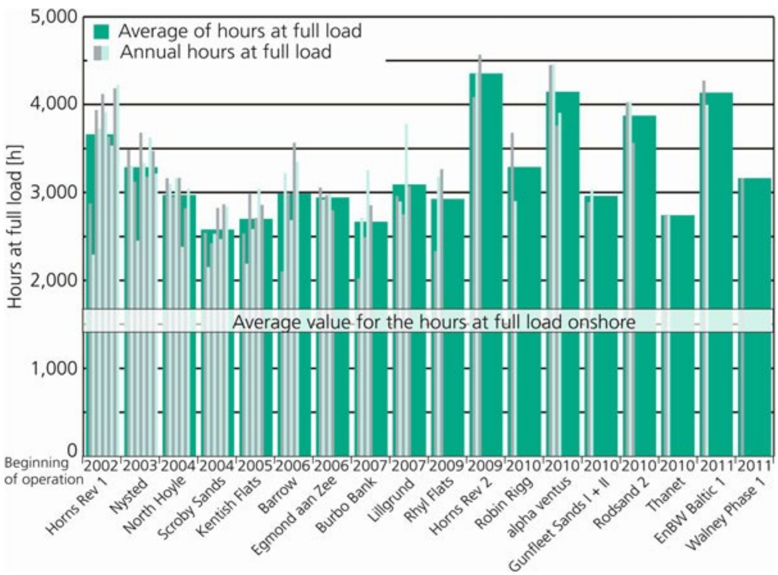

Fig. 19.6 Offshore full load hours of different wind farms from a rated output of 45 MW. © Fraunhofer IWES

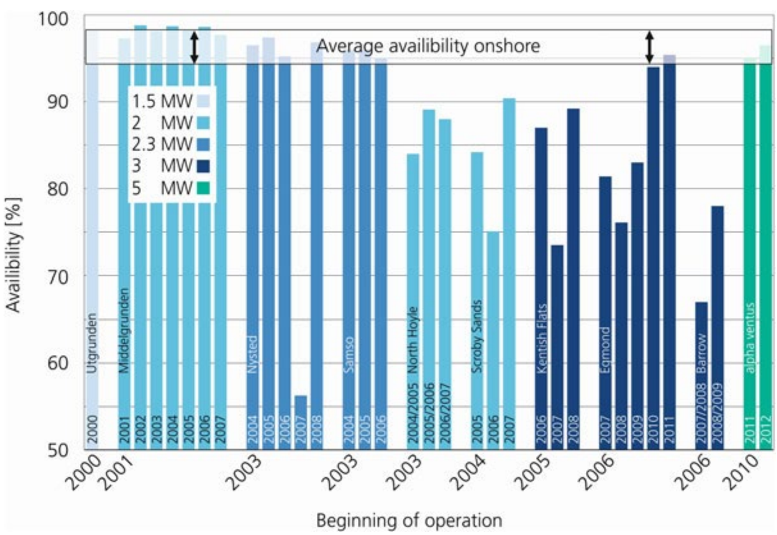

Fig. 19.7 Availability of offshore wind turbines. © Fraunhofer IWES

The report also serves as a benchmark for comparing the individual results of the wind farm with the average value of all the turbines held in the database. Operators can thus compare the performance of their offshore wind turbines with other operators' results (Fig. 19.6) and thus at an early stage use any noticeable differences to other wind farms as grounds for internal inspections and actions.

In addition to the analyses for the participant wind farm operators, Fraunhofer IWES is also providing support for the development of offshore wind energy in the shape of technology monitoring. This includes operating a database of all offshore projects worldwide that gathers all publicly accessible information, making it possible to make solid statements about the development of turbine engineering, yields, availability (Fig. 19.7) or cost development (Fig. 19.8).

Experience gained from the first offshore wind farms shows that the operating conditions offshore

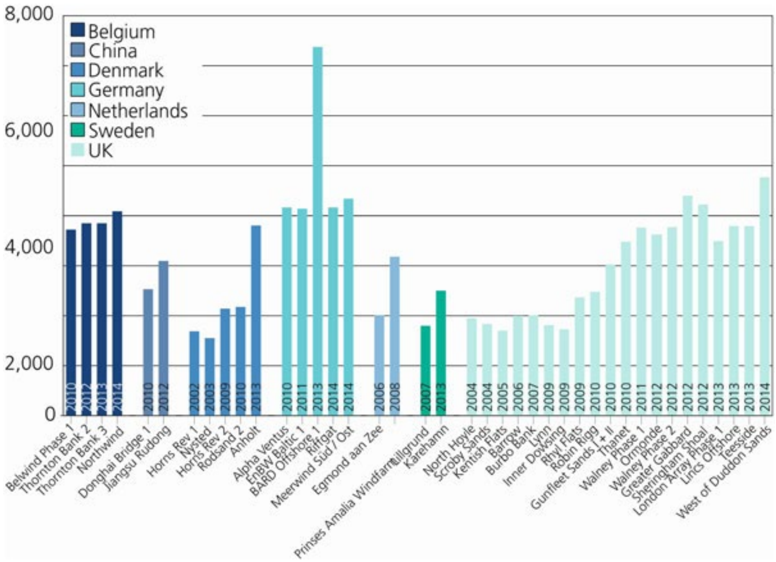

Fig. 19.8 Specific investment costs of different offshore wind farms by country from a rated output of 45 MW. © Fraunhofer IWES

are manageable. But to guarantee long-term reliable and cost-efficient operation it is necessary to detect and record offshore-specific problems independently and at an early stage. The results so determined should create an independent basis and contribute to the further development of the turbines and concepts, so that offshore wind energy can play the leading role it was intended for in the energy mix. To this end the involvement of the players is just as vital as public acceptance of the overall project that is offshore wind energy use.

This is why PR work is also part of Offshore WMEP. The target group is very widely defined, including politicians and society, in particular energy, business, structural and environmental bodies, the interested general public, including school pupils, students, apprentices and trainees, and of course the wind industry's professional audience in industry and science. This is why Fraunhofer IWES publishes its annual "Windenergie Report Deutschland", which comprehensively shows the development of wind energy in Germany and deals with key industry issues.

Other important PR instruments are the Internet platform ► www.windmonitor.de, which provides up-to-date information about the development of wind energy, and the website ► www.wind-pool.com. The Wind Energy Report can be downloaded free of charge from the windmonitor website. These online provisions are just as much part of everyday project life as participation in conferences, trade fairs and exhibitions.

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Grid Integration

Chapter 20 Wind, the Wild Boy in the Power Plant Family – 171
Arne Wessel, Sebastian Stock, Lüder von Bremen, Copy edited by Björn Johnsen

Wind, the Wild Boy in the Power Plant Family

How Grid Integration of Offshore Wind Farms is Achieved

Arne Wessel, Sebastian Stock, Lüder von Bremen,
Copy edited by Björn Johnsen

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power*, DOI 10.1007/978-3-662-53179-2_20

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- Magdeburg-Stendal University of Applied Sciences
- Otto von Guericke University Magdeburg
- Senvion GmbH
- University of Kassel
- WEPROG GmbH

20.1 The Grid and Nothingness

In 2015 renewable energy is expected to be the biggest power provider in Germany for the first time – ahead of coal, gas and nuclear power. Of all the renewable energy sources, the lion's share will be produced using wind energy. How wind farms with different energy supply can be reliably integrated into the German grid is of primary concern – also for the research project "Grid Integration of Offshore Wind Farms". The expansion of wind energy in Germany stands and falls with its integration into the German grid, and all the more so for the combined output of the offshore wind farms with their own "offshore wind power grids".

For a long time the only variable, unpredictable component in the traditional German power plant fleet was the consumer. The energy consumption of private German households and industry for the following day was estimated on the basis of prior experience and consumption figures, and the required amount of power was provided by conventional coal, gas and nuclear power stations. This electricity supply system must be kept stable at all times as far as frequency and voltage are concerned. In other words, only as much power can be taken out of the grid as is being produced, otherwise it would have undesired consequences for the grid frequency and voltage. In extreme cases the grid would simply break down causing a complete blackout. And then there is nothing.

Peripheral Anecdote (I): The grid cannot store anything

In Europe, energy is transferred to the grid with alternating current; in other words, the current constantly changes its polarity. The advantage of this is that the generators produce alternating current, which is easier to transform into another voltage. In the trans-European grid, the frequency, in other words the change of voltage from plus to minus, is at best 50.00 Hz. The good thing about the frequency is that it is the same across the whole grid, and reacts to imbalances in it. The grid can store virtually no energy; everything that is taken out must be fed back in at the same moment. The grid must always be in balance. If more is taken out than is fed in, the grid frequency drops, and if the opposite is the case, then the frequency increases. The balance can be constantly monitored and power plants can react quickly to deviations.
Björn Johnsen

20.2 Maintaining Voltage and Frequency

The balance in the power grid is monitored with the aid of the frequency. If the frequency in the grid drops, too much electricity is being taken out. If the frequency increases, the power plants are feeding too much into the grid. A power plant has to compensate for every deviation in order to keep the grid frequency stable. This is achieved in two ways, via a fixed schedule for the power plants that is orientated on the predicted consumer behaviour and now also on the predicted wind and solar output, and also via the operating reserve from conventional power stations which balances out the "unscheduled" short-term fluctuations.

Every electric cable and every transformer in the grid generates reactive power when it creates and dismantles its electromagnetic fields. The reactive power is expressed as a phase shift between the oscillating current and the oscillating voltage. This shift means that the total amount of energy in the alternating current cannot be converted into power at the point of consumption, which results in voltage drops at individual grid nodes. To keep the voltage stable at the individual grid nodes and to minimise the loss through reactive power, this reactive power must be compensated for. Up to now this service has been provided primarily by conventional power stations. Unlike the operating reserve, which can be made available to a large-scale network, voltage stability is managed locally.

Operating reserve and reactive power are system services that the new wind turbines will have to provide, services that the grid operator must be able to rely on absolutely.

20.3 Together We Are Strong – Let's "Cluster"!

A wind farm produces significantly less energy than a single conventional power plant, whereby the wind farm also has fewer possibilities for intervening in the grid. A "cluster" of wind farms could offer many more opportunities to provide system services that support grid stability, so the best option would be to form a "cluster".

But we will not get very far without suitable control concepts for the wind farm and the newly developed wind farm cluster.

The Wind Farm Cluster Management System (WCMS) designed by Fraunhofer IWES was further developed within the scope of the project for managing Alpha Ventus and other offshore wind farms. The aim was to combine the output of multiple wind farms and develop management methods that would enable the offshore wind farms to operate almost like a conventional power plant, with a generation "schedule", including the provision of operating reserve and reactive power.

20.4 The Main Thing Is What Comes out at the Other End

How does the WCMS know how much wind power will be available in the next few minutes, hours or days? How is it possible to forecast the future amount of power fed in from wind farms so that it is possible to control the wind farm cluster?

To this end the organisations involved in the "Grid Integration" project have developed an improved system for predicting the wind energy output. This should not just reproduce the weather forecast and wind speed as accurately as possible ahead of the weather front, but also include an accurate forecasting system for the power that will be fed in from multiple offshore wind farms. "The main thing is what comes out at the other end" – in this case the wind power at the main grid feed-in point on land.

20.5 Most Frequently at Rated Output: Energy Yields and Power Fluctuation in Alpha Ventus

But do the wind turbines in Alpha Ventus provide the promised results? How much do the turbines block one another, and how often is maximum output achieved? One research package investigated these questions, though it was only possible to start with the turbine evaluations quite late on because the data gathered over a long enough period needed for reliable evaluations was only available at the end of 2011 and beginning of 2012.

Power curve

The power curve illustrates the relationship between wind speed at the wind turbine and the electric power produced. It already takes into account the loss caused by the rotor, gears and generator. The power curve can generally be subdivided into four sections (Fig. 20.1):

- Below the start-up speed (A) the wind speed is too low to turn the rotor. This value is usually 3–4 m/s. Above this wind speed the turbine begins to produce energy.

- The dependence between output and wind speed in the partial load area (B) is almost the square due to the losses until rated capacity is achieved.
- At about 14 m/s (50.4 kph) the wind turbine reaches rated speed (C), the generator now runs at full speed and the wind turbine controller pitches the blades so that the output remains constant.
- If the wind speed is too high it enters the cut-off range (D), where the turbines switch off for safety reasons. Older turbine types are shut down straight away, whereas newer turbines can be shut down gradually in order to avoid sudden, large voltage drops in the grid when there is a storm shutdown. Depending on the turbine type, the shutdown speed is around 30 m/s (108 kph).

Conclusion: every one of the twelve turbines in Alpha Ventus achieved the rated output range, five megawatts (MW) output, for over 30 % of its operating time during 2011, its first year of full operation. The second most frequent area of the individual evaluation of the turbines is the "low output" range below one MW (c. 20 % of cases). The differences are due to the shadowing effects, the respective prevailing wind direction and the wind farm operator's intermittent experimental control phases.

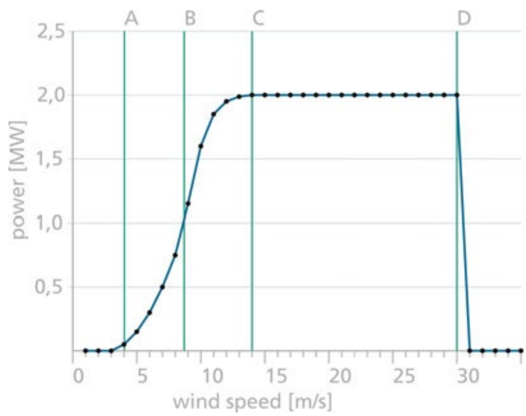


Fig. 20.1 Power curve. © Fraunhofer IWES

In order to be able to consider the output values of the entire wind farm, the output measurement was standardised with the rated output of the individual turbine to create the average value (arithmetic mean) for all 12 wind turbines. The same system applies for the wind farm as for the individual wind turbines, and by far the most frequent value for the whole wind farm lies in the rated output range with five megawatts (Fig. 20.2). Alpha Ventus achieved full rated output (= 100 %) during almost 30 % of its operating time. The lower power ranges of 0 to 1 MW and 1 to 2 MW occur second most frequently with 15 to 18 % each, and the higher power ranges with 40–60 % of the standardised output (2 to 3 MW), 60–80 % (3 to 4 MW) and 80 < 100 % only occur 10 % of the operating time.

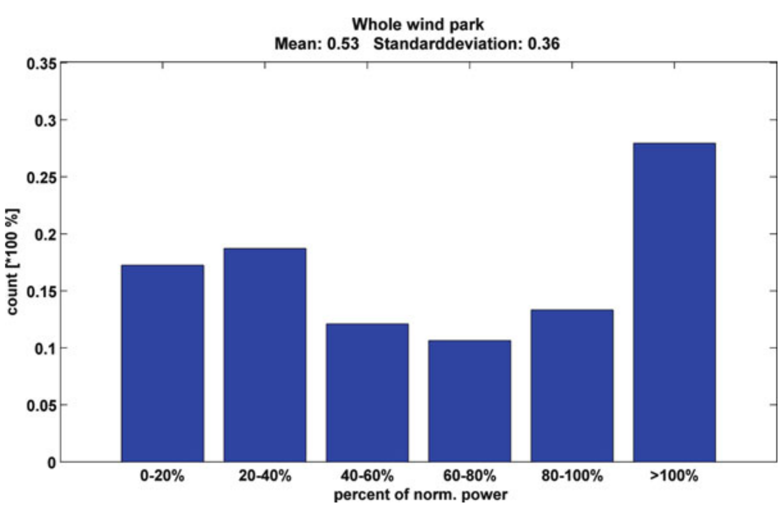


Fig. 20.2 Histogram of the mean output of the entire Alpha Ventus wind farm. © Fraunhofer IWES

On average the whole wind farm achieves 53 % of the rated output, in other words, around 2.65 MW per turbine.

20.5.1 Fluctuations: The Wind Farm Compensates for Individual Turbines

The physicists broke the output data for the individual wind turbines and the entire wind farm down into small time intervals of 10, 30, 60 and 120 minutes and then investigated it. Fluctuations in this sense mean the difference to the measurements standardised to the rated output. The fluctuation is to be seen as the measure of change in feed-in from one measuring interval to the next.

In addition to the data from the twelve turbines in Alpha Ventus, combined data from twelve wind farms in Lower Saxony, Mecklenburg-Western Pomerania, Thuringia and Saxony was used for comparison. At the 60-minute interval (see ◘ Fig. 20.3) in the range of slight fluctuations of up to 10 % of the rated capacity, the onshore wind farms are higher than Alpha Ventus. On the other hand, the maximum fluctuations in the upper rated capacity range differ widely. Individual wind turbines displayed maximum values of over 90 % of the rated output, and offshore more frequently than onshore. For the entire Alpha Ventus wind farm the maximum fluctuations were at 70 to 80 % of the rated output, compared to 50 to 60 % of the rated output at the onshore wind farms used for comparison. Compared with the individual wind turbines, with up to 90 % power fluctuation at sea, the Alpha Ventus wind farm thus has a balancing effect on its individual turbines.

20.5.2 It Gets Shady Starting with the Second Row

Wake effects is the term used to describe the drop in output of wind turbines in the "back rows" caused by the turbines standing upwind of them. The turbines in the first row are faced with a more or less undisturbed wind field. The turbines behind them, in the second, third or even fourth row of the wind farm, experience lower wind speeds because the turbines in front of them have already taken energy out of the wind, thus reducing the wind speed. On top of this, the resulting airflow is more turbulent and unequal.

This phenomenon occurs below the rated output range of the turbines that is achieved in Alpha Ventus at a wind speed of 12.5 m/s. The distance between the wind turbines in Alpha Ventus is 800 metres, which corresponds to around six times their rotor diameter. The wake effect caused by a wind turbine is still noticeable up to ten times the rotor diameter windward, and turbulence as much as twelve times the rotor diameter.

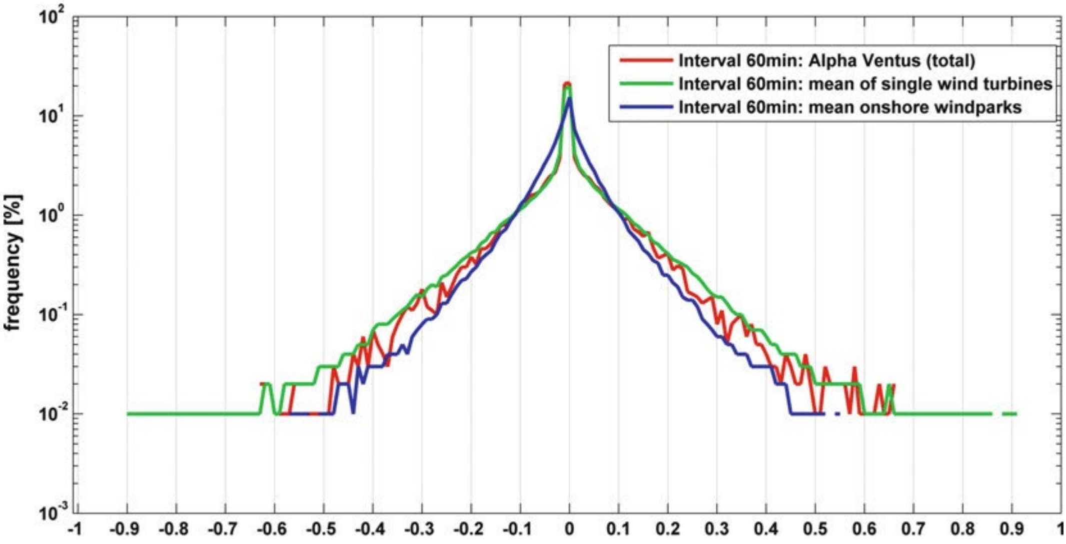
Above the rated output range the wake effects are less distinct, because as of a certain wind speed all the turbines are running in rated output range. In easterly wind direction there are wake losses of approximately 25 % in the range below 12.5 m/s. In westerly wind direction the wake losses due to the "front turbines" are with 15 to 25 % not so great across the board as with an east wind.

20.5.3 Never Quiet on the Western Front

A prerequisite for many calculations is a good knowledge of the wind conditions at the location in question, be they yield forecasts or profitability or load calculations. At Alpha Ventus it is possible to draw on data from the Fino 1 met mast for such analyses. Fino 1 is situated at a distance of 400 m and thus in direct proximity. The measurement data acquired here provides valuable additional information for a lot of research work for the RAVE initiative.

For their analysis, the researchers used the data from the met mast to determine the wind conditions on site. The wind measurements at a height of 80 metres were evaluated. In 2011, the first full year of operation, the prevailing wind direction was southwest as expected. The layout of the wind farm means that in this direction the distances between the wind turbines are the greatest and thus the shadowing effects are the smallest.

The data from the easterly direction could not be considered because it is impaired by the Alpha



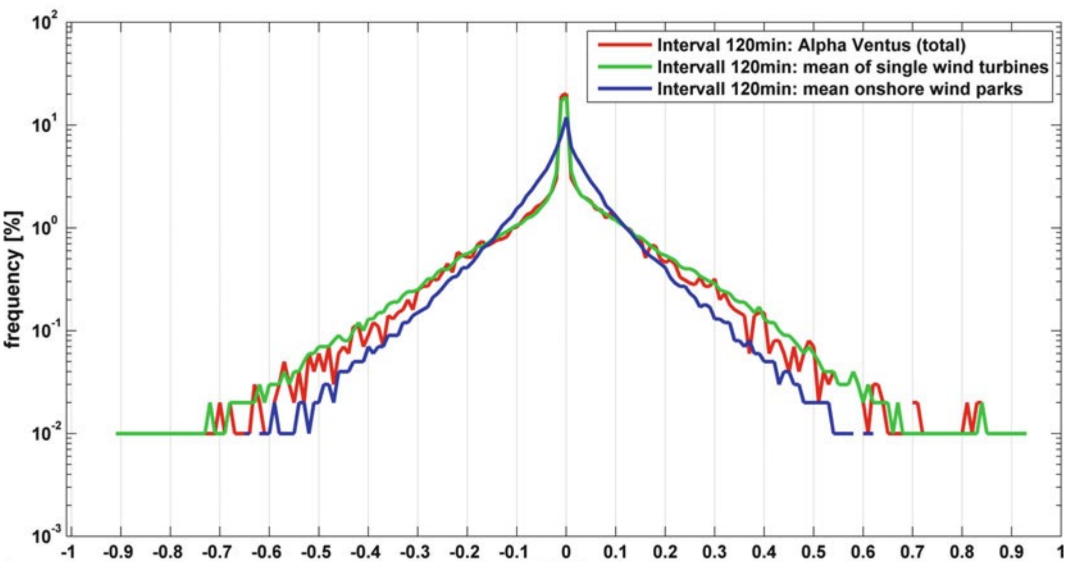


Fig. 20.3 Power fluctuations of the individual turbines, Alpha Ventus in total and onshore over 60 minutes (**a**) and over 120 minutes (**b**). © Fraunhofer IWES

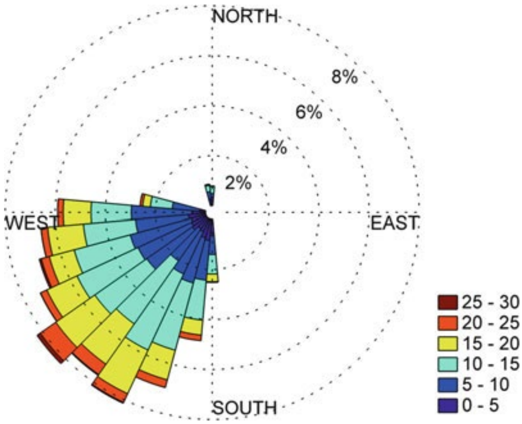


Fig. 20.4 Histogram of the wind speeds at the Fino 1 measuring mast in 2011 without the easterly directions. © Fraunhofer IWES

Ventus wind farm in front of it. What is noticeable is the frequent wind speeds of over 12.5 metres per second – when the wind turbines run at highest performance (rated output) and deliver the maximum yield (Fig. 20.4).

A rose for the wind farm planners
A fundamental prerequisite for the planning of a wind farm is the recording of the possible wind potential at the site. To this end wind measurements are taken at the location and then evaluated. Two representations are used to interpret the results, the distribution of the wind direction frequency and the wind speed frequency distribution. In both cases this is simply a case of counting how often an event occurs. In other words, how frequently there is a change of wind direction, usually in 10° steps, or in the case of wind speed, usually in steps of 1 m/s. The results are then either shown as a compass rose for the wind direction or as a bar chart for the wind speed. In this book they are even combined so that you can see the wind speed frequency for every wind direction.

Meteorological measuring tower on Fino 1
The Fino 1 measuring platform is situated to the west of the Alpha Ventus wind farm and was erected before the wind farm to measure the actual wind conditions far out into the North Sea. This meant it was undisturbed by any wind turbines in front of it or any other disturbing influences.
The first measurement data was available in August 2003. After the construction of Alpha Ventus in 2009 it was still always exposed to free wind flow from the west, the main wind direction. The mast has an overall height of 102.5 m, whereby cup anemometers are installed at 10-metre intervals on one side. There are also wind vanes and ultrasonic anemometers on the other side, attached alternately at height intervals of 10 metres (Fig. 20.5). This enables the gathering of vertical high-resolution wind profiles as well as temporally high-resolution measurements with the ultrasonic anemometers. The mast is also equipped with other meteorological sensors such as temperature or air pressure measuring instruments in order to measure all the relevant meteorological values. For example, two hygrometers are attached at two different heights, which take ten readings per second. These supply important data for the RAVE research project "Turbulent Humidity Fluxes" (see ▶ Chap. 17).

