Final report

1.1 Project details

Project title	IEA Wind Task 33 - Reliability Data IEA Wind Task 33 – Pålidigheds data
Project identification (program abbrev. and file)	Journal nr.: 64013-0507
Name of the programme which has funded the project	Energiteknologisk Udviklings- og Demonstrationsprogram (EUDP) – 2013 -II
Project managing company/institution (name and address)	Danmarks Tekniske Universitet DTU, Institut for Vindenergi Risø Campus, Frederiksborg Vej 399, 4000 Roskilde
Project partners	IEA
CVR (central business register)	30060946
Date for submission	August 14, 2016. Project period: 12.2013 – 09.2015

1.2 Short description of project objective and results

The IEA-Wind Task 33 is dealing with databases for optimizing reliability and maintenance procedures for wind turbines. The objective is to address different developments of data collection and failure statistics and to agree on recommendations for standards and overall structures. The IEA Task will finish with the final report September 2016. But the main results are expected to be a report with the recommended best practices which link the reliability ambitions of wind farm owner / operators with a range of use cases, examples, standards and taxonomies to assist in the identification, collection and analysis of reliability data. The recommend best practices are also intended to be input to the development of an IEC standard within Reliability data for wind turbine reliability and operation & maintenance.

IEA-Wind Task 33 beskæftiger sig med databaser med henblik på at optimere pålidelighed og vedligeholdelsesprocedurer for vindmøller. Målet er at løse forskellige udviklinger af dataindsamling og fejl statistikker og at blive enige om anbefalinger til standarder og overordnede strukturer. IEA Task 33 slutter med den endelige rapport september 2016. Men det vigtigste resultatet forventes at være en "recommend best practices", som kombinerer ambitioner for pålidelighed på en vindmøllepark som ejer / operatører har, sammen med en række bruger eksempler, standarder og taksonomier for at hjælpe med identifikation, indsamling og analyse af pålideligheds data. Anbefalingerne i " recommend best practices" vil ligeledes også beregnet til at være input til udvikling af en IEC standard indenfor pålidelighed data for vindmøllen, den pålidelighed samt drift & vedligehold

1.3 Executive summary

Costs to Operation & Maintenance can be significant contributors to the Levelized Cost Of Energy (LCOE). Further, OM costs are highly dependent on the reliability of the components and systems implying that it is important to be able to estimate the reliability based on available failure data.

The main result of the IEA-Wind Task 33 is a Recommended practices for reliability data collection for reliability and planning of operation & maintenance. The recommended practices try to lead users finding existing appropriate guidelines for collecting valuable data sets from wind turbine control systems and maintenance reports. It has not been the intention to develop new standards, guidelines, or taxonomies.

In the wind industry is generally recognized that reliability and reliability data are becoming increasingly critical to estimate and assess the LCoE, and that there is a lack of standards associated with reliability data for especially the Owners / Operators. Historically, reliability data is rarely considered by the Owners / Operators at the early stages of wind asset development.

A major difficulty with reliability data for wind turbines is that it is very difficult to get access to failure data for wind turbine owners / operators and others, due to confidentiality reasons. Only very general failure data or old reliability data are to some extent available. This is also the situation in Denmark.

The main recommendations by Task 33 are for Owners / Operators, see the final formulations in the final report with ‘Recommended practices for reliability data collection for reliability and planning of operation & maintenance’:

- Consider reliability data to be of high value from the early stages of wind asset development and a key operational factor throughout the life of the wind asset. Ensure access to reliability data and required data are factored into negotiations with developers / OEMs / suppliers / service providers.
- Organizational reliability ambitions should be linked to the use cases and examples provided in this study.
- All staff engaged directly, or indirectly, in the production, collation and analysis of reliability metrics should be educated on the strategic significance of reliability data and empowered to improve related business processes and practices.
- Map all wind asset components and maintenance activity to one of the taxonomies / designation systems identified in this study. This will allow for improvements in both the consistency and integrity of reliability data throughout an organization and at the interfaces with the supply chain.
- Align operating states with those specified in IEC 61400-26 1/2 the standard for time and production based availability assessment for wind turbines.
- Whenever practical seek to automate the data collection / collation process as a means of reducing the risk of human error and improving data quality.
- Wind farm Owner / Operators should engage in external, industry-wide sharing of reliability and performance data. This will align data collection methodologies, drive organizational improvements and achieve statistically significant populations of data for reliability analyses

And for development of standards for the wind industry:

- Develop a wind specific version of the ISO 14224:2006 standard. This would provide a core standard for the language and scope of reliability and maintenance data for the wind industry (based on accepted reliability data best practice in oil and gas industry), while minimizing the time and cost associated with the development of the standard.
- As a longer term recommendation, there is a need to develop standard definitions for damage classification and severity for structural integrity issues.

