PROJECT DELIVERABLE REPORT

OPTIMUS

Demonstration of Methods and Tools for the Optimisation of Operational Reliability of Large-Scale Industrial Wind Turbines

Collaborative project

Deliverable number: D1.1

Deliverable title: Collection of failure data for onshore and offshore wind farms

Due date of deliverable: 28/02/2014
Actual submission date: 30/04/2014

Authors: Mayorkinos Papaelias (UoB), Stuart Hillmansen (UoB), Pietro Tricoli (UoB), Jun Zhou (UoB), Gerard Fernando (UoB), Fausto Pedro Garcia Marquez (UCLM), Diego Pedregal (UCLM), Spyridon Kerkyras (Feldman Enterprises), Alexandros Karyotakis (TERNA Energy), O. Panagoiliopoulos (TERNA Energy), V. Karakassidis (Terna Energy), Jose Enrique Camacho Questa (INGTEAM), Luis Moreno (INGTEAM) Chantal Roldán De La Cuadra (INDRA), Miguel Murillo Calleja (INDRA), Paul McKeever (NAREC), Chong Ng (NAREC)

Dissemination Level (PU/PP/RE/CO): PU

Project coordinator: Paul McKeever, NAREC
Tel: +44 (0) 1670 357613
Fax: +44 (0) 1670 359666
E-mail: paul.mckeever@narec.co.uk
Project website address: www.optimusfp7.eu/

OPTIMUS/322430/Deliverable 1.1/2014/Version 1.0
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Summary

Wind turbines are complex systems consisting of a variety of critical components (e.g. tower, blades, rotor hub, sensors, gearbox, power electronics, yaw, brake mechanism, controller, anemometer, etc.). Failure of any of these critical components will most likely result in unnecessary downtime and associated costs due to the loss of production and repair requirements. Depending on the type of component and mode of failure the effect on the overall downtime, repair timescale and financial losses can vary significantly. Thus, gearbox failures may result in far longer downtime and maintenance costs than failures associated with sensors. Furthermore, certain types of failures may result in significant damage to other components or even complete loss of the wind turbine. For example, an overheating bearing causing combustion of the lubricating oil will probably lead to the complete loss of all the equipment installed on the nacelle. Also failure of the braking mechanism under severe windy conditions may also result in catastrophic structural failure of the blades and possibly the wind turbine itself.

The purpose of this deliverable report is to present the data collected with the help of the industrial partners of the consortium about the failure modes that affect wind turbines. Due to confidentiality issues the distinction between onshore and offshore wind farm data is not always straightforward but the report contains sufficient detail in order to enable satisfactory conclusions to be drawn with regards to the main problems faced in wind turbine operation whether these are onshore or offshore. To the extent that it has been possible public releases have been considered to increase the amount of useful information contained in this report. According to the findings the gearbox condition is a critical factor for both onshore and offshore wind farms as it can result in significant downtime and repair costs. Although wind turbine manufacturers and operators demand that the gearbox is designed for an operational lifetime of at least 20 years this is far from being achieved. According to reports most operators are faced with gearbox refurbishment or even replacement at least twice or thrice within a 20 year period of operation. In recent wind energy projects the costs associated with gearbox problems are always taken into consideration during budgetary planning.
1. Onshore and offshore wind energy

The growing effects of global warming are a serious threat to the economic and societal stability of the European Union as well as the rest of the world. The strong growth in the amount of energy provided by renewable energy sources and wind energy in particular contributes substantially into the meaningful reduction of greenhouse emissions [1].

Over the last three decades, wind energy has experienced substantial growth rates becoming the most important renewable energy source within Europe [2]. The renewable energy industry as a whole, with the wind energy industry leading the way, has made significant advances since the Kyoto Protocol was signed in Japan, 1997 [3].

The decisions of the Kyoto Protocol were boosted during the United Nations Bali Convention in 2007 which emphasised the need for the decarbonisation of the global economy before the 21st century expires [4]. The EU has been in the forefront of this effort with approximately 13% of the energy mix of the EU-28 being generated from renewable energy sources as of 2013 [5]. Under normal annual wind conditions the EU-28 can produce 257 TWh or 8% of its annual electricity demand [6]. The pie graphs Figure 1 show the increasing importance of wind energy in the EU-28 energy mix with respect to installed rated power capacity.

![Figure 1: EU energy mix in 2000 (left) and 2012 (right) in terms of installed rated capacity.](source: EWEA)

Wind energy represented 11% of the overall installed rated power capacity in Europe [Source: EWEA].