20.5.4 Calm Is when It Still Blows: 16 Hours Bad, 20 Sad

In these parts "calm" means a condition of virtually completely still air. That is not the case for the Alpha Ventus research project, because for the researchers on Alpha Ventus the term "calm" encompasses considerably more. Even if the wind is blowing with a speed of 3.5 m/s (12.6 kph) and more, it is still a calm. This is because wind turbines only slowly start to turn at a wind speed of 3.5 m/s. Because at that speed little or no power is fed into the grid, wind speeds of up to 5.5 m/s (19.8 kph) count as calm. For the "Grid Integration" research project even a light breeze at wind force 3 with a speed of about 20 kph still counts as "calm".

For the grid integration, in other words the integration of the offshore wind energy produced

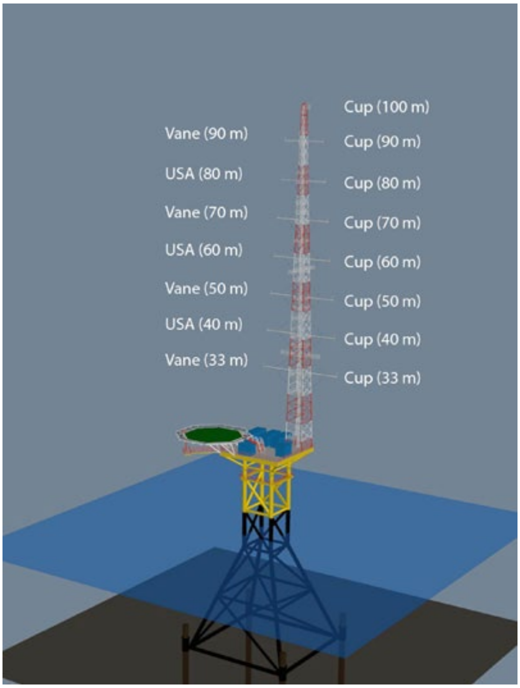


Fig. 20.5 Wind measuring devices on the Fino 1 met mast: *Cup* cup anemometer, *USA* ultrasonic anemometer, *Vane* wind direction. © Forschungs- und Entwicklungszentrum Fachhochschule Kiel GmbH, edited by Fraunhofer IWES

into the existing energy supply structures, it is all the more important to be able to predict the maximum amount of time the calm will continue for. This is so that when there is the threat of a calm, it is possible to predict how long the shortfall of offshore wind power will have to be made up for in some other way. In 2011, the first year of operation, wind speeds under 3.5 m/s lasted a maximum of 16 hours, and wind speeds under 5.5 m/s lasted a maximum of 21 hours (Fig. 20.6). Relating to Alpha Ventus this means that the planned wind power deliveries had to be otherwise made up for a maximum of 16 hours in the event of a calm, and that low energy supply could last a maximum of 20 hours in the worst case.

20.6 Everything Flowing? From the Beginning of all Wind Power Forecasts to "Total Fluc"

How important an accurate and early wind power forecast is, is best demonstrated in practice. An area of low pressure detected a couple of hours too late means that in an extreme case the scheduled wind turbines might have to be switched off within a matter of seconds of a storm arising – so instead of full capacity they deliver nothing at all. The result is that expensive replacement and balancing power is needed in a hurry, which in turn means that less environmentally friendly conventional power stations remain connected to the grid longer or have to be expensively "booted up" to generate the power needed.

The accurate wind power forecast is drawn up based on weather forecasts and – for short forecast periods – the wind farm's measured performance values. The typical forecast period often begins with less than an hour and ranges up to several days ahead, whereby the values are updated every fifteen minutes. The offshore application, with higher wind speeds than on land, poses a great challenge for the scientific weathermen; the forecast models have to work in a significantly higher performance range – with twice as many full load hours and more – and have to be correspondingly optimised anew. There are also many more high wind speed cut-offs out at sea. On land the wind turbines are spread out over a vast area across the whole of Germany – offshore they are relatively close together in the exclusive economic zone in the North Sea. Every inaccurate prediction – whether it be a weather forecast or that of the available wind cluster output – has a far greater impact offshore than it does on land.

In their initial work phase, the researchers first had to process the recent past and investigated massive forecasting errors with the weather model used. Why were the strong winds in 2009, the year of construction, (as on 16–18 March 2009) not predicted? Why did the storm winds forecast (as on 24 to 27 April 2009) not materialise? The answer sounds typically scientific: "it all depends on …"

After simulations with a variety of models it became clear that the horizontal model resolution has a major influence on the wind flow in com-

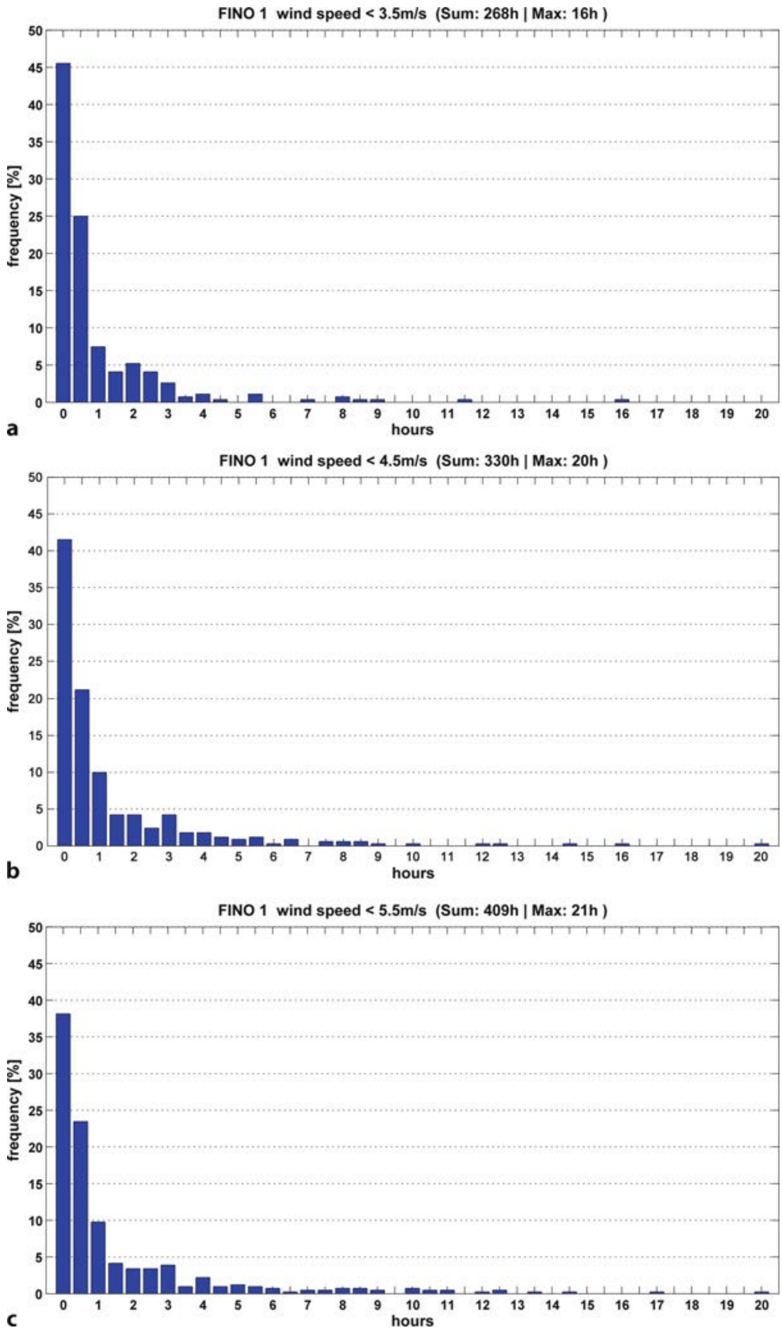


Fig. 20.6 Frequency of the duration of the calm periods with wind speeds < 3.5 m/s (**a**), < 4.5 m/s (**b**), < 5.5 m/s (**c**) in 2011. © Fraunhofer IWES

plex areas – as in the Norwegian mountain chain on 16–18 March 2009, when apparently the wind suddenly blew south from the Scandinavian Mountains towards Germany. In another incorrect forecast the topographical data, the information about the terrain surface, especially that of mountains and mountain ranges, had been inadequately parameterised.

Here we see that the implementation of the weather models requires a compromise between accuracy and terrain modelling, the computer time needed and precision of the forecast results. The forecast models have to provide as accurate results as possible for grid integration, almost in real time. The best forecasts in this application are useless if they need weeks of computer time using high-performance computers.

Nevertheless, in a one-year, improved simulation for the Alpha Ventus location it was possible to achieve an improvement of the absolute error of the wind speed forecast of approximately 0.5 % for all forecast horizons. Every little bit helps, and with an annual production of 267 million kilowatt hours – as it was in 2011, the first full operating year, at Alpha Ventus – half a percentage point is quite a lot. In another research sub-project the sea temperature was combined with the weather forecast model. Does the inclusion of the sea surface temperature in the model impact on the atmospheric forces and the wind forecast? This is a question that could not be answered with a definitive yes – although that might have something to do with the fact that the three-month investigation period was somewhat short.

20.6.1 More Accurate by the Dozen? A Weather Forecast Ensemble

In another Alpha Ventus research study, eleven different weather prediction models were evaluated using a comparison with the actual wind measurements taken on the Fino 1 offshore platform. The declared objective was to generate a better wind performance forecast with the aid of an ensemble of weather forecasts, because every member of the ensemble or weather model describes the weather slightly differently and makes different errors. When multiple models are combined, the errors can in the best case compensate for each other and the forecast is better.

In such a case one speaks of a "poor man's ensemble", in that the individual members come from different weather models as opposed to other models where all members come from one weather model that runs with different configurations and input data. In reality, the "poor man's model" is in fact the more expensive of the two, because the data has to be purchased from different weather providers.

This allows the conclusion that in partial ranges the results fluctuate greatly, and by using the mean value of the entire "ensemble" there is an improvement of approximately 7 % of the forecast error. For longer-range forecasts – up to 48 hours – this value even increases up to 18 %. But despite this, the actual measured wind speeds often deviate significantly from their forecasts – in both directions.

With wind energy forecasts a differentiation is made between point forecasting, which expresses a value for the expected power, and probabilistic forecasts, which also assign a probability to the expected power value. With the aid of ensembles it is possible to generate a probabilistic forecast; if the individual forecasts from the various models are close together then it is more likely that the forecast mean value is right. If they are spread well apart then the forecast is less safe. In order to be able to generate real probabilities from these values, in other words statements like "the forecast lies between the values A and B with a probability of 90 %", the results from the ensemble still have to be calibrated.

To this end methods were developed that ensure that probabilistic forecasts can deliver reliable results even under offshore conditions in order to minimise the risk involved in the grid and market integration of the wind power. For every time increment the forecasts (for example wind speed 3.1 / 8.3 / 2.2 m/s) of the individual ensemble members are sorted by size (2.2 / 3.1 / 8.3 m/s). The measured value (for example 2.9 m/s) is subsequently assigned to the most suitable ensemble member. The position is filed as the result (here Position 2). This is carried out for all the forecasts (the result for ten measurements would for example then be 4x Pos. 1, 3x Pos. 2, 3x Pos. 3). The result is shown in the form of a histogram (Fig. 20.7). If the measured value is less than all the ensemble members it is given Position 1, and when higher than all of them, it takes the last position. An ensemble should cover all results as evenly as possible. In other words, the measured value should be well distributed and cover all the positions in the ranking from time to time, but it would however be best if it was around the "mean". If for example the first or last value in the histogram is too high, then the measured value is frequently outside the forecast value range of the ensemble, which means that the ensemble does not cover all possible events and a probabilistic forecast would be inaccurate. It would not for example be possible

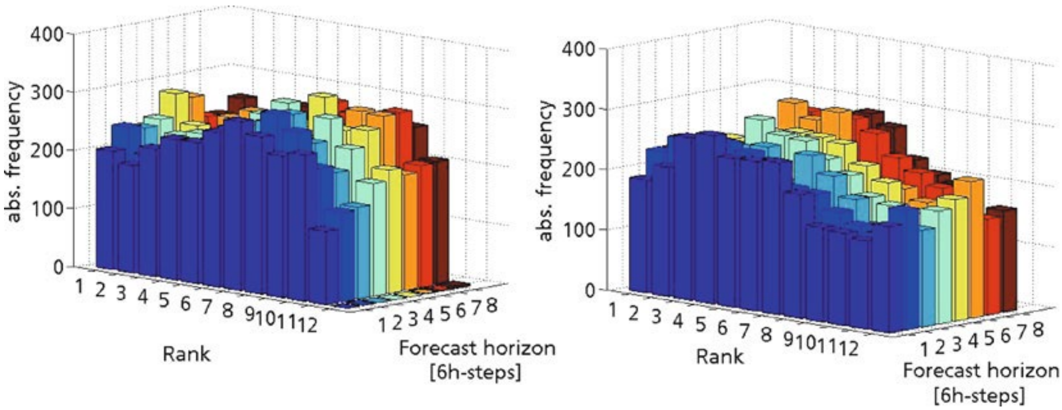


Fig. 20.7 Ranking histogram for checking the quality of ensembles. © Fraunhofer IWES

to state that "the forecast value has a probability of 99 % between 4 and 7 m/s", if 4 and 7 represented the minimum and maximum values of the ensemble, and these have been set too high or too low. Here there are possibilities of recalibrating the ensemble in a further processing operation.

» **Only forecasts can guarantee system reliability**

The integration of offshore wind energy into the electric grid poses new challenges for the existing infrastructure. We will be getting a large number of wind farms in a small area. This means a great dependency on the local weather. Effects like calms, switching off in storms or strong power fluctuations always affect several wind farms at the same time. Specially adapted wind power forecasts, as were developed in the project, will in future help to reduce these effects on the grid and thus guarantee system reliability.

Dr. Arne Wessel, project leader for RAVE Grid Integration and physicist at Fraunhofer IWES

20.6.2 Fluctuations Especially with North-Westerly Currents

Not every second-long wind calm is important. Power fluctuations that are relevant for the grid integration of wind energy are those lasting from five minutes to two or three hours. The grid operator has to maintain a permanent operating reserve for abrupt fluctuations in wind power during this time. Up to now this value was fixed in advance for three months, but with the further expansion of offshore wind energy it is likely that there will be stronger fluctuations, even over a period of hours, which could exceed the amount of operating reserve available. If the size of the fluctuations could be predicted several hours in advance, in times of strong fluctuations it would be possible to notify power stations to provide more operating reserve in good time, thus avoiding a supply bottleneck that could endanger the stability of the grid.

It has become evident that the greatest wind power fluctuations in the North Sea occur when there are north-westerly currents, especially combined with rain and/or cold air masses. Weather predictions must therefore also attempt to take so-called convection cells into account, cloud parts and formations that are created when there are currents and which are an indicator of cold air above warmer surfaces, such as ocean currents. It appears however that power fluctuations in the rated output range of the turbines hardly ever occur, no more than they do at low wind speeds – so here the flat power curve mutes the power fluctuation in this range.

Classical weather models have only ever been able to represent the "power fluctuations within an hour" to a limited degree. An alternative could be the power fluctuation quantity developed during the research project, the "totalfluc", which should be able to be predicted from the existing parameters of the weather models (wind, temperature, turbulence). In the project this performance measure "totalfluc" was developed using synthetic performance data and the first analyses of the dependency on the weather model parameters were undertaken. Future projects will deal with the verification of the fluctuation measure using actual measured data from Alpha Ventus and carry out more investigations of the relationship between weather model parameters and the fluctuation measure.

In addition to the weather forecast, the short-term forecast of "totalfluc" also includes the current output of the wind farm measured over the last few hours as an additional quantity, and this significantly improves the quality of the forecast.

The forecasting of wind power fluctuations is still in its infancy, and its quality is not yet good enough for reliable operation. There is still a great deal to do. With a government target for the expansion of offshore wind energy to 15 GW by 2030, the 10 % power fluctuations within an hour would be 1.5 GW. With a current operating reserve capacity of around ±5 GW that is quite a relevant proportion. In such cases, forecasting wind power fluctuations can help to keep the grid stable.

20.7 From "Wild Bunch" to Power Plant Network

In previous projects, Fraunhofer IWES developed a concept for the combination, or so-called "clustering", of wind turbines, and tested it on large-scale wind farms in Portugal. These wind farms were directly connected to the grid and the subordinate grid level was not intermeshed, in other words not connected with one another by means of one or more nodes. With this direct connection it was possible to realise system-conducive operating modes using the Wind Farm Cluster Management System.

None of this is valid for offshore wind farms because it has to take a different power grid into consideration. An important factor here is the connection of the offshore wind farms via a very long cable, of 70 kilometres and more, with the corresponding compensation units. This strongly influences the reactive power control range, which is an important factor for the control operation of the wind farm to the grid node point. In addition to the electrotechnical changes for the "offshore power plant network", special forecasting systems were developed for offshore wind farms that had to be integrated into the WCMS. The developers also had to take care to design this cluster management system modularly right from the start in order to provide a necessary series connection and linking of cluster systems across multiple voltage levels, because with this cascading it is possible to achieve a far greater effect than with just one module.

The Fraunhofer IWES Wind Farm Cluster Management System was adapted to offshore conditions and developed further so that it could work for the Alpha Ventus wind farm and its special electrical properties – and to create an interface for the integration of additional wind farms. This was however initially just as a simulation model because real management of the Alpha Ventus wind farm was not possible during the course of the project.

20.7.1 Trans Europe Express: What a Future Offshore Grid Might Look Like

The Fraunhofer IWES concept for the connection of future wind farms in the North Sea assumes two main connection points on land, by Norden in Lower Saxony and between Büsum and Brunsbüttel in Schleswig-Holstein. There is an additional connection to a trans-European "supergrid". This approach combines the wind farms planned in the German North Sea – about 20 gigawatts have been approved – into individual but interconnected clusters. This can result in a more flexible distribution of the wind power feed-in to the main points of connection, which also have different intake capacities (Fig. 20.8). In the event of grid faults it will not be necessary to switch off the affected wind farms, just redirect the power to be fed in at other main connection points.

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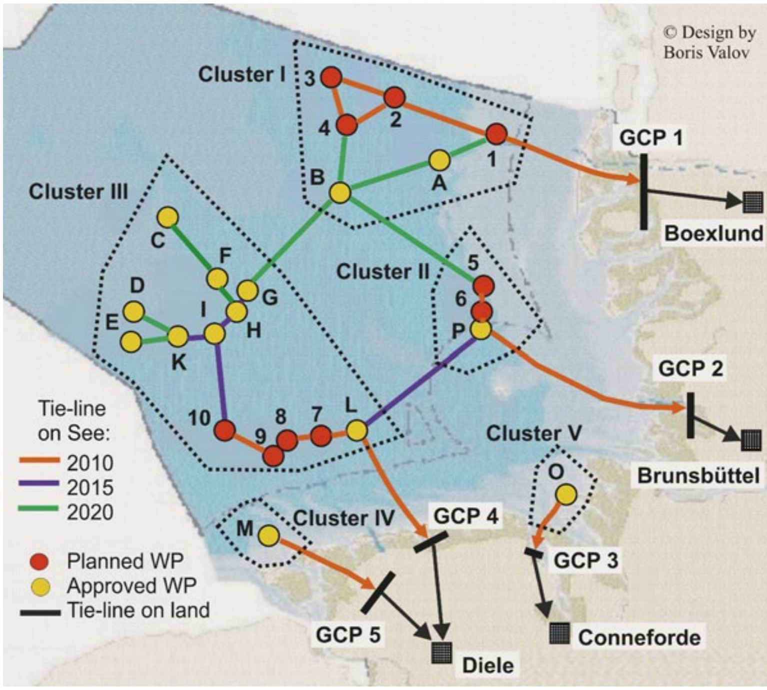

Fig. 20.8 Concept for a future offshore network for the North Sea. © Fraunhofer IWES

The integration into a trans-European supergrid, a Europe-wide network of high-voltage grids in the countries bordering on the North Sea, provides additional operational flexibility of the offshore network. This can also serve to reduce the need for the expansion of the national grids. With its larger main connection points the supergrid can intercept power peaks of individual offshore wind farms and this European grid network – with connections to Norway, Denmark, the United Kingdom and the Netherlands – can increase the reliability of the offshore transmission grid in the North Sea.

20.7.2 Orderly Cluster Formation

Most of the wind power in Germany to date is installed at medium-voltage level (MV) to high-voltage level (HV). The challenge in integrating wind energy into the grid is to take on tasks, with many units and in partly different voltage levels, which have up to now been the domain of the conventional power stations. In detail it is about voltage and frequency stability within low tolerance limits.

The voltage in the energy system will initially be dictated by the big generation units. Voltage drops, active and reactive power flows, transformers and their tap changers alter these values, so that different voltage quantities occur locally. The consequence is that voltage is a local quantity that follows a central directive. The aim of wind farm clustering is initially to minimise the local changes in voltage that can result from load change or power fluctuation. Multiple wind farms in single grid regions should behave neutrally with regard to the voltage or in best case also be available for maintaining the voltage.

The second important grid quantity is the grid frequency. Unlike voltage, it is a global quantity because the frequency in the grid is the same everywhere. It is regulated (by means of power-frequency control or transfer-power-frequency control) by the synchronous generators in the main power stations that are directly coupled with the grid. This requires primary control, secondary control and tertiary power control. The grid operators in Germany tender the requirement and award it by auction. If as a result of a power station breakdown there is suddenly a shortfall of a large amount of power, this staggered system for switching power in will be activated in order to compensate for the resulting deficit. A single wind turbine with a rated capacity of five megawatts cannot compensate for this deficit, nor can an entire wind farm – but a cluster of several wind farms with several hundred megawatts can. All this would theoretically be the case for offshore and onshore wind farms.

Peripheral Anecdote (II): That was a close call!

Originally thought up for the construction of motorways, bridges, airports, railway lines and canals, the new "Infrastrukturplanungsbeschleunigungsgesetz" (Acceleration of Infrastructure Planning Act) has a name as long as a tapeworm and was finally passed by the German Bundestag in October 2006. But just before the final reading a short passage was quickly included that was crucial for offshore wind farms. It obliged grid operators to provide grid connection for offshore wind farms in their control zone. It was this last-minute obligation that first enabled Alpha Ventus' grid connection to be completed in time. Otherwise they would probably still be negotiating, suing, and then negotiating again about responsibility and cost distribution …
Björn Johnsen

20.7.3 Offshore Clustering Is Both Easier and More Difficult

The clustering of several offshore wind farms to create an "aggregate" is very different from wind farm clustering on land. The offshore wind farms create large-scale grid networks that only contain wind turbines – pure "wind grids". Their distances to the grid connection points or transformer substations are very great, up to as much as 70 kilometres, and therefore have a great reactive power requirement. Because of these great distances it can be assumed that high-voltage direct current (HVDC) power transmission will be used as connection technology for offshore wind farms, where the power is transmitted using direct voltage that is converted back into alternating voltage at both ends of the cable using inverters. Unlike with alternating current, the HVDC cable suffers only minimal losses and has the advantage that the grids can be uncoupled from the grid frequency at both ends. This way future offshore grids can directly connect several countries and control zones with one another as shown in a trans-European supergrid. One such example is the connection between the Scandinavian "Nordel" grid and the European integrated grid UTCE, where although both work with a grid frequency of 50 Hertz, their phase positions are so different that they can only be connected with HVDC.

20.7.4 Over 70 Grid Calculations for a Four-Hour Forecast

With a further developed WCMS for Alpha Ventus, the whole network area – from the individual wind turbines to the grid connection points on land (in the case of Alpha Ventus the Hagermarsch substation near Norden) – will be considered with the appropriate forethought. As input data the WCMS uses power forecasts with a ten-minute output preview of the wind farm. A confidence interval is defined for each forecast value, which gives the precision of a parameter, for example a mean value. The limits of this range of values – the maximum and minimum values – and the probable mean value are factored in for the network calculation. So for each point in time three calculations are made in addition to an alignment calculation. A forecast horizon of four hours is also implemented in the further developed WCMS. The WCMS carries out 73 grid calculations for just the relatively short period of time – plus additional grid calculations in case any grid problems are detected that need to be fixed. The Alpha Ventus wind farm is treated as a cluster element – the interfaces to other wind turbines and wind farms already exist for cluster expansion.

20.7.5 Operational Management Strategies

The operational management of offshore wind farms is influenced by a variety of factors, especially by the wind turbine characteristics. There are therefore dif-

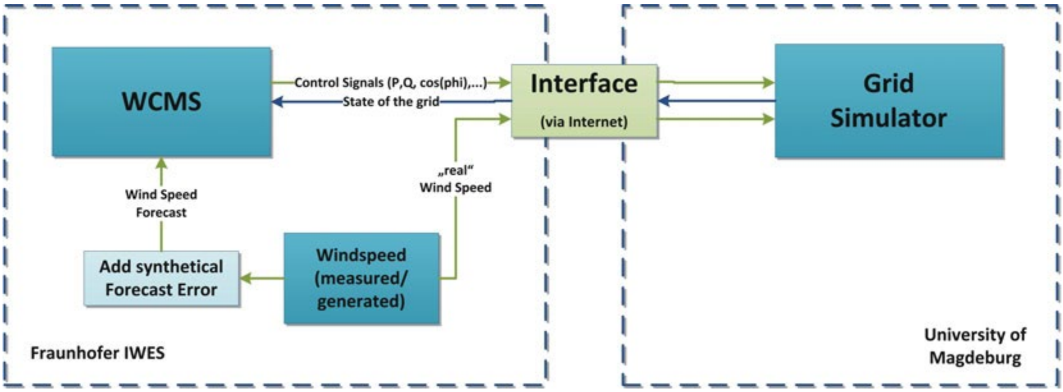

Fig. 20.9 Coupling concept between WCMS and wind farm model. © Fraunhofer IWES

ferent operating strategies for the different turbines available on the market. Wind turbines with dual feed asynchronous generators (like the Senvion 5M) and with permanent-magnet synchronous generators (like the Adwen AD 5-116) have different control characteristics. Both models can be connected with one another in the WCMS.