More details can be found on http://www.ieawind.org/task_33.html

1.4 Project objectives

The IEA-Wind Task 33 is dealing with databases for optimizing reliability and maintenance procedures for wind turbines. The objective of the IEA Wind Task 33 is to address different developments of data collection and failure statistics for reliability assessment and for operation & maintenance, and to agree on recommendations for standards and overall structures.

An initial, state of the art report: “Initiatives concerning reliability information” were prepared in 2013 before Denmark joined IEA Wind Task 33. It contains an overview of different initiatives of failure statistics (past and present/other sectors), a comparison of approaches and methodologies for data collection, and identification of possibilities of merging the experience gathered.

Since then focus has been on preparing a report with IEA Wind Recommended Practices for Reliability Data related to standardized set of reliability relevant data, harmonization of overall data structures, an improved maintenance process with defined interfaces and data transfer, requirements for more sophisticated O&M-Tools and a basis for sound reliability analyses and maintenance optimisation.

Input has been obtained at an industry O&M workshop ‘Data collection and maintenance modelling methods for improving wind turbine reliability’ in September 2015. One of the main challenges for the IEA Wind Task 33 has been the confidentiality related to wind turbine failure data. It has been very difficult to get access to both failure data and even descriptions of how to categories and organize failure data. Further, partly based on the difficulties to get access to data, it was decided to extend the completion of Task 33 until September 2016, i.e. the Task 33 is not yet finished. A wind industry seminar at Wind Europe 2016 ‘Data collection and reliability assessment for O&M optimization of wind turbines’ will be used to present the final results and recommendations.

The contributions and results related to the present EUDP project has been contributions to presentation of the overall theoretical framework for operation & maintenance, reliability issues related to structural reliability, and deterioration modelling, see below.

1.5 Project results and dissemination of results

Wind turbines have the potential to contribute significantly to the production of renewable energy. For both onshore and offshore wind turbines costs to Operation & Maintenance can be significant contributors to the Levelized Cost Of Energy (LCOE). Further, OM costs are highly dependent on the reliability of the components and systems implying that it is important to focus on increasing the reliability as much as is economically reasonable, i.e. to find the optimum reliability level minimizing the total costs also accounting for the loss of electricity production in case of failures.

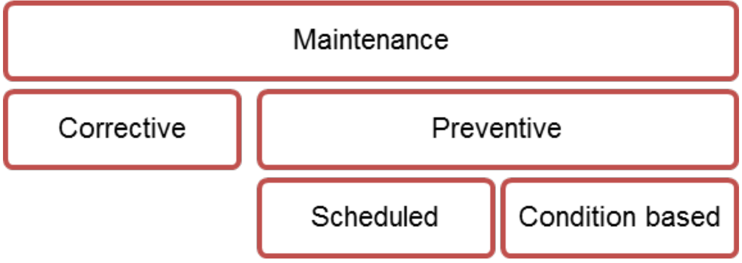
To improve the reliability of wind turbines, a detailed statistical analysis of the reliability characteristics of systems, components and subassemblies is required. This must be complemented by qualitative assessments of operational and maintenance information sources. For achieving this, an broadly accepted guideline on “how to” would strongly support the existing initiatives dealing with reliability issues, would ease merging individually set up databases and would allow for comparing results and benchmarking.

The IEA Wind Task 33 workgroup has representation from industry and research, from OEMs to service providers, and from research institutions to owner operators. Through a series of workshops, web and teleconferences, the workgroup explored the challenges, opportunities and value associated with the collection, analysis and value of reliability data and associated standards, guidelines and taxonomies.

Focus has been on examining the scope of reliability data in terms of what reliability data is and how it should be gathered from a range of sources and what tools. The recommended best practices contained within this study link the reliability ambitions of wind farm owner / operators with a range of use cases, examples, standards and taxonomies to assist in the identification, collection and analysis of reliability data.

In the following a short overview of the results within Task 33 is presented including a more detailed description of the contributions and results related to the present EUDP project, i.e. the Danish part of the Task. Here it is mentioned that Denmark joined the Task after it started, and that the Task has been delayed, and is not yet completely completed (the Task will be completed ultimo September 2016).

