



Contract number 212966

# Reliawind

Reliability focused research on optimizing Wind Energy systems design, operation and maintenance: Tools, proof of concepts, guidelines & methodologies for a new generation

Collaborative Project: Large Scale Integrated Project  
FP7-ENERGY-2007-1-RTD

## **Deliverable D 1.1 – Report on previous publications dealing with wind turbine reliability**

**Workpackage WP 1– Field Data Reliability Analysis**

**Task 1.1 – Collation of data**

**Month of delivery: M 8**

**Deliverable leader: GH**

<b>Decisional Workflow</b>		
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<b>Reviewer (s)</b>	Peter Tavner	
<b>Scientific Director</b>		

## Description of work

### **Objective of the WP:**

The overall objective of this work package is to identify the critical failure modes at the component, sub-system and system scale within wind turbines based on the analysis of available long term operational data and fault records logged by SCADA systems operating on wind farms around the world.

### **Task description: Task 1.1: Collation of data**

The partners involved in this work package each have access to a large body of SCADA data recorded from wind farms operating in different locations around the world. Each partner will collate information from the SCADA datasets available to them which is relevant to the reliability analysis to be undertaken in this project.

On completion of this task each partner will have established a database of raw SCADA data for further processing and quality control. In order to carry out this task, the Users Working Group (wind farm owners such as Edison and Iberdrola) will be associated also.

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**Workflow**

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	<input type="checkbox"/> <input type="checkbox"/> Ecotecnia	3 MM	MM
	<input type="checkbox"/> <input type="checkbox"/> LM	MM	MM
	<input type="checkbox"/> <input type="checkbox"/> Hansen	MM	MM
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**If any difference between estimated resources and allocated resources, please justify:**

**Results achieved**

**Explain here the results that have been achieved so far and differences between the plan work and final results.**

The deliverable has been completed by Durham University with feedback from WP1 Partners and other Consortium members. The report first justifies the necessity to study the reliability of wind turbines. It then gives a brief introduction to the reliability analysis, and explains what kind of the field data should be collected when the reliability analysis is performed on wind turbines. Finally, it provides a detailed literature review on the research of the reliability of wind turbines, the methods and libraries which are most frequently used in reliability analysis, and the IEC series publications on wind turbines.

**Quality Assessment**

**Task Leader**

See comments from WP Leader.

**WP Leader**

The WP Leader considers that this report satisfies the quality criteria required for the deliverable.

**Scientific Director**

**Project Officer (European Commission)**

## **Abstract**

This report first justifies the necessity to study the reliability of wind turbines. It then gives a brief introduction to the reliability analysis, and explains what kind of the field data should be collected when the reliability analysis is performed on wind turbines. Finally, it provides a detailed literature review on the research of the reliability of wind turbines, the methods and libraries which are most frequently used in reliability analysis, and the IEC series publications on wind turbines.

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# 1. Background

## 1.1 Penetration of Wind Power

Wind power is the fastest growing renewable energy resource, which can also be considered as Distributed Generation (DG). Widespread utilization of wind power generating electricity imposes considerable effects on the planning and operation of the electrical power system. Reliability evaluation and enhancement is an important factor in modern power system planning and operation. Consequently, the reliability assessment of wind turbines is of great importance and will receive more attention in the future with increasing generation from wind turbine resources.

High penetration in power systems of wind power has occurred in some countries in Europe, notably Denmark, Germany and Spain. Denmark for instance has almost a 20% penetration of wind power into the electrical power system.

Although there are a number of studies considering the impact of wind power on the reliability of a large power system [1] [2] [3] [6] [7] [11], there has been relatively little effort to consider wind turbine as an isolated system to give more accurate results for reliability evaluation except [4].

The wind turbine is a complex electrical generator consisting of several assemblies and subassemblies, therefore considering it as only a component of the power system could give unreliable results. As the wind power penetration in power system increases the accuracy of the aggregated wind turbine reliability model will become more important to the accuracy of the power system reliability model.

## 1.2 Market Growth

A brief review of world wind power growth will show the importance of better availability and reliability of wind turbines. Figure 1 taken from an International Energy Agency (IEA) report shows the global cumulative power capacity of wind power until 2005 [18].

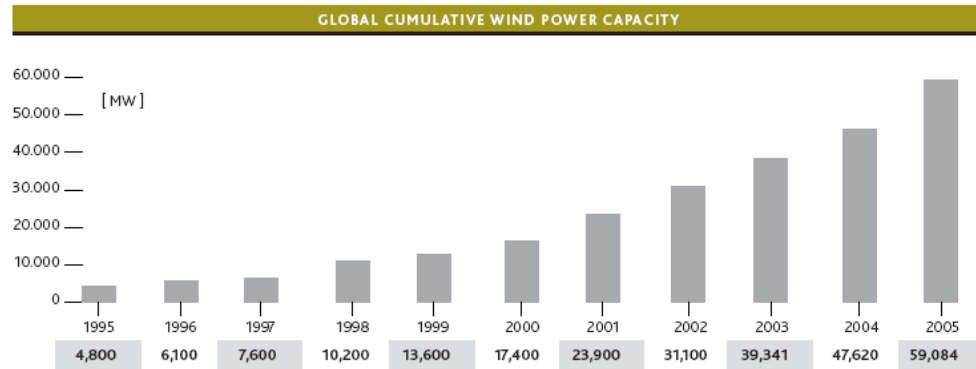


Figure 1 Global cumulative power capacity of wind power.

The IEA has proposed three different scenarios for wind power expansion, summarized in Figure 2 and shown graphically for the east and the west in Figures 3 and Figure 4.