The graph in Figure 2 shows the confirmed contribution of renewable energy sources (i.e. energy produced) in the EU-28 energy mix up to 2011. Despite the turbulent economic conditions of recent years, the EU-28 is currently on the way of meeting and possibly exceeding the target of 20% being produced from renewable energy sources by 2020.

The plot in Figure 3 shows a comparative graph of the share of energy from renewable energy sources in gross final consumption of energy in 2011 between the EU-28 and other countries around the world.
Figure 2: Contribution of renewable energy sources in the energy mix of the EU-2020 from 2004-2011. A steady increase is evident with minor fluctuations indicating that the EU is currently on its way of achieving the target of 20% energy production from renewable energy sources set for 2020 [Source: EUROSTAT].

Figure 3: The share from renewable energy sources in gross final consumption of energy in 2011 between the EU-28 and other countries around the world [Source: EUROSTAT].
At the moment Sweden is the EU-28 leader in renewable energy production with almost half (48%) of its power needs being produced from sustainable energy sources [7]. However, the majority of renewable energy production is based on hydroelectric power generation with wind energy accounting for approximately 4% of the overall energy production only despite the 2000 wind turbines already installed. Denmark on the other hand has achieved a 45% contribution from wind energy to its energy mix with a target of at least 50% by 2020 and is in close pursuit of Sweden. Thus, Denmark is currently the EU-28 leader in wind energy production in terms of contributed amount to its energy mix [8].

The graph in Figure 4 shows the wind energy installed capacity, amount of electricity generated and contribution to the energy mix in Denmark over a period of more than three decades from 1977 to 2011. A significant amount of Denmark’s wind power capacity is installed offshore (approximately 30%).

![Installed wind capacity, annual generation and capacity factors, Denmark 1977-2011](image)

Figure 4: Wind power installed capacity, power generation and contribution to the Danish energy mix. It can be seen that the installation of new capacity accelerated to its highest at the end of the last decade [Source: Wikipedia article on Wind energy in Denmark].

Germany and Spain are the EU-28 leaders in terms of total installed wind energy capacity. Germany has installed in excess of 32 GW wind power capacity as of 2013. The wind energy produced from the installed wind turbines contributes more than 11% of the overall electricity demand in Germany [6]. The plot in Figure 5 shows the installed wind energy capacity in Germany by 2011.
The graph in Figure 6 shows the power output achieved between April, 1\textsuperscript{st} and April 25\textsuperscript{th} in 2013 from all German wind farms.

![Figure 5: Total installed capacity and average generated power in Germany from 1990 to 2011 (Source: Wikipedia article on Wind power in Germany).](image1)

![Figure 6: Wind energy feed-in in Germany from April 1 – 25, 2013, Total installed rated capacity is 32 GW. Peak output reached 18 GW briefly on April 18 (Source: EIKE reader Ralf Schuster).](image2)

In Spain the total installed capacity has exceeded 23 GW in 2013 [6]. Latest reports suggest a 21.1\% contribution in the Spanish energy mix production from wind turbines, thus exceeding for the first time the annual power production from nuclear power plants in the country [9].
The graph in Figure 7 shows the increase in cumulative capacity in Spain over a ten-year period from 2002 to 2012.

![Graph showing growth in cumulative wind power capacity in Spain from 2002 to 2012](source)

**Figure 7: Growth in cumulative wind power capacity in Spain from 2002 to 2012**

[Source: AEE].

In 2012 a total of 1,111.8 MW of wind power capacity were installed in Spain. Table 1 shows the wind turbines installed were manufactured almost entirely by European manufacturers.