20.7.6 Not the End, but a New Beginning: The Wind Farm Simulator

In the scope of the project, the University of Magdeburg modelled the Alpha Ventus wind farm in their software. The wind farm model used – the wind farm simulator – is especially suitable for investigating the operating characteristics and strategies, and as main components includes the individual wind turbines, the wind farm cabling plus grid connection, the equivalent simulation of the onshore grid and the compensation systems for maintaining the frequency.

The grid calculations of both programmes – WCMS and the wind farm simulator (Fig. 20.9) – produced very similar, if not identical, calculation results. This is due to the simulation of individual grid components used in the programmes, such as cables, transformers, etc. The few differences are thus determined by the system and are also intentional in order to assume a more realistic operation of the WCMS. Different operational modes of the wind farm were run through in the model, whereby different farm feed-in behaviours were implemented in its onshore grid connection, the Hagermarsch substation. The online forecasts for grid monitoring and set point calculation used high-resolution power predictions in order to be able to model the future grid condition, and to use this information to detect and prevent problems at an early stage. But the current WCMS does not operate alone at model level. Future research and development will include a feasibility analysis for the expansion of the superordinate external grid area, whereby it will be possible to investigate and reproduce possible retroactive effects on the functional capability of the WCMS from the external grid.

20.8 Outlook: Control System and Last Instance

Uniting wind farms via voltage levels, and if necessary even via transmission borders like direct current and alternating current, is one of the core functions of the wind farm cluster management system. The inclusion of other wind farms in the WCMS and their simulation is indispensable for the reliability test of such a system and should be a component of future research assignments. At this stage the WCMS must not only include the wind farms in the calculations, but all the components in its area, including conventional energy generation and grid loads. The new knowledge is then incorporated into the overview of possible operating points and their resolution with regard to the performance characteristics of the aggregated grid areas. The WCMS then works as a kind of superior authority that enables access to such clusters. Algorithms should also be developed in such research areas that consider a cluster as a complete system and must constantly create optimal set points in order to achieve improved grid integration. At the end of such a development process the WCMS would not be just an aggregator, but even more. It would be a superior control authority in which the wind farms are both "positioning elements" and "control elements" at the same time, and which actively contribute to stable grid operation with voltage quality, reactive power management between the voltage levels and "bottleneck management". The individual "wild wind farm boys" will then – controlled and conjointly – be a key component of our grid system of the future.

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The most Important Environmental Project in a German Offshore Wind Farm

Accompanying Ecological Research on the Offshore Test Field Project Alpha Ventus

Anika Beiersdorf, Maria Boethling, Axel Binder, Kristin Blasche, Nico Nolte, Christian Dahlke, Copy edited by Björn Johnsen

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Project information: Accompanying Ecological Research on the Offshore Test Field Alpha Ventus for the Evaluation of the BSH Standard for Environmental Impact Assessments (StUKplus)

Project management:
BSH – Federal Maritime and Hydrographic Agency
Christian Dahlke (until 2013), Nico Nolte
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Project partners:
- Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research
- Avitec Research GbR
- DHI/DHI-Wasy GmbH
- IfAÖ Institute of Applied Ecology
- itap GmbH Institut für technische und angewandte Physik GmbH
- Müller BBM GmbH
- Research and Technology Centre, West Coast (Kiel University)
- University of Veterinary Medicine Hannover

21.1 How It all Began

When the first planning applications for offshore wind farms were submitted to the Federal Maritime and Hydrographic Agency (BSH) in 1999, there was very little existing knowledge about the environmental impact of offshore wind turbines. Only two countries – the United Kingdom and Denmark – had erected wind farms or individual turbines at sea by the turn of the millennium. But their practical experiences were only slightly comparable with the German projects that were planned, because in Germany the planners had planned and applied to build offshore wind farms far out at sea at distances up to 150 kilometres from the coast of the mainland. And instead of near-shore wind turbines in a water depth of just two metres as in the Danish Baltic, the planners of wind farms in the German North Sea were talking about water depths of 25 to 50 metres.

In addition to the technological challenges, with the increasing number of offshore wind farms being applied for there was an increasing demand for a cumulative consideration of the environmental impact of these farms. The BSH is the approval authority for wind farms planned in the German Exclusive Economic Zone (Fig. 21.1). The aim of the ecological research in the Alpha Ventus test field was to get a deeper understanding of the environmental impacts of offshore wind farms. With its six-year investigation period it was the most significant German research project in terms of scope, duration and results to investigate the environmental impacts of offshore wind farms. It also complemented the environmental monitoring that the operator was obliged to carry out at Alpha Ventus in accordance with the Federal Maritime and Hydrographic Agency standard investigation concept ("Standard Investigation of the Impacts of Offshore Wind Turbines on the Marine Environment, StUK"). Based on the findings of the accompanying ecological research it was possible to evaluate and update the StUK for the first time. The Alpha Ventus test field is the first offshore wind farm where the StUK methods were applied in a construction and operating phase.

The "StUKplus" research project attempted to find answers to questions that go beyond the pure research framework. During their extensive field investigations in Alpha Ventus the researchers have also tried out new methods and techniques for collecting data, such as the digital flight data for resting birds or new radar devices for recording and measuring bird migration. With the ever-advancing knowledge it was also possible to further develop the prescribed standard investigation concept for offshore wind farms during the project period. Whereas with Alpha Ventus StUK3 was applicable for a German wind farm for the first time, since October 2013 the third revision of the standard investigation concept, StUK4, is prescribed and valid.

There are naturally conflicts between the economic interests of the wind farm operators on the one hand and the environmental protection of the sea on the other hand, and these different interests pose a great challenge. An environmentally compatible expansion of offshore wind power therefore requires an understanding of the expected impacts on the marine environment from the very start. To-

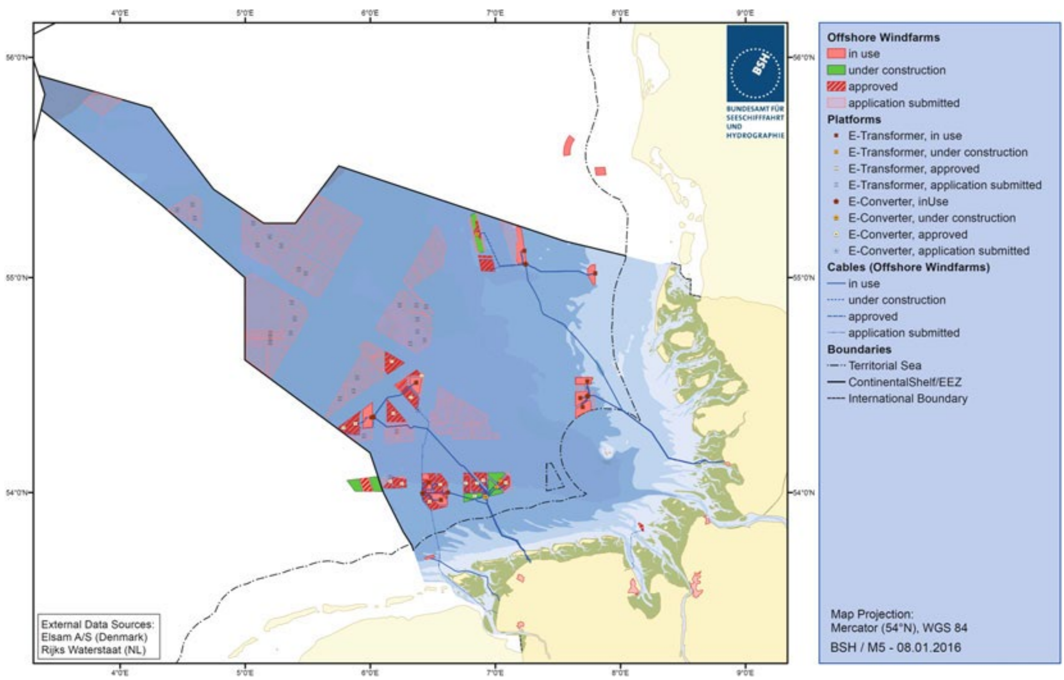

Fig. 21.1 Planning chart of offshore wind farms in the North Sea (Status: 08.01.2016). © BSH

day there are still significant gaps in our knowledge, particularly with regard to the cumulative effects of offshore wind farms.

21.2 The Go-Ahead for Knowledge …

The Alpha Ventus test field gave the go-ahead for the development of such an understanding. With an extensive accompanying construction and operational research and monitoring programme it was possible to investigate for the first time which possible forecasted impacts on the marine environment actually existed. In short, whether what was forecast actually happened.

The StUKplus project at Alpha Ventus had attempted to gain fundamental answers to questions with regard to the many other offshore wind farms that were planned; how does the habitat of fish and organisms that live on the seabed change in the area around the foundations of the wind turbines? How far does the influence of the artificial hard substrates reach? That is, not the natural material that an organism can live on, like rocks and seashells, but artificial hard substrate like bridge pillars, metal sheet piling or even the foundations and supporting structures for an offshore wind turbine. And how does the habitat change in the area of the wind farm as a result of the ban on fishing in the wind farm?

How do seabirds react to the illuminated, rotating wind turbines? Will resting birds avoid the area of the wind farm or get used to the turbines? How great is the risk of migratory birds colliding with the wind turbines? What impact does the loud construction work and the ongoing operating noise have on the noise-sensitive marine mammals and fishes? Will porpoises and seals continue to use the wind farm area as habitat and how can they be protected against underwater noise?

21.3 If You Don't Know What to Do Next, Organise a Workshop

Questions upon questions for new projects that one institution cannot handle alone – at least not at this early stage. As preparation and concept development for the accompanying ecological research during construction and operation the BSH organised a workshop in November 2007 in which representatives of renowned institutions, authorities and independent experts took part. The workshop drew up the following key focuses for the future ecological investigations:

- Monitoring of the benthic communities, i. e. the totality of all living creatures in the sea and on the seabed, and especially the fish stocks around the offshore foundations in the construction area of Alpha Ventus and in the reference area during the construction and operational phases.
- The behaviour of migratory birds and the recording of bird impacts, intensity of bird migration and the range of species.
- The behaviour of resting birds towards the wind farm or individual wind turbines.
- Monitoring of the population density and distribution of porpoises and seabirds during the construction and operational phases in the immediate and wider surroundings of the test field.
- Temporary measurements of the construction and operating noise on the wind turbines and further afield.
- Establishment of quality-tested databases for benthos, fish, resting birds and marine mammals using data from environmental impact studies of offshore wind farms and research data.

The Federal Maritime and Hydrographic Agency outsourced the proposed work to outside experts (enterprises, institutes) (▫ Table 21.1) before the start of construction on Alpha Ventus and managed the implementation of these accompanying ecological investigations. The evaluation of the data was done on several bases; one was the new data gained directly from the StUKplus project and the data series from wind farm projects already available to the BSH and data that came from other institutions. To this end "protected interest cooperations" were entered into with the Research and Technology Centre West Coast, the University of Veterinary Medicine Hannover, DHI Wasy GmbH and the Alfred Wegener Institute, and the Helmholtz Centre for Polar and Marine Research, and quality-tested databases were established. All these institutions were in possession of research findings and historical data series from other research projects in the offshore sector that only they had.

21.4 The Results of the Environmental Research

21.4.1 Impacts on Pelagic Fish

So-called pelagic fish, like mackerel, herrings or salmon, live in the water columns of the sea and therefore differ from fish species that live near the seabed like plaice or cod. The investigations of the pelagic fish at Alpha Ventus and in the reference area were undertaken using hydroacoustic measurements, net sampling and by analysing the stomach contents of these fish. A stationary hydroacoustic measuring system, known as fish sonar, was developed for this project and used for long-term measurements of fish distribution and abundance. The device carrier has a movable unit head and sonar for measuring the number of fish and their distribution around the foundations of offshore wind turbines. The investigation period was divided into three parts: before the construction phase, during the construction phase of Alpha Ventus in 2009, and the immediately subsequent two-year operating phase 2010–2011.

The findings of the investigations show low fish stocks during the year of the construction phase, which suggests they were scared away by ship movement, piledriving and other construction activities. In the subsequent operating phase on the other hand, the ship-based, hydroacoustic investigations and counts show neither a scaring-off effect nor an attraction effect on these species of fish.

21.4.2 Impacts on Demersal Fish and Crustaceans

So-called demersal fish such as cod, sole or haddock, which live on or near the seabed, were inves-

Table 21.1 Overview of the R&D contracts granted by BSH in the project period 2008–2014. © BSH

Contractor	Project title	Project period
Alfred Wegener Institute (AWI), Helmholtz Centre for Polar and marine Research	AWI1: Investigation of the impact of wind turbines on fish (A) and vagile megafauna (B) in the Alpha Ventus test field	01.07.2008–30.08.2012
	AWI2: Joint evaluation of data about benthos and fish for ecological impact monitoring in the Alpha Ventus test field	01.09.2008–30.04.2012
	AWI3: Completion of the time series during the operating phase and determination of changes to the benthos by expanding the turbine-related impact monitoring	01.10.2008–30.08.2012
Avitec Research GbR	Avitec Research1: Test field research into bird migration at the Alpha Ventus pilot offshore farm	01.07.2008–31.08.2013
	Avitec Research2: Analysis of the continuously obtained data on Fino 1 about bird migration (FinoAVIDATA)	01.08.2009–31.08.2013
IfAÖ Institute for Applied Ecosystem Research GmbH	IfAÖ1: Recording of bird collisions with the aid of the VARS system	01.10.2008–31.08.2013
	IfAÖ2: Recording of avoidance behaviour of migratory birds using pencil beam radar	01.10.2008–31.08.2013
West Coast Research and Technology Centre, University of Kiel	FTZ2: Joint evaluation of data about sea birds for the ecological effect monitoring at the Alpha Ventus test field	01.06.2008–30.09.2013
	FTZ3: Investigation of possible habitat loss and behavioural change of sea birds in the offshore wind energy test field (Testbird)	01.10.2009–30.09.2013
University of Veterinary Medicine Hannover	TiHo1: Complementary investigations into the impact of the constructional and operational phases on marine mammals at the Alpha Ventus offshore test field	01.06.2008–30.11.2013
	TiHo2: Joint evaluation of data about marine mammals for the ecological effect monitoring at the Alpha Ventus test field	01.06.2008–30.08.2012
DHI/DHI-Wasy GmbH	Analysis of long-term data and modelling of the distribution of porpoises in the Alpha Ventus test field as the basis of decision-making aids for maritime spatial planning	01.01.2013–30.09.2013
itap GmbH	Measurement of the piling and operating noise at different distances from the Alpha Ventus test field and its model-based processing	01.07.2008–30.08.2011
Müller BBM GmbH	Underwater noise from offshore wind turbines, harmonisation of conceptualisation, procedures and evaluation of dependent variables	01.10.2010–30.11.2011
Meeresmedien	Editorial support for the production of an English-language book about the StUKplus project	01.12.2012–28.02.2014

Fig. 21.2 Colonisation of the foundations of an offshore wind turbine. © Roland Krone

tigated separately, as was the megazoobenthos, i. e. the entirety of living creatures in the bottom zone of the sea or which live on the seabed.

The research project thus collected data on crustaceans and fish that settled on the foundations and in their immediate vicinity. The investigations showed that species that like hard substrates, such as crustaceans, increased on the foundations (Fig. 21.2). There were up to one hundred times more than on the undeveloped soft floor in the reference area. On individual foundations up to 2,300 crabs were counted. There were also large accumulations of hermit crabs on the foundations, and also horse mackerel and pouting. The offshore supporting structures led to a great increase in crabs and shellfish, which in turn provided an attractive food source for fish species that live near the seabed – which accounts for their increased numbers in the area.

21.4.3 Result: Merged and Standardised Environmental Database

Substantial data from environmental impact studies, from the monitoring that accompanied the construction and operation of other wind farm projects and from research projects carried out by the Alfred Wegener Institute about benthos and demersal fish were evaluated, harmonised and analysed for this project. The result was the first standardised and quality-tested extensive database of information about the marine environment in the German Exclusive Economic Zone. The key results of this data analysis are available to the public free of charge on the BSH GeoSeaPortal at ► www.bsh.de.

21.4.4 The Claw, the Trawl Net and the Seabed

The investigations also included collecting extensive, area-wide samples from the seabed. The infauna sampling – of animals living in the sediment – was done with ship-mounted claw samplers. The epifauna sampling was done using a beam trawl, a pouch-like bottom trawl net. Divers also documented the epifauna on the underwater foundation structures of the offshore wind turbines with scratch tests and digital photography (Fig. 21.3).

No long-term negative changes of the benthos on the seabed, the entirety of all living creatures, caused by the construction of Alpha Ventus were discovered. The biomass and number of species on the foundation structures increased continuously after the turbines were erected.

Furthermore, not only was the benthos at a single turbine investigated, but in a second sub-project

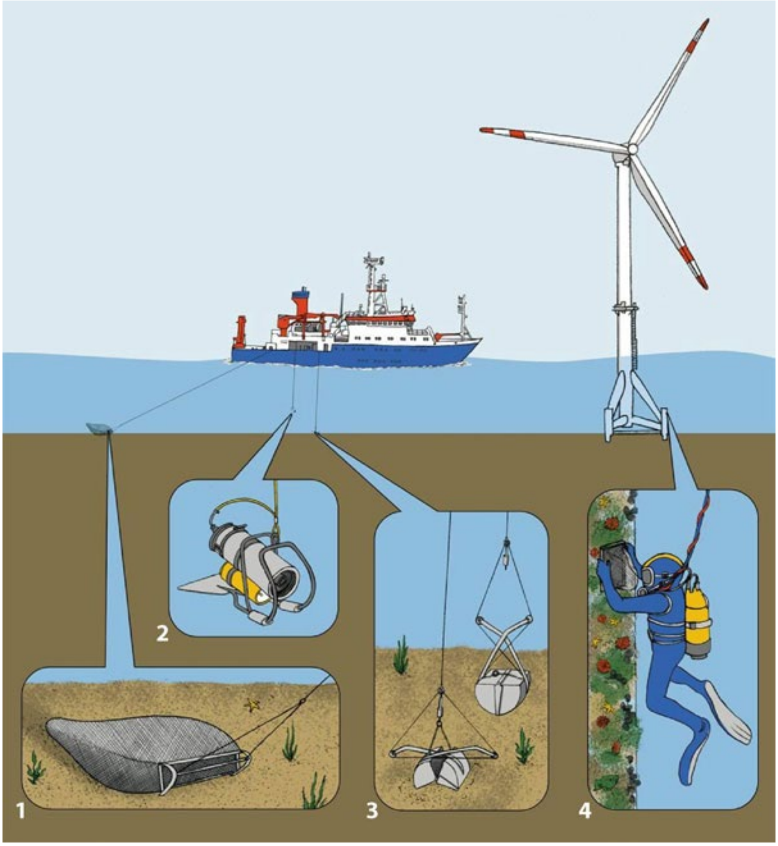

Fig. 21.3 Schematic representation of methods for the quantitative investigation of the benthos in Alpha Ventus: *1* Trawl net (beam trawl) for investigating the epifauna in the sediment, *2* The demersal megafauna on the seabed can be observed using video recordings, *3* The van Veen claw sampler takes small samples of the seabed and the organisms living within it, *4* Divers collect samples of organisms that have colonised the foundations of the wind turbines. © Illustration from BSH & BMU (2014): Ecological research at the Alpha Ventus offshore wind farm (drawing by Britta Kussin)

the benthic communities on the seabed were also investigated over the full distance between two neighbouring wind turbines, a stretch of 800 metres. The conclusion of this evaluation of the stretch between two wind turbines and the surface surveys was that no impact on the benthos and the seabed could be ascertained here either.

21.4.5 Gannets and Friends: The Impacts on Sea and Migratory Birds

During the 2010–2011 construction phase, exploratory trips were made by ship and aircraft sighting flights were undertaken to investigate the incidence of seabirds near Alpha Ventus. The behaviour of the seabirds and their reactions to the wind turbines were comprehensively documented. The flight altitudes of the seabirds were also measured visually and with a rangefinder, a laser-based distance measuring instrument, and it was ascertained as to what extent these coincide with the rotors of the wind turbines.

Six out of eight types or species groups of birds investigated there after the construction of Alpha Ventus exhibited a lower abundance than beforehand, for example in the cases of the lesser black-backed gull, the kittiwake and the northern gannet. The abundance of lesser black-backed gulls up to a distance of 1.5 kilometres from Alpha Ventus remained significantly lower than the average previously calculated for them. However, investigations in the following years showed that the decline modelled here could simply be related to the annual population fluctuations of the lesser black-backed gulls in the German Bight. The model showed a significant increase of auk and loon abundances as of approximately 2.5 kilometres from Alpha Ventus. This means that these types of bird avoid the wind

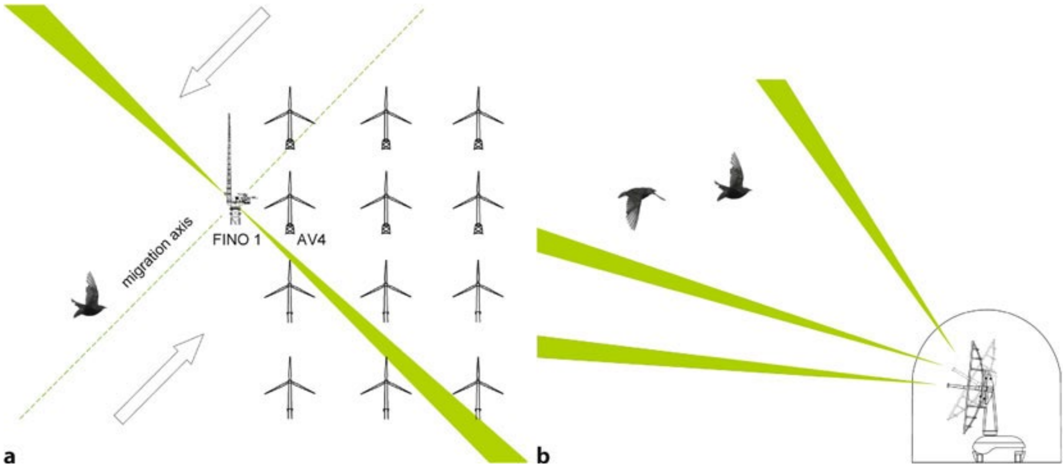

Fig. 21.4 **a** Diagram of the data collection about bird migration inside and outside the Alpha Ventus wind farm using fixed beam radar, **b** Variation of the vertical angle of tilt of the radar beam for surveying birds at various altitudes, *green* radar beams. From *Ecological Research at the Offshore Windfarm alpha ventus*, p. 115; © IfAÖ GmbH

farm area and only settle down on the water surface at a distance of 2.5 km from the wind farm.

The flight altitudes of seven different kinds of seabird were surveyed with laser devices on the offshore wind turbines and then analysed. The large gull species herring gulls, lesser black-backed gulls and great black-backed gulls were often found at the altitude of the rotor blades and it was also observed that these species passed by the wind turbines at rotor height or even flew through them. The smaller species – little gull, kittiwake and common gull – as well as the fairly large northern gannet mainly flew less than 30 metres under the rotor blades.

The StUKplus research project developed new methods and approaches of finding evidence of the endangerment of migratory birds (Fig. 21.4 and 21.5) using measuring devices it developed itself for the operational monitoring of offshore wind farms. The aim of these investigations was to determine to what extent the 150-metre-high wind turbines with a rotor diameter of around 120 metres represented an obstacle for birds migrating over the German Bight in spring and autumn. The bird migration is extremely variable and strongly dependent on the weather. A minority (around a third) of the migrating birds fly during the day, the majority by night, whereby mass migration activity is concentrated on a few nights a year. Under good conditions most migratory birds fly by night at such great altitudes so that it is unlikely that wind turbines pose any danger. If the birds encounter poor weather, usually in conjunction with rain and unfavourable winds, they tend to fly much lower, usually at less than 200 metres above sea level. If the birds are attracted by the lights on the wind turbine it can lead to an increased risk of collision.

During the investigations at the Alpha Ventus test field it was proven that most of the bird species (groups) observed avoided the wind farm during the day. There were occasional flights through the test field, though no collisions were observed. On the other hand, before and after comparisons showed that during the night-time autumn migrations in the vicinity of the wind farm more birds flew in the lower altitude levels than beforehand. The greatest number of birds registered at night were songbirds. Projections showed that some species (e. g. sandwich terns, Brent geese, lesser black-backed gulls) passed over the sea area around Alpha Ventus every year in such great numbers that they constitute over 1 % of their respective populations. The comparisons of the flight movements in the rotor area when the wind turbines are in operation and when at rest exhibit significant differences between the operating mode: both during the day and at night fewer birds were observed when the rotor was turning.

Fig. 21.5 Camera on the Fino 1 research platform for observing sea birds. © Marine Monitoring Networks/BSH

21.4.6 Viewing and Evaluating Data on Seabirds

Distribution maps were drawn up for the following types of seabird in the North Sea based on the database developed during the project, taking into consideration the specific species and the seasons: loons, fulmars, northern gannets, little gulls, kittiwakes and sandwich terns using airborne geospatial data acquisition, and for the following species sighted during observations from ships: common gulls, lesser black-backed gulls, common terns, arctic terns, common guillemots and razorbills.

Special attention was paid to the species listed in Appendix I of the EU Birds Directive. The new database mentioned above makes it possible to determine the density and distribution pattern that helps to designate sensitive areas for seabirds – especially with regard to any possible loss of habitat, such as the loss of a (partial) area of a biotope, posed by new offshore wind farms. For the first time, it was possible to describe the direct impacts on resting birds before and after the construction of a German offshore wind farm. These vary from species to species and are described in the sections below.