SUMMARY OF GLOBAL WIND ENERGY OUTLOOK SCENARIO FOR 2030							
Global Scenario	Cumulative wind power capacity (GW)	Electricity output (TWh)	Percentage of world electricity (High Energy Efficiency)	Annual installed capacity [GW]	Annual investment (€ bn)	Jobs [million]	Annual CO <sub>2</sub> saving (million tonnes)
Reference	364	892	5 %	24.8	21.2	0.48	535
Moderate	1,129	2,769	15.6 %	58.3	45.0	1.14	1,661
Advanced	2,107	5,176	29.1 %	129.2	84.8	1.44	3,100

SUMMARY OF GLOBAL WIND ENERGY OUTLOOK SCENARIO FOR 2050							
Global Scenario	Cumulative wind power capacity (GW)	Electricity output (TWh)	Percentage of world electricity (High Energy Efficiency)	Annual installed capacity [MW]	Annual investment (€ bn)	Jobs [million]	Annual CO <sub>2</sub> saving (million tonnes)
Reference	577	1,517	6.6 %	34.3	28.8	0.65	910
Moderate	1,557	4,092	17.7 %	71.0	54.2	1.39	2,455
Advanced	3,010	7,911	34.3 %	168.6	112.0	2.80	4,747

Figure 2 Summary of global wind energy expansion.

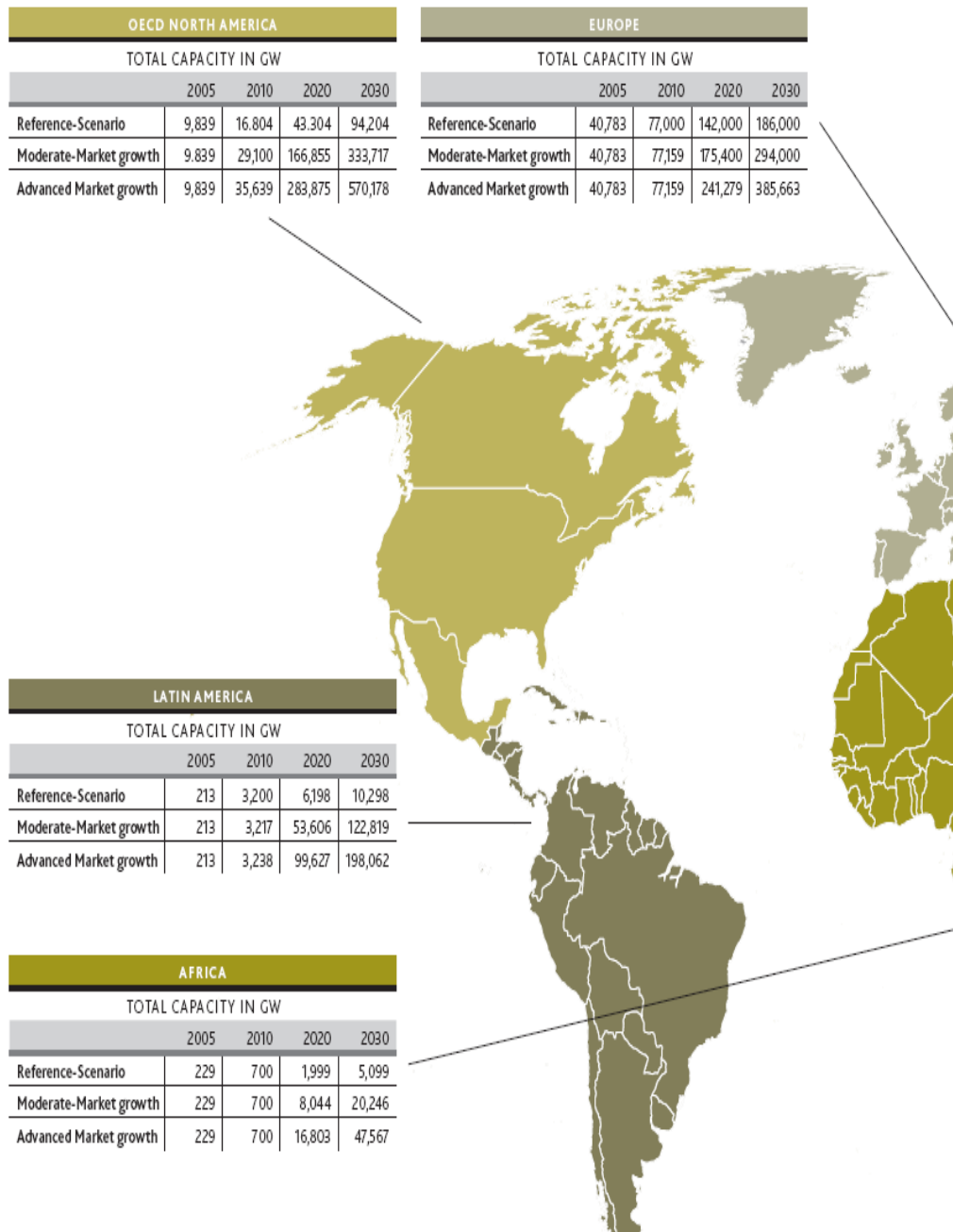


Figure 3 Wind energy expansion in west.

