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Report

Surveillance and condition monitoring of offshore wind turbines

D5.2-47

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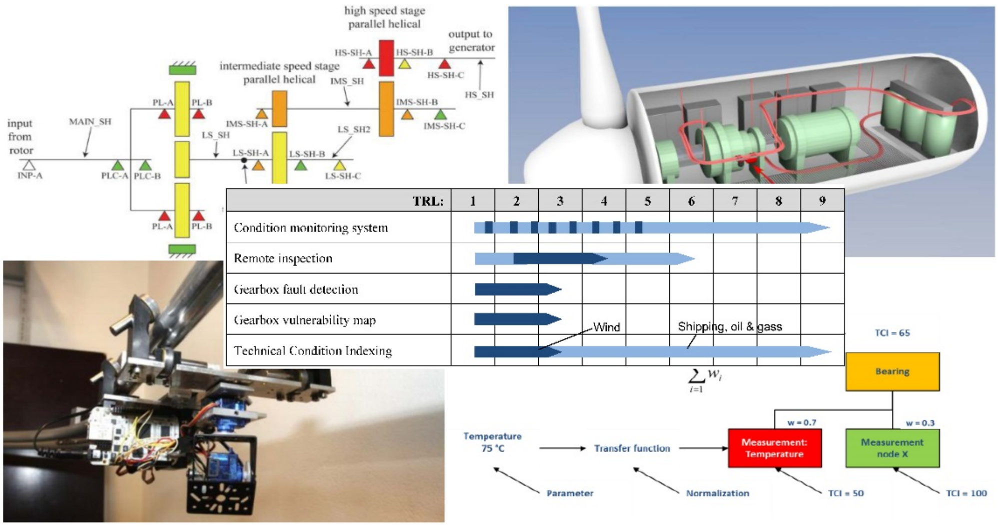

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ABSTRACT

This report summarizes results from the activities on surveillance and condition monitoring in work packages WP 5 (2009-2014) and WP B (2015) in the NOWITECH research centre. The research covered both condition monitoring systems, remote inspection technologies and models for estimating and monitoring technical condition of wind turbine components. Furthermore, pre-studies and state-of-the-art studies have been conducted on various topics, such as wireless communication and remotely piloted aircraft systems (RPAS). This report is restricted to brief descriptions of the research results, whereas further details can be found in the references presented and summarized here.

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1 Introduction

The goal of the activities related to Operation and Maintenance (O&M) organized in work packages "WP 5 - O&M" (2009-2014) and "WP B - O&M and Materials" (after 2014) in the Norwegian Research Centre for Offshore Wind Technology (NOWITECH) was to develop a scientific foundation for implementation of cost-effective O&M strategies and technologies for offshore wind farms. Besides various other solutions, it is expected that new solutions for condition monitoring and surveillance will contribute to cost-effectiveness of offshore wind turbines.

NOWITECH included a number of different research activities on surveillance and condition monitoring that have been organized in an own task (task 5.2/task B.2) in WP 5/WP B. One aim in this task was to adapt and develop condition monitoring methods and tools for predictive maintenance strategies, seeking to integrate condition monitoring and predictive component degradation models into the control system. Hence, the following milestone was included in the original NOWITECH research centre application that was sent to The Research Council of Norway in 2009: "Description of novel condition monitoring system for offshore wind farms".

International standards in the field of maintenance and reliability/dependability define *Condition monitoring* as:

<u>condition monitoring, <of an item></u> **IEC 60050-192:2015** [1]
obtaining information about physical state or operational parameters
Note 1 to entry: Condition monitoring is used to determine when preventive maintenance may be required.
Note 2 to entry: Condition monitoring may be conducted automatically during operation or at planned intervals.
Note 3 to entry: Condition monitoring methods include: vibration analysis, tribology and thermography.

<u>condition monitoring</u> **EN 13306:2010** [2]
activity, performed either manually or automatically, intended to measure at predetermined intervals the characteristics and parameters of the actual state of an item
Note 1 Monitoring is distinguished from inspection in that it is used to evaluate any changes in the parameters of the item with time.
Note 2 Monitoring may be continuous, over time interval or after a given number of operations.
Note 3 Monitoring is usually carried out in operating state.

This means that many of the activities and results from WP 5 task 5.2/ WP B task B.2 constitute a contribution to the milestone. This report summarizes these activities and results. NOWITECH partners that have been involved are:

R&D partners:
SINTEF Energy Research
MARINTEK
Norwegian University of Science and Technology (NTNU)

Industry partners:
Statkraft
Statoil
EDF R&D
Kongsberg Maritime
Fedem
Norsk Automatisering

1.1 Activities

In the following, the NOWITECH research and activities related to surveillance and condition monitoring are grouped in five topical areas:

- Condition monitoring system (Chapter 2)
- Remote inspection (Chapter 3)
- Gear box reliability and fault detection (Chapter 4)
- Condition monitoring data modelling (Chapter 5)
- State-of-the-art and pre-studies (Chapter 6)

A short description of these five areas can be found below. More detailed information and references to NOWITECH publications can be found in chapters 2 – 6.

<u>Condition monitoring system (Chapter 2)</u>
The development of a condition monitoring system for wind turbines was the aim of the cooperation between NOWITECH and the NOWITECH spin-off project "Windsense – Add-on instrumentation system for wind turbines". Windsense was a three-year (2012-2014) Innovation Project for the Industrial Sector (IPN) lead by Kongsberg Maritime and financially supported by the Research Council of Norway. The goal of the Windsense project was to develop an instrumentation system that increases flexibility regarding collection and usability of data.

<u>Remote inspection (Chapter 3)</u>
A robot prototype for remote inspection of the equipment in the wind turbine nacelle has been developed and the prototype has been used to evaluate the benefit and feasibility of the remote inspection concept.

<u>Gear box reliability and fault detection (Chapter 4)</u>
Models for the drivetrain and the reliability of different gear box components (bearings and gear wheels) have been developed, including models for fault detection.

<u>Condition monitoring data modelling (Chapter 5)</u>
NOWITECH research activities included degradation modelling and use of inspection and monitoring data in models for evaluating technical condition (e.g. technical condition indexing) of wind turbine components and prediction of remaining life.

<u>State-of-the-art and pre-studies (Chapter 6)</u>
State of the art studies and pre-studies related to surveillance and condition monitoring are summarized in Chapter 6.