Figure 1: Operation & maintenance strategies



Maintenance strategies can be divided in two categories, see Figure 1:

- Corrective Maintenance
- Preventive Maintenance

In corrective maintenance repair / maintenance is performed whenever there is a failure of a component or a (sub)system. Corrective maintenance is often of an emergency nature requiring immediate performance. Therefore it is usually more costly than preventive maintenance. For offshore wind turbines this is mainly due to restrictions in access imposed by limited weather windows.

Generally, there are two methods for preventive maintenance, scheduled and condition-based, see Figure 1. For scheduled preventive maintenance, maintenance actions are scheduled already in the planning phase, and the method can be used if the lifetime of the component is known with large confidence. Scheduled maintenance is typically time-based and is performed e.g. each year. In case of larger uncertainty in the deterioration models, and thus in the lifetime, condition-based maintenance can be used. Here the maintenance decisions are made based on information about the actual condition / health of the component / (sub)system, which can be obtained by use of for example condition monitoring or structural health monitoring.

In a corrective maintenance strategy is used, then for estimating the expected maintenance costs information about failure rates and costs are needed. If a preventive, schedule maintenance strategy is used, then in addition information about the expected lifetime and costs of preventive maintenance actions are needed. Further, if a preventive, condition-based maintenance strategy is used then also information about deterioration of the component / (sub)system and costs of obtaining information from e.g. condition monitoring are needed.

Reliability

Wind turbine components can generally be divided in two groups. One group comprising mainly electrical and mechanical components where the reliability is assessed using 'classical reliability methods' based on failure data in terms of 'time to failure' statistics, failure/hazard rates and bath tub curves. Further, the reliability can be updated if information from condition monitoring is available. This type of reliability modelling is often applied within RAMS methodologies and Reliability Centered Maintenance strategies.

A range of reliability techniques are described and assessed in relation to application for Operation & Maintenance and with respect to requirements for data. These include Qualitative assessments; Functional failure analysis (FFA); Failure Mode, Effect and Criticality Analysis (FMECA); Reliability of pairable vs. non-repairable components; and Data-driven models and artificial intelligence.

Reliability of structural components and systems is generally estimated using methods from structural reliability. Structural reliability can for wind turbines be applied for components such as blades, tower and cast components incl. e.g. the main shaft. The main steps in the reliability assessment is 1) identification of failure modes in considered structural elements and modelling the failure modes by systems of limit states (reliability elements), 2) formulation of limit state equations for the considered limit states, 3) identification of uncertain parameters and stochastic modelling, 4) estimation of the probability of failure of limit states e.g. using the so-called reliability index, 5) system modelling of failure modes by limit states and 6) risk assessment where the probability of failure of failure modes are combined with the consequences.

Reliability of structural systems can be defined as the probability that the structure under consideration has a proper performance throughout its lifetime. Structural reliability methods are used to estimate the probability of failure. The information used to formulate the models which the reliability analyses are based on is generally not complete. Therefore the estimated reliability should be considered as a nominal measure of the reliability and not as an absolute number. However, if the reliability is estimated for a number of structures using the same level of information and the same mathematical models, then useful comparisons can be made on the reliability level of these structures. Further design of new structures can be performed by probabilistic methods if similar models and information are used as for existing structures which are known to perform satisfactory. The reliability estimated as a measure of the safety of a structure can be used in a decision (e.g. in design or during operation) process.

In order to be able to estimate the reliability using probabilistic concepts it is necessary to introduce stochastic variables and/or stochastic processes/fields and to introduce failure and non-failure behavior of the structure under consideration. Typical failure modes to be considered in a reliability analysis of a structural system are yielding, buckling (local and global), fatigue and excessive deformations.

The fundamental quantities that characterize the behavior of a structure are modelled by stochastic variables. Typical examples of basic variables are loads, strengths, dimensions and materials. The basic variables can be statistically dependent or independent. The uncertainty modeled by stochastic variables can be divided in the following groups:

1) Aleatory uncertainties:
Physical uncertainty: or inherent uncertainty is related to the natural randomness of a quantity, for example the uncertainty in the yield stress due to production variability.

2) Epistemic uncertainties:
Measurement uncertainty which is the uncertainty caused by imperfect measurements of for example a geometrical quantity; Statistical uncertainty which is due to limited sample sizes of observed quantities; and Model uncertainty which is the uncertainty related to imperfect knowledge or idealizations of the mathematical models used or uncertainty related to the choice of probability distribution types for the stochastic variables.

