Wind Energy Research in The Netherlands

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Chapter

9

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9.1 INTRODUCTION

Interest in the application of modern wind energy grew in the Netherlands in the 1970s when the limit of fossil fuels became clear. Wind energy has been important source of energy in The Netherlands for centuries and the country was known for the many wooden wind mills especially in the coastal regions. At the same time, research activities in the modern wind energy were started, which have led to the relatively large wind energy research community in the Netherlands today.

Wind energy research activities in the Netherlands are predominantly performed at the Energy research Centre of the Netherlands (ECN) and the Delft University of Technology (DUT). Both institutes are involved in wind energy research since the start of the modern wind turbines, the 1970s. These institutes match their research programs with each other as close as possible. ECN Wind Energy has a research staff of 55 scientists and DUT has a research staff of 15 permanent researchers and more than 35 PhD students. Another institute dedicated to wind energy research is the foundation Knowledge Centre WMC that has been founded by the DUT and ECN in 2003 with an additional research staff of 25 scientists. Although the major part of the wind energy research is concentrated in these institutes, many other universities and scientific institutes contribute to the research with dedicated and specialized research.

The current wind energy research and associated industrial activities are taking place in an international context, mostly the European context, therefore the research activities not only take account of the long term energy research program of the Dutch government, such as the long-term energy research program EOS [1], but also of the R&D priorities defined in the international context, such as the Strategic Research Agenda (SRA) of the wind energy sector [2]. The three wind energy research organizations are well represented in international bodies such as European Wind Energy Association (EWEA), European Academy of Wind Energy (EAWE), International Energy Agency (IEA), International Electrotechnical Commission (IEC), International Network for Harmonised and Recognised Measurements in Wind Energy (MEASNET), European Wind Energy Technology Platform (TPWind) and the European Energy Research Alliance (EERA).

9.2 WIND ENERGY IN THE NETHERLANDS

In the last 20 years, the amount of wind energy has grown at a rate of approximately 30% per year. In Europe, at the end of 2008 a total amount of 64,5 GW wind energy has been installed onshore and 1,5 GW offshore. In the Netherlands, the installed wind energy capacity amounts 1921 MW onshore and 228 MW offshore. During 2009 the Netherlands decommissioned 106 turbines (total capacity 34.8 MW) and installed new turbines totaling 101.4 MW to have a total of 2216MW installed wind power which generated 4% of the national electricity demand. Wind energy has an important role in the extension and replacement of electricity production capacity.

The official target for the Netherlands for the implementation of renewable energy, set in an European context, is 14% in 2020. However, the Netherlands has the ambition to reach the share of renewable energy of 20% in 2020. In order to reach that ambition, the share of renewable electricity generation in the total electricity production should reach 35%. Based on this ambition, the Netherlands has set the target for installed wind energy capacity in 2020 at 4000 MW onshore and 6000 MW offshore.

Currently, the cost of electricity production using onshore wind turbines reaches the cost of fossil Electricity production (6 - 8 €ct/kWh). Offshore, the cost of wind energy electricity production is strongly depending on the complexity of the wind farm, such as distance to the coast, water depth, soil etc. The cost offshore is in the order of 12 - 18 €ct/kWh. However, it is expected that the relatively young offshore wind technology will experience a strong learning curve, leading to significant cost reductions. This is one of the reasons that the Dutch government balances its funding between supporting the implementation and funding further innovation by supporting wind energy research with a focus on the further development of offshore wind energy.

Geographically, the Netherlands has a central position with regards to the North Sea. In the next decades, offshore wind energy will be a significant part of the total wind energy capacity in the countries surrounding the North Sea. The conditions are relatively favorable: the average wind speed is high, the water depths are moderate (20-50m), and there are many harbors to access the farms. In order to realize the ambitious targets, substantial R&D effort is required. The wind energy research program in the Netherlands has therefore been focused on offshore applications since the beginning of the century. Not only because most capacity must be installed offshore, but in addition, the offshore application has the highest challenge in knowledge, technology, reliability, installation and maintenance that is also applicable to onshore applications. The knowledge institutes in the Netherlands active in the field of wind energy are collaborating intensively. The long-term collaboration between the Energy research Centre of the Netherlands ECN and Delft University of Technology DUWIND has led to among others the common foundation Wind turbine Materials and Constructions WMC where blade tests are performed.

In the 1990s, the Netherlands had several wind turbine manufacturers, among which Lagerwey, Nedwind en Windmaster. Although these manufacturers did not develop to large global players, the Netherlands still has significant knowledge in the field of development and manufacturing of wind turbines. Currently, in the Netherlands wind turbines are being developed by for instance XEMC Darwind, 2B-energy, VWEC, Lagerwey Wind, STX-Harakosan and EWT. In addition, the Netherlands has a strongly developed industrial sector in the field of offshore technology, which is heavily involved in the installation of offshore wind energy. The activities range from offshore engineering to the development of installation and maintenance vessels and foundations. Large Dutch players are among others Ballast Nedam, Mamoet van Oord, Heerema, IHC Merwede, Fugro and MSC Gusto. Because of the strong Dutch knowledge position in offshore wind energy by the collaborative applied research activities, the Dutch industry is involved in the Construction of offshore wind farms in The Netherlands, Denmark, Germany and the United Kingdom.

9.3 HISTORIC VIEW TO 1990

The first proposals for producing electricity from wind in The Netherlands date from the 1920s. After some experiments in the 1930s there were more experiments until the 1970s without too much success. Especially in the 1960s, the fossil fuels were cheap and the general idea was that nuclear energy would provide cheap energy for a long time. The Energy research Centre of the Netherlands in that time was called Reactor Centre of the Netherlands (RCN). In 1975 a national committee reported that wind energy is the preferred option for large scale renewable energy, and remarkably, these large numbers would not be installed only onshore, and specifically offshore wind energy in the North Sea should be investigated. A committee guided by RCN had the assignment to define the first Dutch national research program on wind energy.

The first funding of Dutch wind energy research was organized by the National Wind Energy Research Program (NOW) phase in the period 1976-1985 which was followed by the 1986-1990 NOW phase to stimulate technological, economical and environmental research related to wind energy. The intention of these programs was to give The Netherlands a leading role in the development of wind energy given the rich wind history. And indeed, these programs facilitated the development of wind energy as a realistic energy option for the next decades. The 1986-1990 Integral Wind Energy Program (IWP) was intended to initiate the large-scale application of wind energy in the Netherlands and to provide an incentive for the further development of cost-effective wind turbines. In 1990 these programs led to a large involvement of Dutch industry in wind energy research and contributed to the accumulation of wind technology know-how in the Netherlands. Examples are the know-how developed in the field of noise emission reduction, material expertise and fatigue properties that led to significant improvements of wind turbines. However, while The Netherlands significantly invested in wind energy research, the development of large scale wind energy was not realized. The national realization of wind turbines always was far below the targets and also the national industry was largely overtaken by international competition.

In the first phase of the NOW research program the comparison was made between horizontal and vertical axis wind turbines. Technical options were investigated and no choice could be made then. Both options were considered for the exploratory phase and experimental turbines of both types were realized. Although there were no solid arguments to not further develop the vertical axis wind turbine and given that the horizontal axis turbine was the dominant design in the international market, a decision was made to stop the further development of vertical axis wind turbines. In the mean time Polymarin built a floating 15m Darrieus turbine in the Gaasperplas in Amsterdam in the early eighties.

From 1977 to1978 a larger turbine with horizontal axis was designed, the HAT25. The name indicated the rotor diameter of 25m of this turbine. ECN, the National Aerospace Laboratory NLR and Eindhoven university of Technology were responsible for parts of the research program. The 25m HAT (horizontal axis turbine) experimental wind turbine was erected at the site of ECN and the turbine had the typical half concrete, half steel tower. It has been operated by ECN since August 1981 and extensive measurement campaigns have been performed at this turbine. The experiments have been used for validation of codes, testing of control strategies, analyses of load cases etc. Alternative rotors have been installed, such as the FLEXHAT rotor and many more. Some prominent measurements on the 25m HAT turbine are the axial force measurements to verify the computer program PHATAS, which calculates static and dynamic loads in the large wind turbine components and dynamic loads in the large turbine components. These were used to determine excitation and response frequency spectrums for different modes of operation and to determine the fatigue characteristics of the machines by means of the rain flow counting method.

In 1985 a prototype of the advanced 1 MW NEWECS-45 was built and in 1986 a start was made with the experimental wind farm Sexbierum, near the city of Sexbierum in the Netherlands. This wind farm consisted of 18 turbines with rotor diameter of 18m rated at 300kW totaling 5.4MW. Seven towers were installed for meteorological measurements. Especially the wake measurements in this wind farm were unique for that time. Also the effect of the wind farm on the environment, and especially birds, was part of the research, where it was concluded that wind farms do not pose an excessive threat to birds.