**Table 1: Manufacturers of wind turbines installed in Spain during 2012** [Source: AEE].

<table>
<thead>
<tr>
<th>Manufacturers</th>
<th>Capacity installed in 2012 (MW)</th>
<th>Percentage of total installed in 2012</th>
<th>Cumulative capacity to end 2012 (MW)</th>
<th>Cumulative market share (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAMESA</td>
<td>423.45</td>
<td>38.1%</td>
<td>11,925.59</td>
<td>52.3%</td>
</tr>
<tr>
<td>VESTAS</td>
<td>338.35</td>
<td>30.4%</td>
<td>10,071.99</td>
<td>17.9%</td>
</tr>
<tr>
<td>ALSTOM</td>
<td>107</td>
<td>9.6%</td>
<td>1,736.54</td>
<td>7.6%</td>
</tr>
<tr>
<td>ACCIONA WIND POWER</td>
<td>102</td>
<td>9.2%</td>
<td>1,658.13</td>
<td>7.3%</td>
</tr>
<tr>
<td>GE</td>
<td>48</td>
<td>4.3%</td>
<td>1,414.64</td>
<td>6.2%</td>
</tr>
<tr>
<td>SIEMENS</td>
<td>0.0</td>
<td>0.0%</td>
<td>772.30</td>
<td>3.4%</td>
</tr>
<tr>
<td>ENERCON</td>
<td>21.1</td>
<td>1.9%</td>
<td>515.05</td>
<td>2.3%</td>
</tr>
<tr>
<td>SUZLON</td>
<td>0.0</td>
<td>0.0%</td>
<td>218.00</td>
<td>1.0%</td>
</tr>
<tr>
<td>NORDIX</td>
<td>35.7</td>
<td>3.2%</td>
<td>183.38</td>
<td>0.8%</td>
</tr>
<tr>
<td>DESA</td>
<td>0.0</td>
<td>0.0%</td>
<td>100.80</td>
<td>0.4%</td>
</tr>
<tr>
<td>LAGERWEY</td>
<td>0.0</td>
<td>0.0%</td>
<td>37.50</td>
<td>0.2%</td>
</tr>
<tr>
<td>M-TORRES</td>
<td>0.0</td>
<td>0.0%</td>
<td>36.90</td>
<td>0.2%</td>
</tr>
<tr>
<td>KENETECH</td>
<td>0.0</td>
<td>0.0%</td>
<td>36.90</td>
<td>0.2%</td>
</tr>
<tr>
<td>SINOVEL</td>
<td>0.0</td>
<td>0.0%</td>
<td>36.00</td>
<td>0.2%</td>
</tr>
<tr>
<td>REPOWER</td>
<td>0.0</td>
<td>0.0%</td>
<td>25.00</td>
<td>0.1%</td>
</tr>
<tr>
<td>NCRYPTO</td>
<td>0.2</td>
<td>0.0%</td>
<td>2.00</td>
<td>0.0%</td>
</tr>
<tr>
<td>ELECTRA WIND</td>
<td>0.0</td>
<td>0.0%</td>
<td>0.15</td>
<td>0.0%</td>
</tr>
<tr>
<td>WINDECO</td>
<td>0.0</td>
<td>0.0%</td>
<td>0.05</td>
<td>0.0%</td>
</tr>
<tr>
<td>OTROS</td>
<td>0.0</td>
<td>0.0%</td>
<td>16.37</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

**TOTAL**                 | 1,111.8                         |                                     | 22,785.57                          | 100.0%                      |
More than 9 in 10 turbines installed in 2012 in Spain were of the geared type. Figure 8 shows the number of installed turbines per power rating and their share with respect to the overall installed capacity in Spain in 2012. The majority of the newly installed wind turbines were rated at 2 MW, followed by 3 MW rated turbines. In total, 576 wind turbines were installed in Spain in 2012 bringing their total number across the country to 20,190.

Figure 8: Breakdown of the size of turbines installed in Spain in 2012 [Source: AEE].

Significant growth in installed wind power capacity has also been seen in the UK with particular emphasis in offshore projects. According to latest news the UK will limit drastically onshore projects and focus only on offshore wind farm development in the future [10]. The graph in Figure 9 shows the cumulative wind energy capacity in the UK for onshore and offshore project.

Figure 9: Graph showing the cumulative installed capacity in the UK for onshore and offshore projects [Source: Wikipedia article on Wind Energy in the United Kingdom].
Some offshore wind farms in the UK have encountered significant problems with their gearbox designs as discussed later in this report.

The graph in Figure 10 shows the contribution of renewable energy sources in the EU in 2011 and the target set for 2020.

![Figure 10: Share of renewable energies in gross final energy consumption in EU-27 countries in 2011 (in %) [Source: EUROSTAT].](image)

The wind energy industry has continued experiencing strong growth in global scale with total installed capacity now exceeding 300 GW as of 2013. The graph in Figure 11 shows the amount of cumulative installed global capacity in 2012.

More than one third of the global capacity or in excess of 120 GW of wind power capacity is installed in EU Member States. From the total European wind energy capacity installed 110 GW concern onshore projects and less than 10 GW concern offshore wind farms.