1.2 Publications

The most important NOWITECH WP 5 and WP B publications that are related to wind turbine surveillance and condition monitoring are listed in Table 1. In addition to the publications listed in the table, several other publications are more or less closely related to the topic, but not listed in the table, because they describe methods and models that represent theoretical background.

Table 1 Deliverables related to surveillance and condition monitoring of wind turbines. The complete reference can be found in the reference list at the end of this report.

NOWITECH publication (deliverable)		
No./Ref.	**Title**	**Type**
Condition monitoring system (Chapter 2)		
[D5.1-44]	Development of optimal maintenance strategies for offshore wind turbine by using artificial neural networks	Journal paper
[D5.2-36]	Data series, results and analysis of measurement data from Hundhammerfjellet Comparison of data-driven and model-based methodologies of wind turbine fault detection with SCADA data	Conference paper
Remote inspection (Chapter 3)		
[D5.2-02]	Pre-Study on Cost-effective, Remote, Environmental Friendly O&M of Large Scale Offshore Wind Turbine Plants	Memo
[D5.2-03]	Remote Presence, Cost-Effective Robotic Inspection and Maintenance of Offshore Wind Turbine	Conference paper
[D5.2-07]	Extending Condition Monitoring of Offshore Wind Farms with Remote Inspection	Conference paper
[D5.2-08]	Prototyping and Evaluation of a Telerobot for Remote Inspection of Offshore Wind Farms	Conference paper
[D5.2-11]	Experimental design of a feasibility study for remote inspection of wind turbines	Conference paper
[D5.2-14]	Two Pilot Experiments on the Feasibility of Telerobotic Inspection of Offshore Wind Turbines (Mediterranean Conference on Embedded Computing	Conference paper
[D5.2-24]	Valuation of Remote Presence Robotics in Offshore Wind Turbines	Report
[D5.2-29]	An Experiment on the Effectiveness of Remote, Robotic Inspection Compared to Manned	Conference paper
[D5.2-39]	Cost-Benefit Evaluation of Remote Inspection of Offshore Wind Farms by Simulating the Operation and Maintenance Phase	Journal paper
[D5.2-48]	Remote Inspection of Offshore Wind Turbines - A Study of the Benefits, Usability and Feasibility	PhD thesis
Gearbox reliability and fault detection (Chapter 4)		
[D5.2-40]	Fatigue Reliability-based Inspection and Maintenance Planning of Gearbox Components in Wind Turbine Drivetrains	Journal paper
[D5.2-41]	A prognostic method for fault detection in wind turbine drivetrains	Conference paper
[D5.2-42]	Frequency based Wind Turbine Gearbox Fault Detection applied to a 750 kW Wind Turbine	Journal paper
[DB.2-8]	Development of a 5 MW reference gearbox for offshore wind turbines	Journal paper
[DB.2-12]	Dynamic analysis and design of gearboxes on offshore wind turbines in a structural reliability perspective	PhD thesis
Condition monitoring data modelling (Chapter 5)		
[D5.2-15]	Degradation/failure models for offshore wind turbines	Report
[D5.2-18]	Condition and performance data for wind farms in a life cycle perspective	Report
[D5.2-17]	Technical condition indexing of an offshore wind farm	Report
[D5.2-19]	Probabilistic modelling of a wind farm using the TCI framework	Report
[D5.2-35]	Failure prediction for monitored systems	Conference paper

State-of-the-art and pre-studies (Chapter 6)		
[D5.2-01]	Condition Monitoring of Offshore Wind Farms – State of the Art Study	Memo
[D5.2-04]	Pre-study on expected degradation mechanisms and failures in offshore wind turbines	Report
[D5.2-05]	State of the art: Wireless communication that can be utilised in O&M of offshore wind farms	Memo
[D5.2-20]	Operation & Maintenance of Offshore Wind Parks - Strategic Research Agenda	Report
[D5.2-46]	RPAS for inspection of wind turbine blades	Report

2 Condition monitoring system

In 2012, the three-year research project "Windsense –Add-on instrumentation system for wind turbines" has been started to develop an instrumentation system that increases flexibility regarding collection and usability of data. The project can be considered as a NOWITECH spin-off, and the NOWITECH industry partner Kongsberg Maritime has been leader of the Windsense project. The Windsense-project activities have been carried out in close collaboration with NOWITECH and with participation of the NOWITECH partners SINTEF Energy Research, MARINTEK, Statoil and the Norwegian University of Science and Technology (NTNU). In addition, Nord-Trøndelag Elektrisitetsverk (NTE) Energi, Trollhetta, Light Structures and Høgskolen i Sør-Trøndelag (HiST) participated in the Windsense project. The project was financially supported by The Research Council of Norway.

The final result of the R&D activities and Kongsberg's own R&D effort was the development of a turbine manufacturer independent decision support system that now is ready for the market. The system, called EmPower [3], consists of four main modules: 1. Performance Monitoring, 2. Condition Monitoring, 3. Production Forecasting, and 4. Wind Farm Control.

The activities in NOWITECH WP 5/WP B and the Windsense project were mainly related to the condition monitoring module. Wind turbines are equipped with an extensive number of sensors and associated equipment for surveillance and fault handling. The developed condition monitoring system (CMS) increased the flexibility regarding data collection and improved the utilisation of data. Functionalities include early fault detection, fault diagnosis and prognosis of remaining time to failure. Furthermore, the system shall support decisions for condition-based maintenance.

The Windsense-project and the related work in NOWITECH contributed on several areas to the development of the CMS. Shortcomings in present wind turbine instrumentation have been identified, and alternative methods for additional or improved sensing have been evaluated. These findings are incorporated in the specification for the add-on instrumentation system together with the inputs from operational experience. An important and novel characteristic for the new system is flexibility with respect to extension of both the number and type of measurements it will be able to handle. The system is designed for “plug and play” integration of new sensors / data sources and data analysing services since new instrumentation possibilities most probably will be following the pace of the development of new turbine and sensor technology.

Research work has been carried out on signal analysis for earlier and more precise fault detection based on condition monitoring data. The developed CMS will enable improved analysis of existing data from the turbine’s SCADA system and combine this with information collected by the add-on system. As there is a general lack of open data, data for analysis have been collected from laboratory tests of electrical frequency converters as well as field measurements of mechanical parameters on turbines in normal operation. This work included the evaluation of various optical (IR) and wireless sensors for temperature measurements. Structural health monitoring by fibre optical sensors was another activity in the project.