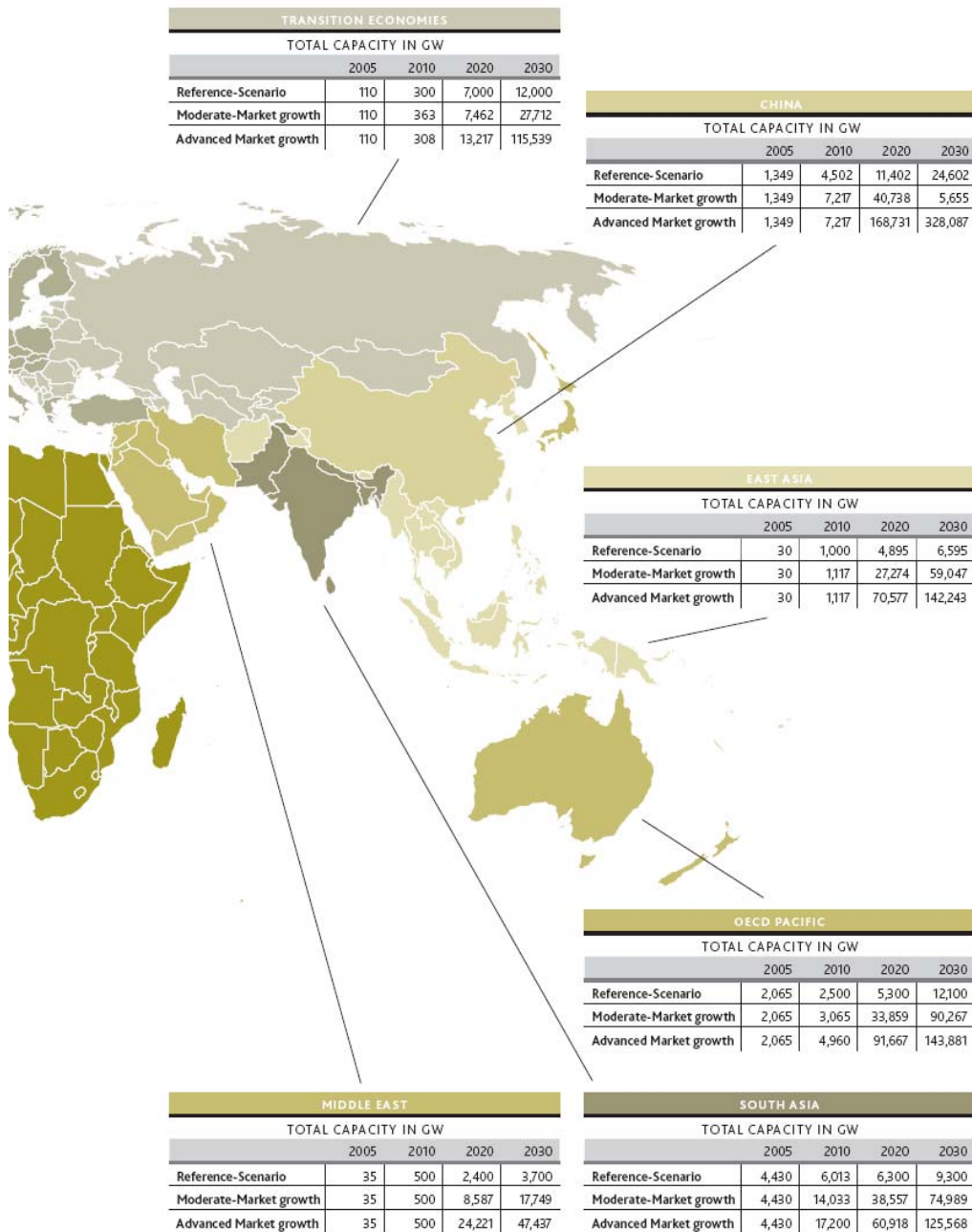
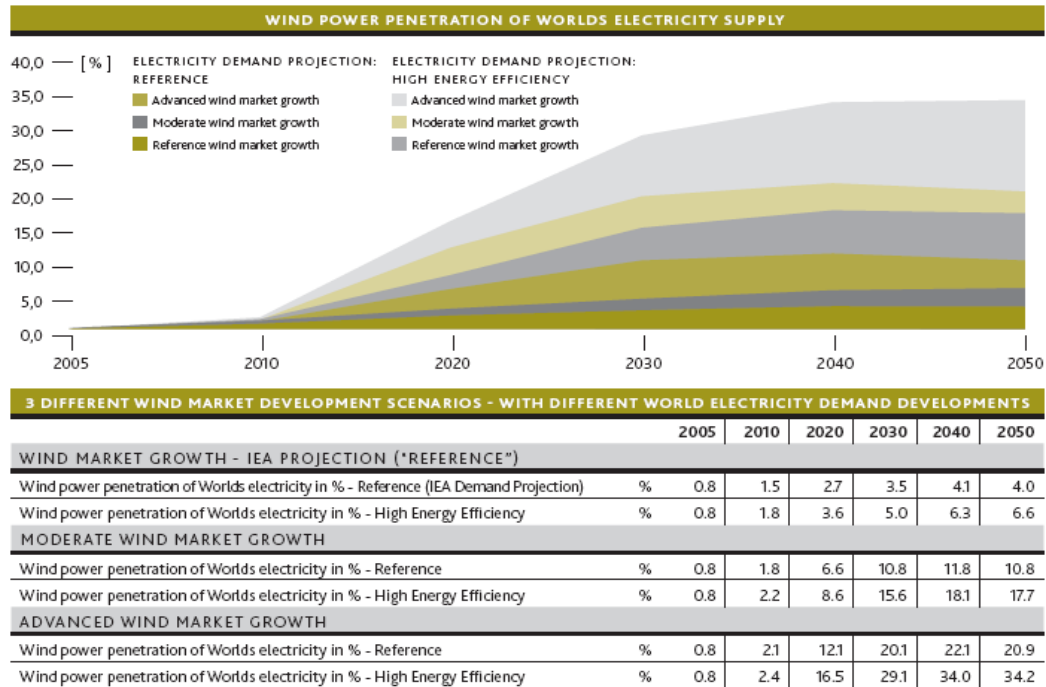


Figure 4 Wind energy expansion in east.

Wind energy expansion and its' penetration into the power system is an important driver necessitating the consideration of wind farm reliability in overall system reliability studies. For example in Denmark it is no longer possible to ignore wind farm reliability in overall system reliability studies. Figure 5 shows the predicted wind energy penetration based on IEA scenarios in coming years taken from [18].



*Figure 5 Wind power penetration into world electricity supply.*

In conclusion the large wind power expansion and expected penetration into the power system in next 40 years emphasizes the importance of wind turbine reliability as these will be the building blocks for future wind farms [15].

