Wind Turbine Operation and Maintenance

Survey of the Development and Research Needs

Elforsk report 12:41

Lina Bertling Tjernberg and Peter Wennerhag

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Preface

Vindforsk III is a Swedish research program that is running in the period 2009-2012. The program is divided into five activity areas:

1. The wind resource and external conditions.
2. Cost-effective plants
3. Operation and maintenance
4. Wind power in the power system
5. Standardization

In the preparation of a final report at the end of the program, and preparation of a new program period, work with survey reports for different research areas is being carried out. This report constitutes the survey report for the area operation and maintenance.

Work with a survey report for this area is carried out by Lina Bertling Tjernberg and at Peter Wennerhag Chalmers.

The report contains descriptions of projects within the program; the status and trends of technology and research; and finally an analysis of research needs within the area.

Conclusions and opinions in the report are those of the authors.

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Stockholm October 2012

Anders Björck

Program manager Vindforsk-III

Summary

This report is the result of an overview of the research and development work performed within the research program Vindforsk III, program area *Operation and Maintenance (O&M)*. The report aims at giving an overview of the performed work within the research program, to put it in a context of on-going international research, and to point out trends and developments and future research needs.

The report summarizes projects funded by Vindforsk within the area of *Operation and Maintenance*. The summary presentation of each project is based on interviews with project leaders and key researchers within each project.

Trends, development and future research needs

Actual trends and development needs in the area of operation and maintenance of wind turbines have been identified. There are several challenges to overcome to fully understand how operation and maintenance can be performed and planned to optimize the asset value of wind turbines e.g. by relating the effect of maintenance equipment to reliability. A crucial factor is to get access to the input data needed, in enough detail and range. One of the suggestions for future work is the development of common templates and databases for data e.g. related to IEA work. Other items are developments of lifetime models and performing LCC analyses. Three different areas have been identified with needs for development: (1) *Maintenance approaches and system optimization and cost analysis, (2) Maintenance supporting processes and data, and (3) Reliability and maintenance component models and analysis.*

In summary, there are several challenges and possibilities in operation and maintenance of wind power turbines, and it is expected in the future that the need for efficient methods supporting maintenance management of wind turbines will increase. The Vindforsk III program has provided some important bases for future needs and developments.

Summary of Vindforsk III projects

The following table gives a quick summary of the results obtained in the different projects. For more detailed information see Chapter 2.

Project	**Some key learning points**
V-315: Gear box failures in onshore wind power systems	Gearboxes fail prematurely, partly due to the lack of refinement/tailoring to their recent larger sizes. This may somewhat be alleviated by taking more care in choosing oil with the appropriate viscosity, correct filtering of the oil and surveillance of the wind farm. In the procurement of a wind farm, the cost for new or overhauled gearboxes during the lifetime should be incorporated already in the investment budget.

V-316: Damage preventing for wind turbines	There is a marked lack of data on reliability and damages. As a result, definite conclusions regarding damages and reliability of components cannot be drawn. Repeated tests and inspections may significantly contribute to higher confidence in the most critical components. Methods for the appropriate methods and intervals for inspections are suggested.
V-327: Reliability modelling and optimal maintenance management for wind power systems	Decision models for cost efficient maintenance for offshore wind power systems were developed. The results show that maintenance costs can be significantly reduced through optimizing the maintenance strategies, the maintenance support organization and the maintenance planning.
V-331: Experience feedback from construction inspections	A third of the wind farms constructed in the period were investigated. 30% did not pass the inspection preceding the handover from construction company to procurer. The most common faults are found on the outer surface of the towers (corrosion and damages), the gear system (lubrication) and gearbox (oil level). Most of the faults are at the time of inspection, not severe.
V-344: RAMS-database for Wind Turbines	A RAMS (Reliability, Availability, Maintainability and Safety) database will be of use to the wind industry, by providing data on component-level. Data input format must be aligned to the existing reporting systems in the industry. A RAMS-database can be used to reduce cost and downtime. The IEA Task 33 will study standardization of such type of data collection.
V-345: Feasibility study of thermal condition monitoring and condition based maintenance in wind turbines	Thermal condition monitoring (measuring the IR-radiation from objects) is useful for surveillance of electrical systems and transformers, early indication of fire and managing fire-extinguishing equipment. The method also has potential for broader use, and may be used for manual inspections as well as continuous surveillance. The cost is on the same level as existing surveillance-systems.
V-365: Wind turbine stethoscope. Measurement of the acoustic emission	Acoustic emission (Wiki "*transient elastic waves within a material, caused by the release of localized stress energy*") for condition monitoring is demonstrated to give results in line with existing methods in use (vibration-acceleration and shock pulses). Acoustic emission has the potential of being more cost effective, simpler and more reliable. A warning/message system from the system was developed in the project.

V-367: Oil cleanliness in Wind Power Gearboxes	Oil cleanliness is essential for the lifespan of gearboxes, and has high influence on the main components such as the teeth. Oil cleanliness may increase the lifespan of up to 50%. The number and size of particles in the oil, as well as types of oil-filters were tested. The way particles are counted (automated or microscopy) and the various dilutants showed large variation. As for filters, tests in real applications are needed. Laboratory filter tests showed differences in flow/permeability.
V-375: Investigation of converter failure in offshore wind turbines	A clear correlation between converter failures and lightening was found. Loosening connections to the IGBT-transistors was surprisingly found not to be a problem. Other possible causes may be condensation, insects, temperature and salt; these must be further investigated. Interestingly, there was no overrepresentation of failures in offshore-based wind farms.

Content

Abbreviations and Terminology

CBM	Condition Based Maintenance
CM	Corrective Maintenance, i.e. maintenance effort that follows a failure event
CMS	Condition Monitoring System
CR	Component Reliability Database
DCR	Database Component Reliability
ECN	Energy Research Centre of the Netherlands
LCC	Life Cycle Cost
OEM	Original Equipment Manufacturer
O&M	Operation and Maintenance
PM	Preventive Maintenance, i.e. maintenance effort that is planned
RAMS	Reliability, Availability, Maintainability and Serviceability/Safety
SCADA	Supervisory Control and Data Acquisition
SWPTC	Swedish Wind Power Technology Centre
WindAM	Wind Power Asset Management Research Group at Chalmers

1 Introduction

Wind power technology is one of the major growing areas in the energy sector. Main drivers are the environmental and political targets summarized as the European 20/20/20 goals. These have implied different incentives to promote large investments in electricity production from renewable energy resources like wind power. A general trend has been towards larger wind turbines at remote sites. However, for the business developments there is a need to maximize the overall asset value. Maintenance management is one tool for such a purpose. Maintenance can either be performed to prevent failures, preventive maintenance e.g. using scheduled intervals, or it can be performed correcting a failure event, corrective maintenance. Maintenance management approaches imply to find a sound balance between the cost and the benefit of performing maintenance. Experience and studies show that there is a large potential to reduce overall costs in the maintenance of wind turbines [1].