In the Netherlands, the research activities on wind energy always did have a large international focus and was based on international cooperation. Already in the IEA R&D WECS [3] program that was initiated in 1977, the Netherlands participated with the objective to perform cooperative research, development and demonstration, and exchange of information in the field of wind energy utilization. From the early 1970s, the Netherlands, just as many other countries were exploring the use of wind energy. After the oil crisis, an urge to collaborate between R&D institutes in wind energy led to the start of the International Energy Agency Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems [4]. A manual for structural safety analysis of wind turbines was prepared and technical feasibility studies were carried out on multi-unit offshore wind farms. Already in 1981, it was concluded that it was technical feasible to install a large, multi-unit offshore wind farm with 50-200 turbines on individual support structures, with rotor diameters between 50 and 110m in water depths of 10-45m. The study group on recommended practices completed a study of power performance testing and studied recommended practices for wind turbine costing, evaluation of fatigue, acoustics, safety and reliability, quality of power, etc. As early as 1980, a new task was initiated by ECN on wake effects of wind turbines. The objective to better estimate the performance of arrays of wind turbines led to the theoretical and experimental modeling of turbine clusters, among others experiments in the Dutch TNO wind tunnels [5, 6]. The measured data still are used for analyses and validations today. In addition, generated turbulence levels and associated dynamic effects were part of the studies. The Dutch TNO wake interaction model MILLY was tested against wind tunnel experiments. In 1983 the Netherlands joined the IEA agreement for cooperation in the development of Large-Scale Wind Energy Systems [3] with ECN as the contracting party. One of the activities was to prepare the specifications for the 3MW 80m GROHAT turbine with an industrial consortium.

9.4 HISTORIC VIEW 1990-2000

The wind energy research activity in The Netherlands in the period from 1990 to 2000 period was concentrated at ECN Wind Energy and the Delft University of Technology. Additional activities were carried out by the Dutch organization for Applied Scientific Research TNO and research and development by the industry. ECN focused on aerodynamics, durability and fatigue, electrical conversion and regulation, criteria for certification and standards, and offshore applications. The primary focus of the ECN program is the improvement of the institute's research potential in order to be able to react adequately to possible assignments from industry and therefore the program is oriented towards the development of measuring methods, simulation models, test procedures etc. The development of measuring methods is facilitated by the availability of the HAT25 turbine at the Petten site. In the same period, the Delft University of Technology plays an important role in research and researcher training, with predominant focus on fundamental aspects, such as aerodynamics and loads. The 1991-1995 TWIN program administered by NOVEM was followed by the 1996-2000 program. The main focus in these programs are further research in rotor aerodynamics, especially dynamic and 3D effects and development of engineering rules; design tools for rotor development, o.a. buckling and optimization through cost functions; inventory of extreme wind conditions; reduction of emission noise, o.a. through design and field testing of rotor blades with serrated edges and empirical research in which serrated edges and tip shapes are tested in wind tunnels; standards and certification; and design and construction of light weight turbine concepts such as the FlexHat research [7]. The FlexHat program aimed at diminishing internal peak loads, by employing the dynamics of the rotor instead of withstanding them. Flexibility is introduced in the four main degrees of freedom of the rotor, resulting in a variable speed conversion system with soft characteristics, rotor control by means of passive activation of the tip in combination with variable speed, an elastomeric teeter with elastomeric teeter limiters (bumpers), and a flex beam which is moderately flexible in flap wise direction and stiff in torsional direction. The components were tested on the HAT25 research turbine, located at ECN Petten.

In 1997, NOVEM carried out a feasibility study of a demonstration project of a near shore wind farm. The wind farm is meant to gain experience and knowledge of offshore installation, construction and operations. The idea to have a demonstration offshore wind farm was steadily further developed and the wind farm became operational in 2007. The realization of the farm included an extensive monitoring and evaluation program. The farm is highlighted further in this Chapter.

Around the same time, engineering design codes came available, like the wind field generator for aeroelastic codes SWIFT, an aerodynamic correction method for 3D effects TIDIS, an optimization tool for blade design BLADOPT, and a tool for calculations on noise emissions from blades SILANT. In 1999 the DUT developed the method NewGust to quickly generate extreme turbulence gusts for load calculations. These codes have been used by industry and most of these codes are still in use today.

The objective of the project 3D effects in stall was to improve methods that are used in order to predict the effect of rotation on sectional aerodynamic coefficients, particularly the lift coefficients. The project was a cooperation between ECN, DUT and the National Aerospace Laboratory NLR. In the first stage, following the ideas of Herman Snel, boundary layer equations in a rotating frame of reference were developed by NLR and subsequently put in integral form. In parallel, the aerodynamic analysis program XFOIL was purchased and improved by ECN and DUT resulting in a more accurate prediction of lift coefficients near stall. In the second stage, the integral form of boundary layers in the rotating frame of reference was implemented in the improved XFOIL by NLR. The resulting program called RFOIL was validated using the experimental aerodynamic field data from ECN's HAT25 experimental wind turbine. In addition, power curve predictions were validated by experimental data. In the third stage, an engineering method was developed by ECN, allowing the effect of rotation on the lift coefficient to be obtained without having to perform a calculation with RFOIL. The main result of the project was the code RFOIL, which is more accurate than its predecessor in rotating cases like wind turbines. The RFOIL code is to date still freely distributed by ECN and is in use with most wind turbine manufacturers and wind energy researchers.

ECN coordinated the JOULE II project Dynamic Inflow [8], research on the validation of 3D effects in stall. These effects describe the wake induced unsteadiness and non-uniformity of the flow in the rotor plane. Aim of the project was the definition and implementation of engineering models within computer codes for dynamic load calculations. These models have been qualified by means of comparison with both existing sophisticated models (dynamic vortex wake calculations) and experiments on turbines with a large range of rotor diameters. Important dynamic inflow effects were found at fast pitching transients and at yawed flow conditions. The effects were predicted well with the newly developed engineering methods. The projects provided many insights in the behavior of the induced velocities in the rotor plane under several conditions. Measurements and calculations showed important effects of dynamic inflow on the mechanical loads at fast pitching transients and at yawed conditions. At fast pitching transients large overshoots in the loads were apparent. At yawed conditions, the influence of the skewed wake on the induced velocities effected the phase and amplitude of the azimuthally binned averaged flat wise moments. For partial span pitch conditions and for wind gusts, the dynamic inflow effects were much less. Direct evidence of dynamic inflow was found in the wake flow measurements in the wind tunnel at pitching transients and yawed conditions. An interesting result was that under yawed conditions, the skewed wake does not only effect the axial induction (which was expected from helicopter aerodynamics), but also the in plane velocities. The dynamic inflow effects were predicted well with the engineering methods, developed in the project.

Delft University of Technology coordinated the Joule project 'Structural and Economic Optimization of Bottom Mounted Offshore Wind Energy Converters (Opti-OWECS) with the aim to reduce cost of electricity by extending the technology and demonstrating practical solutions for offshore wind turbines. An innovative integral design methodology was developed, the OWECS design approach, considering all components of an offshore wind farm. The design solution is then considering criteria like levelised production costs, adaptation to local site conditions, dynamics of the system, installation effort as well as availability of the turbines. This also required a novel offshore wind farm cost model which was developed at DUT.

During this period, the Dutch wind energy research was strongly involved in international cooperation, like numerous

European projects and participation in IEA Annexes. The Dutch researchers have been heavily involved in the development of design guidelines and IEC International Standards.

For instance TASK XVIII - Enhanced Field Rotor Aerodynamics Database has been operated by ECN [9]. In 1998, the ExCo approved Task XVIII to extend the database developed in Task XIV and to disseminate the results. The objective of the ANNEX-XIV was the coordination of full scale aerodynamic test programs on wind turbines, in order to acquire the maximum of experimental data at minimum costs. In these full scale aerodynamic test programs local aerodynamic quantities (forces, inflow velocities, inflow angles) are measured at several radial positions along the blade. The supply of local aerodynamic data, is a major step forward in understanding the very complicated aerodynamic behavior of a wind turbine. In conventional test programs only blade (or rotor) quantities are measured. Usually these quantities are integrated over the rotor blade and they are not only influenced by aerodynamic effects, but also by mass effects. Then the local aerodynamic properties of the blade can only be derived indirectly, introducing an uncertainty. Since aerodynamic field experiments are typically very time consuming, expensive and complicated because of the large volumes of data and the extensive data reduction it is very advantageous to cooperate. And because specific turbine configurations that are investigated experimentally may exhibit a very different aerodynamic response characteristics, the combination of measurement data on very different facilities will provide much more insight about the general validity of aerodynamic phenomena.

In 1999 a new Dutch wind energy research strategy was formulated by the government, and with input from Dutch wind turbine and blade manufacturers, engineering firms and end users such as utilities, insurance companies and certifying institutes the following priority subjects were set:

1. New developments: offshore, innovative materials and recycling.
2. Testing and measuring: condition monitoring systems, wind turbine test facilities.
3. Databases: failure statistics of wind turbines and components.
4. Design tools: reliability, wind turbine control and aerodynamics.

The research programs at ECN and DUT were shaped after these priorities and the research projects were defined accordingly.

In 1999 several projects were started under the Ecology, Economy and Technology funding scheme: One of the projects researches the possibilities of producing large blades from ecologically friendly materials. The other is the DOWEC project.