In addition to these uncertainties gross errors / human errors can be important for assessment of the reliability. Typically such errors are handled by quality control, and will not be considered further in this section.

In structural reliability theory it is assumed that a limit state equation can be formulated for the considered failure modes. The limit state equation thus becomes a function of the stochastic variables and it is possible to estimate the probability of failure and the corresponding failure rate.

Reliability modelling based on structural reliability methods are often used to model reliability of deterioration of the structural components, e.g. fatigue of welded details. It is noted that the information needed for application of structural reliability methods is more comprehensive than when applying classical reliability methods. In Task 33 and in the recommendations these important aspects have been introduced.

Further a number of O&M methods and tools are investigated. These include Interval optimization; Grouping of maintenance activities and Cost modelling.

Deterioration modelling

For condition-based preventive operation & maintenance strategies modelling of deterioration is needed taking into account both the physical characteristics and the uncertainty. In physics based models the development with time of the degradation/damage is based on a physical mechanism or process. The parameters typically have a physical meaning related to the deterioration process considered. The models to be established are thus:

- A deterministic model for damage / deterioration accumulation – as a function of time.
- A stochastic model for uncertain parameters in the damage accumulation model such that a probabilistic model for the damage accumulation can be obtained, i.e. the probability of certain damage levels can be calculated.

Information from e.g. continuous monitoring systems and from quality control can be used to establish and/or update the stochastic models.

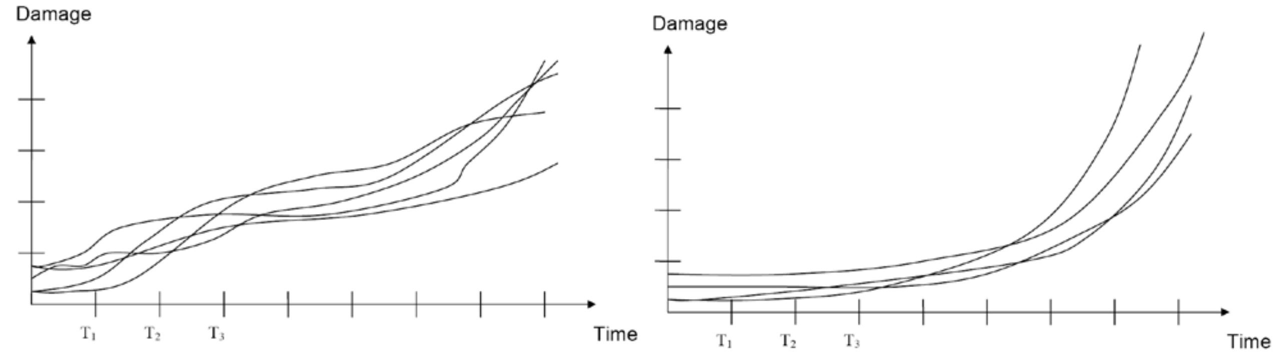


Figure 2 Examples of damage models.

The above figure 2 shows two examples of damage models:

- The example to the left shows realizations of a damage model where the damage development with time is almost linear. It also shows that uncertainty in the loading and the material behaviour may result in random variations in the damage development. Such a model could for some components be related to corrosion and erosion.
- The example to the right shows realizations of a damage model where the damage development is almost exponential with time. Such a model could be related to defects and fatigue cracks in e.g. welded details, cast steel, and composite materials.

One example of establishing a damage model for cracks is to use a fracture mechanics based damage model where the crack / defect growth is determined by the load cycles applied to the considered fatigue critical detail. The loading can e.g. be due to temperature variations or mechanical load variations from wind. Typical realisations based on the above fracture mechanics model are shown in the above figure to the right.

This model gives a measure of the physical deterioration / damage as a function of time. Failure is assumed to occur if the damage exceeds a critical value. Similar physics based models can be established for other degradation types, such as corrosion, scour and erosion. An important part of the modelling is to provide stochastic models for those parameters I the model that can be considered uncertain.