Operation and maintenance of wind turbines has been one development and research area including several projects within the Vindforsk III research program. The objectives of this survey report are: to give a brief overview on the projects performed within Vindforsk III on this theme, to show some main results and findings, and to discuss trends and developments resulting in recommendations on future research needs.

This survey study has involved:

- Collecting information about projects within Vindforsk III, including interviews with project leaders and main performers.
- Contacts with Vindforsk III steering group members, and members in the Nordic network within operation and maintenance of wind turbines (including members from Finland, Norway, Denmark and Sweden). Including a one-day workshop with steering group members and the Nordic group to discuss a draft report and future trends and developments. Participants can be found in Appendix 1.
- Summarizing the results including identifying the developments and research needs in this report

The work for this study has been performed within the research group Wind Power Asset Management (WindAM) at Chalmers with support from CIT Energy Management AB to perform interviews and for the workshop (Peter Wennerhag and Catrin Heincke). Some more details about the research group are given in Section 3.2.1

2 Projects within Vindforsk III

2.1 About the Vindforsk program 2009-2012

Vindforsk III is a co-financed research program that provides funding for basic and applied wind energy research. The Swedish Energy Agency is financing 50 % of the costs within the program. The other half is financed by energy companies and other companies with connection to wind power. The total budget of the program is 80 million SEK over a four-year period.

The overall objective of Vindforsk is to strengthen the conditions for building and operating wind power by:

- Producing generalizable results concerning wind energy characteristics and opportunities conducting research at the international forefront within a number of technology areas to preserve and strengthen the skills of existing research groups at universities and of engineering consultants.
- Strengthening the recruitment base for Swedish wind power industry.
- Making wind energy research visible and disseminate its results.

The program is divided into five project packages:

1 The wind resource and external conditions.
2 Cost-effective plants
3 Operation and maintenance
4 Wind power in the power system
5 Standardization

This report is focusing on the third project package of *Operation and maintenance*.

2.2 Projects within the research area of Operation and Maintenance

The overall objective of this activity area is to identify aspects that affect the maintenance management for a wind turbine due to both predictable and unpredictable incidents. The overall goal is to increase the availability of wind power systems along with a cost effective life cycle that together will benefit in establishing wind power as a competitive source of energy production. Specifically the use of condition monitoring systems (CMS) for PM, and life cycle analysis methods have been studied. The overall target is to develop maintenance strategies, which will strengthen the competiveness of wind power on the energy market.

In total nine projects within the area of operation and maintenance of wind power were involved within Vindforsk III. The total budget for the nine projects is around 6.9 Million SEK, in which Vindforsk funds 5.6 Million SEK. Table 1 shows an overview of the nine projects.

Chapter 2.3 summarizes the projects and main results.

Table 1. Project summary

Project number	Project title	Project leader	Financing
V-315	Gearbox failures in onshore wind power systems	Andreas Horste, AB Respond Industry	SEK 400 000 cash funding and SEK 200 000 in kind.
V-316	Damage preventing for wind turbines	Magnus Dahlberg, Inspecta Technology AB	SEK 520 000 cash funding and SEK 75 000 in kind.
V-327	Reliability modelling and optimal maintenance management for wind power systems	Lina Bertling Tjernberg, Chalmers	SEK 1 875 000 cash funding and SEK 350 000 in kind.
V-331	Experience feedback from construction inspections	Bertil Andersson, EnergoRetea	SEK 350 000 cash funding.
V-344	RAMS-database for Wind Turbines	Lasse Pettersson, Vattenfall Power Consultant	SEK 600 000 cash funding.
V-345	Feasibility study of thermal condition monitoring and condition-based maintenance in wind turbines	Mats Dalberg, IUC in Kalmar AB	SEK 212 000 cash funding and SEK 75 000 in kind.
V-365	Wind turbine stethoscope. Measurement of the acoustic emission	Krystof Kryniski, ÅF Infrastructure AB	SEK 392 000 cash funding and SEK 439 000 in kind.
V-367	Oil purity in wind power gearboxes	Jan Ukonsaari, Vattenfall Research & Development	SEK 560 000 cash funding and SEK 230 000 in kind
V-375	Investigation of converter failure in offshore wind turbines	Katharina Fischer, Chalmers	SEK 570 000 cash funding and SEK 100 000 in kind

2.3 Summaries of projects in Vindforsk III

In this section each project is briefly summarized. Information of the project leader, main performer, and the time period for the projects are also presented. These summaries are the results of interviews with the project leaders of the different projects.

2.3.1 V-315: Gearbox failures in onshore wind power systems

The background of this project was based on the high frequency of failures and breakdowns in onshore gearboxes that occurred in the early stages of their life cycle (5-10 years). The overall aims of the study were to investigate why the lifetime of the gearboxes was so short, as well as to provide input to help the owner to take actions to extend the lifetime [2].

A breakdown of a gearbox is devastating because of the long downtime during reparations or replacements as well as the extreme costs associated with the replacement. The expenses related to the crane needed for a replacement can be as high as 1 000 000 SEK depending on the wind turbine placement and availability. The suppliers of the wind turbines promise a lifetime of 20 years and provide owners with a service plan that does not cover measures like exchange of gears and bearings. Considering this background information three important questions have been posed:

1. Why isn't the lifetime longer?
2. What measures can be taken on existing gearboxes to extend their lifetime?
3. What is a reasonable lifetime of a gearbox?

The project covered wind turbines with a gearbox that has a planetary gear and two consecutive parallel steps. The investigated wind turbines are smaller than 2 MW and placed onshore.

The study showed four possible reasons why breakdowns occur in gearboxes.

1. *Alignment*: An error due to alignment starts in the rotor shaft and transmits during the whole gearbox. This will lead to defective load on integrated components.
2. *Problems with vibration analysis on monitoring systems*: On planetary gears vibrations are hard to measure, which makes it harder to receive actual values from the monitoring system and hence difficult to analyse the damage on bearings.
3. *Lubricating oil:* The oil is a transporter of different particles which may spread contaminations from one component to another. The viscosity at cold starts is an important aspect that must be optimized.
4. *Broken or damaged components:* Since the components of the gearbox are included in a closed system, one defective component can affect

the others. This may lead to a replacement of all bearings and gears because of one damaged component.

The design is fundamental for having a high-quality working gearbox. Overloads occur as a consequence of faulty construction and under dimension of gearboxes. This creates problems like cambered shafts and overloaded bearings. This in turn leads to contamination of the lubricating oil.

The study showed that the lubricating oil is not suited for cold starts in cold climates. The system allows low running temperature, which leaves the bearings with the wrong lubricating amount.