» **A unique opportunity**

The Alpha Ventus test field provided the first-ever opportunity to systematically and scientifically investigate the environmental impacts of an offshore wind farm in Germany, before, during and even after its erection. This particularly applied to its impacts on porpoises and migrating and resting birds. The results of the research work were included in the revision of the BSH Standard Investigation Concept and help to answer questions of practical relevance. Dr. Nico Nolte, head of department Management of the Oceans at the Federal Maritime and Hydrographic Agency

Fig. 21.6 Porpoise. © Klaus Lucke/Fjord & Bælt

21.4.7 Porpoise and Friends: Impacts on Marine Mammals

Another project investigated the impacts of the construction and operating phases of Alpha Ventus on marine mammals – porpoises, grey seals and common seals. Supplementary to the StUK3 monitoring, additional airborne monitoring was carried out on a large-scale survey area with additional C-pod measuring positions. These C-pods (Cetacean Porpoise Detector) are measuring instruments installed underwater for detecting porpoises, and which work as stand-alone data loggers, recording, processing and storing the clicking sounds of the porpoises. The measurements taken by the porpoise detectors are supplemented by visual observations from ships and by acoustic detections using drag hydrophones (underwater microphones) in the vicinity of Alpha Ventus.

This showed that porpoises (Fig. 21.6) kept well away from the area during the noisy piledriving. The erection work had a negative impact up to a distance of 10.8 kilometres from the construction site; in other words, there were fewer porpoises counted. At a distance of 25 to 50 km there was on the other hand a positive impact – increased numbers of porpoises were found at this distance. The duration of the absence of porpoises was relative to the piling activity at the wind farm. The longer the piledriving activity lasted, the longer it took until the porpoises returned to the area under investigation. During the piledriving activity and aversive conditioning, which sometimes took a very long time, these marine mammals were absent for an average of 16.5 hours in a radius of 25 kilometres.

The airborne observations confirmed the significant impact that the piledriving had. This was however mostly not very marked because the overflying and the piling activity were often not concurrent. Between 2008 and 2012 the researchers flew over and investigated a distance of 23,338 kilometres. Porpoises were sighted 1,999 times, with a total of 2,392 creatures, 107 of which were calves. Findings showed that the lowest density of porpoises recorded was in 2009 – the construction phase – whereas the greatest number was recorded in 2011 – the second year of the operating phase. Statistical analyses that incorporate an enlarged data set covering 2002 to 2012 showed that there has been a positive trend with regard to the overall abundance of porpoises in the German Bight since 2005. And this is even though the German Bight is one of the busiest shipping lanes in the world. The investigation of the subsequent operational phase of Alpha Ventus showed no negative impact on the number of porpoises.

21.4.8 Joint Evaluation of Data About Marine Mammals

The results of the visual, aircraft-based survey of marine mammals from the StUKplus projects and the environmental impact studies were combined with those from the monitoring accompanying the construction and operation of other wind farm projects. Here the aim was to create a standardised database from all (!) available data, i. e. from research projects, monitoring data, environmental impact studies, etc. This quality-tested database serves to determine large-scale distribution patterns of porpoises in the German Exclusive Economic Zone (EEZ) in the North Sea and to verify earlier impact forecasts.

21.4.9 Marine Mammals and Ecological Habitat Modelling

This new database made it possible to produce the first ever large-scale charting of porpoises in the vicinity of Alpha Ventus and in the German Bight as a whole. It included the logging of their potentially sensitive concentration areas with regard to prevailing environmental conditions, such as sea currents, waterfronts and tides, as well as "man-made" noise input from shipping, for example.

The scientists have drawn up distribution maps for the probability of presence of porpoises in the German Bight for both summer and winter. This shows three regions with greater abundance in the summer, the largest area of concentration stretching from Helgoland along the 30-metre isobath (depth contour) that goes off to the northwest. The second region is on the southwestern edge of the Exclusive Economic Zone, also on the 30-metre isobath. The smallest region is in the area of Dogger Bank – the largest sandbank in the North Sea – on the extreme northwestern edge of the EEZ. There are similar distribution patterns in winter, though with significantly fewer numbers of individuals.

21.4.10 Piling and Operating Noise

The measurement of the underwater noise during the construction and operation of Alpha Ventus complemented the noise monitoring in accordance with the Standard Investigation Concept (StUK3) in the shape of additional measuring points and extensive evaluation. The results are dealt with in greater detail in the chapter on underwater noise (▶ Chap. 22, "Much hubble-bubble about nothing?") and in the chapter on operating noise (▶ Chap. 23, "Like the din in a university canteen").

21.4.11 Underwater Noise: New Measuring Specifications

The scope of this sub-project included investigating the measuring and evaluation method of carrying out underwater noise investigations for offshore procedures in more detail. The aim was to create clearer definitions and determine criteria for possible evaluation procedures in order to enable a comparison of technical specifications and prognoses with regard to the evaluation of the impact of underwater noise on the marine environment, and especially the impact on porpoises. The measuring method used up to now in accordance with StUK3 was revised and is now summarised in a detailed measuring specification (Specification for Underwater Noise Measurements, BSH 2011). This is also a component of StUK4. The metrological investigations prescribed and described therein cover all four phases of the approval and implementation procedures for offshore wind farms in the German Exclusive Economic Zone: baseline survey, construction phase, operating phase, decommissioning phase.

21.4.12 International Publication

The results of the accompanying ecological research have been summarised in an English-language book so that it can be accessed throughout Europe and internationally. "Ecological Research at the Offshore Windfarm alpha ventus – Challenges, Results and Perspectives" was published by Springer Spektrum in 2014.

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21.4.13 Standard Investigation Concept: Where It Goes from Here

The Standard Investigation Concept (StUK) was first applied in the construction and operating phases of a wind farm for the construction of the first German offshore wind farm, Alpha Ventus, in 2009, the second update (StUK3) having been published in February 2007. The evaluation of StUK3 took place between November 2011 and July 2013 by several thematic working groups made up of experts from StUKplus Research, StUK Monitoring, the official bodies involved, such as the Federal Agency for Nature Conservation, the German Environment Agency, the BSH and various scientific institutions. The final version of StUK4 also included knowledge gained from the consultation process with the environmental associations NABU (Nature And Biodiversity Conservation Union), WWF, Greenpeace and BUND (Friends of the Earth Germany), the Offshore Wind Energy Foundation and the German Wind Power Plant Association (Wirtschaftsverband Windkraftwerke). Since its launch at the StUKplus Conference in October 2013 the Standard Investigation Concept StUK4 has been the binding standard for investigations for environmental impact studies prior to construction begin as well as the accompanying construction and operation monitoring of offshore wind farms in Germany.

21.5 The Most Relevant New Features in StUK

If the time between the end of the baseline survey and the start of construction of an offshore wind farm is more than five years there must be a new, complete two-year baseline survey. If the investigation findings show that there has been no significant change of the site conditions, after six months – subject to the submission of an interim report – the investigation period can be reduced to one year. Several projects can jointly carry out so-called cluster studies, although for benthos and fish the investigations in the respective project areas have to be carried out individually. The investigation of benthos, biotope structures and types is also prescribed for the laying of cable runs for offshore wind farms.

As far as fish are concerned, in the North Sea the investigations are to be carried out using a beam trawl, and in the Baltic Sea with an otter trawl. The surveys have to include representative information about the weather, temperature, salinity and oxygen content. Turbine-related investigations are to be carried out using state-of-the-art technology, such as fish sonar.

With regard to migratory birds, the reactions of flying birds to wind turbines, such as evasive movements or possible incidents of attraction, have to be considered. Here also, in coordination with the BSH, the monitoring of birds in the rotor area must be done with state-of-the-art equipment such as radars and modern optical systems. For resting birds and marine mammals, eight to ten digital aerial counts are prescribed, depending on the project, region and seasonal presence of the species, including photographic or video documentation. All the year round counts of shipping must be carried out, once a month and wherever possible at equally spaced intervals. Depending on the site or any project-specific characteristics, the investigation must include at least six further counts.

Acoustic investigations have to be carried out with regard to the marine mammals using at least one C-pod station per project, but at least two of these porpoise detectors if the planned wind farm is close to an important conservation area for porpoises – with a distance of at least 20 kilometres from the wind farm. In order to determine possible scaring-off effects during the noisy construction work, four to five individual stationary C-pods are to be positioned at suitable distances from the wind turbines. During the noise-intensive piling work, two mobile individual C-pods have to be installed 750 and 1500 metres from the pile site. During the operating phase, depending on how big the wind farm is, at least three stationary porpoise detectors have to be deployed in the wind farm. The relevant BSH guidelines are to be applied for underwater noise measurements, forecasts and the definition of noise protection measures. For wind farms planned in the German Baltic Sea it is also necessary to record the migratory behaviour of bats over the Baltic Sea, especially on nights without any wind and wherever possible in parallel with the nocturnal recording of the calls of migratory birds.

The conclusion of the environmental surveys for Alpha Ventus is that initial fears that it could result in mass bird strikes or the loss of marine mammal habitats have not been borne out, although it must be said that the Alpha Ventus test field investigated consists of only twelve turbines. Only future studies will show if the results and knowledge gained from Alpha Ventus can be valid for large wind farms with up to 80 turbines or for the cumulative impact of several wind farms.

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Much Hubble-Bubble About Nothing?

Research into the Little Bubble Curtain Method of Noise Reduction

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Text written by Björn Johnsen

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22

Project information: Research on the mitigation measure "Little Bubble Curtain" in the test field Alpha Ventus

Project management:
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- Bode und Wrede GmbH
- Hydrotechnik Lübeck GmbH
- Karl Wrede Stahl- und Maschinenbau GmbH
- Menck GmbH
- Prokon Nord Energiesysteme GmbH
- Prokon Nord Offshore Installations GmbH
- UL International GmbH (DEWI)

Just imagine giant steel piles of up to 40 metres in length being rammed into the seabed with full force to pin down the foundation of an offshore wind turbine. With equally gigantic, fully automatic hydraulic piledrivers (Fig. 22.1). And all this going on at one-second intervals, time and time again, with construction noise that can be heard over 50 kilometres away. With up to 20,000 strokes of the piledriver all day long this is enough of a problem for the construction workers involved, but all the more of a problem for noise-sensitive marine mammals like porpoises and seals. They use their sensitive hearing in communicating with each other, for noticing prey or danger or for finding the nearest stretch of coast or dry land. The ramming noise that occurs during the erection of offshore wind turbines can permanently damage the hearing of these marine mammals. But what can you do if there is no way of avoiding building a secure, pinned foundation without ramming piles?

The fundamental idea is to introduce millions of air bubbles around the pile to reduce the ramming noise, like with an "aquarium stone" used to introduce air bubbles into the fish tank. Here however the "bubble curtain" should extend all around the driven pile to reduce the construction noise and the stress for the marine mammals.

In the beginning there was pressure; the "Little Bubble Curtain" research project was under massive time pressure right from the very start, because the decision was made at short notice and the various constructions had to be planned and built at equally short notice. The time pressure started with the commissioned supplier, who realised the design, including operating concept, design, manufacture and assembly on a tripod construction, within just two months. On 17 April 2009 the two construction modules of the "little bubble curtain" stood, fully assembled, on the quay wall in Eemshaven, Holland, ready to be shipped out into the North Sea. Sometimes plans proceed on schedule …

And in the beginning there was also construction noise. Previous measurements of ramming during the erection of earlier offshore wind turbines in the North and Baltic Seas had shown that the local underwater noise levels significantly exceeded the prescribed limits set by the Federal Maritime and Hydrographic Agency (BSH), the Federal Environment Agency (UBA) and the Federal Agency for Nature Conservation (BfN), in other words massively above the permitted "single-event sound pressure level" of 160 decibels (dB) and "peak sound level" of 190 dB.

Shortly before Christmas 2008 a work meeting of the Offshore Wind Energy Foundation therefore decided to try out a prototype noise reduction method in the Alpha Ventus test field – the "little bubble curtain" directly on the foundation construction of an Adwen AD 5-116 offshore wind turbine. The time involved between the "pre-Christmas resolution" in 2008 and the aforementioned delivery of the construction to the Dutch quay wall was less than four months.

22.1 Scaring off Porpoises and Soft Starts

At the site of the wind turbine chosen for the prototype trial the water depth was around 29 metres and the average diameter of the driven piles was about 2.50 metres. The maximum ramming energy required to bring both the piles (northeast and southeast piles) equipped with bubble curtains to their final depth was 375 kJ.

In order to rule out any injury to marine mammals like seals and porpoises, acoustic signal generators were used to scare them off before ramming

Fig. 22.1 The Menck MHU 800S hydraulic ram used at the Alpha Ventus offshore wind farm. © Menck GmbH

started. The first devices to be used were so-called "pingers" – also used in Norway for example to protect salmon farms from seals. These pingers only have a small range of 200 to 300 metres and while they are rather loud, they do not injure the animals. They are a kind of advance warning for porpoises and seals, telling them they have to leave the area. The real scarer-offer is what is activated underwater about ten minutes later. This transmits a high-frequency signal of around 12 to 16 kHz – a frequency range in which porpoises can hear very well. At 190 decibels, the sound is pretty loud, almost like a fire alarm for humans. Studies have shown that marine mammals feel most uncomfortable as a result of these eviction signals in an area of up to two kilometres away, and that they therefore leave the area immediately.

The ramming work at Alpha Ventus also started with reduced ramming energy – a so-called "soft start". With a soft start, the piledriver is not allowed to start driving the pile in with full force straight away, but initially runs with lower energy for several minutes or it takes longer breaks between impacts.

22.2 Small Bubbles, Big Impact

The term Little Bubble Curtain or LBC primarily describes the overall sound reduction concept. The system consists of nozzle pipe rings arranged all around the pile that is to pin the foundation structure of the offshore wind turbine to the seabed. The actual bubble curtain first comes into effect when these horizontal pipe systems are filled with compressed air and air bubbles escape through the nozzles and rise to the surface like a curtain or veil.

These air or gas bubbles can significantly alter the hydroacoustic properties of the water. A substantial impedance leap takes place due to the great difference in density between water and air. The noise excitation of air bubbles near their natural frequency causes a large reduction of the sound amplitudes, whereby both scatter and absorption effects occur. Close to the resonance frequency, the acoustic surfaces of the individual air bubbles account for a multiple of their geometrical surface – which explains the particular effectiveness of bubble curtains. In other words, little bubbles – big impact. The arrangement of a bubble curtain close to the offshore foundation structure in direct proximity to the piledriver, pile and foundation however also poses a special technical challenge. To minimise piledriver malfunctions as much as possible, the engineers broke the bubble curtain down into two part systems, a preassembled lower section consisting of four nozzle pipes around a tripod pile and one mobile, upper section (Fig. 22.2). Two of the tripod's piles (NE and SE piles) were equipped with bubble curtains in this manner.

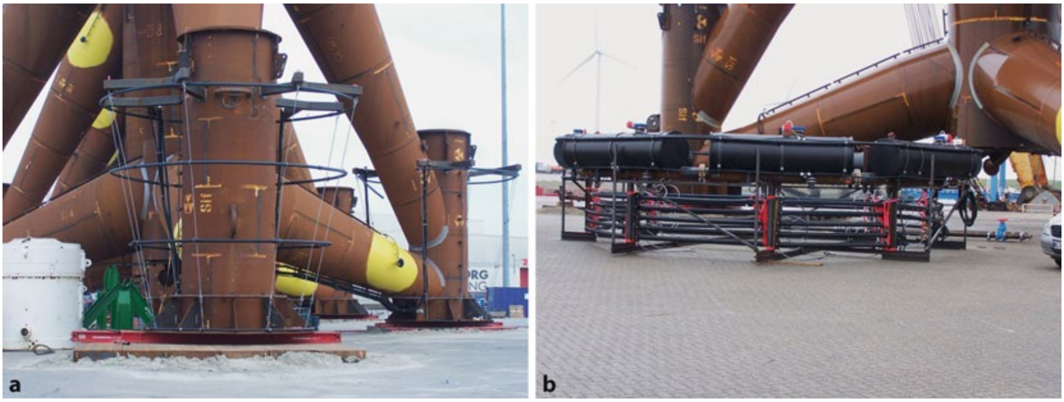


Fig. 22.2 Lower, preassembled, section on the tripod (**a**) and the mobile upper section of the little bubble curtain (**b**). Source: Hydrotechnik Lübeck GmbH, © Cay Grunau

On 31 May 2009, the day of the foundation construction for Turbine AV9, the lower, preassembled system could be put into operation as planned. The mobile upper system was ready to go on the transport ship before ramming began, but was not used after all. Because of the small weather window and the danger that the uncertainty about how long it would take to assemble offshore could delay the erection of the foundations for too long, in the morning the construction supervisors decided to forgo the assembly of the upper mobile system at short notice. The original plan was that a crane would lower the upper bubble curtain over the pile and slowly lower it into the sea. The flotation bodies would fill with water and divers would connect the bubble curtain to the tripod's cantilever arms with eight grommets. After this the divers would connect the air supply for filling the flotation bodies and the air pipes for the upper bubble curtain. This was not without risk; filling the flotation bodies (Fig. 22.2b) only takes a few minutes, but because of the strong wave loads it represents a critical phase of the construction process. And the safety of the divers also has to be guaranteed, and they are only allowed to work when there is minimum current. Considering the weather conditions at the time – poor weather was forecast for the next few days – and the advanced installation time, it was necessary to forgo the practical trials for the second subsystem. This was a decision agreed by all parties involved.

The underwater sound measurements were taken during the operation of the lower subsystem as planned. They recorded the effect of the bubble curtain and its dependency on the relevant influencing parameters such as current and sea state. The scientists measured the sound level in and against the direction of the current at a distance of approximately 500 metres from the sound source. Measurement buoys at distances of 2.4 and 17.5 kilometres also recorded the acoustic pressure level.

22.3 Three Levels and One Curtain

Sound is a rapid, often periodic, fluctuation of pressure that is additively superimposed on the ambient pressure – in water the hydrostatic pressure. In sound technology, sounds are mostly not directly described in terms of sound pressure coefficient (or sound particle velocity), but in terms of the level used in communication engineering in decibels (dB). For the "Little Bubble Curtain" research project it was primarily the equivalent continuous sound level (average level), the single-event sound level and the peak level that were significant.

The measurement of the effect of the bubble curtain was made by simply directly comparing the ramming periods with and without bubble curtain operation. To do this, the bubble curtain was twice switched off and on again. Due to the omission of the mobile upper system and the subsequent reduced amount of air pressure it was not possible to carry out any variations of this.

22.4 It's the Current that Does It

A main finding of the trial was that the effect of the bubble curtain is strongly dependent on the current in the surrounding water. This is because the current pushes the generated air bubbles way in such a manner that the pile is no longer completely enveloped in air bubbles around its whole circumference and full depth. This is due to the immediate proximity of the bubble curtain to the pile, resulting in a strong direction-dependent and temporally changing reduction effect in the surrounding area. Only in the vicinity of the slack water point – where there is minimal current at the turning point of ebb and flow – does the bubble curtain display a sound absorbing effect that is equally good in all directions.

Only late in the evening of the erection day, 31 May, at 9.21 and 10.13 p.m. was it possible to determine the effect of the bubble curtain with the most accuracy – namely when the bubble curtain was switched on. In contrast, when the air compressors were switched off it took quite a while until the little air bubbles rose to the surface. During this time the sound pressure level still scattered relatively strongly. It is thus safest to determine the sound-reducing effect of the bubble curtain as soon as it is switched on. At Switch On Point l the ramming energy on this evening remained constant at 375 kJ. The waves were almost a metre high. The Fino 1 research platform measured a current between 0.5 and 0.6 m/s with slight increasing tendency, and flowing in a westerly direction. The depth of penetration of the pile and the movement and the rocking of the research vessel with the hydrophones anchored 500 metres away also affected the underwater noise level. In order to eliminate these influences, additional collateral times for measurements were evaluated, with the bubble curtain switched on and also with it switched off.

At 9.21 p.m. the pile had been driven about halfway into the seabed, and the sound reduction was found to be around 13 decibels (dB) on average or 14 dB at peak level in current direction, and 2 or 0 dB against the direction of the current. At the second time of measuring, just about an hour later, at 10.13 p.m., the pile had almost reached its final penetration depth. Here the sound reduction was about 10 dB (average value) and 12 dB (maximum value) in westerly current direction and 4 dB (average) and 5 dB (maximum) in the opposite direction to the current. The researchers observed that the reduction in sound level was far greater in the west than in the east – which was down to the westerly current. The air bubbles of the bubble curtain drifted off to the west, where they created a complete bubble curtain across the whole water depth, and this reduced the underwater noise radiated in this direction.

In the easterly direction, the opposite direction, on the other hand, between the pile and the easterly measuring point there were only the air bubbles that were generated in the bottom third of the water column. Shortly after leaving the nozzles the air bubbles drifted past the pile and so could not reduce the sound radiated against the direction of the current. In the easterly direction the bubble curtain only provided protection in the lower level of the water column. While sound reduction in the easterly direction was hardly noticeable when the bubble curtain was switched back on at 9.21 p.m., it was once again clearly noticeable with the second attempt at 10.13 p.m. This is due to the pile penetration depth – at this later point in time it had almost reached its final depth. The length of pile not protected by the bubble curtain was by this time also significantly shorter than before. This is why when you take the reduced pile length into account it is possible to detect a reduction in sound when the bubble curtain is switched on again. It should however be noted that in this test the erection limit value set by the Federal Maritime and Hydrographic Agency (BSH) of 160 decibels at a distance of 750 metres (Fig. 22.3, Table 22.1) can only be kept to in the direction of the current.

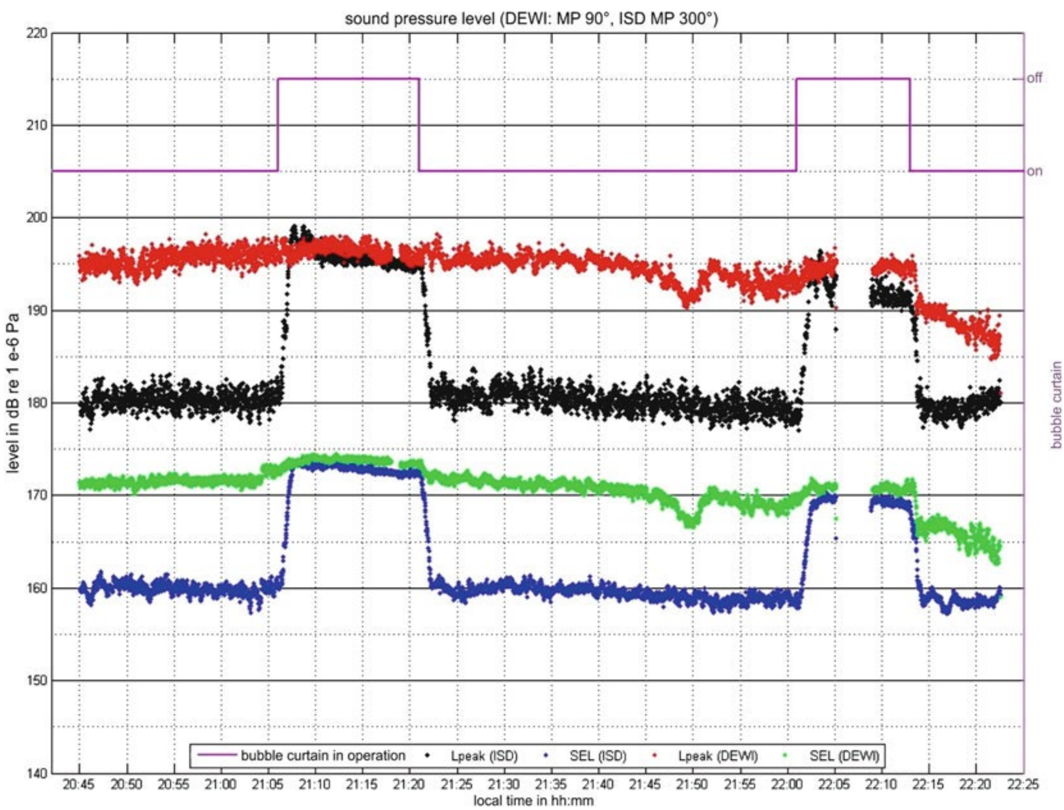
Peripheral Anecdote: The last man leaves at 2 a.m.