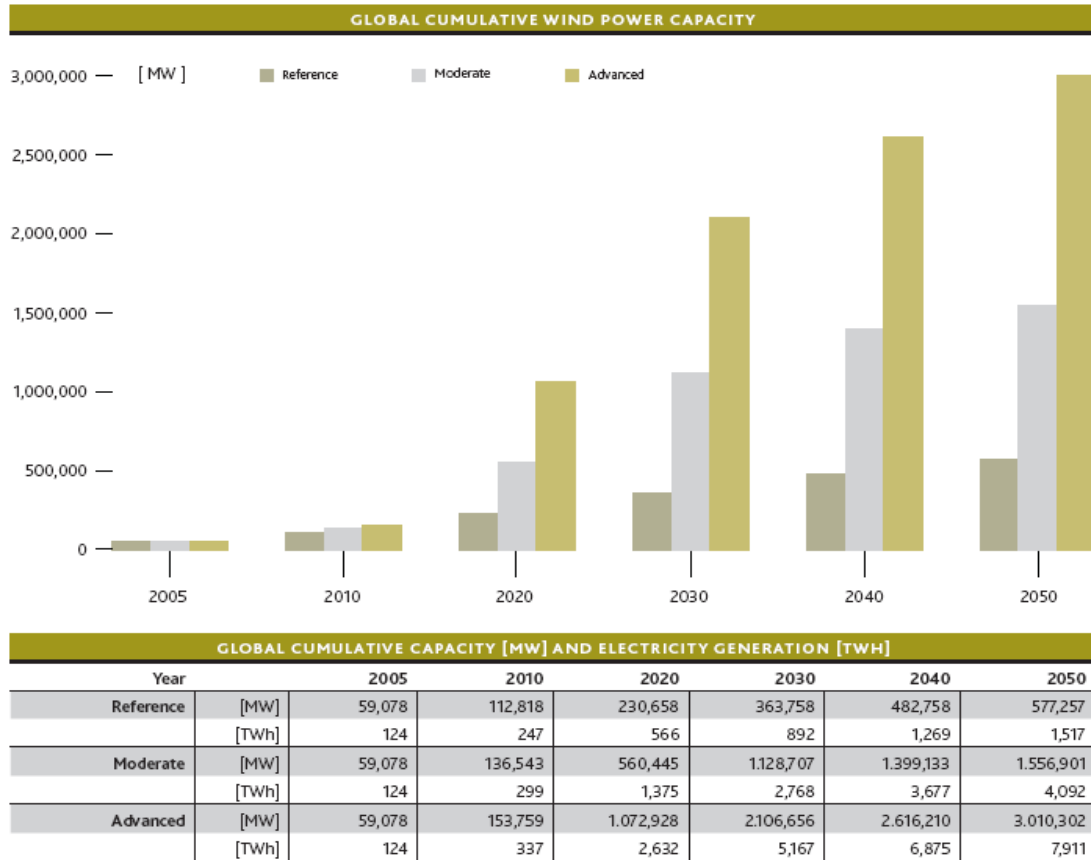


Figure 5 Predicted global cumulative wind power capacity.

## 2. Research Motivation

### 2.1 Economic Benefits

More reliable system results in less operation and maintenance costs. Although in standard definition for Cost Of Energy (COE), reliability affects not only the Operation and Maintenance (O&M) cost but also Levelised Replacement Cost (LRC). Also as reliability improvement results in better availability the Annual Energy Production (AEP) of wind turbine could be increased, so with the definition for COE:

$$COE = \frac{(ICC * FCR) + LCR}{AEP} + O \ \& \ M$$

in which ICC represents Initial Capital Cost and FCR used for Fixed Charge Rate, reliability improvement would increase the denominator, AEP, and decrease LCR and

O&M costs. Feedback from reliability studies, especially the FMEA, could increase the Initial Capital Cost (ICC), but as a long term interpretation increased would decrease LCR &, O&M costs and increase AEP, thereby reduce COE.

## **2.2 Improving Design**

A principal objective of reliability analysis is to gain feedback for improving design. Reliability analysis of wind turbines could help to identify weaknesses in parts and subassemblies. Sensitivity analysis, based on reliability evaluation, could indicate the spread of unreliability between parts and subassemblies in the wind turbine and a ranking of critical subassemblies could be achieved.

Some researchers believe that the main outcome of FMEA for each system is identification of weak points. In fact it is possible to rank the assemblies, subassemblies and parts of the wind turbine in a critical part ranking order. It is important that the combination of reliability and availability factors have to be considered in such a ranking. For example, although the failure rate of gearbox is not as high as it was claimed but its' down time is considerable.

Identification of weak points is a hint to improve configuration design and optimised maintenance facilities allocation. If it is economic the redundancy could be considered for weak parts otherwise more frequent inspection and maintenance are recommended for these parts.

However, in some situations the improvements may not be economical compare to use redundancy, for example in electronic devices used in power electronic converter or other controlling sub-systems.

## **2.3 Optimising Maintenance**

The traditional strategy for maintenance is corrective maintenance, which means waiting until system malfunction, but it is clear that this method is not economic at all. A better plan could be preventive maintenance, which is a periodic inspection and replacement or repair if it is necessary. The main factor for optimal preventive maintenance, both from technical and economical point of view, is the time period selection for inspection.

Optimum time period selection for preventive maintenance could not be achieved without a comprehensive reliability analysis. As stated before one of the results of

such an analysis would be critical subassembly ranking, so with limited maintenance resources, more important subassemblies, from reliability point of view, could be assessed first.

Reliability study of systems could help to optimise the maintenance strategy, which is called reliability centred maintenance. In such a maintenance program the assemblies should be ranked from failure prone property. This could be achieved by reliability study and especially by FMEA. Although some condition monitored based policies was suggested [26].

## **3. Introduction to Reliability Analysis**

### **3.1 FMEA**

As stated above FMEA is a powerful method for improving reliability during the design stage. It could be also helpful in modifying existing turbine configurations to improve reliability, as different alternative configurations can be compared during the design stage.

FMEA is a subjective analysis tool, using a qualitative approach to identify potential failure modes, their initiating causes and the associated risk to a system in the design, manufacture or operational phase. Hence the FMEA drives designs towards higher reliability, quality, and enhanced safety. It can also be used to assess and optimise maintenance plans. The FMEA procedure could be shown in a flow chart form as shown in Figure 6.