The Dutch Offshore Wind Energy Converter project (DOWEC) included NEG Micon, LM Glassfiber, Van Oord ACZ, DUT and ECN and was started as a concept study for offshore wind turbines [10]. The goal of the DOWEC Concept Study was to make an inventory of all wind turbine concepts in order to select the most optimal concept for a 5 to 6 MW offshore wind turbine. In the first phase the DOWEC concept study aimed at the choice of the optimal wind turbine concept. These turbines should be able to withstand the severe wind and wave conditions at the Dutch North Sea. In the design process, the wind turbine was not treated as an isolated system, but the designs of different wind turbine concepts were evaluated as an integral part of a complete large-scale offshore wind farm. All significant properties like the structural loads, the power performance, the system reliability, the costs of the electric infrastructure, maintenance costs and installation costs were determined for the optimized designs. The concept study resulted in five feasible concepts for far offshore wind turbines of 5 to 6 MW. These concepts were quantitative ranked based on the cost of generated energy. Furthermore, qualitative criteria like development risk and market potential were taken into consideration when finalizing the choice of concept. From these concepts, one was selected by industry for further development. The industrial tasks resulted in the engineering, purchase, and construction of a 2.75 MW wind turbine. The turbine has been erected and tested at the ECN Wind turbine Test site Wieringermeer. The final result of the DOWEC project should have been the realization of a 6 MW offshore wind turbine which is optimized for exploitation in large wind farms in the North Sea addressing all design and operational aspects in a cost-effective way. The realization of this turbine never happened, but the design of the 6MW turbine was delivered in 2003. The design is publicly available and the information has been used extensively. For instance the 5MW reference turbine defined by NREL is largely derived from it and many aspects of the DOWEC 6MW design can be found in modern offshore wind turbines installed today.

Figure 9-1: The NM90 2.75MW wind turbine (also known as DOWEC turbine) at the ECN test site in the Wieringermeer as seen from the measurement mast (109m) Source: [ECN, taken by R. Nijdam]

At the end of the decade, ECN developed and patented a novel technique to visualize the stall behavior of rotor blades. The power performance of stall regulated turbines in some cases varied considerably and to quantify the cause, a measurement technique was required, which could be applied on large commercial wind turbines, was fast enough to monitor the dynamic changes of the stall pattern, and was not influenced by the centrifugal force and most importantly did not disturb the flow. The technique developed and patented at ECN was called Stall Flag Method [11] and was composed by small reflecting sheets covering with a hinged non-reflecting sheet. When glued to the blade the hinged non-reflecting blade will open upon stall and the reflecting part becomes visible. During night time, the reflecting parts can be recorded by camera if the turbine is lit by a light source. With this technique problems can be searched for, optimum locations for stall strips and vortex generators can be found and insight can be obtained into the problem of multiple stall. The statistical stall behavior is characterized from the sequences of thousands of analyzed images. This leads to the visualization of the stall pattern, the blade azimuth angles and the rotor speed. It also measures the yaw error and the wind speed from the optical signals of other sensors, which are recorded simultaneously. For example, the delay in the stall angle by vortex generators can be measured with an accuracy of one degree from the stall flag signals. Many experiments have confirmed the independence of stall flags from the centrifugal force and that stall flags respond quickly to changes in the flow.

9.5 HISTORIC VIEW 2000 to 2010

In 2000, almost 40 MW of wind capacity was installed in the Netherlands. This is a continuation of the slow but steady installation rate of 40 to 50 MW in the last 4 years. At the time, the national target was 2,750 MW installed wind power in 2020 and therefore it was necessary to go offshore. In 2000, preparations for the necessary step to offshore were taken at the technical and administrative level. The research in wind energy became focused on offshore application and a demonstration offshore wind farm was tendered. The consortium which was called Noordzeewind and consisted of Shell Renewables, energy company Nuon International, bank ING Bank, engineering firm Jacobs Compimo, and NUON owned project developer WEOM won the tender for the Near Shore Wind farm. According to the requirements in the environmental effect report for the Near Shore Wind farm, a monitoring and evaluation program had to be carried out. The outlines of this program, which cover environmental, economical and technical aspects were drafted early 2000. According to these outlines, this program started with an evaluation of the undisturbed situation. The entire program aimed at learning as much as possible from the near shore demonstration wind farm in order to better realize the future larger offshore wind farms that are necessary to reach the national targets.

As a follow-up to the JOULE project 'Database on Wind Characteristics', Sweden, Norway, United States, The Netherlands, Japan, and Denmark formulated IEA Task XVII. There was an urgency to initiate an international effort to collect, describe and store high-quality wind data measured by several wind energy related projects. The unique database on wind characteristics consists of quality controlled and documented wind field time series supplemented with tools that enable easy access and a simple analysis through an internet connection. The statistics database contains a list of all time series, the derived statistics together with other parameters. The raw time series (74.6GB) consist of files of 10-minute periods in a common format. The accessibility of the database has been developed during the operational years of the database and is quite easy to use and it is comprehensive. From numerous areas over the world, controlled and high quality data have been added to the database. Important data consists of wake measurements, three component offshore measurements, extreme complex terrain measurements and long term data sets covering time spans of at least 20 years. Reports [12, 13] are available on description of data that have been added by ECN to the international wind database [14].

An interesting spin off of the research at DUT is the development of the Ampelmann [15]: a motion compensated platform to safely access offshore wind turbines. The initial feasibility study, preliminary design, and proof of concept of an offshore access system named Ampelmann was supported by SenterNovem. The Ampelmann is a ship-based self stabilizing platform that actively compensates all vessel motions to make offshore access safe, easy and fast. The base of the Ampelmann is mounted on the deck of the vessel or barge and takes care of the motion compensation, keeping the top side of the Ampelmann stationary. The gangway, which is mounted on the top side, can now be easily deployed onto the offshore structure enabling safe offshore crew transfer. To achieve this, the vessel is equipped with a set of motion sensors and a Stewart platform. The motions of the ship are continuously registered in six degrees of freedom by the motion sensors on the deck of the vessel and instantaneously fed into a control system in order to keep the top plate of the Stewart platform motionless compared to the fixed world. On this top plate, a transfer deck is installed. By extending a gangway between the transfer deck and the offshore structure, the structure can be accessed in an easy and safe way, even in high waves. The Demonstrator project was sponsored by We@Sea, Delft University of Technology, Shell, Smit, Heerema fabrication, SMST, and Ecofys with the common goal to further develop and test its design, compensation performance, operational procedures and safety systems in the harsh offshore conditions of the North Sea. Currently, various Ampelmann systems are in use for daily delivery of personnel to fixed platforms in the North Sea.

In 2005, ECN completed the wind resource atlas of the Dutch part of the North Sea for several heights. ECN developed the atlas by combining data from two sources: the numerical weather prediction model Hirlam and the meteorological stations at the North Sea, thus combining a source with dense spatial sampling and a source with accurate (measured) values. At the ECN website, maps with the mean wind speed at 60, 90, 120, and 150 meter above sea level are published. ECN can for every location at the North Sea and for each height produce a time series of 10 years based on the Hirlam data which is validated by using the measurement stations. The wind resource in such a location is expressed in terms of the wind speeds and wind directions, the turbulence intensities, and the stability classes.

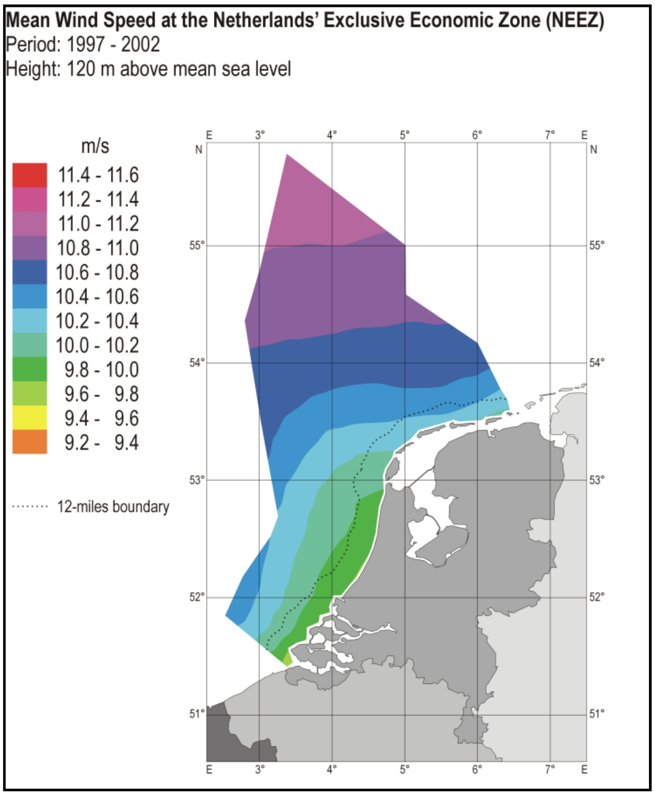

Figure 9-2: Mean wind speed at the Dutch part of the North Sea at 120m height. Source: [ECN, Arno Brand]

9.5.1 UPWIND

UpWind is a large European project funded under the EU's Sixth Framework Programme (FP6). The project looks towards the wind power of tomorrow, more precisely towards the design of very large wind turbines (8-10MW), both onshore and offshore. Furthermore, the research also focuses on the requirements to the wind energy technology of 20MW wind turbines. The challenges inherent to the creation of wind farms of several hundreds MW request the highest possible standards in design, complete understanding of external design conditions, the design of materials with extreme strength to mass ratios and advanced control and measuring systems geared towards the highest degree of reliability, and critically, reduced overall turbine mass. The aim of the project is to develop the accurate, verified tools and component concepts the industry needs to design and manufacture new, cost effective type of turbines. UpWind focuses on design tools for the complete range of turbine components addressing the aerodynamic, aero-elastic, structural and material design of rotors. The UpWind consortium, composed of 40 partners, brings together the most advanced European specialists of the wind industry. In most work packages, researchers from the Netherlands are involved and the following work packages have coordinators from the Netherlands: Metrology, Upscaling and Rotor structure and materials.