The compromise of using the same gear oil for all bearings and gears in the gearbox affects the components that have the highest rotational speed negative. Separate oils for shafts and bearings can be a solution for the future, but at the same time the weight of the gearbox must be as low as possible.
The possibility for the owner to lengthen the lifetime of the gearboxes can be summarized in the following points:

1. Optimizing the lubricating system and cold starts
2. Operations monitoring (temperatures, vibrations, wind, rotational speed)
3. Service controls (alignment, contamination, deterioration)
4. Preventive maintenance
5. At maintenance services exposed components should be replaced by optimized components instead of standard components.

Data and analyses showed that the average lifetime of a gearbox is between 8 and 10 years. During this period of time the reparation of the outgoing shaft of the gearbox is more a rule than an exception. To establish a fair calculation for the purchase of wind turbines owners should expect to either renovate the existing gearbox or buy a new one during the lifetime of the turbine.

2.3.2 V-316: Damage preventing for wind turbines

This project was divided into two parts where the main goals were to analyse how damages depend on important parameters such as age and type, and to define recommended damage prevention measures for components respectively.

In recent years the gathering and reporting of reliable data and the cause of failures and damages are becoming more difficult. In this part of the project data from publicly available databases and the open literature represent the main sources for information material. This information was then complemented with interviews and reports from other operators and insurance companies. In this part of the project the damage dependence on important parameters such as age and type of turbines was analysed, and in the end a component breakdown structure suitable to connect to damage preventing measures was proposed.

The first part of the project aimed at investigating the current state of reliability and failure data in the public sources and alternative sources and investigating how damages depend on important parameters such as age and size and defining the needs for improvements.

Information was collected from five databases with wind turbines located in Sweden, Denmark, Germany, and Finland.

In the first part of the project related papers were studied with information obtained from the different databases. Almost every one of these papers was based on the same databases, which all have severe limitations. Lack of details, failure data on component level are two things missing. A substantial part of the data is on the entire unit. The results of this part can be summarized: The level of detail is far from sufficient and the quality of reporting is decreasing. This in turn makes it impossible to analyse the damage dependency on parameters such as age and size. However, from interviews with operators and insurance companies one can tell that they are demanding improved insight into damage collection, maintenance, and overall damage preventing measures, which will be positive for the future. The project V-344 “RAMS-data” has looked deeper into how such failure databases could be structured.

During the project, a simplified version of how a wind turbine could be split up into different components was made. The proposed structure aims at connecting the failure to a proposed damage preventing measure and may be integrated in a database with a more general purpose. The first part of the project was reported in the “Phase 1” report [3].

The second part of the project aimed at defining recommended damage prevention measures for wind turbine components. The evaluation of the damage prevention measures was based on analysis of the physical properties of the damage process. Sometimes the damage evaluation could be modelled mathematically, which was based either on empirical observations or on basic physical observations.

The components that were evaluated are some of the most common safety critical mechanical components according to the authors in the second paper, “Phase 2” [4]:

- The primary (low-speed) shaft, the secondary (high-speed) shaft and the rotor hub
- The bolted joint between the blades and the hub and the bolted joint between the steel tower and the foundation
- The gearbox
- The rotor blades
- The steel tower

Except for these safety critical components some low-risk components have also been evaluated.

The evaluation showed that programs for recurrent inspections and non-destructive testing are a good way of preventing serious and costly damages for most of the components. Since the load on a wind power turbine is dynamic, fatigue is the dominating degradation mechanism. Since fatigue is hard to detect it is a challenge to prevent damage in this area. The effect of corrosion itself is not believed to be safety critical, but it can form a starting point for a fatigue damage that can lead to failure in a very short time. This is why the generation of corrosion can be important to monitor.

Beside recurrent inspections and non-destructive testing some fatigues of components can lead to final failure in a very short time, this is why a proper design with sufficient safety margins against fatigue failure during the whole lifetime is of great importance.

2.3.3 V-327: Reliability modeling and optimal maintenance management for wind power systems

The overall goal for this project is to develop methods for optimizing maintenance decisions and estimating operation and maintenance costs over the life cycle of offshore wind farms by using achievable reliability and cost data.

This project is a continuation of the V-210 Optimal Maintenance Management for Wind Power Systems project which was financed by Vindforsk II and presented in a TechLic report at end of 2009 [4]. After the TechLic the project has focused on application of developed theories involving collaboration with Vattenfall. It is a research project performed within a research group at Chalmers referred to as the Wind Power Asset Management Group (WindAM). During 2012 the WindAM group involved two PhD students, one post-doc and one senior researcher.

The project has focused on the developing methods for optimizing the maintenance decisions using Condition Monitoring Systems, CMS, and for estimating the operation and maintenance cost during a full life cycle.

The project is dedicated to further investigation of the cost benefit of CMS, where the maintenance planning model from Vindforsk II has been further developed to integrate weather forecasts and more decision variables, such as size of the maintenance staff and transportations vessels. The research project has been performed in close cooperation with Vattenfall. A model for estimation of cost of O&M developed by ECN has been further enhanced for the ability to account for a full life cycle. It was decided to focus on Horns Rev, an offshore wind farm located in Denmark, since it was possible to gain data from that farm. This was done by analysing work orders and SCADA data from 2009-2010.

Another investigation that was carried out covers the life cycle analysis for the maintenance support strategies for offshore wind farms. The model considers decisions for location of the accommodation platform, choices for transportation vessels and helicopters as well as the number of maintenance technicians. The model is divided into three parts, one statistic model, one queuing model and one economic model. The statistic model covers the waiting time due to environmental data both with and without a helicopter. The queuing model covers the evaluation of downtime due to lack of maintenance technicians. The last model evaluates the cost benefit for different support strategies.

Main results from the work have been published in the following papers [5]-[8], and a summary presentation of the project is reported in a PhD thesis [9].

The analyses and results have been divided into three categories: maintenance strategies, maintenance supporting organizations, and maintenance planning. In the following the main findings for these areas are summarized [9]:

- **Maintenance strategies.** Two stochastic LCC models are introduced to optimize the maintenance strategies by evaluating the benefit of CBM strategies based on inspection or continuous condition monitoring. The models are proposed for the drive train and for the blades respectively. The results show under what conditions the maintenance strategies are optimal, and how these strategies can reduce the economic risk. The results show that that condition monitoring of the drive train reduces the risk of high maintenance costs, and results in an economic benefit of 190,000 € over the lifetime. Furthermore, it is shown that the cost-benefit of inspection based on CBM techniques or continuous monitoring of blades is very much dependent on the reliability assumptions.

- **Maintenance support organization**. Two models, one analytical and one simulation model, have been proposed to optimize the maintenance support organizations for offshore wind farms. The models enable to determine the optimal support organization for a given wind farm given the reliability of the wind turbine, distance from shore, logistic costs including different types of vessels, and seasonal weather variations. The model is applied for a case study for a wind farm of 100 wind turbines with 5MW rated capacity. Results show that an economic benefit in the range of 0.6 M€-5.2 M€ over the lifetime can be achieved by selecting an optimal maintenance support solution.