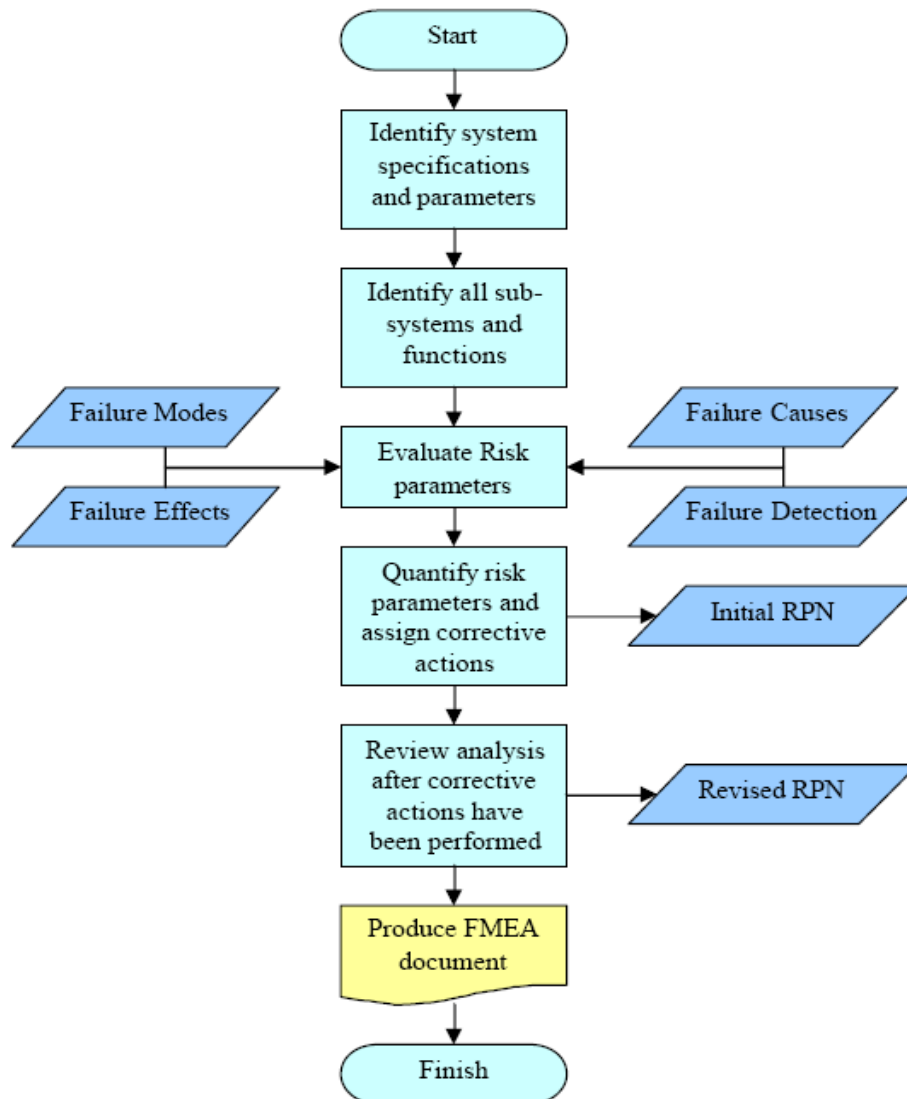


Figure 6 Example of an FMEA flow chart.

From an FMEA, a numerical value is assigned to individual failure modes in order to highlight particular areas of risk. This is done by considering three of the factors associated with the failure mode:

- Severity: To what extent the failure affects the capital operation of the system.
- Occurrence: How likely the failure mode is to initiate.
- Detection: How likely failure is to be detected using current condition monitoring and inspection techniques.

These factors are individually rated using a numerical scale, typically ranging from 1 to 10. These scales, however, can vary in range depending on the FMEA standard being applied. The Risk Priority Number (RPN) is then calculated as follows:

- $RPN = Severity \times Occurrence \times Detection$ .

The RPNs of the individual subassemblies of a system are then summed to obtain the total RPN for a wind turbine. These values are purely dependent upon the analyst's engineering judgment and knowledge of the system being analyzed, hence the subjectivity of FMEA.

For the Wind Turbine FMEA, the main focus is on:

- item specifications
- functions and
- failure modes.

This ensures correct values being assigned to the respective Severity, Occurrence, and Detection rating scales and hence obtaining the appropriate RPN. Therefore, prior to commencing the FMEA, fully functional analyses have to carry out on each subassembly of the Wind Turbine. As the first stage a 12 sub assembly subdivision was considered, taken from work in [21] and [28], and each subassembly was subdivided into its components:

Generator

Gearbox

Electrical Control

Air Brake System

Mechanical Brake

Pitch System

Main Shaft Assembly

Yaw System

Grid and Electrical System

Tower, Foundation and Nacelle

Rotor and Blades Assembly

Hydraulic System

### 3.2 Analytical Methods; Failure Rate Function & Markov Model

In reliability studies, systems are divided into two main categories, mission-orientated or repairable systems. The appropriate factor for the first category is reliability while the availability is more useful for repairable systems. A wind turbine can be considered a repairable system and accepting that the equipment continues working throughout its useful life, the Markov process is the best candidate to study its reliability.

According to reliability theory failure and repair rate can be defined respectively as:

$\lambda$  = Number of failures in a given period of time divided by total period of time the component was operated.

$\mu$  = Number of repairs in a given period of time divided by total period of time the component was being repaired.

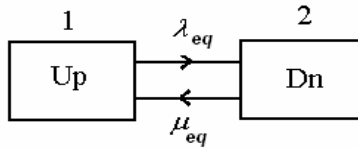
The useful life period assumption for equipment allows the definition of these transition rates as the reciprocal of average duration of operation and repair:

$$\lambda = \frac{1}{MTTF} \quad (5)$$

$$\mu = \frac{1}{MTTR} \quad (6)$$

where MTTF represents Mean Time To Failure and MTTR stands for Mean Time To Repair. Recording the periods of wind turbine operation and repair and taking the average of up-time and down-time gives numerical values for MTTF and MTTR. The same procedure could be conducted for each subassembly to calculate the corresponding failure and repair rates in the time period of the system reliability study. Therefore this analytical method strongly depends on availability of such data.