9.5.2 SMART ROTORS

For many years DUT is carrying out research work on smart rotors in the context of the Dutch INNWIND and the EU UPWIND projects. The objective of smart structures for rotor blades is to alleviate significant blade loads by applying spanwise-distributed load control devices without incurring lower reliability or higher maintenance. DUT concentrates on the investigation of concepts, feasibility, and integrated design; aerodynamics; structural integration; control, identification, and experimental investigation of developed models. DUT proved the concept in their wind tunnel. Researchers observed load reductions between 70% and 90% and concluded a significant amount of fatigue blade load alleviation is possible. This was confirmed by research at ECN that is concentrating on the application of synthetic jets for this purpose. DUT has carried out experiments in the Open Jet Facility with a rotating 2 meter diameter wind tunnel model.

9.5.3 WE@SEA

The 4-year WE@SEA program on offshore wind energy is funded from the Dutch national natural gas fund. This program is run by a consortium consists of companies in offshore technology, wind energy technology, offshore wind farm development, logistics, investors, energy consultants, environment, and other stakeholders and was operated from 2004 to 2008. The program of € 26 million concentrated on medium-term research in the research lines: offshore wind power generation; spatial planning and environmental aspects; energy transport and distribution; energy market and finance; installation, operation and maintenance, and dismantling; education, training, and knowledge dissemination; and the PhD@ Sea project at DUT. The PhD@Sea research subjects were divided over the research lines of the overall program. Its topics are: large blades; wind turbine concepts; morphology of the North Sea bed; grid stability of large-scale integration of wind energy in electrical power systems; park-grid interaction; offshore access through the Ampelmann; reliability, availability, maintainability, and serviceability analyses and scenarios.

9.5.4 Controlling Wind and Heat & Flux

Over the years 1999–2003, ECN invented and patented two wind farm control techniques, the one called Heat & Flux, the other Controlling Wind. The concept Heat & Flux aims at maximizing the power output of a wind farm by adjusting the axial induction of the windward turbines below their individual optimum for power production, which means making them more transparent for the wind than usual by realizing an axial induction factor below the Lanchester-Betz optimum of 1/3. This will reduce the velocity deficit in the wake and increase the output of the downwind turbines. Other benefits are decreased average loading of the upwind turbines and decreased fatigue loading of the turbines in the wake. ECN quantified the effects of “Heat and Flux” farm control. For this purpose models have been developed for calculating the power and energy production with “Heat and Flux” operation. The models have been developed in close interaction with wind tunnel experiments on model turbines and farms and have been tested in full scale experiments on a row of five 2.5MW turbines. Qualitatively, the wind tunnel tests and the field experiments revealed positive effects of simple “Heat and Flux” control settings on several occasions. Quantitatively, the accuracy and reliability of the wind tunnel measurements are questionable because of the large scatter and the conditions that deviate from full scale in various aspects. The full scale experiments point at comparable optima for “Heat and Flux” control settings as model predictions of the model developed by ECN. This method has been implemented in ECN’s Control Tool for designing wind turbine control algorithms.

9.5.5 Wind Tunnel Experiment Mexico And Mexnext

In the past, the accuracy of wind turbine design models has been assessed in several validation projects [16]. They all showed that the modeling of a wind turbine response which can be either the power or the loads is subject to large uncertainties. These uncertainties mainly find their origin in the aerodynamic modeling where several phenomena such as 3-D geometric and rotational effects, instationary effects, yaw effects, stall, and tower effects, amongst others, contribute to unknown responses, particularly at off-design conditions. The availability of high quality measurements is considered to be the most important pre-requisite to gain insight into these uncertainties and to validate and improve aerodynamic wind turbine models. For this reason, the European Union project “MEXICO: Measurements and EXperiments In COntrolled conditions has been carried out [17]. The project was coordinated by ECN and was carried out with ten institutes from six countries. They co-operated in doing experiments on an instrumented, 3-bladed, 4.5-m diameter wind turbine placed in the 9.5 m^2 open section of the Large Low-speed Facility (LLF) of German Dutch Wind Tunnel (DNW) in the Netherlands (see Figure 9.3). The LLF is described later in this Chapter. The measurements were performed in December 2006 and resulted in a database of combined blade pressure distributions, loads, and flow field measurements that can be used for aerodynamic model validation and improvement.

Figure 9-3: The Mexico wind tunnel experiment in the DNW wind tunnel. Source: [ECN, photo Toon Westra]

A similar previous experiment was performed by the National Renewable Energy Laboratory (NREL) in the National Aeronautics and Space Administration (NASA) Ames wind tunnel [18] on a 10-m diameter turbine. An obvious difference between the two types of experiments lies in the larger size of turbine diameter the latter experiment. But in addition to the NASA-Ames experiment, the Mexico experiment also included flow field measurements. Especially the flow field of inflow and wake are interesting, where the flow field is important for the understanding of discrepancies between calculated and measured blade loads. This is mainly because the load calculations are done in two steps. First, the flow field around the blade, the induction, is calculated, and second from that the loads are derived. Where in conventional experimental programs, only blade loads are measured, it is not possible to distinguish between these two sources of discrepancies. The addition of flow field measurements should open up this possibility.

At the end of the MEXICO project, due to budget reductions, the database was still in a rather rudimentary form and only limited analyses had been carried out. Especially since it is a huge amount of data which requires a lot of effort to analyze. Therefore it is beneficial to organize the analysis of the MEXICO data in a joint project under IEA Wind in which various countries share this task. Given the platform for discussion and interpretation of the results the outcome of the data analysis shall be better than the summed result from individual projects.

ECN is the Operating Agent of the IEA Wind Task 29 called MEXNEX(T) which has the objective to improve aerodynamic modes used for wind turbine design. In this task the access of the Mexico data is provided and a shared thorough analysis of the data takes place. This includes an assessment of the measurement uncertainties and a validation of different categories of aerodynamic models. The insights are compared with the insights that were gained within IEA Wind Task 20 on the NASA-Ames experiment and other wind tunnel experiments.

Special attention is paid to yawed flow, instationary aerodynamics, 3-D effects, tip effects, non-uniformity of the flow between the blades, near wake aerodynamics, turbulent wake, standstill, tunnel effects, etc. These effects are be analyzed by means of different categories of models like CFD, free wake methods, engineering methods, etc. As such, the Task will provide insight on the accuracy of different types of models and the following activities are performed.

1. Processing and presentation of the measured data and the associated uncertainties. High quality measurement data are provided to the partners to facilitate and compare calculations.
2. Analysis of tunnel effects. Since the 4.5-m diameter wind turbine model was placed in the open jet section of the LLF facility (9.5 m x 9.5 m) the ratio of turbine diameter over tunnel size may make the wind tunnel situation not fully representative of the free stream situation. The tunnel effects have been studied with advanced CFD models. Supporting information on tunnel effects will also be obtained from eight additional pressure measurements, which were measured with taps in the collector entrance. These pressures measure the speedup in the outer flow (outside the wake) needed for the mass conservation of the tunnel flow.
3. Comparison of calculational results from different types of codes of the various partners with the MEXICO measurement data. This is proving to be a thorough validation of different codes and it provides insights into the phenomena that need further investigation.
4. Deeper investigation into the observed phenomena. A deeper investigation of different phenomena using isolated sub-models, simple analytical tools, or by physical rules. These phenomena that are investigated include 3-D effects, instationary effects, yawed flow, non-uniformity of the flow between the blades (i.e. tip corrections), and the wake flow at different conditions.
5. Comparison with results from other (mainly NASA-Ames) measurements. It is investigated whether these findings are consistent with results from other aerodynamic experiments, particularly the data provided within IEA Wind Task 20 by NREL from the NASA-Ames experiment.

A large variety of results have been obtained, the data are analyzed on quality and tunnel effects. PIV measurements in the wake have been analyzed, and a comparison has been made between the observations from the NASA-Ames and MEXICO experiments. The effects from airfoil imperfections have been estimated which is important for the comparison with models. A typical example of the comparison between calculated and measured results are shown in Figure 9.4 where the results are compared to predictions by the ECN code AWSM, a numerical code based on the Generalized Prandtl's Lifting Vortex Line Method.