How massive the time pressure is when you are erecting a turbine can be seen from the day log in the logbook for 31 May 2009: the third pile for the tripod only arrived at the wind farm at five in the morning. It was meant to arrive the previous evening but the tug had to fight against some very strong currents. The result was that because the tug only arrived at five

in the morning, work on this 31st day of May continued well into the night. At 1.15 a.m. the air hoses for the bubble curtain were cleared away on deck, and according to the log, the last man left the tripod at 2 a.m. …
Björn Johnsen

22.5 There Is Need for Improvement

Another important project finding is that the difference in the sound pressure level measured in and against the direction of the current is very significantly dependent on the strength of the current (◘ Fig. 22.4). The difference between the sound



◘ **Fig. 22.3** Operating condition of the bubble curtain (*violet*) and evaluated sound level at two measuring points (*red and black lines*: 500 m, *green and blue lines*: 750 m distance). © LUH

◘ **Table 22.1** Averages from 80 pile drives both before and after switching the bubble curtain back on. © LUH

Time hh:mm	Operating state of bubble curtain	L_{peak} (west) in dB re 1 µPa	SEL (west) in dB re 1 µPa	L_{peak} (east) in dB re 1 µPa	SEL (east) in dB re 1 µPa
21:19	Off	194.8	172.4	195.8	173.4
21:24	On	180.7	159.4	195.5	171.8
22:11	Off	191.3	169.1	194.7	170.6
22:15	On	179.2	158.7	189.6	166.9

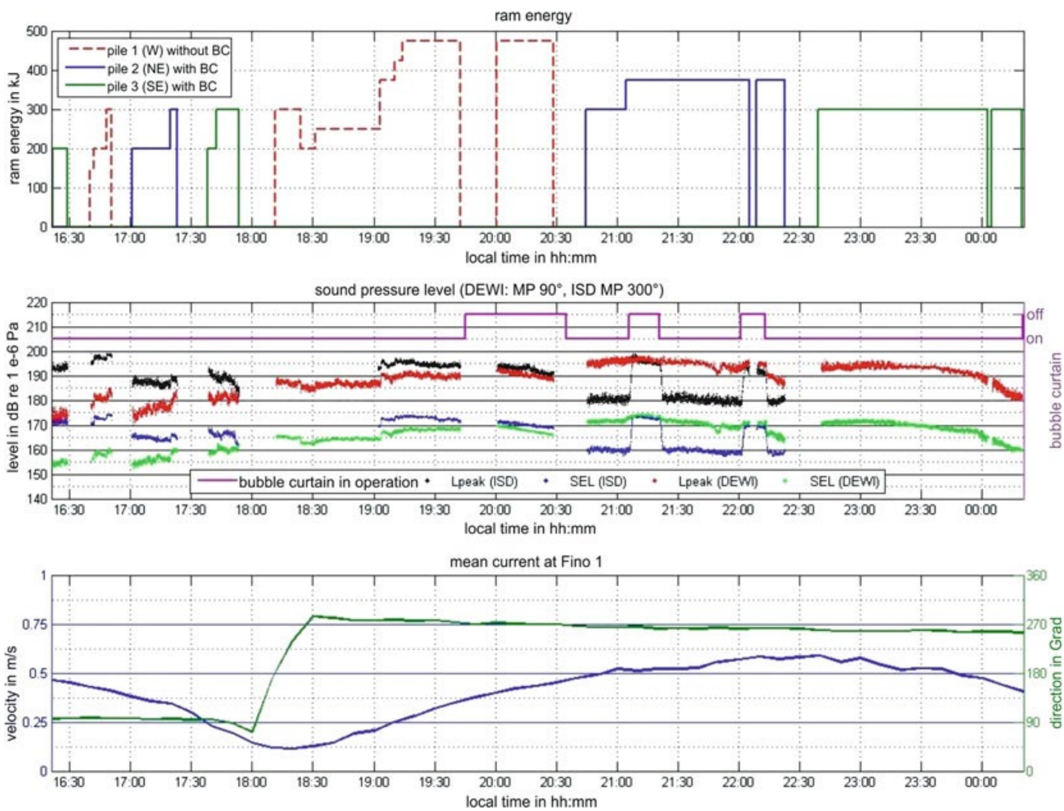


Fig. 22.4 Representation of the chronological sequence of the ramming energy in kilojoules (*top*), the measured sound pressure level (*middle*) and current direction and speed of the tidal current (*bottom*). © LUH

pressure level measured in current direction and that measured against the direction of the current increases with increasing current speed.

It was not possible to further investigate the relationship between the amount of compressed air and the reduction effect during this project because this variation was no longer possible due to the mobile system not being used. Precise knowledge about the absorbing characteristics of the mobile section are however vital in order to optimise the impact of the "Little Bubble Curtain" concept as a whole.

For future offshore applications it will also be necessary to remedy the weaknesses in the directionally dependent and temporally altered reduction potential discovered during this trial. This could be possible if the bubbles can be guided in such a way that the lateral drift is reduced to a minimum and the noise absorption is achieved all around the pile. The preassembly of the underwater sound reduction measures on the foundation structures on land proved to be very advantageous and should be taken into consideration for future noise control concepts.

The first trials with the bubble curtain for offshore wind farms have begun in Alpha Ventus. At first glance you might be inclined to think that because it is only used for one or two days that this is not a major activity, especially when you consider that the "Little Bubble Curtain" (Fig. 22.5) was only used for one foundation. But the knowledge gained from this project was pioneering for noise reduction measures that can be used during the erection of the next offshore wind farm, a case of learning by doing. With constructive alterations the bubble curtain will not drift so far with strong currents and offers great opportunities. This system will make it possible to undertake the noise-intensive installation work on future offshore wind farms considerably quieter.

Fig. 22.5 The "bubble curtain" method of reducing noise surrounds the pile with fine air bubbles while the hydraulic piledriver hammers the pile into the seabed. © LUH

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Like the Din in a University Canteen

The Underwater Operating Noise and its Effects on Porpoises and Friends

Michael Benesch, Hermann van Radecke, Copy edited by Björn Johnsen

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power*, DOI 10.1007/978-3-662-53179-2_23

Project information: Measurement of the operational underwater noise emission of wind turbines at the Alpha Ventus offshore wind farm (Operational noise)
Project management:
Flensburg University of Applied Sciences
Dr. Hermann van Radecke

What noise do wind turbines make when they are in continuous operation? And how far does the noise carry? What effects does it have on noise-sensitive marine mammals like porpoises and seals? And to what extent might other sound sources be perceived under water, such as shipping or other, distant offshore wind farms?

These are questions that need to be answered if the continuous operational impact of an offshore wind farm is to be judged. The Flensburg University of Applied Science investigated the underwater operating noise at the Alpha Ventus offshore wind farm. Their objective was to measure the underwater noise and identify the sound sources and sound paths in the water. Particular attention was paid to assessing the significance of the measured noise level for marine mammals in the North Sea.

23.1 Measurements Virtually Only in the Baltic Sea to Date

It's hard to believe, but it's true: previous underwater sound measurements of offshore wind turbines in operation made before Alpha Ventus was erected were done almost exclusively in just a few wind farms in the Baltic Sea. And these were far closer to the coast and in significantly shallower depths ranging from just two and a half metres (Vindeby Wind Farm) to a maximum of ten metres (Utgrunden Wind Farm). Even on the first wind farm measured to date in the Danish North Sea – Horns Rev – the water is significantly shallower and nearer to the coast than Alpha Ventus. The measuring results are therefore not comparable. The highest measured sound level in any of these projects was 124 dB (decibels under water). The underwater noise was frequently measured in just a few operating conditions or even in only one operating condition of the offshore wind turbine. This is not enough, however, since even a minor change in wind speed can fundamentally alter the sound radiation. Measurements made at Alpha Ventus showed that the greatest noise impact does not occur at full rated output but especially during partial-load operation of a wind turbine.

23.2 Divers at Work

To determine and evaluate the noise during constant wind turbine operation, an Adwen AD 5-116 and a Senvion 5M wind turbine were equipped with special measuring instruments: divers fixed underwater microphones, known as hydrophones, on the two turbines (Fig. 23.1). They were also fitted with acceleration sensors above and below the water to measure the vibration, and with measuring computers. The Fino 1 research platform, located just 400 metres away, was also fitted with a hydrophone and measuring computer. Divers anchored two hydrophones to the seabed at a distance of approximately 75 and 140 metres from the Senvion turbine, at a water depth of about 30 metres. The hydrophones themselves were fixed to the stands around three metres above the seabed. The hydrophone on Fino 1 was unfortunately only available for a period of almost two months. For contractual reasons it was also not possible to carry out some of the originally planned measuring cycles, but despite this the extensive amount of data gathered made it possible to draw well-founded conclusions about the sound impact.

The sound measurements were made on the edge of the wind farm and the measuring computers were time synchronised with GPS signals, so that a cross-correlation could be made. The data was recorded at high resolution, with 50 kHz for measuring the time series. Measurements were made three times a day, each for a period of 300 seconds, and the data was then transferred to land via the farm's internal RAVE network. With three functioning hydrophones (two on one of the turbines and one on Fino 1) it was possible to measure the noise on 27 days in 2010 and on 138 days in 2011. This gave a total of 165 days, almost half an operating year. The

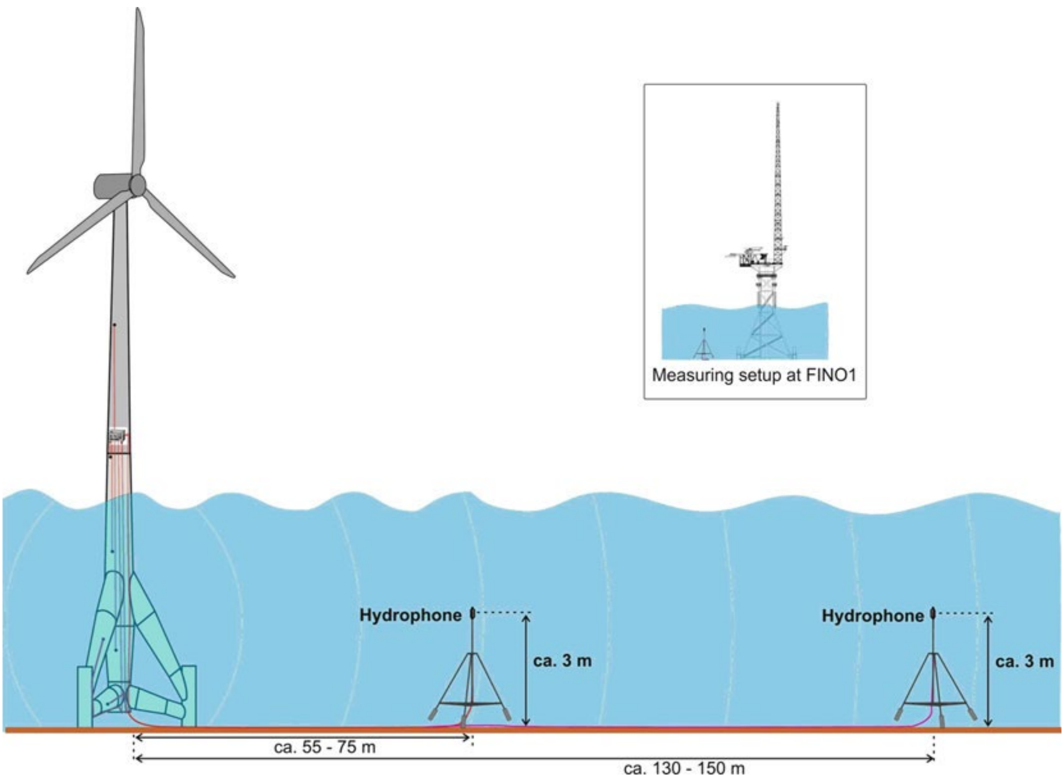

Fig. 23.1 Measurement set-up on the Adwen turbine. © Flensburg University of Applied Sciences

average of all measurements under water, the so-called "equivalent continuous noise level", was 118 decibels (dB under water). To make a comparison with the airborne sound on land it is necessary to subtract 62 dB. The continuous noise level of 118 dB under water thus corresponds to 56 dB in the air – and is thus as loud as the noise level in a university canteen.

The occasional temporary peak value in the water was around 15 dB higher than the average.

Peripheral Anecdote (I): Calibration impossible

Originally it was planned to exactly calibrate the measuring distance from the underwater microphone along the cable to the measuring computer, but this could no longer be done out at the wind farm. So all that remained was the lab calibration. But the researchers placed great value on being able to show the signals of all three hydrophones simultaneously. This showed that they very frequently exhibited the same curve, which shows the measured signals are also reliable without exact calibration.
Björn Johnsen

23.3 Wind and Waves Make It Possible: The Greater the Output, the Less the Noise

It was apparent that the noise level is heavily dependent on the respective output of the wind farm and on the environmental parameters wind and waves. It was discovered that the wind farm in general became increasingly quieter as the output increased, especially with increasing wave height. This is due to the fact that the measured and identified back-

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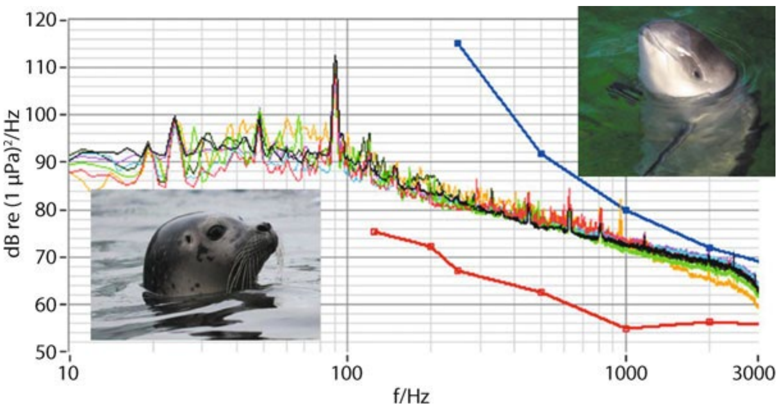

Fig. 23.2 Results of hearing thresholds of porpoises (and dolphins) *blue line*, seals *red line*, and in between measurements in the Alpha Ventus wind farm (coloured lines). Graphic © Flensburg University of Applied Sciences, Photos: seal Luna, J. Steffen GEOMAR; porpoise Wikimedia AVampireTear licence: CC-BY-SA-3.0 ▶ http://creativecommons.org/licenses/bysa/3.0/, accessed 5/2013

ground noises caused by ships etc. were initially of similar volume to the wind turbine noises – and that despite the distance. This means that ships in operation, which like offshore wind turbines generate low-frequency range noise, are significantly louder than the offshore wind turbines. These background noises in the wind farm decrease with increasing wind, and the sound level in the wind farm also decreases with the damping effect of air bubbles created in the water by wind and waves. In the end, the loud shipping, wind and wave noises were even louder than the turbine noise.

23.4 Distant Shipping in the Background

The background noises were very probably generated by ships, and in part from the shipping lanes 14 kilometres away. The measurements made on the turbines equipped with acceleration sensors identified individual, distinctive tonal noises on the two turbine types. One very distinct tonal noise with 90 Hz could be clearly attributed to one turbine type, which dominated the noise in the wind farm, especially at full load. The harmonics of the tone were also detectable in the spectrum up to 1 kHz. The manufacturer undertook construction measures to avoid individual projecting tones in the sound spectrum.

23.5 Offshore Piledriving Carries over here from 50 Kilometres

The hearing threshold of porpoises and seals, and the results of the measurements from Alpha Ventus, are illustrated in Fig. 23.2. The seven coloured measurement lines show the aforementioned "rogue tonal peak measurement" at 90 Hz, the harmonic lines and the overall spectral behaviour. No auditory thresholds were available for this tone with 90 hertz, so it was not possible to make any statements about the audibility of the most distinct tonal sounds measured. The source strength of this turbine type with the tonal noise was determined to have an equivalent continuous noise level of 129 dB.

The noise made by the two turbine types is so weak compared with the background noise that it is almost unmeasurable, even though the hydrophones are situated comparatively close to the turbines. There were also times when the sound of the piledriving from the seven- to fourteen-kilometre distant construction site of Borkum West II wind farm (construction start 2011) and the 50-kilometre distant offshore wind farm Bard Offshore 1 (construction start 2010) carried over and was measured.

Peripheral Anecdote (II): Serious setback in the autumn

Both of the hydrophones on one of the turbines were retrieved on 6 October 2010 because of work on the wind farm's internal cabling, and because of poor weather the cable work was only finished in March 2011. An alternative location for the two recovered hydrophones was not to be found and during the subsequent standstill time the hydrophone cable was damaged on the turbine in de-installed condition. This meant new procurement, exchange and refit using divers. It was thus only possible to start with measurements again in July 2011. The log of the research report reads: "Extreme setback … the missing measuring period up to now was the biggest blow to the measuring programme".
Björn Johnsen

23.6 Hearing Damage Improbable

Although porpoises are very noise-sensitive, the sound level caused by continuous operation – not to be confused with the sound of the piledriving during construction – is not dangerous for marine mammals like porpoises and seals. The research findings were that the sound level measured during turbine operation is partially below the auditory threshold of these animals, and when it is slightly above the hearing threshold then it is highly unlikely to be damaging.

Especially because of the expected accumulation of many offshore wind farms and the continuous sound impact of background noises (waves and ships) and turbine noise, further investigations by marine biologists and bioacoustics scientists will be necessary in the future. Another consideration is the legal requirements regarding noise avoidance. As with sound measurements for wind turbines on land, underwater sound measurements should be carried out by independent institutes as a requirement of the planning approval procedures, so that anomalies in the sounds, such as single tonalities, can be detected and eliminated. The prescribed onsite measurements will mean that when offshore wind turbines are being designed, they will be built and erected as quietly as the advancing state of the art permits.

» The noise accumulation from many wind farms alone means that investigations by marine biologists and bioacoustics scientists remain necessary.
Dr. Hermann van Radecke, Flensburg University of Applied Sciences

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Out of Sight, out of Mind?

Existing Offshore Wind Farms Are More Accepted Than Planned Ones

Gundula Hübner, Johannes Pohl, Copy edited by Björn Johnsen

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M. Durstewitz, B. Lange (Eds.), *Sea – Wind – Power,* DOI 10.1007/978-3-662-53179-2_24

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Project information: Acceptance of Offshore Wind Energy Use

Project management:
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24.1 Introduction

Offshore wind farms have existed in Europe for over two decades, but until recently there had not been any long-term scientific study of the acceptance of offshore wind farms: about the impacts of offshore wind farms on residents and tourists – prior to their erection, during construction and later, during their operation – that at the same time includes comparison regions without offshore wind farms.

The research project "Acceptance of Offshore Wind Energy Use" carried out by the Working Group on Health and Environmental Psychology (Psychology Department, Martin Luther University Halle-Wittenberg; Medical School Hamburg) entered new territory here, both with regard to extent and approach. To measure the impacts of the construction of offshore wind farms on residents and the region, the scientists chose a long-term approach: residents, tourists and local experts were surveyed three times at intervals of one to two years (2009, 2011, 2012; ◘ Table 24.1). The first survey wave began before or, in the case of Alpha Ventus, during construction of the offshore wind farms investigated.

The complex issues called for collaboration between several specialist disciplines: planning sciences, tourism science and environmental and social psychology. As their project input, the planning sciences carried out an analysis of the conflict lines at approval, planning and local level of the offshore wind energy, and investigated the impact of offshore wind farm design on the acceptance by the local population. The tourism scientists dedicated themselves to the impact of offshore wind farms on tourism and the local economy. The environmental and social psychologists analysed the local acceptance of offshore wind farms and drew up concepts for achieving improved acceptance and information provision.

24.2 Intensive Surveys

The survey of residents was long and intensive, the standardised questionnaire for all those interviewed consisted of between 210 and 260 questions. It was therefore not surprising that it took over an hour for each person. To avoid selectively choosing the people to be surveyed – such as only using those with a particular interest who had made contact – the interviewers telephoned randomly selected residents. The source used for this was simply the publicly accessible telephone directories, so no confidential data was accessed.

The questionnaires for the second and third waves of the survey were only altered slightly, so that the results from all three points in time could be compared with each other. A new topic introduced into the second survey wave in 2011 was the current one about the nuclear disaster in Fukushima and its impact on people's opinions about electricity generation from such sources as onshore and offshore wind turbines, solar plants, coal and nuclear power plants etc. Residents were also explicitly asked what conditions would have to be met for them to feel fairly treated with regard to the planning and construction of future offshore wind farms.

Only residents who lived on the chosen islands and sections of coast for at least four months of the year were allowed to take part in the survey. It was found that the residents surveyed had lived there on average for 22 years. Almost half the residents who took part (49 %) worked in tourism, whereas the proportion of the sample working in the fish industry (2 %) and wind industry (1 %) was insignificantly small.

Table 24.1 Survey regions and number of participants in the survey waves. © Martin Luther University Halle-Wittenberg 2015

OWP region	1st wave 2009	2nd wave 2011	3rd wave 2012
Borkum/Norderney (Riffgat and Alpha Ventus)	Residents: 109 Tourists: 100 Experts: 12	Residents: 79 Tourists: 110 Experts: 6	Residents: 55 Tourists: 104 Experts: 7
Darss (Baltic 1 and Baltic 2)	Residents: 103 Tourists: 100 Experts: 12	Residents: 78 Tourists: 85 Experts: 7	Residents: 55 Tourists: 103 Experts: 6
Comparison region			
Föhr	Residents: 97 Tourists: 85 Experts: 12	Residents: 72 Tourists: 102 Experts: 8	Residents: 53 Tourists: 100 Experts: 7
Usedom	Residents: 114 Tourists: 100 Experts: 12	Residents: 71 Tourists: 100 Experts: 5	Residents: 50 Tourists: 100 Experts: 9

Some 423 residents took part in the first wave of the survey (women 41 %, men 59 %). Their average age was 55. The dropout rate between the first and second waves of the survey was around 29 %. A further 87 people dropped out between the second and third waves, which still left 213 residents to take part in the final part of the survey – corresponding to a total dropout rate between the first and third waves of around 50 %. Among those who dropped out there was no selective shrinkage of "extreme opinions".

24.3 2+2 Comparisons in the North and Baltic Seas

The surveys were carried out in two regions on the German North Sea coast and two regions on the German Baltic coast. To ensure that any changes that might occur were actually due to the construction of offshore wind farms or were independent of this, the researchers always compared two regions: one region with a planned or installed offshore wind farm compared with a region without any plans at all for offshore wind farms.

In the North Sea examples chosen for planned/built wind farms were those off the islands of Borkum and Norderney. The offshore wind farms Alpha Ventus (outside the 12-nautical-mile zone, within Germany's Exclusive Economic Zone) and Riffgat (within the 12-nautical-mile zone, northwest of Borkum) are close to these islands. The cable route runs via Norderney, connecting Alpha Ventus with the mainland. At the time of the first survey Alpha Ventus was already under construction, Riffgat not yet. The island of Föhr in Schleswig-Holstein was chosen as the comparison region in the North Sea where there were no plans for offshore wind farm development. In the Baltic Sea, the Fischland-Darss-Zingst peninsula with the Baltic 1 and Baltic 2 wind farms was selected as the offshore region and the island of Usedom was chosen as the region in the Baltic Sea where there were no plans for any offshore wind farms.

24.4 There Is Support, if …

The most important result first off: there is a prevailing acceptance of offshore wind energy, by coastal residents as well as by tourists and regional experts. The continuous results of the surveys in all regions over a period of three years (2009 to 2012) were on average positive attitudes, though with differences. Acceptance is the greatest when the turbines are erected far from the coast, at a distance of at least 40 kilometres. There is also support as long as the safety of shipping is afforded priority. All in all, tourists had a more positive attitude towards near-shore wind farms than the residents.

In the chosen wind farm regions there was a close relation between the general attitude towards offshore wind energy and towards near-shore and far-shore wind farms. The most frequently expressed accusation, that people are only in favour of wind energy as long as it is not in their back yard, does not apply here.

In general tourists see wind farms in a more positive light than the residents, though with two exceptions: tourists view the impacts on the marine environment and the safety of shipping far more critically.

Offshore wind farms are associated with both positive and negative feelings, but which were hardly pronounced at any points in time during the survey – with the exception of curiosity. On Borkum/Norderney those surveyed were far more curious than those in the Baltic Sea regions. This may be because it is in the nature of things that there is greater inquisitiveness in regions where wind farms have been or are to be built than in regions where there are no plans to build any offshore wind farms. The most frequently given reason for curiosity was the "fascination with the technology". Only on Darss in 2009 were there more negative feelings such as threat and mistrust, though in the following years the positive experiences with Baltic 1 weakened these feelings.

24.5 Safety of Shipping Desired

The possibility of a shipwreck is primarily associated with a fear of oil pollution of the beaches, which could ruin the livelihoods of many a tourist region. As far as the safety of shipping is concerned, in general those surveyed expected a slight impairment due to offshore wind farms (Fig. 24.1). "Slight impairment" in this case means an average value of −0.86 for near-shore wind farms on a given scale of +3 to −3. On the neighbouring islands to Alpha Ventus, Borkum and Norderney, the residents' reservations with regard to shipwrecks were less distinct than on Darss in 2009. They remained stable over the whole survey period, meaning that there was no substantial decrease after the erection of Alpha Ventus. The residents particularly criticised that the distances between the offshore wind farms and the shipping lanes were too small, and that there was not enough attention paid to the "human risk factor" of the passing ships. In the final part of the survey in 2012, almost half of those surveyed (47 %) saw a risk to shipping safety as the "biggest problem".

24.6 Problem Animals: Marine Mammals and Birds

Coastal residents feared that offshore wind turbines would cause a moderate impairment to the living conditions of birds and marine mammals. As far as birds were concerned, near-shore wind farms were seen more critically than those far from shore. Seen over the long term, negative expectations regarding damage to birds even increased on Borkum/Norderney, whereas they decreased on Darss. The survey showed that the residents had fewer concerns about the impacts on fish and inhabitants of the seabed, the so-called benthos. The survey also showed that the presumed "negative environmental impact" of sea cables was considerably less than expected – especially on Darss, where in 2011 it was considerably lower than when surveyed in 2009.