China and the U.S. have also been exhibiting strong growth in recent years with the majority of installed wind power capacity outside the EU being found in these two countries. The majority of the newly installed wind turbines have been of the geared type, representing around 80% of the overall market in 2012.
The graph in Figure 12 shows the ten countries with the highest amount of newly installed wind power capacity in 2012. The graphs in Figure 13 show the leading wind turbine manufacturers for 2010 and 2012. Despite the volatile economic climate European wind turbine manufacturers still control almost 45% of the overall market.

However, in 2012 the highest market share has been won for the first time by a non-European company. European offshore wind turbine manufacturers are likely to come under significant pressure from international competitors (particularly from manufacturers in South East Asia with vast expertise in offshore structures and maritime construction) in the medium to long term.

These are additional signs of the difficult road lying ahead for European wind turbine manufacturers in terms of competition from non-European companies who are continuously trying to penetrate the European wind energy market.

Figure 11: Global cumulative growth in installed wind power capacity from 1996 to 2012 [11].

Figure 12: Top ten countries for newly installed wind power capacity in 2012 [11].
The overall investment in new renewable energy projects however did dwindle in 2012 recording a significant drop in new investments in comparison to 2011. Early indications show that the situation has somewhat improved in 2013 but uncertainties regarding the performance of the European economy have an adverse effect on the implementation of new projects. Reliability issues concerning offshore wind farms have also contributed to the slowing down of further investment.

Figure 14 shows the total investment in new renewable energy projects from 2004 to 2012 in billions of U.S. $. The global investment in new renewable projects also declined in 2012 as shown in the plot in Figure 15.
Although the majority of wind energy projects are constructed onshore, in Europe there has been a significant investment in offshore wind farm construction. Practically all European offshore wind farms are located in the North Sea.

At the end of 2013 there were 8 GW of installed offshore wind power capacity. Offshore wind farms represented 7.5% of Europe’s annual wind energy installations. The EU-28 objective is to achieve a 40 GW installed capacity by 2020. It is unlikely that under the current economic uncertainty this is an objective which is realistically achievable before 2025.

Twenty-two out of the twenty-five major offshore wind farms around the world are located in Northern Europe. The other three are located in China. Certain wind farms have encountered substantial problems with their gearboxes which are still not entirely certain that they have been solved yet. About half of these offshore wind farms are in the North and Irish Sea with the rest being installed in the Baltic Sea.

The wind turbine manufacturers who have succeeded in entering the offshore market include Siemens, Vestas, REpower, Bard, Areva, Nordex, Gamesa, Alstom, Goldwind (China), Sinovel (China) and Shanghai Electric (China).
The pie graphs in figure 16 shows the offshore wind turbine market share from 2010 until the end of 2013. European manufacturers continue to dominate the market although REpower has been acquired by Suzlon Energy since December 2009.

**2010**

![Pie chart for 2010 showing market share](image)

**2011**

![Pie chart for 2011 showing market share](image)
The graphs in Figure 17 show the offshore wind turbine manufacturer market share for 2010 and 2013.

In total there are 2080 offshore wind turbines which have been grid connected so far.
The graph in Figure 18 shows the annual growth and cumulative offshore wind energy capacity in Europe over a period of twenty years and more specifically from 1993 to 2013. It is evident that offshore wind energy in Europe is growing rapidly. The graph in Figure 19
shows the cumulative installed wind energy in Europe. Onshore wind farms currently represent more than 90% of the total installed capacity.

Figure 18: Annual growth and cumulative installed offshore wind power capacity in Europe from 1993 to 2013 [Source: EWEA].

Figure 19: Annual growth and cumulative installed wind power capacity in Europe from 2000 to 2012. Onshore projects account for more than 90% of the overall installed capacity [Source: EWEA].
However, as shown in the graph in Figure 20 newly installed offshore wind energy capacity is experiencing stronger growth rates than onshore wind energy projects. Nonetheless, the onshore wind energy market remains significantly larger than offshore wind energy.

![Figure 20: Annual growth for onshore and offshore installed wind power capacity in Europe from 2001 to 2012. From 2010 onwards offshore wind energy has achieved a 1 to 10 analogy with respect to onshore [Source: EWEA].](image)

The graph in figure 21 shows the average rating of wind turbines installed offshore which over the last three years has stabilised above 3.6 MW. In the case of onshore projects the average rating hovers at around 2 MW. Figure 22 shows the cost fraction for each of the main components of a typical 2MW turbine.

![Figure 22: Average power rating for wind turbines installed offshore from 1991 to 2013. [Source: EWEA].](image)
The graph in Figure 23 shows the average offshore wind farm output in Europe which in 2013 exceeded 450 MW. The average size of onshore wind farms is normally much smaller and rarely exceeds 100 MW.