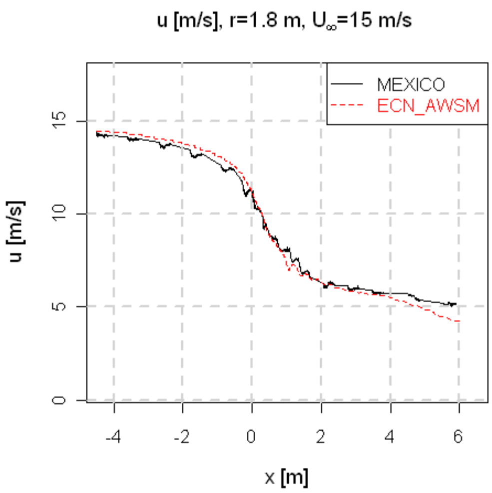

Figure 9-4: MEXNEXT result: axial traverse from PIV measurements compared to AWSM predictions. Source: [ECN]

9.5.6 DU Airfoil data

In the last 15 years DUT has developed many airfoils for wind turbine application [19]. These airfoils are called the DU airfoils and are applied world-wide in wind turbine blades ranging from 6 to 60 meters. The development of the DU airfoils has been supported by the European Commission, the Dutch Ministry of Economic affairs and the DUT in the framework of the educational and research program of the section Wind Energy of the Faculty of Civil Engineering and Geosciences, which is at present the Wind Energy section of the Faculty of Aerospace Engineering. The two-dimensional aerodynamic characteristics of the DU airfoils have been extensively verified in the Delft University low-speed low-turbulence wind tunnel for various Reynolds numbers. In addition to the clean configuration for Reynolds numbers ranging from 1 million to 3 millions, the characteristics of several airfoils with vortex generators, zigzag tape, trip wires, trailing edge wedges or Gurney flaps of 1% and 2% chord heights have been established. In some cases a stethoscope was used to determine the transition location. The DU airfoils are included in the ATG software package of ECN.

9.6 RESEARCH PROGRAMS

The research programs described here concern the programs of ECN Wind Energy, Knowledge Centre WMC and the Wind Energy group at DUT, DUWind

9.6.1 Energy Research Centre of the Netherlands ECN and Knowledge Centre WMC

The Energy Research Centre of the Netherlands is dedicated to the research in efficient use of energy and infrastructure, deployment of renewable energy sources, clean conversion of fossil fuels and development of energy analyses and policies. While targets for the near and medium term have been set in Europe, substantial further acceleration of new technologies is required to meet the long term goals of reducing the dependence on fossil fuels and the CO_2 emissions. ECN aims to carry out groundbreaking research that will have a major influence on energy transition and brings technologies to every stage of development. The strength of ECN lies in it's portfolio, which enables the development of new generations of technologies. Many technologies developed by ECN have reached maturity in recent years, increasingly resulting in third-party economic activity. ECN focuses on the needs of government and industry. In addition, it conducts contract research for companies and governmental institutions and to a large extent for the European Union. ECN collaborates intensively with other knowledge institutes and universities.

ECN Wind Energy has the mission to develop high-quality knowledge and technology for large-scale cost effective application of wind energy and transfer these to the market. ECN Wind Energy has the ambition to contribute substantially to lowering the production costs of offshore wind energy to a level at which it is competitive with fossil-fuel generation in 2020.

The long term research program of ECN Wind Energy is combined with the long term research program of Knowledge Centre WMC because of the close co-operation between the two organizations and the fact that the programs are complementary and dependent on each other. ECN Wind Energy and WMC organize their research in four priority areas:

1. Rotor and Farm Aerodynamics
2. Integrated Wind Turbine Design
3. Operation and Maintenance
4. Materials and Structures

The research is supported by extensive experimental facilities and an Experiments & Measurements group that is MEASNET and ISO17025 accredited.

In the field of **Aerodynamic** research, ECN Wind Energy aims at optimizing the aerodynamic performance of the wind turbine rotor and of the wind farm as a whole. By developing new knowledge, methods and design software, the results of the long term research can directly be transferred to the industry. An additional result of the research is that Intellectual Property is generated. The tools and Intellectual Property are used for research purposes of turbine and blade manufacturers and project developers or are directly applied. A unique feature of its research is the combination of theoretical and numerical research with the various experimental test facilities: wind tunnels, scale wind farm and full scale test wind farm in the Wieringermeer. The aerodynamic research is divided in rotor aerodynamics and wind farm aerodynamics.

Research in the field of rotor aerodynamics aims at the development of advanced aerodynamic design tools. ECN has a tradition in developing BEM, but also developed the aerodynamic free wake model based on lifting line panel method AWSM. A new code is being developed where also the boundary layer is being modeled. This method where the external pressure field of the rotating panel method that includes the wake is combined with a three dimensional unsteady boundary layer model will lead to an accurate method that is significantly faster than full Navier-Stokes field solvers. It is called ROTORFLOW. In a Dutch consortium ECN has developed the RFOIL 3D code, a modified version of the XFOIL software. The progressively advanced aerodynamic design tools are used to design and model future large wind turbine rotors with increased accuracies.

Research in the field of wind farm aerodynamics aims at the understanding of the flow field in and around wind farms, which is especially relevant for the construction and operation of large offshore wind farms. Insight in wake effects in wind farms is essential. Computational fluid dynamics (CFD) are applied for the further understanding of flow phenomena in wind farms. The research comprises the development of validated wake models and CFD wind farm models using commercial solvers as well as the development of dedicated wind farm aerodynamics CFD solvers. Interesting model challenges are combined, such as the modeling of the atmospheric boundary layer, the flow inside the wind farm, the modeling of the turbine including its control, the wind farm control as well as the optimization of this system.

The FarmFlow program is a validated tool developed by ECN to calculate the wake effects of large offshore wind farms. It is unique that it calculates both wake losses and added turbulence levels with an accuracy currently unmatched. The FarmFlow tool allows the user to accurately optimize the lay-out of the wind farm with respect to power output and, in conjunction with aero-elastic codes, the possibility to perform design calculations on wind turbines that are placed in wind farms.

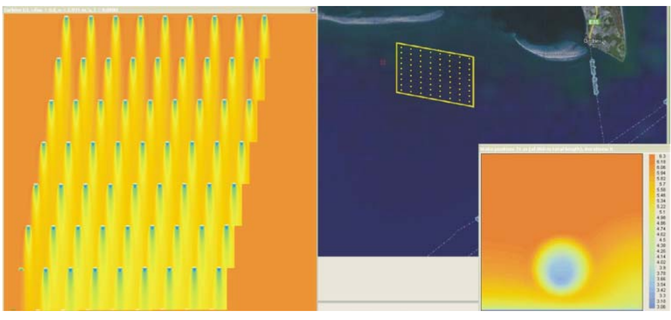

Figure 9-5: ECN FarmFlow wind farm calculation model.

Source: [ECN]

In the field of **Integrated Wind Turbine Design** research, ECN Wind Energy and WMC aim at the improvement of the design process in industry by developing new, improved models, concepts and tools for the integrated system design. ECN focuses on aero-elasticity, control and concept studies. WMC is dedicated to the development of the integrated design tool and the blade design module. The research in the field of integrated design is among others

Aero-elasticity: rotor aerodynamic models are coupled to structural dynamic models and the resulting aero-elastic models are verified and validated against measurements and used for integrated design. Improvements are needed for simulations concerning oblique inflow, individual pitch, large deformations and complex drive train and support structure geometries. Coupling the improved aerodynamic models to structural dynamic models (multi-body or FEM) improves the results obtained from simulations. To enable a straightforward coupling the ECN develops the Aero-module. This module couples the aerodynamic codes to aeroelastic codes, such as TURBU and PHATAS which have been developed by ECN.

Research in wind turbine control aims at the improvement of the present control algorithms, and the development of new ones, mainly targeting reduction of the cost of energy. To this end, the following objectives are pursued:

- optimal power and rotor speed control,
- load reduction in the mechanical components of the wind turbine,
- high availability and reliability of the wind turbine,
- easy and robust commissioning of the controller,
- coping with all grid requirements.

ECN developed the user-friendly ECN Control Design Tool which provides the wind turbine control engineer with an excellent set of tools in an open-source MATLAB environment, covering the complete process of turbine modeling, control design, stability analysis and compilation of the final controller into executable code for linking to advanced simulation software for load calculations or to dedicated hardware. Furthermore, the following four major control components of the integral approach are investigated

- Optimized feedback control (OFC), aiming at removing limitations for up-scaling of wind turbines, such as high turbine loads and stability problems,
- Extreme event control (EEC), dealing with prevention of unnecessary standstill and/or increased loads due to extreme events,
- Fault-tolerant control (FTC), having the task of detection of minor (sensor) faults followed by recovery actions,
- Optimal shutdown control (OSC), for preventing the accumulation of damage in cases of a turbine shut-down caused by a severe failure.