Valuable test data have been obtained from a turbine with a known bearing fault which can be directly compared to a neighbouring healthy turbine. By implementing Artificial Neural Network (ANN) analysis, a potential of 2-3 months earlier detection of a bearing fault has been demonstrated [D5.2-36], see Figure 1.

Another focus area was models for prediction of remaining useful lifetime of critical components. This is still an area of research where the theoretical models are not yet ready for implementation in commercial systems. Some methods rely on long term statistics based on reliability data which is not publically available. Research project activities are hardly able to generate internally such statistics within the timeframe of the project. However, NOWITECH has been involved in international activities which are aiming for improvement of reliability data collection (IEA Wind Task 33 on "Reliability Data").

Results from the aforementioned activities can be found in NOWITECH publications [D5.1-44] and [D5.2-36] and the following Windsense publications [4]-[13].

- ①: The first important deviation from the model estimates occurred from the start of October 2010.
- ③: the turbine was stopped because of overheating.
- The operator try to solve the problem two times in point ③ and ④ but not successful.
- ⑤: the turbine was completely stopped because of the overheating
- 3 months early warning
- 10 days close alarm

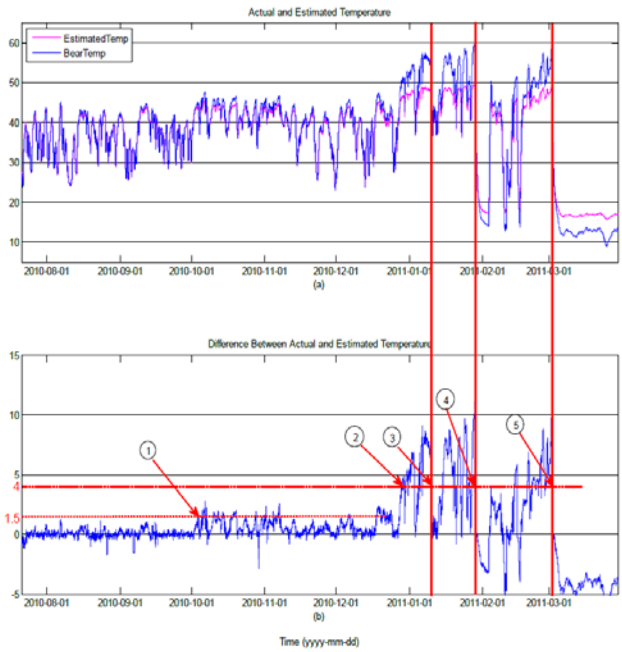


Figure 1 Detection of fault in wind turbine rear bearing [D5.2-36].

3 Remote inspection

Remote inspection (remote presence) is a novel concept for inspection of wind turbines developed in NOWITECH WP 5/WP B. The major part of the remote inspection concept development was carried out by Øyvind Netland as part of his PhD work. The work and the research results are extensively documented in Netland's PhD thesis [D5.2-48] and the related publications.

The remote inspection concept is implemented by a remotely controlled robot intended to be installed on a rail inside wind turbine nacelles (Figure 2). The robot has been developed and tested in lab scale by Netland during his PhD work. Further development, including real life testing is planned by the NOWITECH industry partner Norsk Automatisering, in the NOWITECH spin-off project LEANWIND (EU FP7, 2013-2017), and through a User-driven Research Based Innovation initiative (Brukerstyrt innovasjonsarena - BIA).

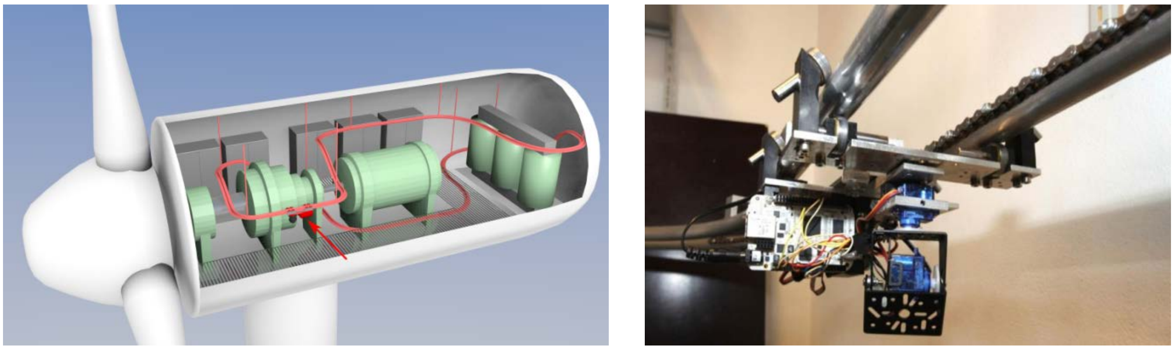


Figure 2 Remote inspection robot installed in nacelle (left) and lab prototype of remote inspection robot (right). Photos: Ø. Netland.

The remote inspection technology enables low cost remote inspection of offshore turbines and can reduce the need for manned inspections, consequently contributing to reduced turbine downtime and lower costs for O&M. Remote inspection can contribute to move on-site offshore maintenance activities onshore [D5.2-03]. This is illustrated in Figure 3. The figure also illustrates that remote presence is intended to work together with a condition monitoring system and manual inspections on site, i.e. that remote inspection will not replace all on-site maintenance and traditional condition monitoring systems. An optimal maintenance strategy will include all concepts.

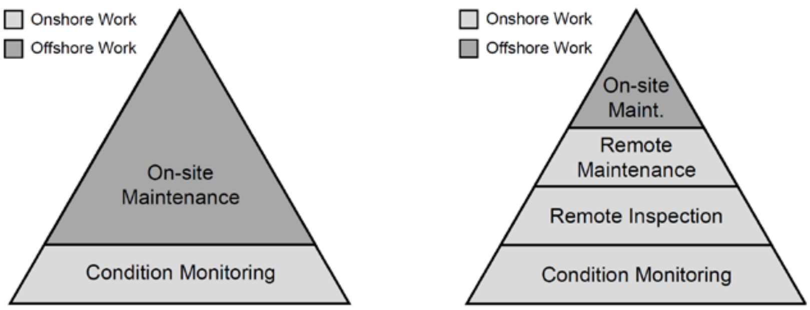


Figure 3 Maintenance with condition monitoring (left) and remote inspection and maintenance (right) [D5.2-03].