State space diagrams could be defined based on Markov modelling approach. The failure and repair rates, calculated for each assembly, would be the transition rate between these performance states. The simplest form of such a state space diagram for a subassembly is shown below.



### 3.3 Monte Carlo Method

Another method which can be used for both mission-orientated and repairable systems is the Monte Carlo or simulation method. The system being studied is simulated using random variable generator techniques. The first step is to assume the appropriate probability density functions for each phenomenon. For example the wind speed can be simulated using the Weibull function, as advocated by many researchers in this field.

The simulation method has the advantage, compared to the analytical method, of including all variables of the system studied, but it is a time-consuming and expensive due to the amount of data processing.

## 4. Data Collection

### 4.1 Failure Data

The recording of failure data is an essential step in reliability analysis. For analytical methods, like Markov modelling, is not possible without failure data. More detailed failure data about wind turbine assemblies and subassemblies is needed for more accurate interpretation of wind turbine reliability.

The mentioned data bases, in previous works section, gathered the number of failures for each assembly based on their own subdivision. Although these data are the only information about wind turbine reliability now, but it would be better if a standard, unique subdivision for wind turbine assembly and subassembly is accepted by all the organizations which are involved in such studies. The other important factor is the diversity of wind turbine technology and configuration in each wind farm. Present data about wind turbine reliability is from the mixture of different wind turbine types and ratings in a wind farm, so clustering the wind turbines in some identical groups could improve the failure data.

## **4.2 Downtime**

The other important factor, in wind turbine reliability analysis, is the downtime of a wind turbine due to the specific failure. Also the down time of wind turbine caused by each assembly failure could be helpful, especially in analytical analysis in which Mean Time To Repair (MTTR) is an important factor. One of the main parameters in Markov modelling, which is repair rate, is calculated based on down time data. In fact if the assumption of useful life period for wind turbine was a reasonable hypothesis, the repair rate would be the reciprocal of MTTR. It is identical to failure rate and MTTF values.

One of the important factors in down time's data recording for wind turbines is a clear definition of down time. Some considers the down time equal to repair time, but more accurate down time would be the time period of failure diagnostic, repair and reinstallation. So similar to the necessity for standard definition of wind turbine assembly subdivision, a standard, clearly defined acceptance of down time could improve the wind turbine reliability analysis.

## **4.3 Root Causes of Failures**

One of the main goals for reliability analysis is design improvement. In fact it is intended to get helpful feedbacks from reliability analysis for design improvements or new configuration designs. The important data, apart from failure data, which could help to get such feedbacks, is root causes of each failure modes. Although failure data could identify more frequent failure modes and critical assemblies, but as each failure mode would be due to several different root causes, root cause data could make a good sense about more frequent root causes.

## **4.4 Operation and Maintenance Conditions**

It is evident that failure and repair procedures are influenced by operation and maintenance conditions in wind farms, so recording such a conditions data as well as failure and down time information could help to get a better understanding of wind turbine reliability. Also one of the results of wind turbine reliability analysis could be some advisements for better or optimised operation and maintenance in wind farms.

## **4.5 Environmental Conditions**

Other important factor for wind turbine failure and repair procedure understanding is weather conditions. Considering weather conditions with each failure could be helpful both for design improvements and operation and maintenance policies.

# **5. Literature Review**

## **5.1 Reliability of Wind Turbines**

Various organizations and institutions have studied the reliability of wind turbines as set out below.

### **Electric Power Research Institute (EPRI), USA**

EPRI conducted some investigation of the reliability of wind turbines installed in California in the early 1980s but these results are not available in the public domain.

### **Sandia National Laboratory (SNL), USA**

SNL has been active in studying the Operation and Maintenance of wind farms. Most of their output is in published reports, see [17].

### **Kassel University, ISET, Germany**

The Institut für Solare Energierversorgungstechnik, ISET, at Kassel University has been responsible for collecting and analysing the data from the German Wissenschaftliches Mess- und Evaluierungsprogramm im Breitentest (WMEP) or 250 MW Wind Scientific Measurement and Evaluation Programme, a survey of up to 1540 turbines in Germany. Their output is published in annual reports of the WMEP, but also some papers are published, see [23].

### **Royal Institute of Technology, KTH, Stockholm, Sweden**

The KTH has also been studying wind turbine reliability in Scandinavia with results from Sweden and Finland, see [24] [26].

### **Energieonderzoek Centrum Nederland (ECN)**

ECN has been active in the investigation of wind turbine reliability through Dutch and European programmes including the Dutch Offshore Wind Energy Converter (DOWEC) and the EU FP5 Condition Monitoring of Offshore Wind Turbines (CONMOW) they have strong collaborators with TU Delft. Most of their output is in published reports, but some papers exist, see [5] [31].

### **Technical University, Delft, Netherlands**

TU Delft has been active in a number of Operation & Maintenance and reliability programmes, including the Dutch Offshore Wind Energy Converter (DOWEC) and the EU FP5 Condition Monitoring of Offshore Wind Turbines (CONMOW), see [22] [25] [29].

### **Risoe National Laboratory for Sustainable Energy, DTU, Denmark**

Risoe has been active in a number of programmes to improve wind turbine reliability and to understand the effect of changing turbine configuration on that reliability. Most of their output is in published reports, but a paper exists on the prevalence and experience with different turbine configurations [27].

### **Garrad Hassan, UK**

Garrad Hassan, wind industry consulting engineers, have published a number of papers on wind turbine reliability and availability, see [13] and [29].