ECN develops design tools for large wind turbines and these tools are constantly improved in order to address aeroelastic stability issues and to minimize cost of energy. The advanced tools are developed to reduce uncertainties in design load calculations, through an improved modeling of the physics involved. ECN upholds the quality and validity of its computer programs through participation in European benchmark studies and through feedback from field experiences. Aeroelastic and hydromechanical behavior of a wind turbine are modeled using sophisticated tools like e.g. AeroModule (including BEM and AWSM for rotor aerodynamics) and PHATAS and TURBU for dynamic load modeling of the turbine and support structure in time domain and frequency domain respectively. Wind and wave fields for use in the time domain code are generated with the SWIFT and ROWS code respectively. For quick assessments of aeroelastic turbine behavior the code BLADMODE is used and development and testing of custom made commercial control algorithms for wind turbines is done with the Control Design Tool. The BLADOPT: program optimizes rotor blade geometry for lowest cost of energy. WMC has developed the FOCUS code which includes several of these design tools.

Research in the field of Electrical Systems and Components aims at the design and optimization of electrical systems in a wind turbine that is connected to the wind farm grid; statically and dynamically. ECN developed, in collaboration with TUD Electrical Power Processing, two types of models: EeFarm and DynFarm. These programs are used with the developed FarmFlow code that calculates the wake losses in wind farms to optimize offshore wind farm designs.

For more than 15 years ECN Wind Energy is developing methods and tools to optimize the **Operations and Maintenance** (O&M) of offshore wind farms and in fact, ECN is one of the few institutes carrying out long term R&D on this topic. The scope of work comprises the development of models and software (Decision Support Tools) to analyze the O&M aspects, to determine costs and downtime, identify cost drivers, and to optimize the O&M strategy and the development of diagnostics and measurement techniques for those situations where condition based maintenance is preferred instead of preventive or corrective maintenance. ECN’s leading role in the field of O&M for offshore wind farms has been recognized for many years. Major project developers make use of ECN’s knowledge and models to develop O&M strategies for their offshore wind farms. Turbine designers apply the knowledge in the design process of offshore wind turbines.

WMC aims with the research on **Materials and Structures** at increasing its knowledge of the structural behavior of the blade and its materials under the complex loading and the environmental conditions and to make this knowledge applicable for wind turbine and blade manufacturers. With this knowledge current designs and the design of the next generation of blades are further optimized.

9.6.2 Delft University of Technology DUT

Research on wind energy at the Delft University of Technology began 30 years ago, starting with the tip vane project, an aerodynamic research project at the faculty of Aerospace Engineering. Nowadays DUWIND is the wind energy research organization of the Delft University of Technology. Since an increasing number of research questions require a multi-disciplinary approach, DUWIND was established in August 1999 as a interfaculty research organization, specifically for wind energy. World-wide, DUWIND now is one of the largest academic research groups in wind energy. Its research program covers almost all aspects of modern wind turbine technology, and is undertaken across 5 faculties in 13 groups. The five faculties are 1. Faculty of Aerospace Engineering, 2 Faculty of Civil Engineering and Geosciences 3.Faculty of Electrical Engineering, Mathematics and Computer Science, 4 Faculty of Mechanical and Materials Engineering and 5. Faculty of Technology, Policy and Management. Each of the research groups at these faculties has its own specific expertise therefore the DUWIND research group covers a wide area of wind energy research.

The research program of DUWIND has been reformulated and is published in October 2008. The program encompasses approximately 60 PhD positions, which implies a doubling in size of DUWIND compared to 2007. From the start the core of the research program is the technology development of wind turbines and wind farms, including the underlying basic research. The program focuses on long term research efforts, mainly performed by PhD researchers. Long term is to be understood as leading to useful results in a 5-10 years time frame after starting the PhD research. The program is made up and executed by the research groups at the five TU-Delft faculties, and is 'bottom-up': a new topic is included only when it can be embedded in an existing expertise group, and when funding is found. The PhD students will have activities in five sub-programs:

- Unsteady aerodynamics
- Smart structure rotors
- Design methods
- Offshore components and design
- Dutch wind energy in Europe

The focus of DUWIND program is on the development of turbine and wind farm technology, ranging from basic research through technology development to design support for the industry. Being a university, DUWIND provides courses for students and for professionals in the wind energy industry. As is indicated before, DUWIND closely co-operates with the wind energy group of ECN. Many projects are performed jointly, and mutual use is made of the research facilities. DUWIND and ECN together form the Dutch node of the European Academy of Wind Energy EAWE. DUWIND is part of the international wind energy research community. It is one of the founding members of the European Academy for Wind Energy and has started the Academy conference series ‘The Science of making Torque from Wind’. DUWIND contributes to the Wind Energy Technology Platform of the European Commission, the European Energy Research Alliance (EERA) and to the wind energy programs of the International Energy Agency. It has participated in all Framework Programs of the European Commission.

9.7 EXPERIMENTAL RESEARCH INFRASTRUCTURE IN THE NETHERLANDS

9.7.1 Blade Testing and Material Research at WMC

Knowledge Centre WMC is a research institute for materials, components and structures. The major activities are fundamental and applied research on fiber reinforced plastics and wind turbine structures. WMC is active in research projects for the European and Dutch governments and industry and performs blade and material tests on contract basis for the international industry. WMC develops design tools, the FOCUS software, that are being used worldwide by many of the largest wind turbine manufacturers. Results of the research work are published and presented internationally.

The Knowledge Centre WMC has a history from 2000, when it was started as "WMC-Group" in the Delft University of Technology doing quite a lot of full scale testing work on rotor blades. However, the test facility at Delft University of Technology became too small for the next generation of large rotor blades. Therefore, in order to keep track with the market's needs another, larger location needed to be found to continue the activities. A larger test facility was built in Wieringerwerf, in the northern part of the Netherlands where a new industrial site and yacht-basin "Waterpark Wieringermeer" was developed.

For the new laboratory a location was chosen close to open water, on the borders of the IJsselmeer. Now the sometimes very large structures that are brought for testing can also be transported by water. Starting 2003, as the centre moved from Delft to Wieringerwerf, the former "WMC-Group" of the DUT continued its work as a new foundation with a new name: Knowledge Centre WMC, established by the Delft University of Technology and the Energy research Centre of the Netherlands ECN. With its links to both organizations the new Knowledge Centre WMC can continue to combine fundamental and applied research on wind turbine and fiber reinforced plastics structures.

With the background of continuous testing and development of tests, WMC is actively involved in international standardization committees. For the experimental research WMC has a laboratory for material research and a large test area with a dedicated strong floor enabling testing of structures of over 60 meters in length, such as rotor blades for large wind turbines. Testing machines up to 300 ton are available for material and component testing, both static and fatigue. The facility is one of the largest of its kind and has its own mechanical, electro technical and hydraulic workshops for development and maintenance of equipment and test rigs.

The research topics for WMC in national and European research projects are amongst others:

- Material behavior under complex and fatigue loading
- New materials
- Condition monitoring
- Reliability of design codes
- Reliability of full scale testing
- Connection methods
- Design recommendations and standards on full scale testing of wind turbine rotor blades

On the other hand, WMC is performing more fundamental research activities in the context of many international projects. WMC initiated the EU project OPTIMAT BLADES to investigate the behavior of Fiber Reinforced Plastics and WMC is work package leader for materials research in the UPWIND project. The projects executed for industrial research purposes include:

- Testing of materials
- Numerical analyses
- Design evaluation
- Verification tests on mechanisms
- Strength and fatigue behavior of components and connections
- Development of design software: the integral wind turbine design software FOCUS
- Full scale verification tests on (sub)components such as:
  - Wind turbine rotor blades (or parts thereof)
  - Wind turbine pitch bearings and hubs
  - Connections

For larger wind turbines, the potential power yields scales with the square of the rotor diameter, but the blade mass scales to the third power of rotor diameter (square-cube law). With the gravity load induced by the dead weight of the blades, this increase of blade mass can even prevent successful and economical deployment of very large wind turbines. In order to meet this challenge and allow for the next generation of larger wind turbines, higher demands are placed on materials and structures. This requires more thorough knowledge of materials and safety factors, as well as further investigation into new materials with a higher strength to mass ratio. Furthermore, a change in the whole concept of structural safety of the blade is required. WMC is performing research activities in this field in order to improve both the empirical and fundamental understanding of materials, extend the material database, study effective blade details, establish of tolerant design concepts and probabilistic strength analysis and establish material testing procedures and design recommendations.

9.7.2 ECN WIND TURBINE TEST SITE WIERINGERMEER

At the Petten site, ECN has operated a wind turbine test site for many years. The size of the turbines allowed at the site is limited and therefore it is not in use anymore since the year 2000.

Figure 9-6: ECN Wind turbine Test site Petten
Source: [ECN, Picture by Aris Homan]

From 2003 ECN has expanded its wind turbine facilities with a wind turbine test site in the municipality of Wieringermeer. The site is located just south of the village Kreileroord, at about 30 km distance from ECN's main offices in Petten. This unique facility is a combination of:

- Four locations for prototype wind turbines upto 6MW, recently expanded with a fifth location for prototype wind turbines upto 10 MW.
- Five Nordex N80/2500 research wind turbines; these wind turbines are equipped for experimental research.
- Three meteorological masts, 108m, 108m and 100m high equipped with atmospheric measurement equipment.
- A scaled wind farm consisting of ten turbines rated 10kW and 14 meteo masts upto 19m height.
- A measurement pavilion with offices, a computer centre and advanced glass fibre based data acquisition system.