A cost-benefit evaluation of the remote inspection concept has been carried out [D5.2-48, D5.2-39]. Three simulation cases have been defined that share the same set of possible failures, failure rates and type of maintenance. In the base case, neither condition monitoring nor remote inspection is included. In the second case, a condition monitoring system is included. The third case includes a remote inspection system in addition to the condition monitoring system. Calculations of availability and costs have been carried with the O&M simulation tool NOWIcob [D5.1-52, D5.1-66]. The results showed that the use of remote inspection can result in further improvements (compared to the base case and the case with CMS only), see figure below.

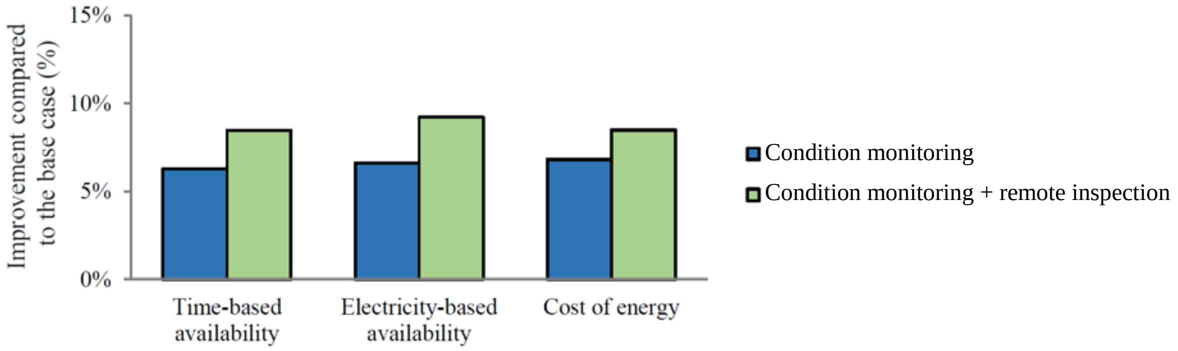


Figure 4 Improvement in availability and cost of energy, compared to the base case [D5.2-48, D5.2-39].

4 Gearbox reliability and fault detection

The wind turbine drive train, consisting of main shaft, gearbox and generator, is often considered the "heart of the wind turbine". Even though gear-less wind turbine concepts have been entered the market in the recent years, most of the turbines still have geared drivetrains [DB.2-12].

The gearbox has been pointed out as one of the "problematic" components of wind turbines. Even though gearbox failures are not very frequent (compared to other wind turbine components), gearbox failures result often in a very long downtime of the wind turbine [DB.2-12, p. 5, Figure 1.6].

Gearbox failures can often be traced back to the design phase [DB.2-12, p. 9, Table 1.1]. Thus, better knowledge about the relation between gearbox design, operational loads and failure mechanisms in gears and bearings is important to improve reliability and lifetime and reduce number of gearbox failures and maintenance costs. The work of NOWITECH PhD student Amir Rasekhi Nejad [DB.2-12] targeted the mentioned challenges and resulted in new knowledge and models that can be utilized for surveillance and condition monitoring of wind turbine gear box components (gears and bearings).

Nejad developed a drivetrain model based on a de-coupled analysis approach consisting of different modelling steps (Figure 4):

1. Global analysis
2. Drivetrain loadings from global analysis
3. Detailed gearbox model (multi-body simulation)
4. Gear load and load response analysis

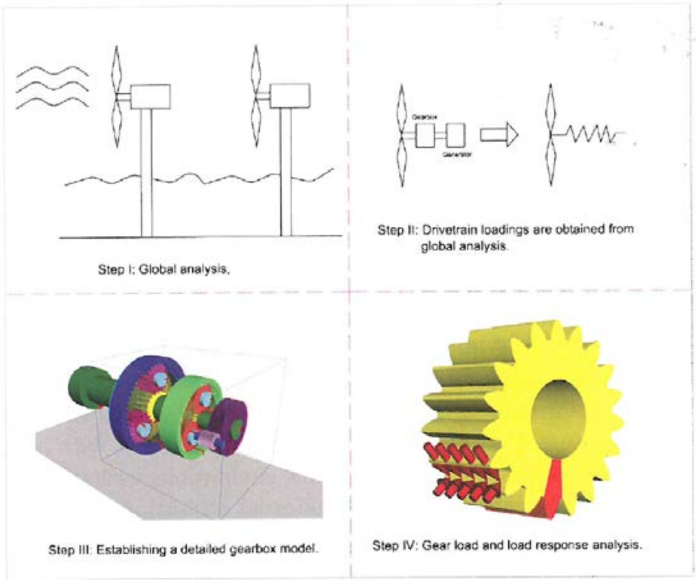


Figure 5 Drivetrain de-coupled analysis approach [DB.2-12]

The following two examples illustrate the applications of the results and models for condition monitoring and fault detection [D5.2-41], and for risk-based inspection and maintenance planning [D5.2-40]. Applications for other purposes can be found in [D5.2-25], [D5.2-26] and [D5.2-37].

4.1 Model-based fault detection

Nejad has shown that the models that he has developed during his PhD work can be used as basis for early detection of gearbox faults [D5.2-41]. The proposed method is based on angular velocity measurements from the input and output shafts, which are standard measurements already obtained in wind turbine control systems, and two additional angular velocity measurements from the intermediate shaft inside the gearbox. This approach is relatively simple, yet accurate enough to identify defects prior to failure and system damage.

The method is exemplified using a case study of bearing defect detection in a 750-kW NREL GRC gearbox model. The main novelty of the proposed method, apart from its simplicity, is that this approach can be implemented using an existing control system and does not require an additional condition monitoring platform. The developed method tries to detect the potential faults before they turn to a catastrophic failure.