24.7 Landscape, Sense of Home, Quality of Life

Sea view and a view as far as the horizon are two features of coastal life. The overall opinion was that impairment of the coastal panorama and the disturbing effect of light signals were only to be expected from near-shore wind farms. Because of the nearby Riffgat coastal wind farm, this concern was greater on Borkum than on the neighbouring island of Norderney. Taken all together, the fear of "landscape impairment" was greater with regard to near-shore wind farms that those far from the coast. As far as a "sense of home" or the "image of the community" is concerned, the residents considered wind farms far from shore to be almost neutral. On Borkum/Norderney and on Darss there was interestingly even a slight shift in the assessment over

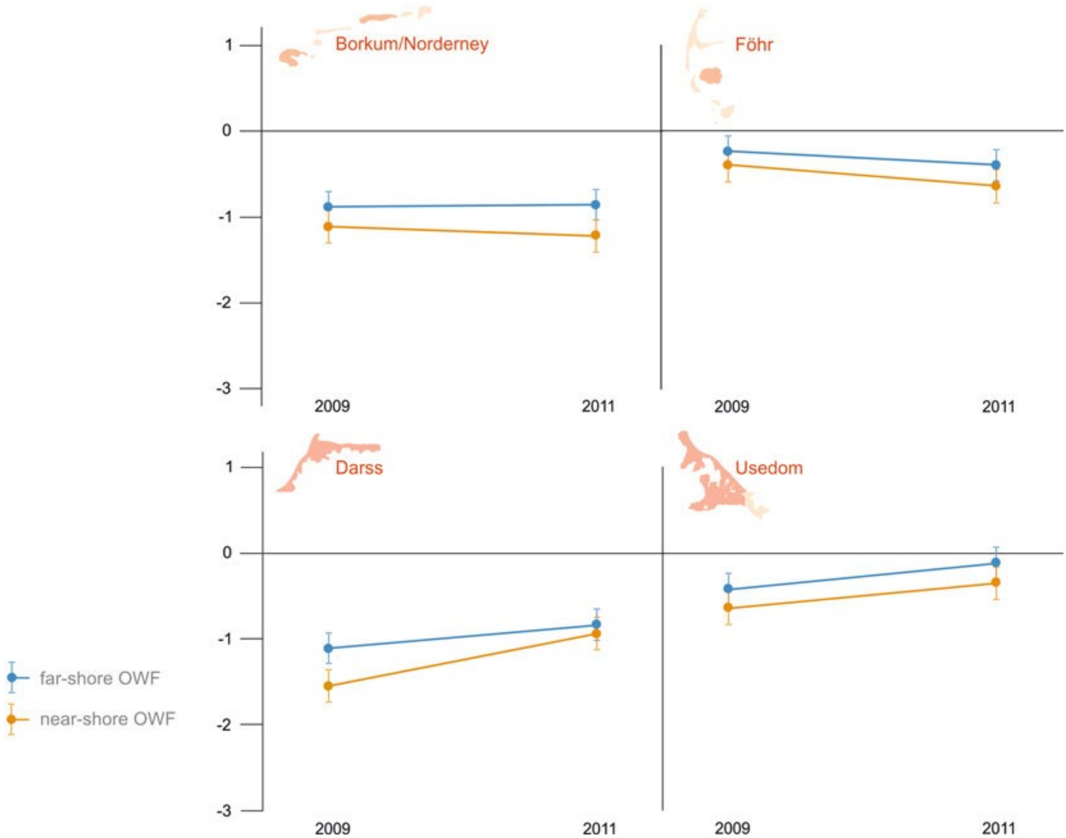


Fig. 24.1 Expected impacts of offshore wind farms on shipping (M ± SEM). This and the other figures only show the first two waves of the survey because there was no significant change between 2011 and 2012. © Martin Luther University Halle-Wittenberg

the course of the years of the survey: from a "foreign body" to a "characteristic feature of the region". This trend was not to be found in the comparison regions, although on Borkum/Norderney there was a slight shift of opinion in the last phase of the survey in 2012 towards "foreign body".

On Borkum the offshore wind farm was associated with more negative impacts on the sense of home than on the neighbouring island of Norderney. As far as the effects of offshore wind farms on sense of home and community image is concerned, there was only a considerable shift of opinion on Darss: those surveyed in 2011 associated the offshore wind farm with a negligible "image enhancement" and a marginal positive sense of home.

With regard to the impact on the marine landscape – the Wattenmeer (North Sea shallows) or the Boddenlandschaft National Park (Baltic Sea) – the evaluation was slightly critical: offshore wind farms were assessed to be "somewhat unsuitable" (average rating –0.76 on a scale of +3 to –3), whereas near-shore wind farms were then again seen slightly more negatively than those far out at sea.

In the beginning the residents rated the impacts of offshore wind farms on their quality of life as marginally negative (average rating –0.39); see Fig. 24.2. Two years later, in 2011, the rating was nearly neutral. Residents' opinion of offshore wind farms far out at sea even became marginally positive and stable over time. The Norderney residents assessed the impact of both near-shore and far-shore wind farms as "marginally positive", whereas the attitudes of the Borkum residents were neutral.

Fig. 24.2 Impacts of offshore wind farms on quality of life (M ± SEM). © Martin Luther University Halle-Wittenberg

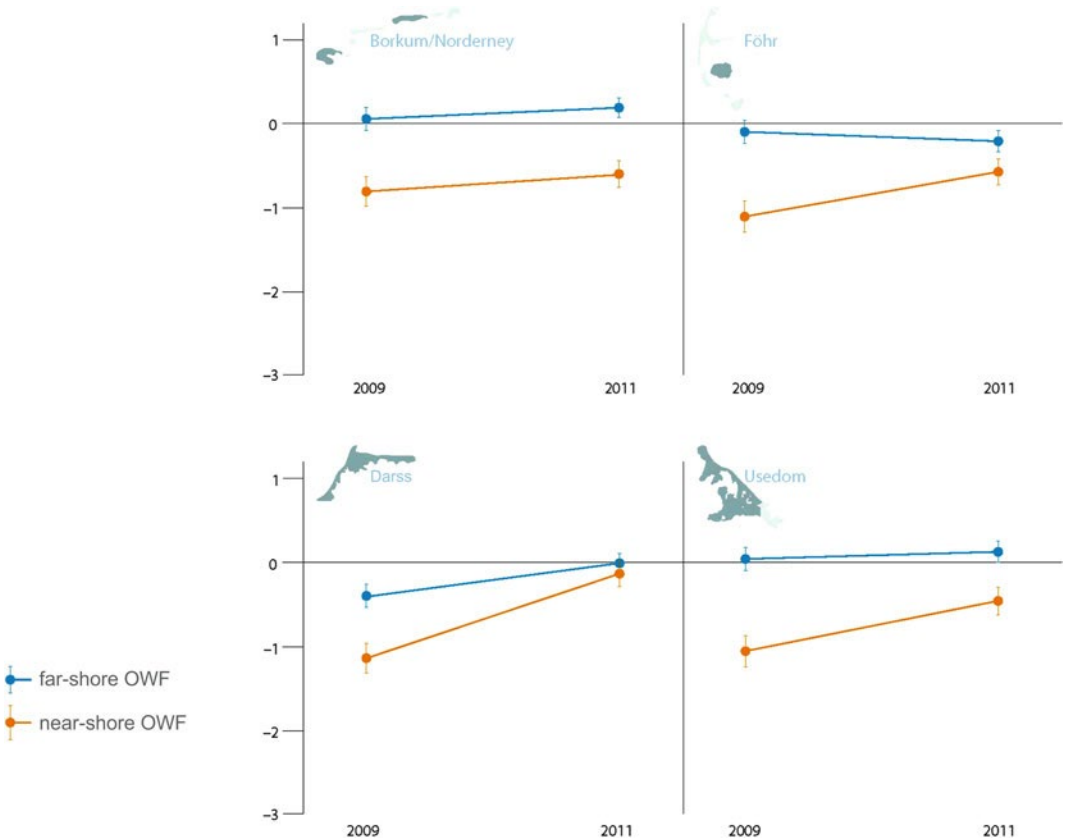
24.8 Reassuring Experiences After Start of Operation

The surveyed residents feared negative impacts of near-shore wind farms on tourism across the board (Fig. 24.3), though this decreased with time. This was however not the case with wind farms far from shore. There was no decrease in holiday bookings on Borkum/Norderney (Alpha Ventus) or on Darss (Baltic 1) during the survey period. On the other hand, hopes that the "offshore wind farm on the doorstep" could become a tourist attraction were not fulfilled: only 15 % of those surveyed were interested in a boat trip to see the offshore wind farm, although 32 % of those surveyed (in 2011) wanted to visit a wind farm information centre on the island.

The construction of offshore wind farms in the regions was often associated with the hope that they would create jobs, slightly more so with regard to far-shore wind farms than those near the coast. After the start of operation of Alpha Ventus and Baltic 1 these positive expectations increased slightly on Borkum/Norderney as well as on Darss.

» **Acceptance requires a common process**
Wind energy has a good reputation as an environmentally friendly source of energy generation, on the coast and also inland. But when there are some changes to the landscape, the planning process and the construction work need acceptance. Acceptance results from a process that has to be designed in unison.
Professor Gundula Hübner, Psychology Department, Martin Luther University Halle-Wittenberg and MSH Medical School Hamburg

The initial slight concerns that property prices would decline as a result of the offshore wind farms continued to decrease. There was greater concern about fears of a negative impact on fishing. These



■ **Fig. 24.3** Expected impact of the offshore wind farms on tourism (M ± SEM). © Martin Luther University Halle-Wittenberg

concerns remained more or less stable after the turbines started operation – only on Darss did they decrease. On the whole, the assessment of the local experts surveyed reflected that there had been "reassuring experiences" after the start of operation of the offshore wind farms.

24.9 Lack of Opportunities for Participation

Both on Borkum/Norderney and Darss the residents and local experts were dissatisfied about the lack of opportunities for participation (■ Fig. 24.4). The vast majority (81 %) said that there had not been any chance of civic participation. The predominant opinion was also that the wind farm planning did not deal with the concerns of the local community and the residents particularly fairly. On Norderney those interviewed considered the planning processes for Alpha Ventus and Riffgat to be quite fair.

There were three residents' workshops in total on Norderney, Borkum and Darss. Everyone who took part in the study was invited. The results of the 1st and 2nd waves of the survey (2009 and 2011) were discussed with them. On several occasions during these residents' workshops and in the survey the citizens made it clear that there was a lack of "more balanced information" from the authorities and the operators, and also a lack of effective participation opportunities in the planning and approval phases.

They especially criticised that the local authorities had no right of action or objection, even though they would be most affected by a shipwreck, by contaminated beaches and a decline in tourism. The desire for direct financial participation in the wind farm by the residents was on the other hand

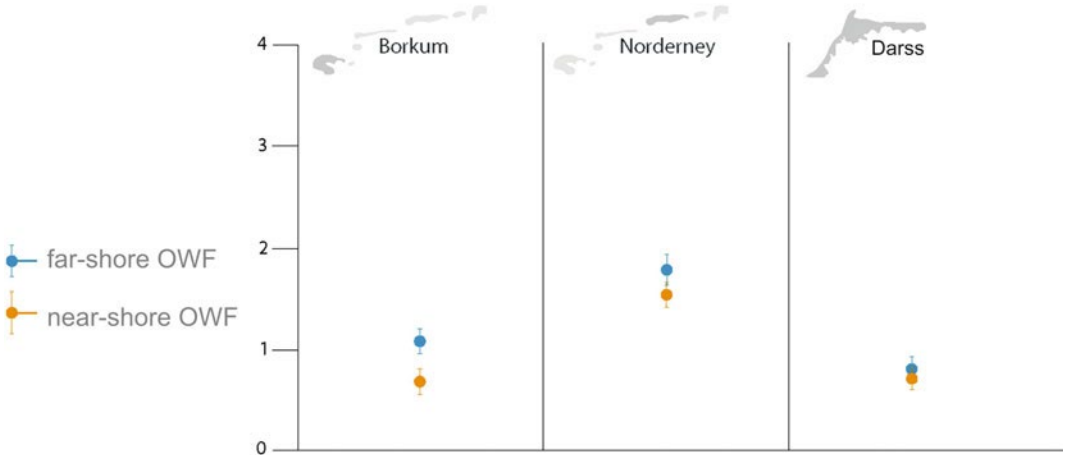


Fig. 24.4 The planning of offshore wind farms has taken the concerns of the local community and the residents into account fairly (M ± SEM). © Martin Luther University Halle-Wittenberg

comparably less distinct. The greatest desires were for local jobs and business tax income for the coastal municipalities.

The workshop participants on Darss in particular had the feeling that the participation opportunities offered were just sham offers (Fig. 24.5). On Borkum the "unconsidered petitions" in the planning process reinforced the mistrust of the authorities. At the same time there were however also positive experiences with the planning process: according to workshop participants the neighbouring community on Norderney was able to achieve some concessions in the planning process for Alpha Ventus and the laying of the cable route.

24.10 World and Values After Fukushima …

The 2011 Fukushima reactor disaster in Japan created a significant moment for thought worldwide, and in Germany it even led to the immediate shutdown of several old nuclear power plants and the reinforcement of the energy transition (Energiewende). Prior to Fukushima, the first survey in 2009 showed that the preferred method of generating electricity was solar panels on individual buildings (average rating of 3.26 on a scale of 0 to 4), wind energy use in general (average value 3.24) and offshore wind farms far out at sea (3.05). Those surveyed were least in favour of nuclear power plants (0.82) and coal power plants (0.70). Nothing changed in this order after Fukushima, although the approval ratings for all renewable energy types increased, the strongest increase for wind energy use in general, solar panels on individual buildings, offshore wind farms far and not visible from the coast, and large-scale solar plants.

In the final survey in 2012 there was just a slight decrease in favour of offshore wind farms far from the coast in the offshore wind farm regions – in contrast to the comparison regions. In the comparison regions without offshore wind farms the favourable opinion remained stable. Those surveyed strongly supported the energy transition in Germany in 2012 (average rating 3.14), in the North Sea regions slightly more than in the Baltic Sea regions.

24.11 Conflict Avoidance and an Increase in Acceptance

In the second wave of the survey in 2011 the residents stated which measures would give them the feeling that they were being treated fairly with regard to the planning, construction and operation of future offshore wind farms. Here there were no clear differences between the regions. The most distinct wish the residents had was that they should get "balanced information" for the planning process (for ex-

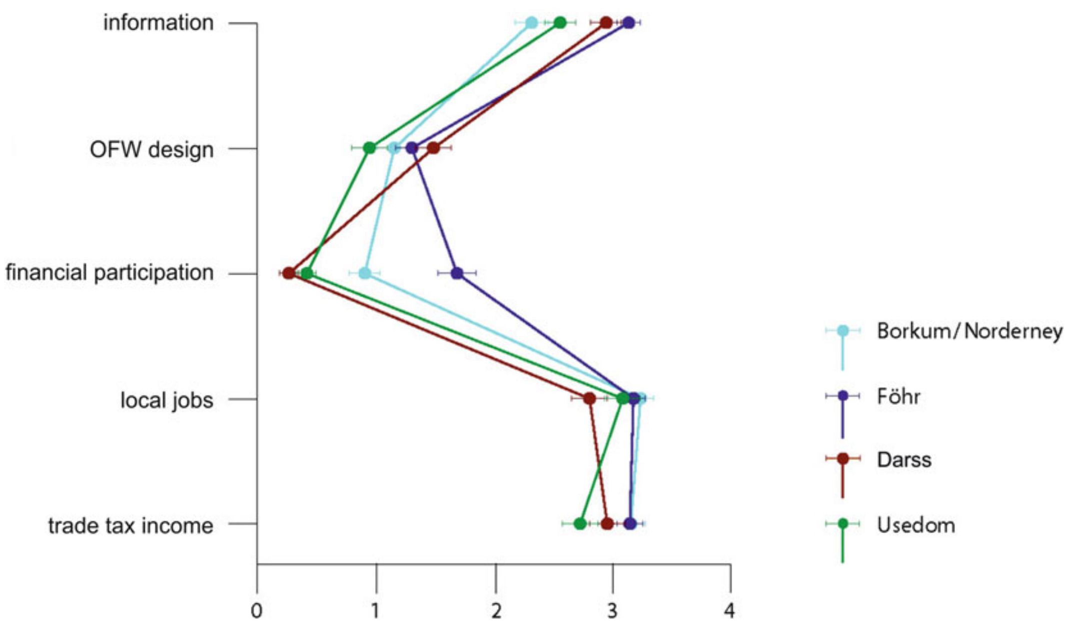


Fig. 24.5 Participation wishes by region (M ± SEM). © Martin Luther University Halle-Wittenberg

ample having events with experts who provide information about the advantages and disadvantages), "active information at the start of planning" from the operators and the authorities, "comprehensible disclosure" of the planning content and the procedural processes through the authorities and also "pointing out planning alternatives".

A continuously updated Internet platform about the wind farm would also contribute to winning acceptance. This wish received somewhat weaker endorsement, but was still rated "medium strength". The content of this permanent Internet presence should provide "continuous information" about the current state of the project, "background information" and "access to view expert opinions and planning documents". But they don't only want passive information; residents and tourists want this Internet platform to give them the possibility of asking the operators and authorities questions – and getting answers from them.

Those surveyed also want that the opinion of "local experts" is taken into account during the preliminary stages of offshore wind farm planning. There was also a distinct desire for "public recognition and appreciation of the residents' willingness to innovate". They also want to have discussions, before and after start of approval and construction, with residents where there are already offshore wind farms, and be able to visit such a wind farm.

24.12 Money Is Not Everything

Here what people wanted most of all was that local businesses would be involved in the construction of the offshore wind farms, and in the maintenance tasks. Part of the business tax from the operation should end up in the coffers of the local municipality. There was hardly any interest in individual shares in the wind farm – as co-owner, so to speak.

24.13 What Do We Do During the Construction and Operational Phases?

During construction residents and tourists particularly want any restrictions of the construction hours for the protection of the marine environment to be adhered to and that mitigation measures are taken to protect against construction noise and loads caused by pollutants. The demand for noise miti-

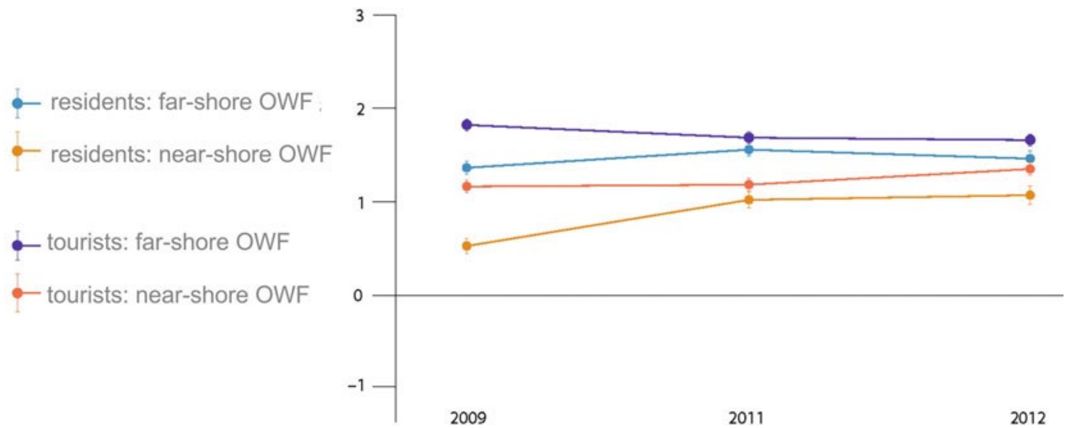


Fig. 24.6 Attitude of the residents and tourists to offshore wind farms (M ± SEM). © Martin Luther University Halle-Wittenberg

gation measures for piledriving and the use of a vibration plough for laying the sea cable were medium strong. Far less pronounced was the wish of those surveyed to be able to take trips out to the offshore wind farm during the construction phase.

24.14 Summary: Participation Processes in Large-Scale Infrastructure Projects

Alpha Ventus is new territory. Also as far as the manner and intensity in which residents, local experts and tourists were surveyed about "their" offshore wind farm in their back yard (Fig. 24.6). Experiences from and in other large-scale infrastructure projects provide reference points for how and with which measures it is possible to successfully design informal participation processes, for example with local information events at an early stage, by including local experts, showing planning alternatives and setting up a continuously updated Internet information platform. At the same time, experiences also show that participation and intensive efforts to obtain a transparent process do not automatically lead to a problem-free procedure or even to consent. Nevertheless, conflicts and public quarrels can be managed far better with participation than without it. This also goes for wind farms supposedly "far off" out at sea.

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Safety

Chapter 25 **When the Nautilus Struggles During a Dive – 229**
Raimund Rolfes, Moritz Fricke, Tanja Grießmann, Text written by Björn Johnsen

Chapter 26 **A Bit too Much Salt of the Earth – 237**
Heiko Hinrichs, Thole Horstmann, Uta Kühne, Monika Mazur, Henry Seifert, Copy edited by Björn Johnsen

Chapter 27 **SOS on Offshore Platform Seven – 247**
Christine Carius, Christoph Jacob, Martin Schultz, Copy edited by Björn Johnsen

When the Nautilus Struggles During a Dive

Development and Use of Sonar Transponders in Offshore Wind Farms

Raimund Rolfes, Moritz Fricke, Tanja Grießmann,
Text written by Björn Johnsen

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Project information: Investigation of Sonar Transponders for Offshore Wind Farms and Technical Integration to an Overall Concept

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Project partners:

- BioConsult SH GmbH & Co.KG
- itap – Institut für technische und angewandte Physik GmbH
- THALES Instruments GmbH
- UL International GmbH (DEWI)

25.1 Finding Solutions for Two Totally Contradictory Goals

We all know the scenario from classic submarine movies: the skipper and his crew are swimming along submerged, periscope down, virtually no visibility, just the "ping-ping" of the sonar to provide some sort of acoustic orientation. Can you imagine a disabled submarine between all the foundations of a wind farm, or several neighbouring wind farms? Probably not a good idea.

It would be better in this case if the wind turbine transmitted a sound signal into the deep to avoid a floundering submarine colliding with the turbine. And it might not be a submarine – it could also be a UUV (unmanned underwater vehicle), a diving robot or mine detector …

The focus of one Alpha Ventus research project was to develop just such a sonar transponder, which when mounted on wind turbines could be located by an "underwater vessel in difficulty" and then transmit acoustic warning signals. The use of sonar transponders is however restricted to emergency situations. Only when a submarine is unable to manoeuvre or surface in the vicinity of a wind farm and transmits signals can the sonar transponder answer with acoustic signals – but not transmit continuously.

It must however be possible to receive these signals clearly even when there are high swells and loud waves – and at the same time not be able to injure noise-sensitive porpoises and seals. These may be two thoroughly contradictory objectives, but the aim was and is to find one solution.

25.2 A Transponder Rarely Comes Alone

The sonar transponder that was developed consists of a control device in a PC housing on land, up to four power amplifiers and up to four sound transducers that are affixed below water to the supporting structure of an offshore wind turbine. Here the development also continued in stages; the first prototype was constructed for just one sound transducer that, under water, covered a maximum angle range of 90 degrees. For Alpha Ventus what was needed was a 180-degree range with a sound level of 200 decibels (dB) at the "source" on the foundation. By altering the geometry of the robust converter housing on the second prototype it was possible to achieve a maximum angle of 120 degrees. At the same time the control device was adapted to allow the connection of up to four sound transducers. This means it could significantly exceed the required "beam area" or angle of 180 degrees. The up to four sound transducers could be employed next to one another with software specially designed for this application. They change the received acoustic signals into electrical signals and vice versa.

The sound transducers can be attached to the foundation pointing in different directions (Fig. 25.1), whereby it is therefore also possible to cover the "round corners" in the wind farm or special turbine installation arrangements.

The sonar transponder automatically monitors its function, in particular its operating voltage, the plug connectors to the sound transducers, the software activity and the receiving level.

That's done and dusted. While the first laboratory prototype was attached to the prepared foundations of a turbine (AV10) on land, divers subsequently attached the performance-extended sonar transponder Wisi TH 1 onto the foundations of an offshore wind turbine. So both are workable; they can either be fitted on land or subsequently attached in deep water. Total preparation on land carries the

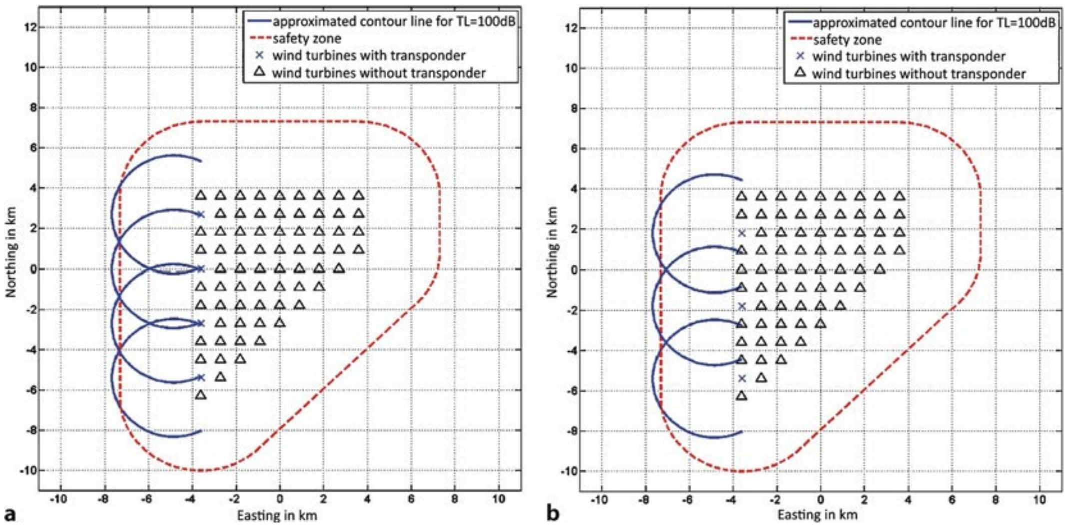

Fig. 25.1 Example of the arrangement of the sonar transponder on the straight edge of a wind farm; transponder distance 1.5 sea miles (**a**) and 2.0 sea miles (**b**). © LUH

risk that the sonar transponder could be damaged during piledriving operations out at sea. A subsequent full installation of the sonar transponder under water however also involves a great deal of work. So it turned out that the best solution was a compromise – extensive preparation on land, such as the attachment of mountings for the sound transducers and the connecting cables, and the finishing work taking place underwater after the piledriving has been completed – using divers to protect the sensitive sensors.

Peripheral Anecdote (I): The final decision is with Fleet Command

The rules are not made for the "defence of the realm". The functional specifications for the "acoustic identification of artificial underwater hazards" are the responsibility of the Federal Armed Forces' Underwater Acoustics and Geophysics Research Institute (FWG) as a matter of principle. Consultation with the German Navy, or with the Military District Administration North to be exact, resulted in slight alterations to the functional specifications for sonar transponders. Whether a sonar transponder has to be installed every four sea miles along the fringes of an offshore wind farm is a decision that is made on a case-by-case assessment by Fleet Command. Unlike the specifications of the FWG, there is no automatic activation of the special transponder via radio – which was originally prescribed for sailing at periscope depth.