- **Maintenance planning.** A simulation model for optimization of scheduled maintenance activities is proposed including the cost for transportation and production losses. The simulation is based on a rolling moving horizon taking into account the knowledge of both short-term weather forecasts and long-term weather statistics. The model is an opportunistic model, which results in PM events being planned taking opportunities of CM events. The results show that an economic benefit of up to 7,170 € per wind turbine per year may be achieved by using the proposed optimization model compared to a classic time-based approach.

2.3.4 V-331: Experience feedback from construction inspections

This project was developed to support the business by helping customers become better in requirement definitions and helping suppliers to fulfil their contracts.

Inspections are made to guarantee the supply of a purchase. During the construction inspection failures and defects that have occurred either at the factory or during the assembly on site are detected. Today these failures stay by the respective plant owner and are not reported further to a shared database.

The report [10] consists mainly of several surveys handed to a number of companies. Beside these surveys some additional deep-going interviews were held. The report contains onshore stations with a power of at least 500 kW and with inspections during 2006-2010.

Answers to 174 surveys were handed in from 19 companies of different sizes. In total 52 of the 174 wind power stations failed the inspection. This accounts for 30% of the inspected stations.

The remarks were divided into four sections; Infrastructure, Towers, Nacelle and General Remarks.

1. The *Infrastructure* section includes roads, base plate and power supply. Not all inspections included roads and it might be the reason why there are not that many remarks on this. For the base plate the ground connection was overrepresented with remarks including lack of marking and that the lead-through did not fulfil the demands. It was not always easy to place the remarks in the “right” section, this was why a remark on marking for example was sometimes put in *General remarks* and the next time under the specific component that was not marked.
2. For Towers the remarks were divided into surface protection and other remarks. The remarks on the surface protection account for one third, with errors like damaged outer and inner surface protections.
3. The *Nacelle* was separated into four sections; Hub, Wings, Lighting and Machine equipment. Machine equipment answered for the majority of the remarks, with an average number of 5.6 remarks for one station.
4. The last section for *General remarks* included quality parameters like documentation, protocols, and markings that were hard to place in one specific section. *General remarks* where highly represented as a reason at the inspections.

There was not a particular remark that led to failed inspection; instead it was believed to depend on the number of s overall remarks.

Examples of remarks that led to failed inspections were:

- Unapproved test run
- Complete information not presented
- Uninspected elevators, which leads to prohibited use.

The average number of remarks for one station was 27, but the way of presenting the remarks can, however, vary from one survey to another. One inspector for example may have split up remarks on different anti-corrosion components into several parts while another summarized them into one remark. The station that was given most remarks had 58 and the one with least had 6. Worth noting is that these two stations come from the same manufacturer.

The distribution between remarks on different manufacturers was quite similar. The same applies to the geographic distribution of remarks. When it comes to the distribution of remarks between age and size, there was no obvious difference between years and sizes of turbines.

This investigation indicated that there were large gaps in facilities at the time of the construction inspections. A lot of the remarks were not serious or difficult to fix but seem to have occurred due to the supplier's willingness to hand over the contract as quickly as possible.

The main recommendation given in the report was that the wind power industry should develop a survey template for construction inspections where both buyers and suppliers are responsible. The contracts should be designed in such a way that it is possible to hold a portion of the payment until the identified shortcomings are corrected.

2.3.5 V-344: RAMS-database for Wind Turbines

Maintenance planning for low costs and short downtimes require understanding of components and their time to failure and expected time for repair. Currently there are no sufficiently detailed data, and this is an obstacle for efficient maintenance planning. Different condition monitoring systems have lately been developed to provide information about components and their time to failure. Yet not all components can be monitored successfully in order to tell the time to failure. This motivates the use of the RAMS- database (Reliability, Availability, Maintainability and Serviceability/Safety).

By increasing the level of knowledge on properties of components, the maintenance hopefully leads to improvements, which in turn leads to high availability and low operating costs. The purpose of this project is to illustrate how the benefit of a RAMS-database will be affected by alternative possible designs and organization of the database. The main goal for the project is to present material for further discussion and work on how to set up a RAMS-database for wind turbines.

The topics of the project were divided into four parts:

1. A description of some existing RAMS-databases
2. A description of state-of–the-art concerning use of reliability within wind power today
3. A discussion on possible organizations of database and data collection
4. A survey of the interest from some major possible stakeholders in a RAMS-database

Today there are several existing databases, but none of which could be considered a proper component reliability database. Most of today's existing databases collect availability and failure statistics on a non-component level and have not got the possibility to execute "RAMS" analyses. Main reasons are that the reporting often is on a voluntary basis and that the reporting is often handwritten, which is likely to account for too much administrative work for the operators to take the time to send reports on failures etc.

In the report the term Component Reliability database, CR-database, is used, which is a database for supplying information for RAMS purposes.

Today a lot of work is being done regarding development and implementation of reliability databases, especially in the US and in Germany. The initiative to collect reliability data is mainly initiated by research institutes in order to create a large statistical database, which will make it easier for further technological progress. Several databases are available today, but of varying extent regarding the amount and type of data collected.

Three different databases were analysed as a part of the state-of-the-art use of reliability within wind power today. These three databases are: OWMEP, Reliawind and Sandia.

OWMEP is a German-funded database used for offshore wind power which collects, processes, analyses and disseminates essential data and results respectively to the public, to the government, to operators, to manufacturers etc.

Reliawind was a European Union Framework 7 project, which aimed at capturing collecting and analysing historical wind farm SCADA data logs and maintenance data to determine which components and failure modes should be subject to a more detailed work.

Sandia National Laboratories is a United States national security lab which is tasked with "creating an industry-wide capability that can track operating experience, benchmark reliability performance, characterize issues, and identify opportunities to improve the reliability of the national wind energy investment".

The conclusion from the state-of-the-art part was that before implementing a CR-database it might be worth to carefully evaluate the OWMEP, Reliawind, and Sandia database structures and what taxonomy to use.

In general there are two ways to operate a database: one in which a stakeholder operates the database and is being compensated by others, and the other in which a (consultant) organization operates the database for a fee.

A main conclusion in this project [10] was that having a stakeholder operating a database is not recommended, because it would probably never be accepted by anyone but the operator of the database. Having a database operated by a consultant or an organization can have many advantages, but there is a risk that data quality may be less good for some operators. The authors suggested that a number of possible stakeholders should be identified to discuss how to proceed. This should be done by sending out a questionnaire, which will be used as a basis for a common discussion.

2.3.6 V-345: Feasibility study of thermal condition monitoring and condition- based maintenance in wind turbines

In recent years CMS have been developed in the wind power industry, although there are still gaps in the control and monitoring systems that need to be filled. Since the power plants are unmanned and often located in inaccessible surroundings with limitations for the service personnel to stay in the machine room (nacelle) while the plant is running, there are relevant arguments for having a well-developed control and monitoring system. Beside the mentioned arguments the strongest one must be that CMS saves money. Since the early detection of problems and faults reduces the downtime and helps the planning of repairs, money will be saved.