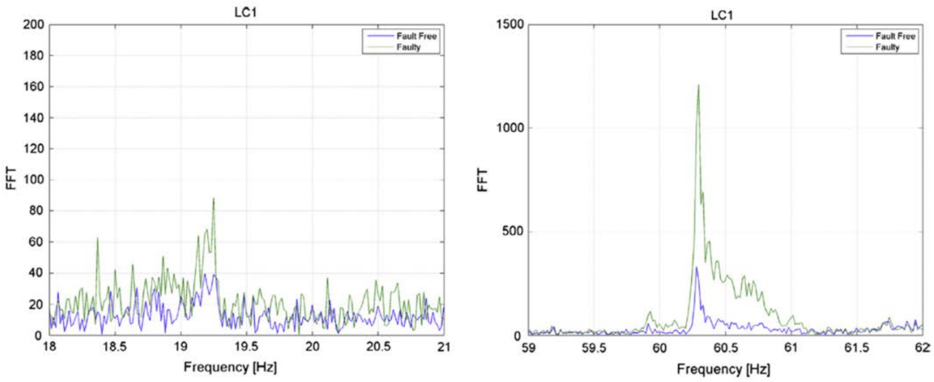


Figure 6 Frequency spectrum comparison between fault free (blue) and faulty (green) gearbox bearing.

4.2 Fatigue reliability-based inspection and maintenance planning

Preventive maintenance and inspection of wind turbine gearboxes is often carried out every six months for each wind turbine, normally within a day, and a major check-up is performed every three years. The wind turbine gearbox routine inspections include oil sampling for particle counting, oil filter checking, observing the possible oil leakage from housing or pipes and identifying any unusual noise from the gearbox. The oil sampling is often offline, even in offshore wind turbines equipped with condition monitoring systems. If the result indicates high debris in the oil, unusual noise or leakage, further internal visual inspection by other means such as endoprobe or fiberscope with camera is then performed. In the endoprobe or fiberscope inspection, the maintenance inspector should examine all gears and bearings, one by one in order to find the source of noise or debris in the oil. Any knowledge about gear box components with higher risk of failure can help the maintenance team to plan their inspections, thus, making inspections more effective and reduce inspection costs.

The components with higher fatigue damage are those with higher probability of failure. Therefore, it is reasonable that the inspection follows a plan which highlights those with the lowest reliability level. In the paper by Nejad et al. [D5.2-40], a procedure is described to create such inspection plans by means of so-called "vulnerability maps". The procedure was demonstrated and exemplified for a 750 kW gearbox. Such vulnerability map should be produced by the gearbox designer in the design stage and made available to the maintenance team. Moreover, it can be used in conjunction with condition monitoring data to find the potential failures, provided that the turbine is fitted with condition monitoring systems.

The interesting result of this study [D5.2-40] was that the map developed for the 750 kW gearbox agrees well with the failure data available for this gearbox. It is important to note that the vulnerability map is valid for a specific design only and should be made available by the gearbox designer for each gearbox design. For example, Figure 8 shows the vulnerability map for the 5 MW reference gearbox [DB.2-8] – note that it is not the same as the map for the 750 kW gearbox in Figure 7.

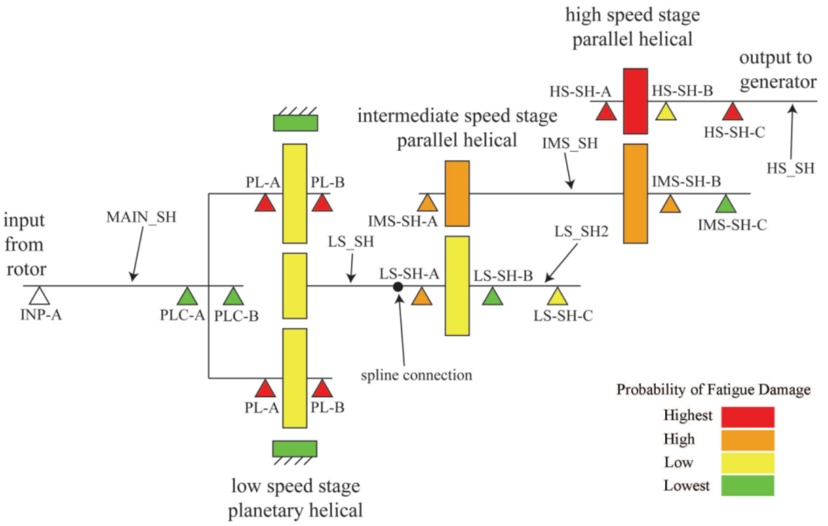


Figure 7 Vulnerability map for 750 kW gearbox [D5.2-40].

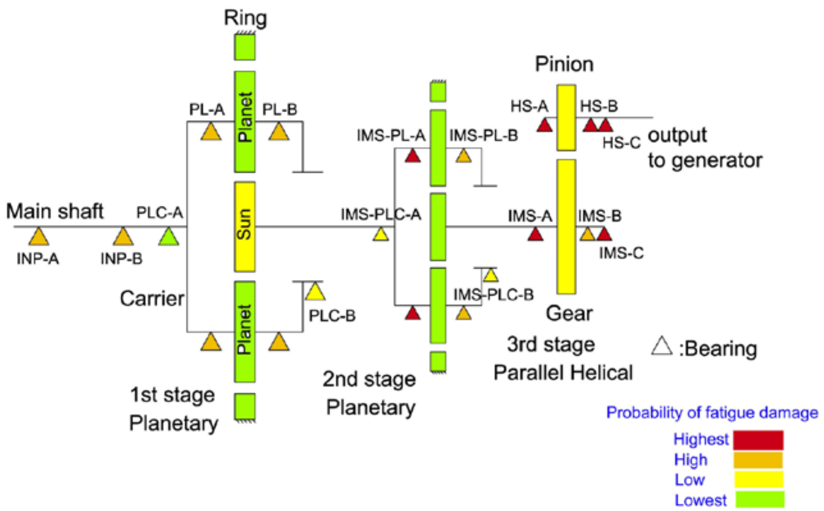


Figure 8 Vulnerability map for 5 MW reference gearbox [DB.2-8].

5 Condition monitoring data modelling'

Apart from the models implemented in Kongsberg's condition monitoring system (Chapter 2) and the gearbox models (Chapter 3), NOWITECH WP 5/WP B worked with different other models where condition monitoring and inspection data are used for either assessing the technical condition of wind turbine components or predicting further degradation and lifetime.

5.1 Technical condition indexing

The Technical Condition Indexing (TCI) concept [D5.2-17], [D5.2-19] developed by MARINTEK has been successfully used within shipping, onshore gas processing and subsea oil and gas production and processing. The potential use of the concept for offshore wind farm technical integrity management has been subject of NOWITECH research activities.