Björn Johnsen

25.3 Between Sea and PC: Sound Absorbers and Simulations

Here again a simulation model was designed and compared with measurements taken on site. The calculation model describes the underwater sound propagation close by and far away from the source – on the foundation of a wind turbine – with all their particularities. So in the direct proximity to the "sound source", i. e. the sonar transponder, the sound is rather reflected or bent, for example due to the neighbouring foundation struts. At greater distances, on the other hand, refraction and absorption effects occur. The sound is then "swallowed". To reproduce the sound transducer on the foundation construction the simulation used a two-metre section of the foundation.

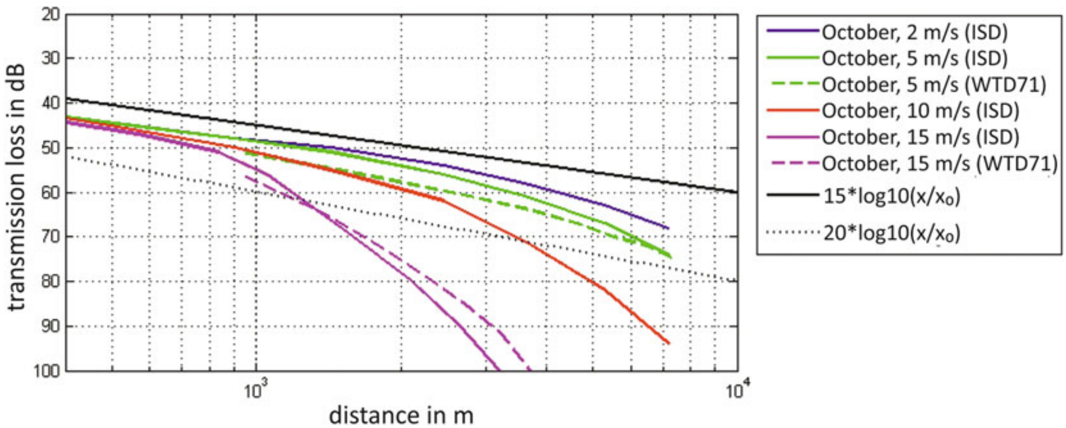

Fig. 25.2 Comparison of simulated transmission losses for different wind speeds. © LUH

The simulation results for the use in Alpha Ventus demonstrate a high level of consistency with earlier work and the specifications from the FWG. The distribution of transponder signals is heavily dependent on wind speed (Fig. 25.2) and wave height. The stronger they are, the more difficult it is to locate the signal. In other words, the stronger and louder the wind and waves are, the poorer the signal transmission and consequently the weaker the signal received.

For a secure identification of the transponder signal at a distance of two sea miles (almost four kilometres) in such unfavourable weather conditions a level of 200 decibels (dB) at the "start source" is indispensable.

25.4 Good Weather Is Something Else – Measurements at Sea State 4

In order to examine all the theories, two measuring campaigns were carried out at sea, in good weather in October 2010 with wind force 3–4 BFT and sea state 2, and in bad weather in February 2011, with wind force 5–6 BFT and sea state 4, where the wave height can reach 2 metres and the wave length 28 metres.

The sonar transponder signals were measured with two hydrophones each at depths of 5, 10, 15 and 20 metres, as well as a measuring buoy at a distance of 450 metres from the wind turbine. Here it was possible to measure the sound transducer with regard to direction, distribution loss and receiving sensitivity (Figs. 25.3 and 25.4).

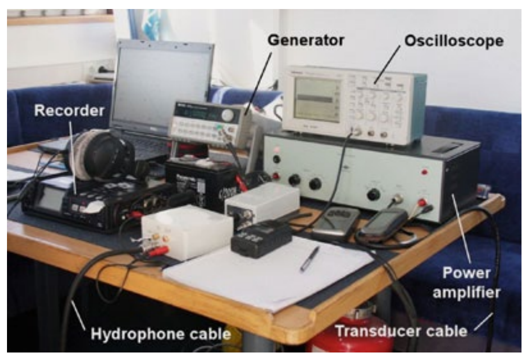

Fig. 25.3 Offshore measuring campaign: measuring instruments on board MS Emswind. © LUH

The two measuring campaigns exhibited clear conformity with the simulation results. They confirm that there is a significantly stronger attenuation of the signal as of a distance of more than two kilometres, thus limiting its range, even though the researchers were no longer able to carry out the measurements at the required "critical" conditions, with a wind speed of 15 metres per second. For this the validated values based on the measurements were then projected. The conclusion is that there is no alternative to a source level of 200 dB on the foundation if the signal is still to be heard at a considerable distance with a heavy sea state. The measurements

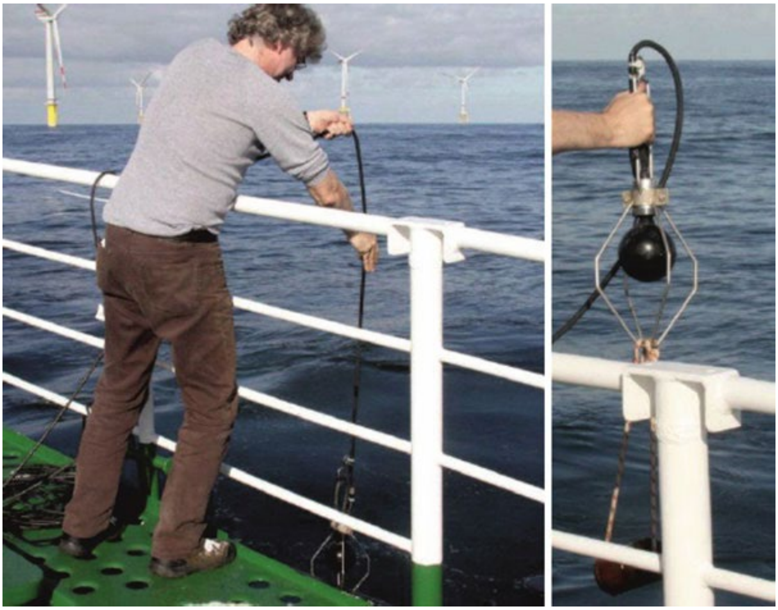

Fig. 25.4 An emitter transducer with ballast weight is lowered into the water from the ship. With this device the sonar transponders can be activated from different distances. © LUH

also showed that sonar transponders transmitting simultaneously do not overlap or negatively influence one another – the temporal and geometrical differences between the sound waves are still too great. At other wind farm locations, different water depths and seabed quality can of course result in a different sound distribution than that at Alpha Ventus.

Peripheral Anecdote (II): Sonar Latinum in Mare Germanicum

Before the invention was the language. In antiquity the Romans did not of course know anything about transponders. And yet the term is made up of two Latin words, transmittere (= transmit) and respondere (= respond). So in the offshore wind farms sonar transponders are being employed in the Mare Germanicum, as the North Sea was known in Roman times. Which, historically speaking, is however not completely accurate. The oldest name for the North Sea actually comes from the Greek, from Ptolemy's map of the world in the second century AD, Germanikos Okeanos. The ancient Greek term for a sonar transponder is not known.
Björn Johnsen

25.5 The Fundamental Question on Alpha Ventus: What Do You Think About the Eco Assessment?

How do the sonar transponder's warning signals affect sea mammals, in particular porpoises and seals? In addition to the noise of the piledriving when the turbines are erected and the operating noise this is one of the three important noise issues for Alpha Ventus – and possibly one of the most crucial questions regarding the wind farm.

The porpoise is the only type of whale that is native to German waters. Grey seals and their breeding and nursing grounds are only to be found on a few islands and sandbanks in the Wadden Sea and not near Alpha Ventus. Germany's most common seal type is the common seal, though in the vicinity of Alpha Ventus you are more likely to see porpoises than common seals.

Sound is absolutely vital for porpoises and seals. It is necessary for orientation and communication, for discovering information about the immediate vicinity, such as the wave movements, distance to the coast or the proximity of predators and prey. Sound is distributed about four and a half times as fast underwater as in the air, so noise reaches porpoises and their friends considerably faster. The sense of hearing of many marine mammals is very well developed, because good visibility is limited at sea and in deeper layers of water the lack of light incidence means there is no visibility at all.

So how does this fit in with the sonar transponders on offshore turbines? The chosen types of sonar transponder only produce signals once they have been activated, and in a very tight frequency range between 7 and 8 kHz. Multiple short sine tones are played, each of which lasts about one second. Including pauses the signal lasts about five minutes. The duration and repetition rate of the signals can be changed by reprogramming. The sonar transponders have – like the devices used for scaring off marine mammals – a relatively narrow range in the medium frequency, can be plainly heard, and are clearly different from many other low-frequency sound sources such as ships' engines or offshore wind turbines in operation.

25.6 The "Seal Bell" Rings for Dinner at the Fishing Net

In the fishing industry, pulsed sound signals have long been used for the protection of seals and porpoises, with "pingers" to warn small whales of the nets. The animals are not able to recognise nets at more than a few metres. "Seal scarers" work similarly, and are designed to protect aquacultures and fish farms from seals using regionally increasing sound volumes. The effect is controversial. Some scientific findings report a habituation and dinner bell effect; instead of being scared out of the area, some seals, which have become used to the seal scarer, feel they are literally being invited to a fish dinner at the net …

25.7 Short-Term Danger at the Foundation

Unlike this fish industry warning system, the sonar transponder is only to be used for a short time, and as an emergency system for disabled submarine vessels. But even short sound events can cause temporary or permanent hearing threshold shifts in porpoises and seals. The scientists see the limit as 179 dB (decibels) – which is under the maximum transponder value of 200 dB directly at the foundation. Hearing damage cannot be excluded in the event that porpoises swim right next to the foundation and the sonar transponder starts to sound – and the porpoises stay right next to the offshore foundation for some time. The device does however have a four-stage soft start, so it does not start to transmit with the full 200 dB. Researchers therefore conclude that the marine mammals will leave the area as soon as they hear the slow start, so that there will be no hearing threshold injury to seals or porpoises.

25.8 Perfectly Normal Behaviour: Scarper, Stress, Avoid

Since the signals for the porpoises and seals will be audible over a wide radius they will not cause any hearing damage, but they could lead to a change in the animals' behaviour. Studies on how porpoises react to seal scarers suggest that they leave the transmission area up to a radius of around seven kilometres, the so-called deterrent area. They expect significant changes such as faster swimming behaviour in a radius of up to 10 km from the signal source. With two and four kilometres, for seals these ranges are significantly smaller (◘ Table 25.1). Once the signal tone has been switched off – programmed standard is after five minutes – it is possible that they will return.

25.9 Recommendations, for Others Also

Whenever there is a "submarine emergency", the sonar transponder must work. Pure function tests should only be carried out when porpoises are not normally giving birth or nursing their young. And the sonar transponders must of course be switched off when divers are carrying out maintenance work on the supporting structures of a wind turbine.

Because it is possible to connect up to four sound transducers it is possible to also cover the very rounded corners of an offshore wind farm.

Table 25.1 Estimation of the distances at which porpoises and seals are expected to be affected by sonar transponders, based on measurements. © LUH

	TTS* Good weather conditions	Deterrent zone Good weather conditions	Noticeable changes in behaviour Good weather conditions	Slight changes in behaviour Good weather conditions
Porpoise	A few metres Unlikely, but not ruled out	Up to 7 km (130 dB re 1μPa)	Up to 10 km (124 dB re 1μPa)	Up to 12 km (< 119 dB re 1μPa)
Seal	A few metres Unlikely, but not ruled out	Up to 2 km (142 dB re 1μPa)	Up to 4 km (136 dB re 1μPa)	Up to 6 km (133 dB re 1μPa)

TTS Temporary Threshold Shift (from absolute threshold of hearing)
Source: Final report on the research project "Investigation of Sonar Transponders for Offshore Wind Farms and Technical Integration to an Overall Concept"

Because the sonar transponders are only rarely activated and because of their four-stage soft starts, no significant impact on marine mammals is to be expected. If however sonar transponders, other than planned, are permanently or regularly in use, that would be a very different matter, and would require a biological reassessment.

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A Bit too Much Salt of the Earth

Environmental Influences on Offshore Wind Turbines

Heiko Hinrichs, Thole Horstmann, Uta Kühne, Monika Mazur, Henry Seifert, Copy edited by Björn Johnsen

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- IMARE – Institute for Marine Resources GmbH
- MPA – Bremen Institute for Materials Testing
- Projekt GmbH
- Senvion GmbH
- UL International GmbH (DEWI)

Salty, sparkling spume, increased humidity, a tremendous amount of salt in the air, and always these gusts of wind from changing directions, high wind speeds and heavy swells – the environmental conditions the high-technology wind turbines are subjected to in the North Sea are anything but soft. These rough environmental conditions – especially the ever-present salt that can cause rust and degradation in the turbines – but also microorganisms that can act on turbine components such as nacelle, hub and rotor blade are also a topic on Alpha Ventus.

This is why two sub-projects in one section of research were dedicated to determining and analysing the environmental influences on the wind turbines. To this end, the project concentrated not only on a turbine in Alpha Ventus but also included the Fino 1 research platform and a near-shore wind turbine just four kilometres from the coast. As well as the actual measurements, the plan was to invent a detection system that could detect salt deposits earlier and better, and also at least think about improvements to offshore wind turbines in this area.

26.1 Look, Don't Touch

This research project also encompassed the triad of field test, laboratory trial and modelling. First of all the scientific curiosity was focused on small rectangular plates. Finely trimmed and thoroughly cleaned, they each consisted of different metals and composite materials – materials used in and on offshore wind turbines. These small plate material samples were attached to a turbine in Alpha Ventus, on the Fino 1 research platform, and on the aforementioned near-shore wind turbine off the coast of Lower Saxony by Wilhelmshaven – and then left in peace. The aim was to then observe how the grass grows – or in this case, the increase in salt deposits. The material samples on the Alpha Ventus turbine Adwen AD 5-116 (in the wind farm, turbine AV7) were attached to a supporting beam in the nacelle and inside the tower at various heights on all nine platforms in order to detect and measure salt and microbe attacks. So that the results of the long-term state of being left undisturbed in the wind turbine were not influenced by human touch or intervention there were signs near the material samples warning technicians and engineers to keep their HANDS OFF! (▫ Fig. 26.1)

26.2 Metal Plates Hung up Like Towels – to Rust

Various material samples were attached to the Fino 1 research platform near Alpha Ventus in 2013. In order to investigate the real offshore environmental influence on different materials the metal and composite samples were hung out on the railing and at different heights on the met mast (▫ Fig. 26.2). They were hung out like towels to dry – only in this case, to rust.

26.3 The Bremerhaven Salt Chamber

Watching is good, measuring is better. With most material samples it is probably possible to detect any surface changes with the naked eye after they have been hanging on a railing out at sea or in the inside of a wind turbine for a year. But how much

Fig. 26.1 Attachment of the material samples on a supporting beam in the nacelle of AV7. © fk-wind:

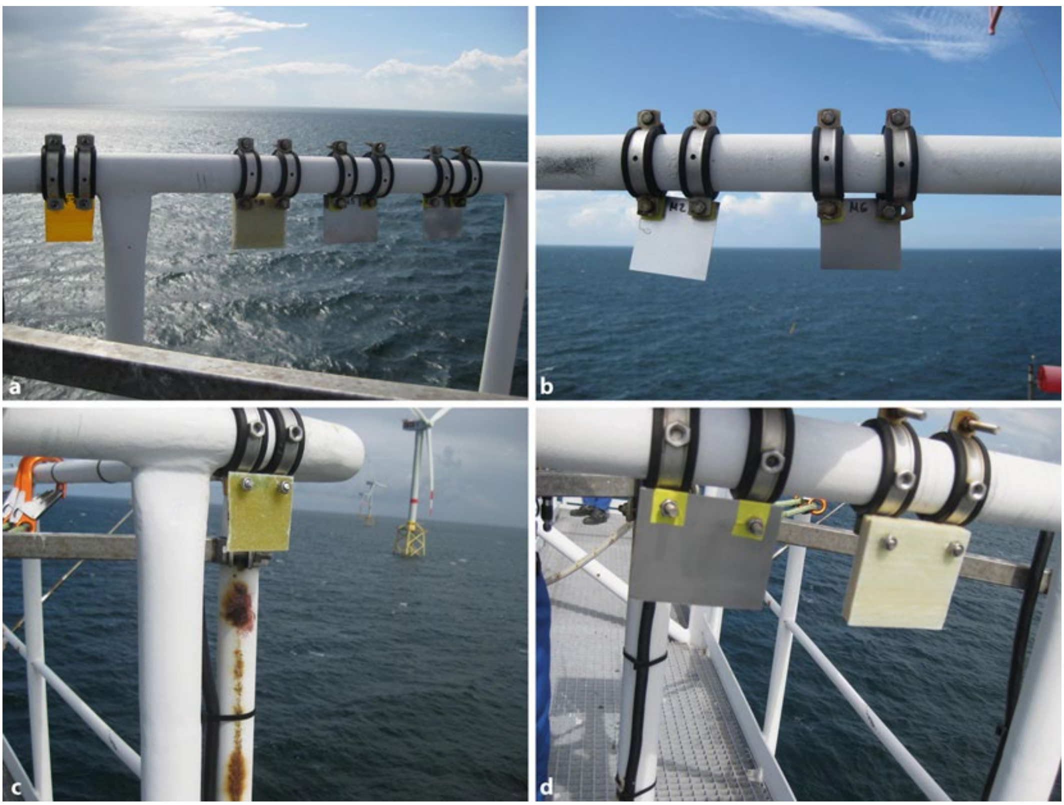


Fig. 26.2a–d Ensemble of material samples (metal plates and fibre composite) on the Fino 1 research platform. © fk-wind:

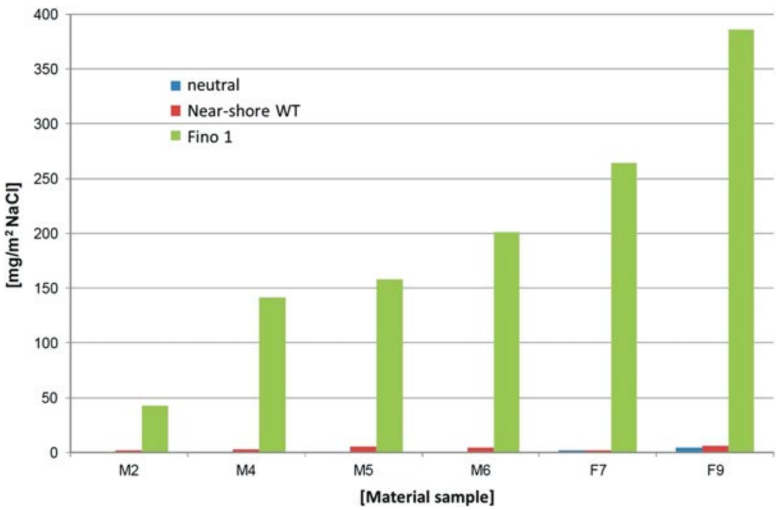


Fig. 26.3 Comparison of salt deposits on material surfaces at different locations. © fk-wind:

have they changed? Ion chromatography was used to accurately determine the amount of salt on the material samples at the Bremerhaven University of Applied Sciences. Each metal plate was rinsed in 10 ml of ionised water, and the liquid samples were then filtered and tested for sodium chloride – a salt that is abundant in seawater.

The result was that the location comparison between Fino 1, the near-shore wind turbine, and "neutral" on land clearly shows that the quantities of salt deposited on the samples from Fino 1 are many times greater than on land and near-shore (Fig. 26.3): depending on the sample up to 25 or 40 times as much. It was also clear that the amount of salt deposited on rough and porous surfaces is greater than that on smoother surfaces. On Fino 1 the aluminium samples changed the least (only 42.3 mg sodium chloride per m^2), in total contrast to stainless steel, steel and iron with values between 141 and 200 mg/m^2. Salt had already begun to be deposited on the fibre composite samples, which have slightly roughened surfaces.

The Fino 1 samples were however subjected to extreme events, the plates hung outside on the railing and exposed to rain, storms and wind without any protection. This can also cause some of the salt deposits to be washed off, so that the actual amount of salt on the surfaces of the plates can at times be greater than is measured at the end.

Corrosion was also detected on the material samples inside the wind turbine in Alpha Ventus, on its platforms next to the air conditioning air-treatment system in the tower (Fig. 26.4). Despite the air conditioning air-treatment system it is still possible for a certain amount of moisture to get into the tower.

26.4 Swab Samples: Please Don't Wipe the Microbes off

The Fino 1 platform, offshore wind turbine AV7 in Alpha Ventus and the near-shore turbine off Wilhelmshaven were swabbed to find signs of microbes. Each of the samples taken were plated onto three different culture media for fungi and bacteria, 'hatched' in an incubator at 25 degrees Celsius and then examined. The near-shore samples showed both fungi and bacteria. As found in previous investigations, this examination once again showed heavy fungal attack of the inside walls of the tower, from the foot of the tower up to heights above 40 metres. The only place where no traces of fungus were found on the tower wall was immediately below the nacelle.

The swab samples from the offshore wind turbine in October 2011 and August 2014 showed no active microbe infestation. Of the intermediate swab samples taken in November 2012, four samples showed some small to moderate microbe attack, whereas all the other swab samples were virtually sterile.

Of the samples taken on Fino 1 only one sample showed any signs of microbes, one fungus and

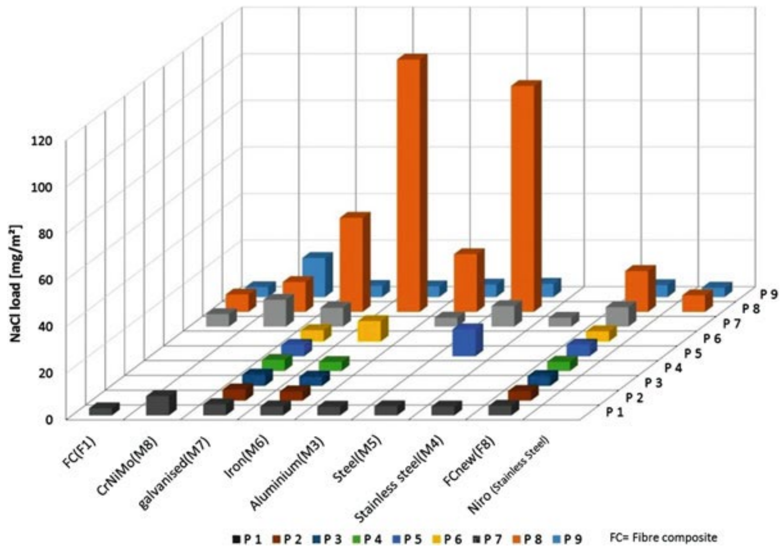


Fig. 26.4 Salt deposits in offshore wind turbine AV7 with regard to material and height inside the tower. The material samples were attached at different working heights of the tower (Platforms P1–P9). © fk-wind:

one bacterium. Here all the other samples were also virtually sterile in this regard. The isolated case of a bacterium was found on a stainless-steel cable duct at a height of 20 metres. Nothing was found on any of the other levels, and especially nothing at great heights. This suggests that there is only a small number of microorganisms at greater heights in the atmosphere, and when they do exist they could possibly be "newly settled" microorganisms that do not stay on the smooth surfaces of the mast structures because of the harsh environmental conditions, the wind, rain and wave action.

26.5 Temperature and Humidity in the Rotor Blade

A temperature and humidity data collection sensor was attached inside the rotor blade of the near-shore turbine near Achtermeer. Two additional data loggers were also mounted in the nacelle and the hub of turbine AV7 in Alpha Ventus to measure temperature and humidity.

The values from the near-shore wind turbine showed that there is a strong link between temperature and moisture content in the rotor blade. If the temperature drops the moisture content frequently rises. The humidity inside the blade varies between 35 and as much as 97 %. This marked temperature–humidity ratio offers ideal living conditions for microorganisms. These are not just harmful for foodstuffs or humans, but can also damage coatings and metals. The phenomenon of corrosion caused by microorganisms is already known from oil platforms and could also be important for offshore and near-shore wind turbines. The inside of the rotor blade is not protected against moisture penetration and consequently not against microorganisms, so increased damp permeation can also lead to greater material fatigue.