### **Durham University, NAREG, UK**

The New and Renewable Energy Group (NAREG), in the School of Engineering at Durham University has studied the reliability of wind turbines, starting with consideration of the electrical machine, see [8] [15] [16] [19] [20] [21] [22] [30] [32]. Much of this work has been based on the evaluation of different surveys:

- WindStats Newsletter Survey (Denmark)

WindStats is a quarterly, public-domain newsletter about the wind industry, gathers reliability data both from wind turbines as systems and their main assemblies. A comprehensive analysis of up to 2000 Danish and 4200 German

wind turbines over an 11 years period was performed by Durham based on this data, see [15].

- LWK Schleswig Holstein Survey (Germany)

A survey undertaken by the Business Sector of the Schleswig Holstein Lande over 11 years of up to 650 turbines..

- WMEP 250 MW Program (Germany)

The main results drawn from these works are:

- To provide a reliability benchmark for wind turbines and their subassemblies comparing wind turbine reliability with other electricity power generation sources as shown in Figure 7.

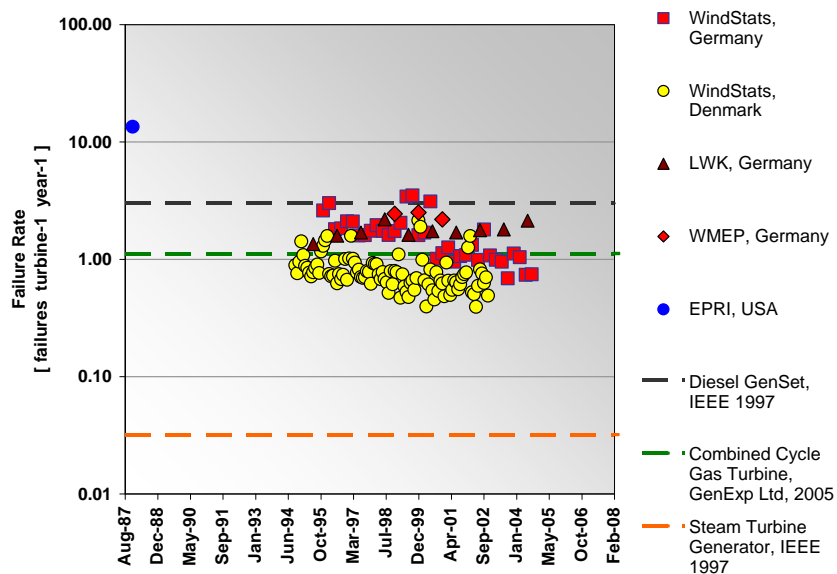


Figure 7 Wind turbine failure rates over 21 years, compared to other power generation sources.

- Verification that in general wind turbine systems and assemblies obey the bath-tub curve. It has been clear from these studies that the Danish Windstats data, for older turbines, lie in the bottom of bath-tub curve whereas German Windstats data, for newer turbines, show a decreasing failure rate or early failures mode or improving reliability. This was verified from the data and by standard statistical tests.
- Some wind turbine subassemblies show improving reliability suggesting that they are still in the early failures mode, opening the opportunity for reliability improvement.

An important method in reliability analysis, especially appropriate for design stage, is Failure Mode and Effect Analysis (FMEA). Durham has carried out projects using this approach with some significant results, which have been compared with the field reliability data described above, and a good correlation found, see [28]. Therefore the FMEA could be used for reliability prediction as well as improving the design. One of the stages in standard FMEA is correcting action advisements, which reduce the Risk Priority Numbers (RPNs) obtained for each subassembly. These correction methods could improve design procedure significantly.

Various FMEA analysis software packages, XFMEA, Isograph Reliability and RELEX, were tested in Durham for application to wind turbine reliability. RELEX has been selected due to its advantages and compatibility with the EU FP7 RELIAWIND project. RELEX can be used not only for the FMEA but also for reliability prediction, Reliability Block Diagram (RBD), Fault tree and Markov modelling, which are all suitable for wind turbine reliability studies.

## **5.2 Reliability Prediction and FMEA**

This section reviews the methods and libraries which are most frequently used in reliability prediction and FMEA.

A wind turbine system is composed of many subsystems which cover the topics such as electrical and electronic engineering, software engineering and mechanical engineering. A number of methods are now available to the reliability prediction of electronic systems and equipments [33] [34] [35], including empirical [37] [38] [39] [40] [41] [42], physics of failure [36], similar item data based [35], test or field data based [35], prediction by operational translation [43], and system reliability assessment prediction [44] [45]. In comparison with various prediction methods in electronics, NSWC-07 [46] is the only prevalent handbook to describe reliability prediction models for mechanical parts.

Empirical prediction techniques are based on modelling past experience and handbook data, e.g. MIL-HDBK-217F [38], IEC-TR-62380 [39], TELCORDIA [40], etc. To assess all factors that can affect the system reliability, such as induced failures, problems arising from design, system integration and manufacturing, the technique in RADC-TR-89-299 [42] determine the translation factors to convert the empirical prediction failure rates to an expected field failure rates. The underlying methods in

PRISM<sup>®</sup> [44] and 217 plus<sup>™</sup> [45] are based on system reliability assessment prediction. They are employed in pre-build and post-build two stages [35]. Bayesian statistical techniques are used in the post-build stage. The test data and process data are combined with the prior prediction from pre-build stage to estimate the failure rate. The comparisons of different methods are shown in Table 1, see also [35].

*Table 1 Comparisons of Different Reliability Prediction Methods for Electronics.*

<i>Methods</i>	<i>Advantages</i>	<i>Disadvantages</i>
Empirical	Easy to use as various models are already existing.	Database may be outdated resulting in inaccurate estimate for new components.
Physics of Failure	Accurate prediction using known failure mechanism can be performed to determine the wear-out function.	Require knowledge of component material, process and design. Difficult to calculate as too many data are required.
Similar Item Data	Quickest way to estimate a new product's reliability and is applicable when limited design information are known.	The similar product for evaluation may be substantially different from the item to investigate.
Test/Field Data	Results can be accurately determined as tests include associated uncertainty.	Difficult to obtain and assess data.
Operational Translation	Easy to use and application of environmental factors for harsh conditions.	Lack of up-to-date data and limited number of translation scenarios.
System Reliability Assessment	Combine the field and test data with empirical prediction through statistical analysis.	More computation.