Knowing the technical condition of the system and its components is a crucial prerequisite for cost effective operation and maintenance. The TCI concept is targeting this problem by providing a quick overview of the technical condition of systems.

The TCI methodology is based on a functional breakdown of a complex plant, i.e. a system tree is established based on the function of systems and components (Figure 9). The system tree also contains information of the criticality of each sub-branch, i.e. how failures in the tree affect higher-order branches with regard to system function. The TCI concept utilises information and knowledge about condition variables and how these changes as the technical condition degrades, and represents the technical condition as an index value (Figure 10). Information on the technical condition of different systems and components can be sampled, processed and presented graphically for comparison reasons, and for trend analysis when the development of the TCI is shown over time (Figure 11). The TCI is very suited where the focus is to monitor the condition of several or many identical or similar systems or components, such as the turbines in in a wind farm. Through monitoring the technical condition it is possible to make sound maintenance prioritisations and plans.

Both the concept of TCI and corresponding software is from MARINTEK available to the industry. It is therefore suggested to test the concept on a wind turbine with real data to verify the usefulness of TCI towards wind farms, and also to investigate possibilities to include prognostic functions in the TCI framework.

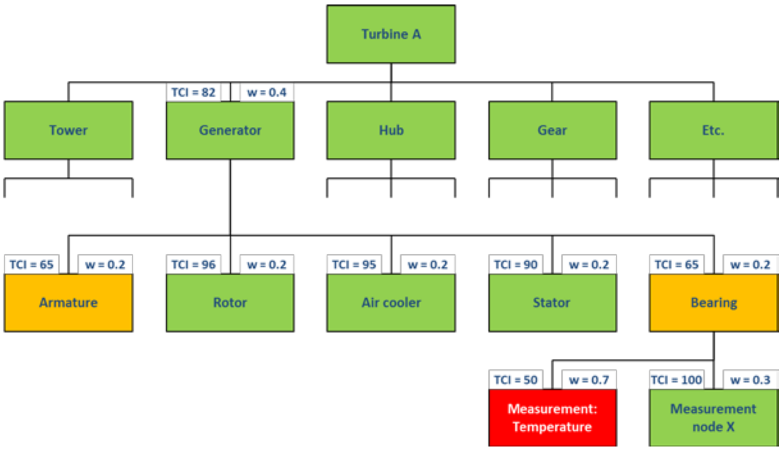


Figure 9 Hierarchical system breakdown of a wind turbine.

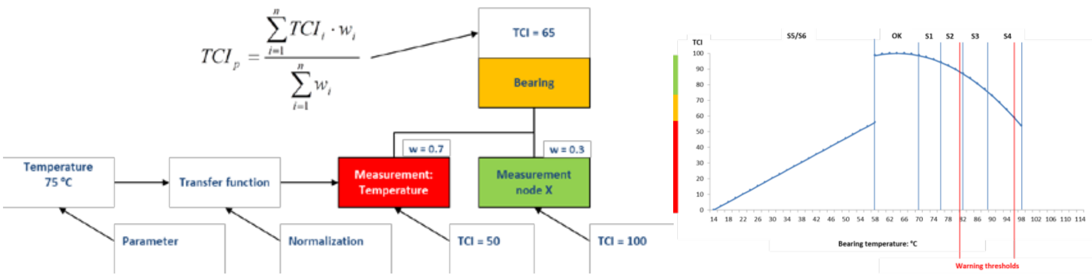
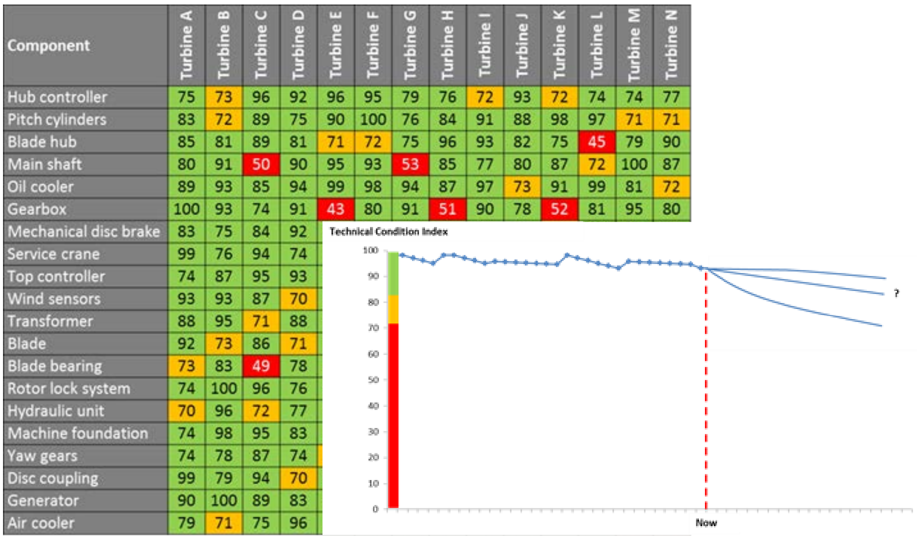


Figure 10 From measurement to TCI.



Component	Turbine A	Turbine B	Turbine C	Turbine D	Turbine E	Turbine F	Turbine G	Turbine H	Turbine I	Turbine J	Turbine K	Turbine L	Turbine M	Turbine N
Hub controller	75	73	96	92	96	95	79	76	72	93	72	74	74	77
Pitch cylinders	83	72	89	75	90	100	76	84	91	88	98	97	71	71
Blade hub	85	81	89	81	71	72	75	96	93	82	75	45	79	90
Main shaft	80	91	50	90	95	93	53	85	77	80	87	72	100	87
Oil cooler	89	93	85	94	99	98	94	87	97	73	91	99	81	72
Gearbox	100	93	74	91	43	80	91	51	90	78	52	81	95	80
Mechanical disc brake	83	75	84	92										
Service crane	99	76	94	74										
Top controller	74	87	95	93										
Wind sensors	93	93	87	70										
Transformer	88	95	71	88										
Blade	92	73	86	71										
Blade bearing	73	83	49	78										
Rotor lock system	74	100	96	76										
Hydraulic unit	70	96	72	77										
Machine foundation	74	98	95	83										
Yaw gears	74	78	87	74										
Disc coupling	99	79	94	70										
Generator	90	100	89	83										
Air cooler	79	71	75	96										

Figure 11 Example of result presentation.