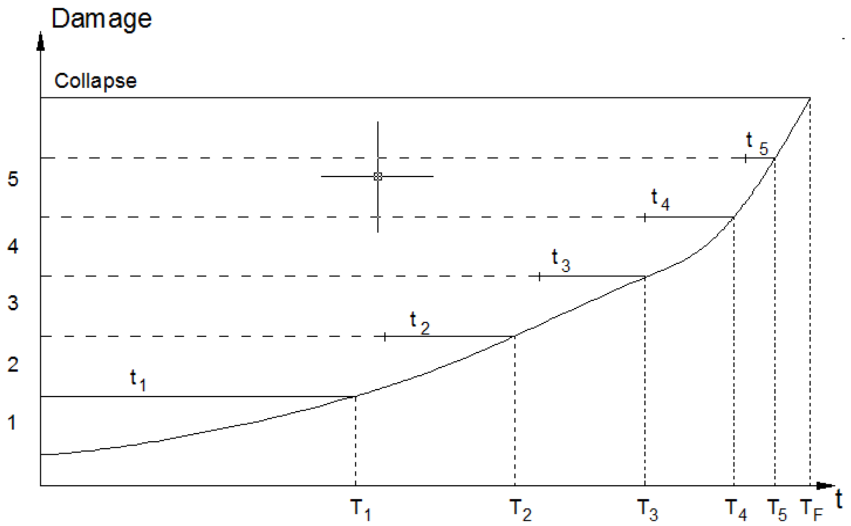


Figure 3. Example with discrete damage state model.

In practical applications a discretization of the damage / crack size in a number of stages is often convenient when applied for maintenance planning. Such a damage state model can e.g. be formulated using for example using the 6 stages defined in the table below and illustrated in the above figure 3.

Stage	*Damage*	*Damage size*
1	Cosmetic	0 to D_1
2	Small	From D_1 to D_2
3	Medium	From D_2 to D_3
4	Serious	From D_3 to D_4
5	Critical	From D_4 to D_5
6	Collapse / failure	Larger than D_5

Discretization of damage in a damage state model.

This model gives a measure of the physical deterioration / damage as a function of time. Such a model is e.g. used for modelling defects in wind turbine blades and as basis for decisions on maintenance and repair.

In order to describe the development in time e.g. a Markov process model can be formulated which models the probability of jumping from one stage to the next assuming that this probability does not depend on the past history. The damage stages and the transition probabilities have to be modelled for the specific applications.

The damage state model can be calibrated using e.g. the following information:

- A known failure rate can be used as basis for obtaining the same annual probability of failure
- Data on measured damage developments with time e.g. from inspections
- Engineering judgement

A discrete damage state model can be very convenient to be applied in connection with Operations and Maintenance planning.

The remaining useful life (RUL) can be estimated from the model describing the damage evolution if the critical damage value is known and all parameters can be assumed deterministic, i.e. with no uncertainty. If uncertainties cannot be neglected, then probabilistic methods have to be applied for estimating the expected value of RUL and also measures of the scatter, e.g. the standard deviation.

Reliability Data Collection

The user of reliability and maintenance data has to systematically collect and treat an enormous amount of information and data. This includes data on the wind turbine itself as well as occurring failures, and maintenance measures. Some information has to get collected only once, i.e. identifiers or technical data of system and sub-systems, while measurement values need continuous capturing.

Structuring these data IEA Wind Task 33 has followed the international standard ISO 14224 from offshore oil and gas industry and suggests the four data groups:

- Equipment data
- Maintenance data
- Failure data
- Operation & measurement data

Examples are provided for what is considered to be included in data groups and subgroups. More details can be found in the referenced standards, guidelines, and taxonomies. In general, each subgroup contains a list of possible entries and several taxonomies present suggestions of entries. However, it is always up to the user looking up the appropriate taxonomy and deciding whether collecting all suggested data or selecting the most relevant for his task.

The taxonomies included in the recommended practices were found capable covering the needs of data collection for reliability assessment best. But only few of these taxonomies were developed directly for the use in wind energy industry and also these may not perfectly fit into a user’s task. Thus, the tables and listings should be considered as suggestions and examples instead of complete recipes.

Task 33 intends leading potential users to existing standards, guidelines, and taxonomies, which suit their individual task. It was generally not intended elaborating new guidelines.

However, in some cases, especially for equipment data, no complete wind specific guideline was found. In these cases Task 33 suggests some data entries.