The aim of this project was to investigate if and how IR thermography can be used for control and monitoring of components in wind turbines.
The advantage of IR sensors is that they do not have to be in contact with the object. Depending on which sensors are used the camera needs to be mounted rather close to the object to get a reliable reading. A placement of an IR-camera on a P/T (Pan/Tilt) bracket admits different line of sights for the camera and thus reduces the need for many cameras. Previously a system consisting of an IR-camera, has been developed by the company *Termisk Systemteknik*. This system could just as well, with some modifications, be used for Condition Monitoring/Predictive Maintenance of wind power turbines. The system can be used both in automatic mode where different parts of the scene are scanned automatically and in manual mode where an operator can follow objects of special interest.

The alarm criteria have to be set in accordance with predefined values, for example:

- Minor problems	1 to 10 °C temperature rise
- Intermediate problems	10 to 35 °C temperature rise
- Serious problems	35 to 75 °C temperature rise
- Critical problems	75 °C temperature rise or higher

These different criteria can tell how quickly a measure must be taken. More elaborate alarms can be designed where the temperature alarm level is combined with temperature trending.

The results from interviews with representatives from the industry show that IR-technology and advanced image analysis could add prognostic information for a number of system components. The result was that IR-Technology could be useful for control and monitoring of *Electrical Systems* (power electronics and control systems), *High Voltage Transformers* and *Nacelle and Turbine* for fire detection [12].

In the study results showed that there could be some other systems of interest for monitoring with the IR-technology. These were *Mechanical Brake, Gearbox, Yaw systems, Hydraulic Systems?* and *Sensors*.

2.3.7 V-365: Wind turbine stethoscope. Measurement of the acoustic emission

The purpose of this project is to present a functional concept for measuring acoustic emission with a wind turbine stethoscope. This will help maintenance technicians in their daily work with detecting failures on the wind turbines.

Acoustic emission methods use signals at frequencies much higher than used in mechanical vibration analyses. The methods use transducers measuring above 20 kHz, i.e. just above the normal hearing range. The current project works with transducers working with frequencies around 100 kHz. High frequency signals are more damped with distance than lower frequencies. Using a high frequency thus makes the method suitable for measuring local effects and to determine local defects since disturbing signals from other parts are damped.

Measurements on several wind turbines – on gearboxes and generator bearings – are carried out in the project in order to evaluate the method.

A major part of the project is about developing a user-friendly notification system. All data collected from the turbines are subjected to digital filtering, spectra and histograms, so that the status of the turbines can be presented on a mobile device. The information shall be easily available and clearly presented, and that is why the maintenance technicians need to have access to the information in their mobile phones. In this way there is no need for surveillance centre technicians to visit the stations every now and then. This means, above all, great benefits for maintenance in remotely situated places like offshore wind power stations. The measured signals are also digitally processed and converted to the audible frequency range, making it possible to use the human ear to listen and judge on the degree of severity of damages.

By storing records on the server, the most recent acoustic emission signals can be compared with the records taken in the past at similar operating conditions.
Obtained results show encouraging results, and a final report is expected before the end of 2012.

2.3.8 V-367: Oil cleanliness in Wind Power Gearboxes

Gearboxes in wind power turbines are known to be exposed to challenging conditions. The lifetime of a gearbox is set to 20 years and any less will lead to economical drawbacks. This project aimed at analysing the cleanliness of oils from different points of view:

- the importance of clean oils
- how to achieve clean oils
- how to measure the oil cleanliness

The project also aimed at developing a guideline for setting up a cost effective oil analysis program. This was done partly by having a review carried out on current analysis programs used in the industry today.

The main purpose of the project was to state the importance of good oil cleanliness. Other oil characteristics are also important for gearbox component life, hence a discussion about some of the gear oil properties, which are also important to monitor besides the cleanliness, was included in the report.

It is well known that particles in oils reduce the life of a component significantly. Oil contamination like water and gases is also known to affect the lifetime of the components. These contaminations will be present in gearbox oil in various amounts and significantly affect the component and the life of the oil.

A lightly loaded bearing can have a reduced life factor of 500 between heavily contaminated oil compared to a clean one. Tests under ultra-clean condition have shown that bearings had 40 times longer life compared to the calculated.

There are several oil particle counters and cleanliness control devices available on the market today. Oil conditions in wind power gearboxes during running can be a challenge for cleanliness sensors to show correct results. One goal for this study was to provide an updated literature survey explaining performance of different main types of sensors and suitability for usage. Available field test data will be included in the final report.

2.3.9 V-375: Investigation of converter failure in offshore wind turbines

The purpose of this project is to investigate the frequent failures that Vattenfall has observed from power-electronic converters in their offshore wind parks. The high failure frequency has occurred both in turbines with doubly fed induction generators (DFIG) and in full-scale power converters (FPC). There are indications that certain operating conditions increase the risk of failure, the underlying causes are not yet sufficiently known today.

The project is carried out at Chalmers University of Technology in close collaboration with Vattenfall Vindkraft AB and an expert group involving Volvo Car Corporation, ABB Corporation Research, Fraunhofer IWES, Vattenfall and Chalmers.

A literature study is carried out and a general description of converters applied in wind turbines is provided. Converter-specific failure and maintenance data from both onshore and offshore sites of Vattenfall are being analysed with the objective to identify environmental factors influencing the occurrence of failures. Beside this data will be gathered from randomly selected turbines. This will be done by collection of information about temperature and humidity from loggers in order to improve the knowledge about the real environment that the turbines are operating in. In addition, thermo-sensitive tape has been put up on a great number of turbines, which provide information about local maximum temperatures. In parallel to the data collection and analysis, several damaged converters are being tested at Chalmers and subjected to forensic analysis.

Based on the results from the different methods mentioned above, a Root-Cause Analysis is carried out together with the expert group with an objective to identify the relevant failure causes and mechanism of the investigated converters as well as potential countermeasures. The build-up of knowledge on converter reliability and particularly the knowledge transfer from the automotive sector through the representative of Volvo Cars in the expert group has turned out to be very effective. The first part of the project included the first expert group meeting has revealed a significantly more comprehensive and clearer picture of the possible failure causes and mechanisms. The second part of the work aims at eliminating factors that are not believed to influence the failure frequency of the converters and identifying the most relevant ones.

The expectations on the outcome of the project are to provide an improved understanding of the factors that affect the failure and life cycle of converters in wind turbines. The project is seen as a pre-study, the results of which are expected to be useful for the recommendation of future work on the topic in general and the identification of future research needs in particular.

3 O&M Trends and Developments

Operation and maintenance provide means to impact on the failure rate of components and outage time in event of a failure. Consequently, a tool for accessing a high level of availability is essential. Maintenance management is one expression for handling that process from management level to equipment maintenance [16].