5.2 Degradation modelling

Models for condition monitoring and degradation data has been the subject of several NOWITECH activities. [D5.2-15] provides a general overview of failure and degradation models. [D5.2-18] discusses methods for time to failure estimation, as input to maintenance planning, and how technical condition can be managed through the life cycle. The use of a stochastic process, such as the Wiener process, is discussed in paper [D5.2-35] for failure prediction for monitored systems.

The models build on the principle that a failure occurs when the technical condition (degradation) crosses an acceptable limit, as illustrated in Figure 12. Many models exist for representing condition development (degradation). Usually, end of life is assumed when a given threshold is reached. However, a challenge is practical application of the models, because, either they require data that is difficult and time consuming to collect (failure statistics, etc.), or the relation between the measured quantity and end of life is not evident. Thus, further work should focus on improving the existing models or developing new models to overcome the mentioned drawbacks.

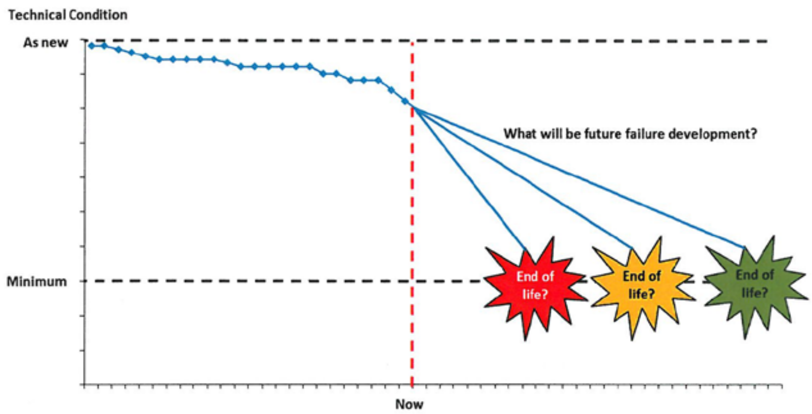


Figure 12 Relation between technical condition and end of life [D5.2-15].

6 State-of-the-art and pre-studies

Different state-of-the-art studies, pre-studies and case studies on topics related to surveillance and condition monitoring have been carried out in NOWITECH WP 5 and WP B. Most of the studies have been conducted to establish a baseline for a NOWITECH research activities, and even though some of the studies have been finished some years ago, they still contain valuable information and can be useful references for future work.

Condition Monitoring of Offshore Wind Farms – State of the art study [D5.2-01]
This study provides an overview of the state-of-the-art of the major condition monitoring process steps: data collection, data processing, diagnostic and prognostic (Figure 13). The study concluded that condition monitoring has been theorized and tested on wind turbines, both offshore and onshore, in several recent research projects. Some of the components of the turbine have a vendor supplied system with condition monitoring functionality. However, there is no full commercial condition monitoring product for the whole wind turbine. The study also showed that prognostic methods to predict the future development are rare. At the time when the study was carried out, no examples of prognostics have been found in the literature about condition monitoring of wind turbines.

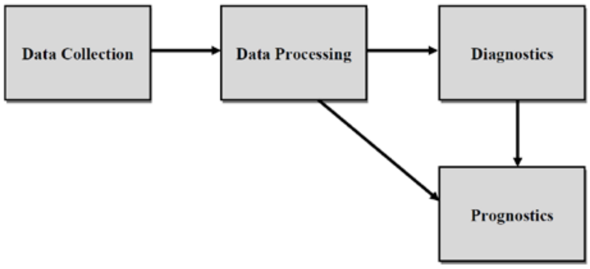


Figure 13 Condition monitoring steps [D5.2-01]

Pre-study on expected degradation mechanisms and failures in offshore wind turbines [D5.2-04]
This study provides a brief overview of literature presenting failure statistics and failure reports for both on- and offshore wind turbines. The report is also discussing the most prevailing failure mechanisms.

State of the art: Wireless communication that can be utilised in O&M of offshore wind farms [D5.2-05]
This report provides an overview of wireless communication technologies. The focus has been on technologies that are commercially available, or believed to be close to commercialization. The following types of communication systems have been considered in the study:

- long range – e.g, for communication between turbines and turbines and vessels
- medium-range high-capacity – for applications like movable cameras, backup data-transfer and some high speed sensor types
- short range – "WSN's" (Wireless Sensor Networks) mainly for low speed data acquisition

Operation & Maintenance of Offshore Wind Parks - Strategic Research Agenda [D5.2-20]
This report is a result of a cooperation between the following European Research and Technology Organisations: Fraunhofer (Germany), TNO (The Netherlands), VTT (Finland) and SINTEF (Norway). The report provides a short state-of-the-art summary of smart structures, fibre optic sensor technology, wireless sensor networks, load and condition monitoring, predictive health monitoring and optimisation & control. The report identifies research needs for the topics listed above.

RPAS for inspection of wind turbine blades [D5.2-46]

This report presents current status of RPAS (Remotely Piloted Aircraft Systems)/UAV(Unmanned Aerial Vehicles) for inspection of wind turbine blades. The report provides a general overview of different types of RPAS. In addition, sensor systems that can be used together with a RPAS for wind turbine inspections are briefly discussed, and selected RPAS available on the market for wind turbine inspection are described. Finally, the report presents RPAS services that are available for wind power industry.

The report is based on information gathered from phone calls with people in the Norwegian RPAS business and the wind power industry, news articles, scientific articles, and different internet sources, such as company homepages. The report concluded that RPAS received significant attention in recent years. The Norwegian RPAS industry is comprised of many small companies, of which most are concerned with photography and filmography. The use of RPAS is starting to become well established in some fields, while others still need convincing in terms of improved solutions. Within the offshore wind industry, RPAS is in general rarely used for inspection. Inspection methods that are traditionally used for blade inspection are high-resolution photography from the ground and vertical climbing ropes for manual visual inspection and ultrasonic tap hammer tests. However, there is currently being conducted considerable amounts of research, for example, to develop various sensor types to supplement or replace traditional inspection methods.

7 Technology readiness and further work

In 2013, NOWITECH has started to use the Technology Readiness Level (TRL) concept for assessing the research project's results and innovations.