The research wind farm – consisting of five Nordex N80 wind turbines – enables ECN to perform wind farm specific research and development programs. The site also comprises five prototype locations. These locations enable manufacturers to test, optimize and certify prototypes together with ECN. Supporting facilities are three meteo towers, a 36 MVA grid connection, data collection equipment and a test site control center. A fourth meteo mast of 100m height is expected early 2011. The test site also accommodates a unique facility, which allows ECN to perform accurate wind field measurements in a scale wind farm. This Scaled Wind Farm - consisting of ten Aircon P10 turbines plus fifteen measurement towers - allows for the development and testing of wind farm specific control strategies. The site has a favorable wind climate: the average wind speed at 100 m height is 8,3 m/s. With this wind climate, not only do the five Nordex N80 turbines produce about 30.000.000 kWh per year from which the income of the green electricity gives a solid base for the financial exploitation of the site, the wind conditions allow for fast fulfillment of the experimental capture matrices of the test turbines.

Many research programs have been carried out at the experimental facility of ECN, also many European programs. The fact that the research turbines are owned by ECN and a proper research agreement has been reached with the manufacturer, allows ECN to optimally use these research turbines for its R&D programs. What was obvious from many defined programs is that it is very difficult to execute these programs in commercial wind farms since wind farm operators are reluctant to facilitate research programs that might conflict with maximum energy production.

ECN investigates aspects like operation and maintenance strategies; wake effects, noise effects, effect on birds and condition monitoring. Other important activities are the development of improved wind farm control strategies and new advanced measurement techniques.

Currently in 2010, plans are made to extend the research wind farm. Some fourteen turbines in the range from 5MW to 8MW are to be set up over the coming years, at least seven will be dedicated offshore turbines. ECN intends to purchase seven turbines for further research activities and a further seven proto-type test locations will be made available. A fifth proto-type location has already been created and a XEMC-Darwind turbine is being built and will be tested in 2011.

9.7.3 ECN Scale Wind Farm

A recent addition to the ECN experimental research infrastructure is the ECN scale wind farm. It has been designed to further advance the knowledge in wind fields in and around wind farms, including the understanding of wakes and turbine-turbine interaction. The development of large-scale offshore wind power implies the construction of even larger wind farms. At the moment, the large uncertainties connected to the wind field in the wind farm leads to financial risks when investing in these large wind farms. Furthermore, the cost of wind energy should be reduced even further. Therefore improved models are required describing the flow within and around wind farms so that optimised wind farm control strategies can be developed. The high quality data of the ECN scale wind farm are used for the development and validation of wind farm aerodynamic models and wind farm control strategies.

Figure 9-7: The scale wind farm in between two prototype turbines. Source: [ECN]

The understanding of unsteady wind fields within and around wind farms could be greatly increased when more detailed models or measurements of the wind field in a wind farm would be available. The same applies to understanding the response of many turbines within a wind farm on the mutual wakes. One reason for this is that adequate measurements are lacking and the models are not (yet) accurate enough. In full-scale wind farms meteorological masts are very expensive and the number of masts is thus limited. On the other hand, the value of modeling wind farms in wind tunnels is limited due to scaling effects. Therefore, ECN has overcome this problem by building the scaled wind farm facility which consists of relatively small wind turbines together with many measurement masts that measure the wind conditions in the wind farm and above the wind farm. The scale of this wind farm is not too small to alleviate the dominant scaling effects and the scale is not too large to permit the building of sufficient meteorological masts.

The ECN scaled farm consists of ten permanent magnet, direct drive, pitch controlled wind turbines. The turbines have 10kW rated power, a rotor diameter of 7.6m and a hub height of 7.5m. It is essential that the researchers have full access to the hardware and software of the wind turbines. The scaled farm has been designed in a way that allows ECN performing experiments without any risks for the environment as well as the turbines themselves. As a result, ECN is able to adapt the controllers as well as the turbines for the dedicated experiments. A dedicated wind farm controller has been installed. Inside and around the wind farm a network of fourteen measurement masts has been installed, which measure the wind velocity field from 3.6m to 19m height. This covers the rotor area and upto one rotor diameter above the rotor. The large number of meteorological masts within the wind farm permits to measure at the same time single, double, triple and quadruple wakes while simultaneously measuring the external conditions with three nearby 108m meteorological masts. The unusually densely spaced wind measurements gives the unique possibility to capture the complete wind field, which gives valuable additional information compared to the usual measurement of the wind speed at a single location. Furthermore, most of the wind measurements will be performed using 3D sonic anemometers thus capturing the three wind velocity vectors of the wind field.

The scaled farm is located in ECN's large wind turbine test field in Wieringermeer in between the prototype turbines. The scaled wind farm and its surroundings are characterized by flat terrain, consisting of mainly agricultural area, with single farmhouses and rows of trees. The lake IJsselmeer is located at a distance of 1 km East of the scaled wind farm. Great care has been taken to ensure undisturbed inflow of the wind in the scaled wind farm.

This worldwide unique research facility shall give further insights in the field of wind farm aerodynamics, wake interaction and wind farm control. The high quality data are used for the development and validation of wind farm aerodynamic models and wind farm control strategies. This will allow operating a wind farm at maximum efficiency while guaranteeing at the same time a maximum in reliability and a minimum in mechanical and electrical loads. A unique feature installed in the wind farm controller is that the controller can adjust the yaw of the turbines to exact positions, as well as the pitch angle. Since it has been measured that the yaw angles of the ECN research turbines are seldom equal when the wind is along the row, this feature will make comparison with models more easy and the experimental results more accurate. The side by side comparison of the two rows allows the demonstration of small differences due to changes in turbine or wind farm control.

Figure 9-8: The scale wind farm. Source: [ECN]

9.7.4 Experimental Facilities at Delft

DUWIND has access to all experimental facilities of TU-Delft. The most important ones that have an important role in the wind energy research are:

- The wave tank of the faculty of Civil Engineering and Geosciences, where the scale model of the motion-compensating offshore access system, the Ampelmann, has been tested.
- The Low Speed Low Turbulence Tunnel of the faculty of Aerospace Engineering, where all of the Delft University airfoils have been measured. The test section is 1.25*1.80 m, with a max wind speed of 120 m/s. The LST has an very low turbulence level: <0.1%.
- Structures and Materials Laboratory of the faculty of Aerospace Engineering, where innovative composite materials, such as thermoplastic composites and smart materials, are produced and tested.
- The Smart Structures laboratory at the Delft Centre for Systems and Control, faculty of Mechanical, Maritime and Materials Engineering is set up to run real time control on structures and to test the performance of active laminates produced at the materials laboratory.

Especially for wind energy research, the wind tunnels are important and are elaborated in the next section.

9.7.5 Wind Tunnels at TU Delft

The Delft University of Technology has a large selection of wind tunnels available with a wide range in wind speed from low speed to large speed. The most recent addition, the Open Jet Facility, is very relevant for wind energy application. The tunnels are applied for fundamental research as well as for applied research and many students use the tunnels for their practical. The wind tunnels available at DUT are indicated in Table 1.

Table 9-1. List of wind tunnels at Delft University of Technology

Low Speed Windtunnels					
Name	**Type**	**#**	**Dimensions Test section (WxH)**	**Cross Section**	**V_{max} (m/s)**
BXF	oj	4	5 x 10 cm	rectangular	25
M-tunnel	oj/cc	1	40 x 40 cm	rectangular	35
W-tunnel	oj	1	40 x 40 cm	rectangular	35
BLT	cc	1	125 x 25 cm (x 540 cm)	rectangular	38
LTT	cc	1	180 x 125 cm	octagonal	120
OJF	cc	1	285 x 285 cm	octagonal	35
Name	**Type**	**#**	**Dimensions Test section (WxH)**	**Cross Section**	**M-Range**
High Speed Windtunnels					
TST-27	bd	1	280 x 270 mm	rectangular	0.5-4.2
ST-15	bd	1	150 x 150 mm	rectangular	0.7-3.0
ST-3	co	1	30 x 30 mm	rectangular	1.5-3.5
HTFD	bd	1	350 mm	circular	6.0-11.0

The Delft Open Jet Facility

In 2009 at the Delft University of Technology a new octagonal 500-kW 30 m/s open jet facility began operation that can test model rotors up to 1.8 m for concepts such as flexible smart dynamic rotors and controls. For this kind of experiments the large advantage of the OJF over the other wind tunnels at DUT is that it has an open jet and an outlet diameter of almost three meters and can handle very large models that may obstruct the airflow quite considerably. The new wind tunnel offers more possibilities than ever before for teaching, such as laboratory courses involving model rotors, and research; parameter studies can be executed effectively and efficiently. The initial plans for the OJF were made in the 1980s in response to growing interest in wind energy. The development was delayed because of several reasons, one of them the large budget that was needed for the construction. When the wind group at DUT became part of the Faculty of Aerospace Engineering in 2003 it was possible to seriously proceed with the construction of the facility. The requirement was that the OJF should be versatile and also be used for other research than research into wind turbines. Construction of the OJF started in November 2006 and the opening of the tunnel was in 2009.