Historically wind turbine projects turned out to be burdened with much higher O&M costs than anticipated in the project-planning phase. There may be many reasons for that: lack of statistics, bad guesswork and an over-estimated belief in the reliability and the lifetime of the machines and connecting systems. It was also in a period when the industry had focus on implementation and building projects rather that discussing issues and costs in the future. When the industry became more mature and utilities were having large assets of wind parks, an increased focus on cost figures for O&M arose. This was catalysing an increased interest in research related to O&M strategies and failure statistics. Strategies for operation and maintenance are becoming more critical with up scaling and deployment offshore. The overall objective of the wind turbine research is typically to optimize O&M strategies in order to increase availability and system reliability. Costs for O&M are one of the major lifetime costs for a wind project.

Different general studies have been made trying to identify the most critical components in a wind turbine and the components making the largest contribution to unavailability i.e. down time. However, it is difficult to get reliable and updated results from such studies. The reason is mainly that this knowledge says with the suppliers of wind turbines and utilities. Owners of the data are not that eager to publish results, which may show shortcomings of their products. In order to show some examples of failure statistics two examples are shown below.

Table 1 presents the top ten components, which are responsible for most downtime caused in the wind turbines. The data have been gathered for wind turbines in Sweden from 1997 to 2005 [24]. It must be emphasised that this is quite old data and technology improvements may have changed the situation, since the study was performed.

Table 1 Failure statistic data for top ten critical components in wind turbines [24]. "Survey of failures in wind power systems with focus on Swedish wind power plants during 1997-2005"

Component	Failure rate	Downtime per failure [h]
Gears	0.045	256.7
Control system	0.050	184.6
Electric System	0.067	106.6
Yaw system	0.026	259.4
Blades and pitch system	0.052	12.5

Generator	0.021	210.7
Sensors	0.054	49.4
Hydraulics	0.061	43.2
Drive Train	0.004	291.4
Mechanical Brake	0.005	125.4

The highest failure rate is shown by the electrical system, but the associated down time is low compared to failure rates in gear, yaw, generator and drive train. In order to get the full picture of the influence of the failures, repair and replacement costs have to be included. When such considerations are done, gearbox failures have been high on the top ten list of cost.

Table 2 presents results from the Reliawind project run between 2008 and 2011. It involves data from 450 wind farm months from both on-shore and off-shore wind turbines operating for varying lengths of time [15]. The results show that the main failure rate is associated with electrical systems such as converters, switchgear and generators. Components in the rotor module such as the pitch system are contributor number two to failure rate and contribution to down time. Table 2 shows the contribution from single components. Gearbox failures are quite low in failure rate, but the resulting cost of a gearbox failure is often quite high compared to other failures. The increasing number of direct drive machines may alter the distribution and number of the different failure types. It is not known at present whether there is a significant difference in failure types between traditional machines and direct drive ones.

Table 2 Failure statistics for critical components of wind turbines [15]. "Report on Wind Turbine Reliability Profiles" from the Reliawind project

Assembly	Contribution to total Failure rate [%]	Contribution to average Time Lost [%]
Pitch system	21.29	23.32
Frequency converter	12.96	18.39
Generator assembly	7.16	10.47
Yaw system	11.28	7.30
Gearbox assembly	5.13	4.66
MV Switchgear	3.32	3.27
LV Switchgear	5.88	3.03
Transformer	1.71	1.84
Tower	2.66	1.75
Hydraulic system	1.19	1.42

This Chapter shows trends and developments for wind turbines focusing on the operation and maintenance aspects. In the first section a brief state-of-art is presented identifying actual research areas and results from different research groups. In the second section related research in Sweden is presented and some brief examples of research and development at other groups mostly focusing on Nordic countries.

3.1 State-of-art on maintenance management for wind turbines

Operation and maintenance have a significant contribution to the life cycle cost of wind farms, in the range of 5-10% for onshore wind farms and 15-30% for offshore wind farms [18]. Therefore the reliability and maintenance aspects of wind turbines need to be analysed and optimized with respect to cost and availability over the lifetime of the system.

The reliability of onshore wind turbines has been reported in several studies [19] - [27]. The analysis was typically based on manual reporting, and the need for automatic data collection and standardization of the structure of the database was recognized [27]. In [26] recent results from a EU project Reliawind, previously mentioned, are presented. The availability of onshore wind turbines is typically in the range of 95-99%, while for early offshore projects, availability as low as 60-70% has been observed at some wind farms [28], [29]. The analysis of the reliability of new wind turbine designs has been investigated based on a Failure Mode and Effect Analysis in [30], [31].

Several publications have focused on determining suitable maintenance strategies based on Reliability Centred Maintenance methodology, see e.g. [32]-[35]. Quantitative models for analysis of maintenance strategies for the major components of the wind turbine were proposed in e.g. [7], [34] and [36]-[38]. In these models statistical methods are used to predict failures and the impact gained by different maintenance activities and strategies.

The diagnosis and prognosis capabilities of condition monitoring systems can provide significant benefit in the planning of maintenance activities. The technical aspects and state-of-the-art of condition monitoring systems have been investigated in e.g. [39] - [43]. The development of a mathematical model for prognoses based on condition monitoring systems has received limited focus. An on-going project within the WindAM research group is focusing on establishing a correlation between external environmental factors like wind speed and temperature and the failures in wind turbines using SCADA data [45]. SCADA data is used to develop a prognosis algorithm that will provide the operator with an easy-to-understand real-time condition status of the major components in the wind turbine [45]. Furthermore, ECN do analyses of relating data from SCADA and maintenance needs [46]. The so-called Flight Leader concept developed by ECN is used to study loads on various components in wind turbines. This information together with dynamic models is used to forecast the remaining lifetime of a wind turbine. Such developments are also on going in Denmark.

The optimization of maintenance scheduling has been investigated in e.g. [47], [48]. With the advances in diagnosis and prognosis capabilities, the area of maintenance scheduling could receive further interest in the near future. Several commercial models have been developed for analysis of maintenance support organization for offshore wind farms, see e.g. [49] for an analytical model, and [50], [51] for simulation models. This area is of particular interest for new offshore wind farms, where the distance from shore and environmental conditions imply the need of new support strategies whose cost benefits need to be analysed. An analysis of spare-part strategy has also been performed in [52].

3.2 Examples of research actives in O&M of wind turbines

This chapter first gives an overview of related research in operation and maintenance of wind turbines Sweden. It also identifies some international related activities.

3.2.1 Sweden

There are two main national research programs within wind power in Sweden. The Vindforsk III program, which is in focus for this study, which focuses on developing and operating wind farms as well as grid issues, and the Vindval program, which studies the consequences of wind power in respect to a human and nature-preserving perspective. Furthermore there is a National Centre on wind power funded by the Swedish Energy Authority [53]. This centre, the Swedish Wind Power Technology Centre (SWPTC), focuses on research and developments for construction and production of wind power. The research in SWPTC is carried out in theme groups that represent construction and operation of wind turbines, and one group focusing on Maintenance and Reliability.