Peripheral Anecdote (I): A mechanical life of its own

It is a well-known fact that man and machine each has a life of its own. The original idea was to install a measuring sensor for the temperature and humidity logger directly in the rotor blade of an offshore wind turbine. This was unfortunately not possible due to time constraints; the blade had already been finished. So the data logger was placed in the hub, in blade proximity as it were. Said, done and checked. Although it was checked once again before it was fitted, the data logger in the hub was not able to switch into measuring mode during the runtime of the experiment. This was due to a spontaneous physical instrument defect.
Björn Johnsen

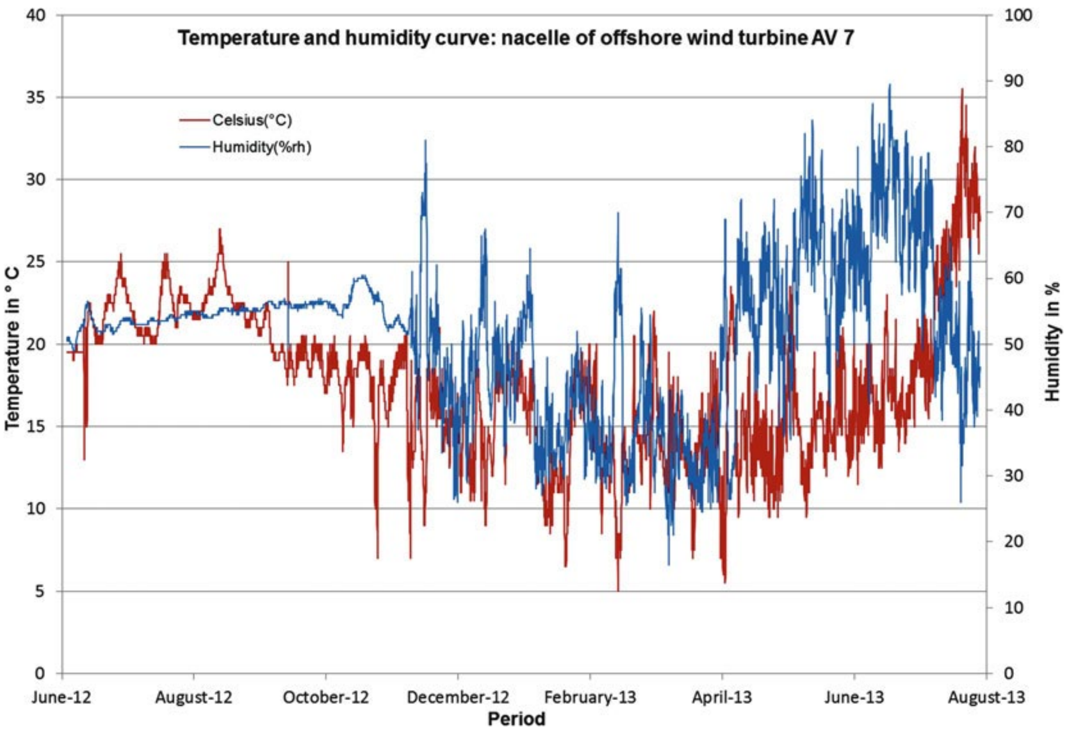


Fig. 26.5 Temperature and humidity curve in the nacelle of the Adwen AD 5-116. © fk-wind:

26.6 Temperature and Humidity in the Nacelle

A similar tendency – increase of humidity as temperature drops – was also observed in the nacelle examined in the offshore wind turbine (AV7) on Alpha Ventus (Fig. 26.5). Here the humidity fluctuated over the whole year between 16.5 and 86.5 %. These pronounced fluctuations are dependent on the seasons and the daytime and night-time rhythms. The temperature fluctuations in the nacelle are also influenced by the waste heat from the drive train and other components. The interrelationships require further research, especially in the nacelle.

26.7 On the Trail of the Salt: The Detective that Never Slept

A mobile, self-sufficient "detective system" was developed for the project for detecting and measuring salt deposits on material surfaces. A laser beam lights up the surface and a camera photographs the reflection of the laser beam. The laser light is scattered back along different paths due to the rough surface, creating what is known as a speckled effect. The photograph of this different pattern makes it possible to recognise changes and deposits on the surface in sub-micrometre range, even under one µ – in other words in an order of magnitude of under a thousandth of a millimetre.

The change in the surface was compared with the previous image with the aid of the cross-correlation coefficients. For lab tests and "salt rearing", for example, a surface was vaporised with salt water (with a salt content of 35 g/l – equal to that of the North Sea) from an ultrasonic nebuliser to simulate the situation in the wind turbines. After successful lab tests the de-

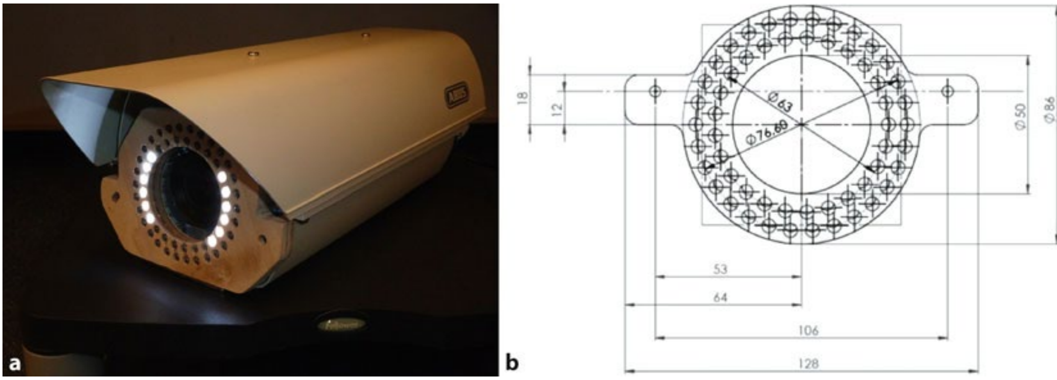


Fig. 26.6 Camera casing with LED ring light (**a**), Technical drawing of the LED arrangement (**b**). © Fraunhofer IWES (Photos: Monika Mazur)

tective system was able to stand the test of taking the first measurements in an operational wind turbine.

Peripheral Anecdote (II): Gearbox damage was faster than the oil sample

Oh, what joy to have not one but two near-shore wind turbines for your comparative tests. Oh, yes? The researchers could only install one temperature–humidity data logger in the rotor blade of a turbine near Achtermeer, because for technical reasons it was not possible to do the same in the foreseen neighbouring machine off Wilhelmshaven. And oil samples were also to be taken from both turbines to check them for salt content. Since the newer of the two turbines had a special moisture separation system the oil sample from a "conventional" turbine without such a system would be more interesting. The scientists had already procured an oil pump for taking their sample, but the wind turbine beat them to it – by breaking down. Gear damage and its subsequent repair meant that it was no longer possible to take an oil sample in 2013.
Björn Johnsen

26.8 Automatic Measurement of Salt Deposits

In the second sub-project the aim was to measure the salt deposits that occurred using a specially designed, special-purpose camera model that used white light – as a sort of "on-site measuring system". You'll not find this model in a camera shop, and certainly not "off the shelf" – this automatic camera detection system for salt and other deposits in the offshore environment, which also had an optimised lens for day and night photography, still had to be invented.

The engineers used a model that can photograph the motif or model from a distance of 13 centimetres with a focal length of 16 mm. With a maximum focal length of 50 mm the lens is relatively short – which of course allows great flexibility of installation in various locations within an offshore wind turbine. The camera housing that was to be constructed should have enough space for all the components, and also be compact and protected against environmental influences. It should have anti-reflection and filter features, a power supply connection and heating, all in the casing. One thing was obvious from the outset: the camera would be no beauty, but it would be highly individual.

To provide good lighting for the images a light ring of white LEDs was constructed around the lens (Fig. 26.6). The parallel connection of all the LEDs should guarantee a good light source for all the photos even if individual LED lamps failed.

As far as hardware connection is concerned, the camera has a connection to a multifunction data logger which has four digital temperature sensors and one humidity and temperature sensor for measuring and monitoring the temperature and humidity at the recording location in the offshore wind turbine.

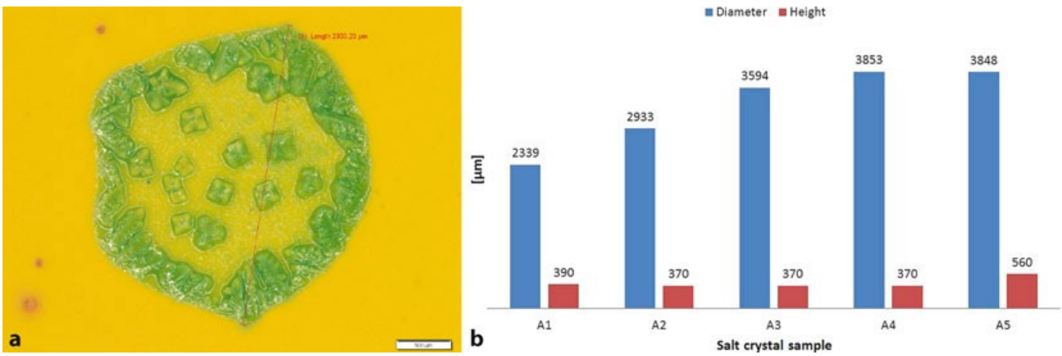


Fig. 26.7 Offshore varnish test series: contrasted salt crystal (**a**) and results expressed as a bar chart (**b**). © Fraunhofer IWES (Photo: Monika Mazur)

26.9 Rearing Salt Crystals in the Lab

In further laboratory experiments an attempt was made to artificially create salt deposits using an air compressor and porous aeration stones that had been dipped in saltwater. The air forced in under pressure and air bubbles bursting on the surface of the water generated the desired cloud of salt spray, which was thus sprayed onto the specimen material. The height and diameter of the crystals so generated were recorded accurately under the microscope. The plan was to continuously expand and enlarge the salt deposits through subsequent additional spraying in saline mist. But despite increased salt spraying there was no constant growth of the salt crystals (Fig. 26.7, designated "A1–A5" in the bar chart). This initially appears to speak for the protective coating used offshore. In other test series the salt crystals only grew indiscriminately and sporadically, not constantly.

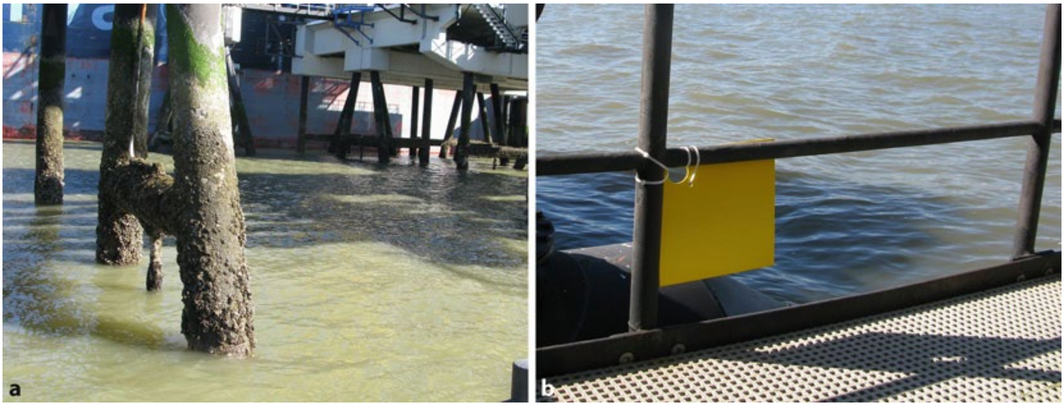
26.10 Rendezvous at the Old Oil Pier

In addition to the lab salt rearing there was also a field test using material specimens on site, in this case in the salty harbour water by a loading dock near Wilhelmshaven. This pier foundation was very suitable for attaching material specimens and for alternative, supplementary experiments to those carried out on the Fino 1 research platform, because being on land it was easy and cheap to access while still being near the sea. The foundation of this loading pier was covered with marine growth and was covered in salt deposits in the spray water zone. There were also plenty of external influences resulting from shipping and other environmental influences in the shape of weathering and wear of the existing work material by structures, lifeboats and cranes.

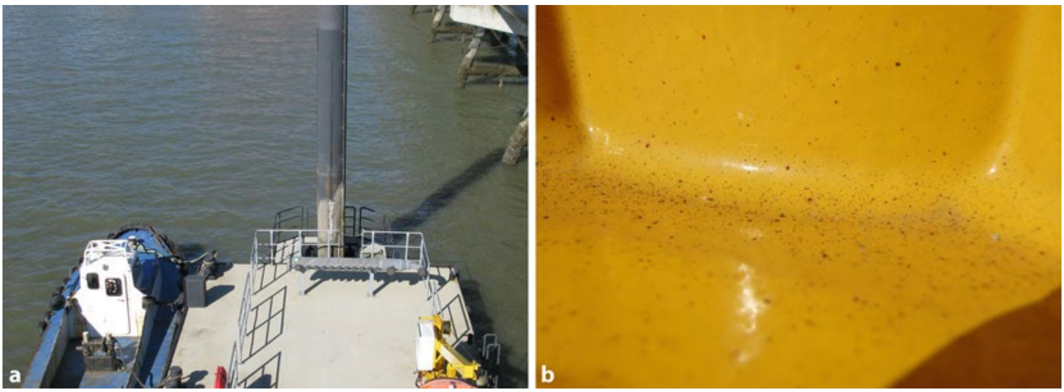
» **We are seeking the weak points**

The evaluation of the salt deposits on nacelle, hub and rotor blade has not yet been completed. It will make important statements about where the weak points of an offshore wind turbine are to be found. And it will be just as important, taking into account the temperature and moisture measurements, especially in the nacelle and the rotor blade, to develop a monitoring system that makes it possible to manage these environmental influences and their consequences.

Uta Kühne, fk-wind: Bremerhaven University of Applied Sciences © fk-wind:



■ **Fig. 26.8** View of the test location (**a**) and a sample plate (**b**). © Fraunhofer IWES (Photos: Peter Rohde)



■ **Fig. 26.9** Platform on the test location (**a**), Close-up of flash rust on the crane boom (**b**). © Fraunhofer IWES (Photos: Peter Rohde)

Material samples were, like on Fino 1, more or less hung out on the railing of the loading pier (■ Fig. 26.8) and examined for salt deposits at regular intervals using a digital USB microscope. Changes were visible under the microscope, but were uneven and superficial. Fields of salt crystal developed on some surfaces, but they were not found on subsequent inspection. The reason for this was the storms in November and December 2013. The salt deposits were simply washed off the sample material by the heavy rain.

The difficult of accessing offshore platforms on the high seas proved to be an obstacle for some of the project work, as well as posing a risk in realising the project work. The scientists therefore suggested that this industrial location, which had been in use for over 25 years, be included in the field trial measurement programme (■ Fig. 26.9). This could enable a "near-sea" comparison of "young" and "mature" material samples.

26.11 Outlook

The evaluation of salt deposits on the important connection points – tower–nacelle, blade–hub and hub–nacelle – still has not been completed – nor has the full evaluation of other material samples from important component material like glass-fibre-reinforced plastic, stainless steel and galvanised steel.

With the exception of one measurement at a height of 30 metres on the Fino 1 platform, the measured salt content increased. It can be assumed that these crystalline salt deposits on the surfaces have something to do with "oversaturation" through moist air, and being a growing, compact layer it cannot then be so easily washed off by the rain. With increasing wind speed, and with the wind as "carrier" of the moist, salty air, the salt grows on the turbines faster and becomes more compact and more firmly bonded. And their surface structure also plays a role – more salt is to be found on iron and steel than on smooth aluminium. There must not be any misconception that heavy rain will easily wash the salt away – quite the opposite. The veritable bombardment with rain containing solid salt crystals in the moist air can lead to devastating corrosion damage, even to corrosion-resistant steel and non-ferrous metals.

It is also a fact that salt grows faster than one might think, even in the "protected" inside of an offshore turbine. Even when it cannot be seen with the naked eye, it is already causing rust and corrosion on the exposed materials. Salt depositing could also be important for near-shore turbines. The development of two different salt deposit detector systems – laser based and white light based – were successfully tested, and there is still a basic need to better understand and characterise the dynamics of salt formation from sea spray. Image analysis can contribute to detecting salt precipitation and the behaviour of materials and component samples under the influence of offshore climatic conditions. The data from the temperature–humidity curves in the rotor blades and those determined by the salt detection system were passed on to the wind turbine control and monitoring facilities, where they can help in offshore wind turbine monitoring. Fibre-reinforced composites are also damaged by erosion in that absorption of moisture reduced the fatigue resistance of the material. In short, the salt of the sea and the microbial attacks show that there is great potential for research here – and potential for possible solutions.

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SOS on Offshore Platform Seven

What a Telemedical Emergency Concept Might Look Like – and How it Could Even Help in Sparsely Populated Regions

Christine Carius, Christoph Jacob, Martin Schultz,
Copy edited by Björn Johnsen

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- EWE Vertrieb GmbH

27

In an emergency the installation and maintenance teams in an offshore wind farm are left to their own devices. Who can help them out on the high seas, when no ship can dock in a storm and no helicopter can land? And even when the sea is flat and calm, how long will it take the doctor on call to get there by ship from the nearest port?

What can help quickly here is "telemedical emergency care", an initial diagnosis and instructions from the specialist or emergency doctor on the mainland for the wind farm personnel on site, transmitted by radio or by audio or video line. This is of course assuming that the personnel are "trained amateurs" with sufficient competence and training to be able to provide medical assistance with the doctor's guidance. What this initial telemedical emergency care until the rescue services and a doctor arrive could look like was the subject of a research project, Sea and Offshore Safety – SOS.

27.1 What Has Happened up to Now

Of course there were emergency medical kits before offshore wind farms were built. There were also ones equipped for audio or video transmission, technically reliable and with a defibrillator, a shock producer for cardiopulmonary resuscitation. Only an emergency medical kit with audiovisual equipment and a defibrillator weighs over 12 kilogrammes. They are therefore far too heavy and very difficult to handle. Not exactly the equipment that a trained layperson can use in a hurry when their colleague has difficulty breathing, has been suddenly taken ill or is seriously injured somewhere in the turbine and needs urgent medical assistance.

27.2 In an Emergency: Nothing Works Without Communication …

As well as first aid one thing in particular is needed: communication, and that on a variety of channels. The emergency response officer or the "trained layman with training for emergencies" who is looking after the injured person in the offshore wind turbine speaks with the tele-doctor. He in return assesses the medical condition, pronounces a recommended procedure, and directs and monitors the first aid emergency care from afar (Fig. 27.1). If the injury is very serious, the tele-doctor may have to transfer the case to an emergency physician in a hospital. The personnel in the wind turbine must of course also be able to report the "incident" to the wind farm control centre and request transport. So plenty of communication is required between the players.

Not only existing audiovisual systems for medical emergencies were tested in the conception phase; in collaboration with utility company EWE, one of the Alpha Ventus operators, the Telemedicine Centre of the Berlin Charité hospital (TMCC) has continued to develop a concept for a telemedical emergency care specially for offshore wind turbines. The Clinic for Anaesthesiology at the Charité contributed the emergency medical expertise to the project and studied the associated medical parameters. The SOS research project also included the setting up of an SOS demonstration room for the technology to be used, which was very similar to the real conditions in a wind turbine (Fig. 27.2).

27.3 … And Nothing Works Without Wi-Fi!

The good news is that good patient care is possible on almost all levels of a wind turbine. The bad news is that nothing works without Wi-Fi. Wi-Fi is a prerequisite, and it must have several access points

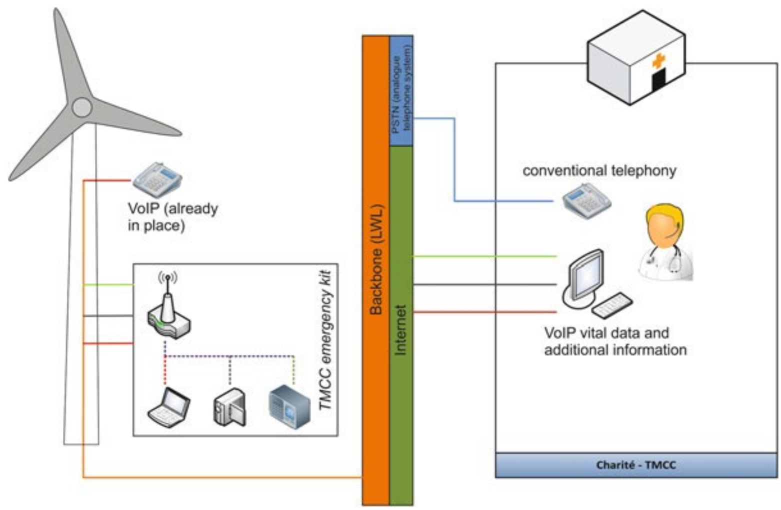

Fig. 27.1 Telemedical communication sequence. © Telemedicine Center Charité

Fig. 27.2 Practical test under real conditions. © Telemedicine Center Charité

within the turbine. Better lighting for camera shots must also be guaranteed, because the lighting conditions inside the tower are not always good enough and the autofocus of conventional telemedical devices still work quite slowly when transmitting images from a dark wind turbine tower.

It is possible to transmit live data, and of course especially medical data like ECG, pulse and blood oxygen levels, from inside the tower. The existing networks are well suited for telemedical use. Directional radio and fibre-optic lines in a wind turbine are also suitable for the transmission of video calls. Project research showed that conventional vital data monitors have proven to be suboptimal; they are too cumbersome for handling in an offshore turbine, too big and not intuitive enough to operate easily. The ergonomics are not good, but instead there are a lot of data fields that are not absolutely necessary. Too many sounds, too many fields – everything is too complicated if one is under time pressure or in shock. These conventional devices also require users to have regular, intensive training. You can forget plug and play.

27.4 Audiovisual System: The Injured Person Feels Safer

Audiovisual systems (Fig. 27.3) for emergency use have advantages and disadvantages. It is certainly advantageous when the headset is comfortable, the images and speech are of high quality and the injured person feels better when a doctor is available. And the doctor also keeps the situation better under control with comparatively little hassle. The communication is more effective because it is not necessary to have to explain everything, and with live streaming it is much quicker to show what to do. But these systems do have disadvantages: the camera angle is too small, and the main thing is that a handheld camera means there is one hand less for looking after the patient. And that has to be more important than operating the camera. In an accident situation this can ultimately lead to concentrating more on the camera monitor and less on treating the injured parts of the body. The "field trials" showed that such a system is too unwieldy, not ergonomic and far too big.

The requirements for the tele-support were therefore: reduce the size of the equipment, reduce the weight, and increase carrying comfort. Operation should be made simpler and more intuitive by reducing the number of functions. Listening and speaking to the emergency doctor (TNA) must of course be possible, also for two paramedics.

There are of course also requirements as far as the emergency tele-doctor is concerned, and for the telemedical centre on shore (Fig. 27.4): it must be possible to have an adapted case file for use in the telemedical centre, and also a live vital data view, including progression chart for the duration of the operation, and a display of the quiescent ECG of the heart functions, as well as having a print function.

Fig. 27.3 Patient monitoring system for collecting vital data (corpuls[3]) with integrated defibrillator. © GS Elektromedizinische Geräte G. Stemple GmbH

Peripheral Anecdote: Project delayed, technical experts gone

The focus of the SOS project was on drawing up a telemedical emergency care concept for offshore wind turbines, developing and technically testing the demonstrator, the "telemedical emergency kit" that was designed. Another thing that was needed was an installed wind farm and scientific personnel suitably qualified for offshore operations. But because the construction of the wind farm was delayed and it was not possible to carry out any offshore trials in autumn and winter because of the weather, the SOS research project was extended until August 2014. The result of this postponement was that back at the Charité hospital in Berlin, the scientific personnel qualified to work offshore had left the SOS project before the last test was carried out. Another problem was that only two years were approved instead of the planned three years. The shortening of the project duration and the delay meant that the content and concept of the SOS project had to be adapted to suit the new circumstances.
Björn Johnsen

27.5 Prototype to Go: The TMBox

The SOS project developed the TMBox as a prototype for use in emergencies on offshore wind turbines, one that could be easily handled in an emer-

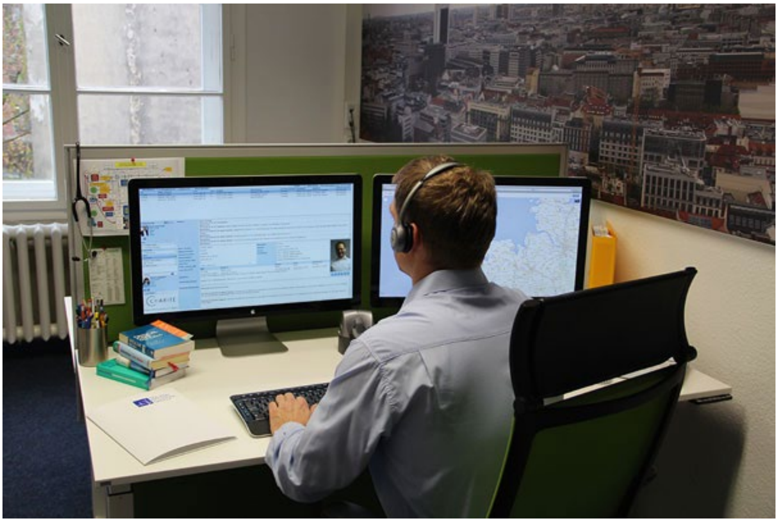

Fig. 27.4 Telemedical workplace. © Telemedicine Center Charité

Fig. 27.5 TMBox prototype (*yellow case in the centre*) and alternative and auxiliary equipment. © Telemedicine Center Charité

gency and that was able to send the casualty's vital data direct from the wind turbine to a telemedical centre via standard IP. It initially encompasses only relevant status information but not any on-screen vital data monitoring. And one very important thing: the one-button operation leaves nine fingers for the injured person. It is possible to integrate audiovisual systems into this TMBox (Fig. 27.5). In the opinion of the Charité, the straightforward operation of the TMBox surpasses currently available emergency systems when it comes to it being handled by laypersons. The system was demonstrated during the closing event.

27.6 In Future an App Instead of an Applicator?

Two field tests of the realisation concept were carried out in Oldenburg and Berlin. These demonstrated that it is quite possible to use a telemedical system on an offshore wind turbine that can also be operated by a layman (Fig. 27.6). This can provide valuable services for someone injured or acutely ill offshore until an emergency doctor or specialist can arrive from the mainland or until a patient transfer is possible by ship or helicopter. The medical issues for both field trials were designed and evaluated by

Fig. 27.6 Emergency: carrying out a simulator study. © Telemedicine Center Charité

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the Clinic for Anaesthesiology and Intensive Care at the Charité.

Maybe in the future it will be possible to find other applications for such a system and/or such a TMBox on land, such as in difficult to access regions in the mountains or sparsely populated stretches of land where the nearest qualified doctor is several hours' drive away.

Sensor technology for telemedicine is also constantly evolving, and there will be an increase of communication units such as smartphones. And who knows, maybe one day the function implemented in the prototype TMBox will be available as a smartphone app, assuming better camera lighting and angles and the appropriate supporting software. This will require developments, certifications and process changes by all those involved.

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