Table 2 summarises some frequently mentioned prediction techniques. Some techniques were initially developed for military or telecommunications, but now they have also been widely applied in many other industries.

*Table 2 Prediction Techniques of Electronics.*

<i>Prediction Techniques</i>	<i>Original Industry</i>	<i>Last Update</i>
MIL-HDBK-217F, Notice 2 [38]	Military	1995
Chinese 299B [41]	China Military	1998
HRD5 [37]	British Telecom	1990
IEC-62380 (formerly RDF 2000), 1e [39]	Commercial/ Telecom	2004
TELCORDIA (formerly BELLCORE) SR-332, Issue 2 [40]	Commercial/ Telecom	2006
FIDES [42]	Commercial/Military	2004
PRISM <sup>®</sup> 1.5 [44]	Military/ Telecom	2003
217 plus <sup>™</sup> [45]	Any	2006

MIL-HDBK-217F standard is the most frequently used reliability prediction method of electronic components, but the development of the standard was terminated. The most recent prediction technique 217 plus™ addresses the shortcomings in earlier models and provides the incorporation of field and test data through Bayesian analysis techniques. 217 plus™ includes 12 component models, i.e. Capacitors, Connectors, Diodes, Inductors, Integrated Circuits, Optoelectronic Devices, Relays, Resistors, Switches, Thyristors, Transistors, and Transformers. The method also contains a basic software reliability prediction model.

The NPRD and EPRD Libraries were developed to provide empirical field failure rate data on non-electronic and electronic components, respectively. They are based on two complementary databases: Nonelectronic Parts Reliability Data (NPRD-95) [47] and Electronic Parts Reliability Data (EPRD-97) [48]. The EPRD-97 database contains failure rate data on electronic components, namely capacitors, diodes, integrated circuits, optoelectronic devices, resistors, thyristors, transformers and transistors. The NPRD-95 database contains failure rate data on a wide variety of electrical, electromechanical and mechanical components.

Many new techniques tend to consider more environmental factors (increasing from 14 factors in MIL-HDBK-217F to 43 overall factors in PRISM® 1.5), and integrate the field and test data with empirical prediction through statistical analysis. Most of the reliability prediction methods and libraries mentioned above (except FIDES) have been integrated into Relex software, which facilitates the research and development. On the other hand, it would be very useful to develop new library and database dedicated to wind turbine industry based on the existing databases and field data.

FMEA standards (e.g. MIL-STD-1629A [49], SAE ARP5580 [50], SAE J1739 [51], AIAG [52], IEC 60812 [53]) define the terminology and specify the procedures to perform a FMEA. Some standards also describe the FMEA report formats. The intention of the failure modes libraries (e.g. FMD-91 [54], FMD-97 [55], MIL-HDBK-338 [56]) is to present failure modes and distributions on parts to support the reliability analysis such as FMEA. Apart from these standard libraries, software tool (e.g. Relex software) could be used to create and customise a failure modes library. Performing FMEA tends to be tedious and time-consuming. But if a customised failure modes library can be built for wind turbine industry, it could save the overall costs in the future.

### 5.3 Wind Turbines Standards: IEC 61400 Series

The well-recognised IEC 61400 series are developed by International Electrotechnical Commission (IEC) Technical Committee 88: Wind Turbines. See Table 3 below for the major international standards, technical reports (TR) and technical specifications (TS) developed by TC 88 for wind turbines.

*Table 3 IEC Series for Wind Turbine Generator Systems.*

Code	Purpose
IEC 61400-1 [57]	It specifies essential design requirements for onshore wind turbines of all sizes. It is concerned with all subsystems of Wind Turbines (WTs).
IEC 61400-2 [58]	It deals with requirements for the safety of Small Wind Turbines (SWTs) including design, installation, maintenance and operation. It is concerned with all subsystems of SWTs.
IEC 61400-3 [59]	It is for offshore WTs, which specifies additional requirements for assessment of the external conditions and minimum design requirements.
IEC 61400-11 [60]	It presents measurement procedures to characterise noise emissions of a WT.
IEC TS 61400-12-1 [61]	It provides a uniform methodology to measure and analyse power performance by WTs.
IEC TS 61400-13 [62]	It deals with mechanical load measurements on WTs and focuses on large horizontal WTs.
IEC TS 61400-14 [63]	It gives guidelines for declaring the apparent sound power level and tonality of a batch of WTs.
IEC 61400-21 [64]	It specifies and defines the quantities to be determined for characterising the power quality of a grid connected WT; It presents measurement procedures for quantification; It includes procedures for compliance assessment with power quality requirements.
IEC TS 61400-23 [65]	It gives guidelines for the full-scale structural testing of wind turbine blades and for the interpretation or evaluation of results.
IEC TR 61400-24 [66]	It reports the current state of standardisation on lightning protection of WTs.
IEC 61400-25 series [67][68][69][70][71]	They focus on the communications between wind power plant components such as WTs and actors such as SCADA systems.
ISO 81400-4 [72]	It specifies the design specification to gearboxes for WTs (mainly from 40 kW to 2 MW).
IEC 60050-415 [73]	It contains definitions used by IEC TC 88 to develop documents for WTs.
IEC WT 01 [74]	It specifies the rules and procedures of IEC for conformity testing and certification of WTs.

## 6. Summary

The intention of this report is to provide a brief introduction on the reliability of wind turbines and review the related research efforts. It surely cannot cover all the concepts and literatures although we have tried our best to reach this target. We believe this report has well answered some important questions: Why do we do the research on the reliability of wind turbines? What do we need to do on this research? What is the state of art of the research? Which important standards and methods we should refer to during the research?

An important observation is that the research of the reliability of wind turbines is quite limited, far behind the research progress of reliability in many other industries. This is the right gap that EU FP7 RELIAWIND aims to fill with in this three-year project. With the advanced software tool, we can perform complicated reliability analysis, and finally improve design and optimise maintenance for wind turbines.

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