The WindAM research group at Chalmers focuses on research within the area of reliability-centred maintenance (RCM) and currently involves two PhD student projects, one performed within Vindforsk and one within the SWPTC, and a post-doc project funded by Göteborg Energy Research foundation (2010-2012).

There are several research groups in Sweden working on different applications on maintenance. UTEK is a national member organization for maintenance, which also has a scientific board representing these different groups. UTEK e.g. award each year the best master thesis in the area of maintenance. Examples of research areas are e.g. in Luleå with extensive research related to railways, and SKF has their research labs on condition monitoring. More information about UTEK from www.utek.se

3.2.2 International examples

This section gives a brief overview on some international on-going work on O&M of wind turbines.

In **Norway** there has been a substantial increase in R&D related to wind energy in recent years, especially on offshore wind power. In 2009 the Norwegian Research Council established two research centres on offshore wind energy under the so-called FME arrangement (Centres for Environment-friendly Energy Research). One of two offshore wind research centres in Norway is NORCOWE (www.norcowe.no) and the other is NOWITECH (www.nowitech.no). The work within NOWITECH on O&M is dedicated to Maintenance strategies (decision support, optimization, cost-benefit analysis), Condition monitoring (degradation modelling, presence, utilization/ aggregation of technical condition indices) and Coatings and Protection against wear and corrosion. A third centre is CEDREN – Centre for Environmental Design of Renewable Energy (www.cedren.no): Interdisciplinary research centre for technical and environmental development of hydro power, wind power, power line rights-of-way and implementation of environment and energy policy. In the CEDREN-context there has been conducted research on bird-friendly localization and design of onshore wind power plants.

Denmark has a strong profile within renewable energy developments. In 2007 Denmark's Risø National Laboratory, the Technical University of Denmark (DTU), signed an agreement to cooperate closely on improving wind energy technologies jointly with the U.S. Department of Energy's National Renewable Energy Laboratory (NREL). Related to the *operation and maintenance* of wind turbines, Risø is dealing with a broad spectrum of activities ranging from reliability of components to maintenance strategies. Examples are given by a national database for *old* wind turbines to support in the maintenance management.

UK has an extensive development of offshore wind industry. At Strathclyde University there is a Centre for Doctoral Training in Wind Energy Systems established in 2009. The Centre has associated industry-funded research clusters e.g. in operation and maintenance of wind turbines focusing on condition monitoring and asset management.

The Netherlands and Germany lead several major developments within wind energy including operation and maintenance efforts. E.g. ECN in the Netherlands has developed a cost calculator for estimation of O&M costs. This tool has been used by utilities to study the influence of different parameters on the forecasted cost of O&M. Fraunhofer IWS in Germany addresses application- oriented research in the wind energy field. One area is Condition Based Maintenance (CBM) of offshore wind farms.

In **North America** the early wind energy developments are from the California area. Sandia Labs in the US is famous for the CREW database (Continuous Reliability Enhancement for Wind) and also the workshops dealing with Reliability, the last one held in 2011. The CREW project has prepared Benchmarks on reliability of the US fleet of wind turbines.

In **China** the wind industry has grown significantly in the last years. In 2011 China contributed with 44% of the new installed capacity during that year [14] and [16]. The strategy in China has been to start with introduction of smaller turbines based on proven technologies. This has limited early design failures.

The “Nordic Countries”

In 2011 a Nordic network within operation and maintenance of wind turbines (including members from Finland, Norway, Denmark and Sweden) was initiated. A joint interest e.g. in access to failure data statistics has been identified.

The newly initiated IEA Wind Task 33 - Reliability Data Standardization of data collection for wind turbine reliability and operation & maintenance analyses gathers partners from several of these areas: China, Denmark, Sweden, Norway, UK, Germany etc. The convener of the task force is from Fraunhofer Institute for Wind Energy and Energy System Technology IWES [17].

3.3 Discussion on Trends and Developments

This Section summarizes trends and developments for operation and maintenance of wind power turbines. As an input for this text a workshop was held within the Vindforsk program in June 2012.

In summary three general trends have been identified related to: cost of O&M and LCC analysis, size of wind turbines and wind farms, and access to data for the wind turbines.

3.3.1 Cost of O&M and LCC analysis

There is a need to reduce the total cost of electricity production including O&M. This is especially true for larger offshore wind farms, which results in higher demands on O&M, e.g. related to accessibility. One approach for estimating these costs and also for comparing different alternative investments and configurations is the *Life cycle cost analysis (LCC)*. LCC models are increasingly used for the wind power systems [16]. The LCC give support in maintenance management focusing on the asset value rather than the investment costs. This might be needed in order to motivate increased cost of maintenance to reduce the total LCC.

The LCC model was used in the research project within Vindforsk, presented in Chapter 2.3.3. Results showed that it is beneficial using life cycle cost models for optimizing maintenance strategies. Specifically results showed that condition monitoring of the drive train reduce the risk of high maintenance costs and results in an economic benefit of 190,000 € over the lifetime. Example on other on going research work pursuing LCC for wind power maintenance is e.g. given by [13].

3.3.2 Size of wind turbines and farm related to O&M

The average size of offshore wind farms is increasing steadily. In 2011 the average size was 200 MW and the average size of wind farms currently under construction is about 300 MW in 2012, and wind farms where construction has not yet started 344 MW. In the UK offshore wind “Round 3” are developers to 555 MW planning the average size. Moreover, offshore wind farms are increasingly being built further from the coast and in deeper waters. In 2011 the average distance from shore was 23,4 km and the average water depth was 22,8 m. For projects now under construction the average distance to shore is 33,2 km and the average depth is 25,3 m. These trends towards larger turbines and larger wind farms result in special requirements on the maintenance management, e.g. requirements on logistics for handling spare parts and personnel. Larger farms are also typically involved with longer distances from land, which results in more challenges for transportation

3.3.3 Access to data for the wind turbine

The access of data is crucial for the efficient operation and maintenance of wind turbines. A general trend is to use more condition-based maintenance (CBM) and opportunity-based O&M. SCADA and CBM data will play an important role in the development of improved O&M methods.

During warranty turbine OEMs have a large amount of data available from their SCADA and CMS systems. These data can be used to dispatch service technicians. Out of warranty the operators have typically access to more restricted SCADA and CMS datasets, depending on their capability. Vattenfall and DONG Energy are well ahead in this area. In general, onshore O&M is very heavily dominated by breakdown repair (corrective), because operators are unable to view online data in a timely way and plan to mitigate deteriorating faults.

4 Future research needs

The current large development of wind power is expected to continue in future, although probably with a lower increase rate than in past years. The technology development is becoming more mature and the O&M is expected to increase in importance for future wind projects. Especially for larger wind farms and offshore sites that are difficult to access and with high costs related to restoring failures. Advanced methods for preventing failures, e.g. based on CMS using information of the equipment, are expected to increase.