Taxonomies based on the following standards / guidelines have been considered:

- Reference designation system for power plants (RDS-PP)
- NERC-GADS
- ISO 14224
- ReliaWind
- IEC 61400-25
- IEC 61400-26
- ZEUS

The following tables show examples on data groups developed and recommend for application for wind turbines. They are described in more details the Task 33 'Recommended Practices' on Reliability Data:

Data group equipment data, sub-groups/objects, possible entries and taxonomies addressing equipment data:

Equipment data		
Sub-groups/Objects	**Entries**	**Taxonomies**
time data		
	Type approval	IEAWT33
	Date of commissioning	IEAWT33
	Start of observation	IEAWT33
geographic information		
	Co-ordinates	IEAWT33, ISO 14224
	postal address	IEAWT33
	wind class	IEAWT33
	altitude	IEAWT33
general machine data		
	average ambient temperature	IEAWT33
	OEM	ISO 14224
	Type	ISO 14224
	serial number	ISO 14224
	type of generator	IEAWT33
	type of tower	IEAWT33
	additional equipment	IEAWT33
technical machine data		
	nominal power	ISO 14224
	nominal wind speed	IEAWT33, ISO 14224
	hub height	IEAWT33
	rotor diameter	IEAWT33
component designation		
	time of restart	IEAWT33
	function	RDS-PP
	product	RDS-PP, GADS, Reliawind
	location	RDS-PP

Data group maintenance data, sub-groups/objects, possible entries and taxonomies addressing maintenance data:

Maintenance & inspection data		
Objects	**Entries**	**Taxonomies**
time data		
	Begin of measure	ISO 14224
	time of restart/duration	IEAWT33
	active maintenance time	ISO 14224
	down time	ISO 14224
	delays	ISO 14224
task / measure / activity		
	category (preventive, corrective)	ISO 14224, ZEUS, GADS
	type of activity	ISO 14224, ZEUS
	impact on plant	ISO 14224
	recommended action	ZEUS
resources		
	man-hours	ISO 14224
	qualification	IEAWT33
	auxiliary equipment	IEAWT33
	spare parts	IEAWT33
maintenance results		
	Recommended subsequent action	ZEUS

Data group failure data, sub-groups/objects, possible entries and taxonomies addressing failure data:

Failure / fault data		
Objects	**Entries**	**Taxonomies**
	date of occurrence of failure	ZEUS, ISO 14224
	date of restart	
description		
	failure mode	ZEUS, ISO 14224
	failure mechanism	ZEUS, ISO 14224
	failure cause	ZEUS, ISO 14224
	failure process	ZEUS, ISO 14224
impact		
	impact/effect on plant	ZEUS, ISO 14224
	impact/effect on component/part	ZEUS, ISO 14224
detection		
	detection symptom	ZEUS, ISO 14224
	detection method	ZEUS, ISO 14224
	occasion for detection	ZEUS
fault properties		
	kind of damage (deviation from target state)	ZEUS
	location of fault (on structural components)	IEAWT33
	Size of fault (on structural components)	IEAWT33

Data group operational data, sub-groups/objects, possible entries and taxonomies addressing operational data:

Operating data / Measurement values		
Objects	**Entries**	**Taxonomies**
	time stamp	IEAWT33
measurement values		
	active power	IEC 61400-25
	reactive power	IEC 61400-25
	rotor speed	IEC 61400-25
	temperatures	IEC 61400-25
operating / functional status		
	operating state (plant)	IEC 61400-26
	functional state (plant)	ZEUS
	functional state (component)	ZEUS
ambient conditions		
	temperatures	IEC 61400-25
	wind speed	IEC 61400-25
	wind direction	IEC 61400-25

1.6 Utilization of project results

The result of the project can be used of the various stakeholders incl. manufacturers, owners, standardization committees for recommendations on how to collect and organize failure data for planning of operation & maintenance and for reliability analysis and assessment of new and existing wind turbines incl. lifetime extension.

A wind industry seminar at Wind Europe 2016 ‘Data collection and reliability assessment for O&M optimization of wind turbines’ will be used to present the final results and recommendations.

1.7 Project conclusion and perspective

The IEA-Wind Task 33 is dealing with databases for optimizing reliability and maintenance procedures for wind turbines.

One of the main challenges for the IEA Wind Task 33 has been the confidentiality related to wind turbine failure data. It has been very difficult to get access to both failure data and even descriptions of how to categories and organize failure data. Based on the difficulties to get access to data, it was decided to extend the completion of Task 33 until September 2016, i.e. the IEA Task 33 is not yet finished.

The IEA Task 33 is expected to finish with the final report September 2016. With the main results expected to be the recommended best practices for reliability data for wind turbine reliability and operation & maintenance.

The difficulties and the delays in the IEA Task 33 resulted in a low activity level reported in the EUDP Journal nr.: 64013-0507.

Annex

More details can be found on http://www.ieawind.org/task_33.html