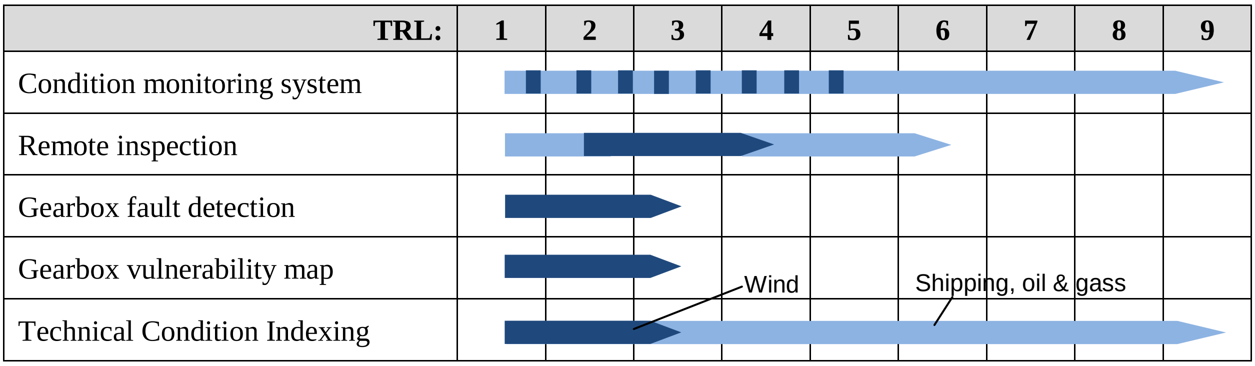
The TRL assessment methodology is a good communication tool to illustrate the maturity grade and the development process from idea to market-ready product. The TRL definition used in NOWITECH is shown in the following table:

Table 2 NOWITECH TRL definition.

TRL	Definition
1	Basic principles observed and reported.
2	Technology concept and/or application formulated.
3	Analytical and experimental critical function and/or characteristic proof of concept.
4	Component and/or system validation in laboratory environment.
5	Laboratory scale, similar system validation in relevant environment.
6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment.
7	Full-scale, similar (prototypical) system demonstrated in relevant environment.
8	Actual system completed and qualified through test and demonstration.
9	Actual system operated over the full range of expected conditions.

The most important innovations that are a result of the NOWITECH research activities on surveillance and condition monitoring, including the development and the current TRL level of these innovations, are illustrated in Table 3. The table also includes innovations where NOWITECH research contributed together with other research activities, e.g. carried out in other projects or by other parties (NOWITECH industry partners, etc.). This is illustrated by the light blue arrows indicating that activities outside NOWITECH had the major contribution. The relation to other projects and parties is commented below.

Table 3 TRL level of different NOWITECH innovations.



Condition monitoring system

The condition monitoring system has been developed by the NOWITECH industry partner Kongsberg Maritime, with contributions from NOWITECH (see Chapter 2) and other research projects (e.g. Windsense). The system is marked-ready and part of Kongsberg's EmPower wind farm decision support system [3].

Remote inspection

The remote inspection concept has its origin in an idea from the NOWITECH industry partner Norsk Automatisering AS (NAAS). The idea has been further developed by NOWITECH PhD student Øyvind Netland. Netland's analysed the feasibility of the concept and built a prototype where he proofed the usability and benefit of the technology. The PhD work brought the technology to a TRL of 4. Further development of the remote inspection technology was afterwards carried out follow up research projects and activities.

Currently, Netland and NAAS are working with increasing the TRL level of the technology. TRL 6 was achieved with a pilot installation at VIVA wind test center at Brekstad outside Trondheim in June 2015 as part of the LEANWIND project. A fully functional, near commercial product prototype has been designed in co-operation with Simpro, Prevas and Norwegian Creations.

Gearbox fault detection

The fault detection method has been developed from TRL 1 to TRL 3 during the work of NOWITECH PhD student Amir Rasekhi Nejad. This method is now planned to be evaluated for larger turbines and specially on floating wind turbines. In addition, this method will be compared with other methods.

Gearbox vulnerability map

The vulnerability map concept has been developed from TRL 1 to TRL 3 during the work of NOWITECH PhD student Amir Rasekhi Nejad. There are no specific plans to develop the concept further at the moment, even though there are some ideas and plans for application and further development in the future.

Technical Condition Indexing

The technical condition indexing (TCI) concept has already been proved as valuable method for different technical systems, such as ships and oil and gas installations. A TCI software already exists. Thus, the TRL of the technology is already 9. However, a demonstration and full-scale implementation of the method and software at wind turbines is still missing, thus the TRL of TCI regarding wind turbines is assumed to be 3.

8 Conclusions

This report summarized the results from the activities on surveillance and condition monitoring in work packages WP 5 (2009-2014) and WP B (2015) in the NOWITECH research centre. These activities and their results constitute the NOWITECH milestone 13: "Description of novel condition monitoring system for offshore wind farms".

Even though the term *condition monitoring system* is mostly associated with a system that continuously provides measurement signals obtained from sensors fixed installed at/in the system to be monitored, the definitions provided in international standards (see Chapter 1) make clear that a system for condition monitoring should be interpreted in a broader context. The development of a condition monitoring system that continuously provides measurement signals was driven by the NOWITECH partner Kongsberg Maritime, and the developed system is now available on the market (see Chapter 2). Other results that also can be considered as a condition monitoring system (e.g. remote inspection, gearbox fault detection method, etc.) have been developed, evaluated, tested and described during the NOWITECH project. These results represent novel concepts or included new elements, aspects and ideas. Thus, it can be concluded that the NOWITECH-milestone "Description of novel condition monitoring system for offshore wind farms" has been reached.

The NOWITECH work is still ongoing (until 2017) and some of the results will be further developed. Obviously, there are remaining challenges, problems and possibilities for improvements in the field of surveillance and condition monitoring of wind turbines. Examples of topics that should be addressed in further work are:

- Development of improved methods for early fault detection, estimation of consumed lifetime and prediction of remaining useful life. This includes:
  - Modelling relations between operational and external loads, loads on components, ageing/wear, lifetime/remaining useful life, and costs.
  - Health management methods for both structural and non-structural components (e.g. electrical components)
- Testing of methods described in this report at real wind turbines, e.g. testing of TCI method (Section 5.1) or the gearbox fault detection method (Section 0).
- Development and testing of new sensor and measurement technologies to be used for continuous monitoring or for inspection (including remote inspection and inspection solutions using new platforms such as drones and robots).

Acknowledgement

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