Although there are several on-going research and development activities, some presented in previous chapters, there are several challenges to overcome to fully understand how maintenance and operation can be performed and planned to optimize the asset value. The future needs identified within this study have been categorized into the three areas of:

1. *Maintenance approaches and system optimization and cost analysis*
2. *Processes and data supporting maintenance*
3. *Reliability and maintenance component models and analysis*

In the following section these different areas will be discussed in more detail.

4.1 Discussion on research needs

4.1.1 Maintenance approaches, system optimization and cost analysis

The overall aim of O&M is to maximize the value of the maintenance assets. Optimization could be made in several layers, e.g. for the maintenance planning efforts, for the maintenance support organization, or for different alternative maintenance strategies.

Results within the Vindforsk program have proposed several models for maintenance optimization and have pointed out benefits. There are several possibilities to further extend and develop these models to be applicable for real case systems.

There are several needs identified for developing models to improve the O&M. Below are some needs that where identified within the workshop in this study listed as follows:

Show on the benefits of maintenance optimization and LCC
There is a need to fully explore different factors for making optimization of O&M. The effects on operational and maintenance control/decision on higher level (i.e. expected lifetime and business performance on park level). Some needs that could be answered with this researh area are: motivating the operators to change from corrective to preventive maintenance and to

develop effective methods and strategies for replacement of large components.

Lifetime extension modelling
Methods to assess the possibilities for lifetime extension could be developed. Today a wind turbine is designed for 20 years of operation. The development of methods, which makes it possible to determine if the turbines can run a few more years, would be very valuable. Develop condition analysis, which assesses the remaining life of the important components and sets conditions for extended life. Load conditions from grid regulations could be a part of this as well. The national database in Denmark, The register of wind turbines, which is available from the Danish Energy Agency, could be used as one input for such a study. Related to the life-time modelling one parameter would be to study if there is any major difference in maintenance needs for different types of wind turbine concepts, especially related to traditional geared concepts vs. direct dive machines.

Condition monitoring
New approaches and further development of existing methods for condition monitoring of wind turbines, based on developed and standardized data collection in combination with novel and developed sensors. This includes better maintenance scheduling techniques that take account of the weather as well as optimal maintenance strategies.

Cost estimations
Forecasting capital costs for wind turbines as a part of LCC is crucial. Various studies over the last decade have attempted to forecast capital costs of wind power. The main assumption underpinning these models is that cost reductions will accrue indefinitely from technological learning over time. Another approach for wind farm capital cost estimation could be based on commodities price and water depth rather than technological learning. With greater simplicity and certainty in the theoretical foundations of such a model, it might be possible to gain realistic estimates of wind turbine capital cost. This will make it possible for wind farm developers to understand their future risk exposure to price fluctuations in capital cost of plant [13]. In combination with this it would be valuable to design components for realistic lifetime, i.e. gearboxes could be designed for replacement after X years, if it is not possible to guarantee a 20 year lifetime.

4.1.2 Maintenance supporting processes and data

With more advanced models for O&M there is an extensive need for more data both as input for the models but also in the process of analysing and improving/validating the models. This opens up for new development and research areas related to data management. Below are some identified needs related to this area.

Structured final inspections
An inspection template for the construction inspections within the wind power business needs to be developed. The template should be developed by suppliers and customers together forming guidelines for which documentation should be handed over from the supplier to the customer. This would be a

development topic rather than research topic, with application of known failure statistics.

Failure statistics
There is a general need for quantitative planning methods and measurement techniques which will make detection of failures possible. However these methods need expensive sets of input data. In IEA Wind there is a new initiative, Task 33 [17], to define common and structured data collection concerning reliability and accessibility. This will probably result in a setup of basic information, which could be extended on national or regional basis. It was discussed at the workshop (See Appendix) that this would be an interesting activity to take part in. Furthermore, this development could include defining the input of a CR-database more in detail containing: Failure reports, Code lists (failure cause etc), Taxonomy, Equipment data, etc. Suppliers have their individual setups of data during warranty time, which are mostly unavailable and incompatible with other data setups. It seems essential to make the suppliers data available in a compatible way without impacting on business secrets.

Intelligent use of SCADA and CMS
Main challenges in the operation and maintenance of wind turbines lies in the handling of large volumes of data, and relating this data into useful models for planning and prediction.

A more structured and automatic approach to the handling of integrated SCADA and CMS data from wind farms will help maintenance managers and asset managers to see clearly in advance where risks lie and schedule maintenance in a constructive way on the basis of condition.

4.1.3 Reliability and maintenance component modeling and analysis

There is a need for future research understanding the underlying failure mechanisms of the components and on how these could be impacted by O&M. The following different needs have been identified:

Methods for failure detection
Fatigue is one of the most frequent component failures that is why it is important to develop better methods for indicating fatigue and methods for monitoring those indicators and in connection with this to develop methods for prevention of fatigue.

Methods for failure prognosis
The resulting systems and data from the use of SCADA and CMS could be used for fault prognoses. There would be a need of research developing models for critical components relating failure events to maintenance impact. Although there is on-going research in this area, there is still a long way to go before quantitative models are used in a systematic way to support in the O&M.

4.2 Summary

In summary, the future needs for development and research within O&M of wind turbines have been categorized into three overall areas of:

1. *Maintenance approaches, system optimization and cost analysis.* This area relates to the overall aim of O&M, i.e. to maximize the value of the maintenance assets. Optimization could be made in several layers, e.g. for the maintenance planning efforts, for the maintenance support organization or for different alternative maintenance strategies. LCC models can be used comparing different alternative maintenance strategies. Results within the Vindforsk program has proposed several models and pointed out benefits. There are several possibilities to further develop these models to be applicable for real-case systems.

2. *Processes and data supporting maintenance.* With more advanced models for O&M there is an extensive need for more data both as input for the models but also in the process of analysing and solving the models. This opens up for new development and research areas related to data management.

3. *Reliability and maintenance component models and analysis.* The advanced models for O&M require knowledge of the components being exposed to different maintenance efforts. This involves the different aspects of how the reliability performance is influenced by maintenance. Some research work has been performed within this area. However, there are no available general models and there is large potential for future developments and research.

Appendix

Workshop on June 15, 2012 Vindforsk III

Participants

Name	Affiliation	Role
Anders Björck	Vindforsk	Program Manager, Steering group
Stig Goethe	Vindforsk	Chairman Vindforsk
Anders Johnsson	Vattenfall	R&D and O&M, Steering group
Solgun Furnes	Energi Norge	Steering group, Nordic Network R&M
Jørn Heggset	Sintef, Norge	Nordic Network R&M
Peggy Friis	DTU, Denmark	Nordic Network R&M
Erkki Jantunen	VTT, Finland	Nordic Network R&M
Ina Jakobsen	Nordic Energy	Nordic Network R&M
Katherine Elkington	Svenska Kraftnät	
Lina Bertling Tjernberg	Chalmers	Professor, Project leader
Peter Wennerhag	CIT Energy Management AB	Project administration

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