The dimensions of the OJF are very impressive. A large fan powered by a 500 kilowatt electric motor enables it to achieve a maximum speed of around 120 kilometers per hour. Air is rotated 180 degrees through a long diffuser and two rows of corner vanes. It then passes through a short diffuser before entering the 'settling chamber'. Here, five fine-mesh screens reduce the turbulence and velocity deviations in the airflow. Via a contraction the air is then blown into the test section as an even jet stream and cooled at the end by an enormous cooling radiator and guided back to the fan. Some of the many unique technical features in this project are the high power motor, the modular adjustable frequency drive, the thermal sensors and the large cooling fan.

Figure 9-9: The rotor of the wind race car of ECN in the OJF [Source ECN, Picture by P. Eecen]

The OJF is mainly used by PhD students, graduates and members of the permanent academic staff. It fulfils an important role in research into the aerodynamic effects that wind can have on buildings and ships as well as in the field of sports. The vast majority of the models are made in the faculty's own workshop. To accommodate these research activities, the OJF is constructed to be extremely versatile. The wind energy group at DUT uses the OJF extensively, for instance for the verification and validation of the various calculation models. In the context of the large scale European research project Upwind experiments in the OJF contribute to the definition of new concepts for wind turbine blades, including smart rotors.

9.7.6 German-Dutch Wind Tunnels at DNW

DNW, the German-Dutch Wind Tunnels, is a non-profit foundation and was established by the German Aerospace Center DLR and the Dutch National Aerospace Laboratory NLR. Its headquarters are in the Noordoostpolder in the Netherlands and it has wind tunnels situated in a number of locations in the Netherlands and Germany. DNW operates its own large, low-speed facility and the aeronautical wind tunnels of DLR and NLR. DNW provides solutions for the experimental simulation requirements of aerodynamic research and development projects. These projects can originate in the research community (universities, research establishments or research consortia) or in the course of industrial development of new products. Most of the industrial development projects originate in the aeronautical industry, but the automotive, civil engineering, shipbuilding and sports industries have also benefited from DNW's capabilities.

The wind tunnel of DNW used for the experiments in the European project Mexico is the large low-speed facility (LLF). The DNW LLF wind-tunnel facility allows testing over a wide range of conditions and flight regimes. Due to the modular design of the wind tunnel a number of test sections can be used. These include open jet, 9·5m × 9·5m ($0 < V < 62$m/s), 8m × 6m ($0 < V < 116$m/s) and 6m × 6m ($0 < V < 152$m/s) closed test sections. The open jet wind-tunnel configuration allows large model heights above the ground at zero to low speeds. The closed jet test sections enable testing to be conducted over a higher range of airspeeds. The Mexico experiment, described earlier has been performed in this wind tunnel.

9.7.7 The Offshore Wind Farm Egmond aan Zee (OWEZ)

In the beginning of the century, the government formulated a target for wind energy that required the development of offshore wind farms due to the restricted possibilities onshore. Besides the focus of the wind energy research on offshore developments, an offshore demonstration wind farm should be built relatively close to shore in order to demonstrate the feasibility, but more importantly acquire knowledge and subsequently decrease the cost of offshore wind energy. The government decided on the final location for the demonstration project 100-MW Near Shore Wind farm. The location is situated in Dutch territorial waters of the North Sea between 10 and 18 km from the coast near the village of Egmond aan Zee. After a tender procedure, the Egmond Building Combination (EBC), a joint venture of Ballast Nedam and Vestas, built the 108 MW wind farm on the order of Shell Renewables and Nuon. The Offshore Wind farm Egmond aan Zee (OWEZ) comprises 36 Vestas V90 wind turbines of 3 MW each and associated support systems. Each wind turbine is connected by a transition piece to a steel monopole foundation, piled to a penetration depth of about 30 m. The power generated is transmitted through three 34kV cables to shore, which land north of IJmuiden harbour. A substation, located near Wijk aan Zee, transforms the voltage from 34kV to 150kV and transmits the power into the national grid. Investment costs are around 200 million € and financed on balance by Nuon and Shell. The wind farm initially has been operated by EBC under a 5-year warranty, operations, and maintenance contract. The wind farm produced approximately 350 GWh per year.

In the context of realizing the wind farm, an extensive Monitoring and Evaluation Program (MEP) was carried out. In that context, a meteorological mast was installed and data from the turbines were collected. The meteorological mast has a height of 106m above sea level and measures the wind conditions at three levels. Data collected in the MEP includes contractual issues, project organisation; permits; technical description of the design, support structure, wind turbines, and electrical design; assembly and installation; planning versus execution; budget; health, safety, security, and environment management; risk management; financing, insurance, and power purchase agreements; quality assurance management; requirements and qualifications; monitoring and evaluation program; and lessons learned [20]. This information has been made available [21]. Commercially sensitive data that has been collected during the execution of the MEP is on the subjects: corrosion and lightning; dynamics of turbines; aero-elastic stability; scour protection; electricity production, disruptions, failure data, availability, maintenance, and reliability; power quality, grid stability, and power forecasts; and wind turbine P-V curve and wake effects. ECN and DUT have executed several projects with selections of this data under an NDA agreement with NoordzeeWind.

9.7.8 The Offshore Wind Farm ‘Prinses Amalia Windpark’

The second offshore wind farm in Dutch National waters of the North Sea is Prinses Amaliawindpark. This wind farm is situated some 23 kilometers offshore from IJmuiden, in block Q7 of the Dutch continental shelf. This is just outside the 12-mile zone south-west of OWEZ. The wind farm consists of 60 Vestas V80 wind turbines of 2 MW each with a total capacity of 120 MW. The water depth at the site is between 19 m and 24 m. The project is owned and developed by a group of companies of ENECO Holding NV, Econcern BV, and Energy Investment Holdings. It was built by Vestas Wind Systems A/S, Van Oord Dredging, and Marine Contractors BV under separate construction contracts. Initially, the windfarm is operated by Vestas Offshore, an affiliate of Vestas, under a 5-year warranty, operations, and maintenance contract. During its operation, more and more research is carried out at the ‘Prinses Amaliawindpark’, also in the context of the FLOW program.

9.8 SUMMARY

This Chapter is an attempt to provide insight in the wind energy research of the Netherlands. The result is not complete and must be regarded as a personal selection of the activities that have been performed in all the years of wind energy research in the Netherlands. A more extensive overview can be found in Verbong [22], written in Dutch. The research in wind energy is concentrated at the wind energy department of the Energy research Centre of the Netherlands ECN and the interfaculty wind energy department DUWIND at Delft University of Technology. Both institutes have been involved in wind energy research from the start in the 1970s and closely match their research programs. ECN Wind Energy has a research staff of 55 scientists and DUT has a research staff of 15 permanent researchers and more than 35 PhD students. Together ECN and DUT belong to the top-5 of the international wind energy research groups.

In the Netherlands, the wind energy research is supported by an extensive experimental infrastructure. The Knowledge Centre WMC that has been founded by the DUT and ECN has a research staff of 25 scientists and is a research institute for materials, components and structures. WMC is performing blade tests for large wind turbines to 60 meters in length. ECN has a research wind farm where proto-type wind turbines are tested, where a research farm of 5 full-scale turbines are used for research activities and where a scale wind farm is located for research on farm control and wind farm aerodynamic research. At DUT a large selection of experimental facilities are being used for wind energy applications. The most prominent facilities are the wind tunnels, of which the Open Jet Facility is the most recent addition.

9.9 ACRONYMS AND INTERNET

2B-energy – www.2-benergy.com

AgencyNL – www.agentschapnl.nl, formerly known as SenterNovem www.senternovem.nl

DUT – Delft University of Technology – www.tudelft.nl

EAWE – European Academy of Wind Energy – www.eawe.eu

ECN – Energy research Centre of the Netherlands – www.ecn.nl

EERA – European Energy Research Alliance – www.eera-set.eu

EWEA – European Wind Energy Association - www.ewea.org

EWT – Emergya Wind Technologies – www.ewtinternational.com

IEA – International Energy Agency - www.iea.org

IEC – International Electrotechnical Commission - www.iec.ch

Lagerwey Wind - www.lagerweywind.nl

LSEO – Landelijke Stuurgroep Energie Onderzoek

MEASNET – International Network for Harmonised and Recognised Measurements in Wind Energy – www.measnet.org

MEP – Monitoring and Evaluation Program executed at the Offshore Wind farm Egmond aan Zee

NLR – Nationaal Lucht- en Ruimtevaartlaboratorium – www.nlr.nl

OWEZ – Offshore Wind farm Egmond aan Zee – www.noordzeewind.nl

RCN – Reactor Centre of the Netherlands

STX-Harakosan – www.stxwind.com

TNO – Dutch organization for Applied Scientific Research

TPWind – European Wind Energy Technology Platform - www.windplatform.eu

VWEC – VWEC Wind Energy Consult

WMC – The Knowledge Centre Wind turbine Materials and Constructions – www.wmc.eu

XEMC Darwind – www.xemc-darwind.com

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