In general the biggest onshore wind energy projects are found in the U.S. and they normally have an average rated capacity which exceeds 100 MW as shown from the plot in Figure 24. However, in Europe the average onshore wind farm rated capacity is less than 100 MW.

![Figure 24: Average offshore wind farm capacity in Europe from 1911 to 2013 (Source: EWEA).](image1)

![Figure 24: Average onshore wind farm capacity in the United States from 1998-2009. In general onshore wind farm projects are smaller in Europe than in the United States and rarely exceed 100 MW in rated capacity [13].](image2)
Figure 22: Cost fraction of different key wind turbine components
[Source: Wind directions, January/February 2007].

Figure 23: Distribution of cost fraction per component for a typical 2 MW wind turbine [12].
2. Operation and maintenance for onshore and offshore wind turbines

Most wind turbines are three-blade units comprising of the components shown in figure 22. Driven by the wind, the blades transmit the energy harvested via the main shaft through the gearbox to the generator. Alignment with wind direction is controlled by the yaw system of the wind turbine. Maintenance is required ensure the wind turbine and the key components that comprise it continue to perform the function they were intended to for the entire design lifetime. The fundamental objectives of maintenance are to deploy the minimum resources required to ascertain that the wind turbine and its critical subcomponents perform their intended operation normally without interruption and ensure reliability [14-15]. In the event were damage has already occurred then maintenance may be required to correct the fault or recover from a breakdown [15].

Classical theory defines maintenance activities either as corrective or preventive (or predictive) [16]. The former (also known as unscheduled or failure based maintenance) is carried out when turbines break down and when faults are detected or failures occur in any of the components. Immediate refurbishment or replacement of parts may be necessary and unscheduled downtime will result. Corrective maintenance is therefore the most expensive of strategies and wind farm operators will hope to resort to it as little as possible. The various stages are shown in Figure 24.

By contrast, the objective behind preventive maintenance (PM) is to either repair or replace components before they fail as shown in Figure 25 [17]. This has most straightforwardly been achieved by scheduled maintenance, also known as time based (or planned) maintenance and involving repair or replacement at regular time intervals as recommended by the supplier and regardless of condition. Scheduled maintenance activities in WT include the changing of oil and filters, and the tightening and torquing of bolts.

Operating and Maintenance (O&M) costs of onshore wind farms normally do not exceed 20-25% of the overall project cost. However, in the case of the offshore projects current experience has shown that O&M costs can be as high as 40% and even exceed this. Although onshore wind turbines are designed with a 20-year operational lifetime in mind this has been proven to be practically impossible to achieve without serious repairs taking place as damage evolves. Offshore wind turbine designers face an even more challenging task as offshore wind farms are supposed to remain in operation for at least 25 years.
One of the key components of a wind turbine is the gearbox. Gearbox manufacturers despite the development of the IEC 61400-4 standard on design requirements for wind turbine gearboxes have failed to manufacture gearboxes which can last for 20 years [18].

It is generally acceptable that an onshore wind turbine may need three or four times to have its gearbox repaired or even replaced during its entire lifetime. In the case of onshore wind farms this is largely attributed to the poor understanding of continuously variable loading conditions arising from turbulent wind that affect the gearbox operation.

On the other hand in the case of offshore wind turbines there has been an underestimation of the loading conditions prevailing out in the open sea and thus most gearbox designs have experienced significant problems very early in their lifetime [19-21]. The majority of wind turbine gearbox failures have been reported to initiate in the bearings (planetary, intermediate and high-speed shaft) [20]. Oil cleanliness and lubrication quality have also been highlighted as part of the problem since they can contribute to excessive wear, surface distress, fatigue spalling and pitting [22].

Nonetheless, there is still a necessity to understand the fundamental loading conditions associated with planetary bearings particularly in the case of offshore wind turbine gearboxes. Examples of damage on bearing and gears are shown in the photographs of figures 25 and 26.

Figure 25: Fatigue spalls on roller bearing inner ring and fatigue pitting (spalling) on pitch line in gear teeth [21-22].
According to several studies oil cleanliness and lubrication quality plays a crucial factor in the deterioration of wind turbine gearboxes.

It is estimated that the oil cleanliness can increase or reduce the lifetime of gearbox components by up to 50% in comparison to a new gearbox [21].

One report has suggested that 82% of machine wear is particle induced and related to oil cleanliness [24].

Therefore, it is crucial that wear particles are removed using appropriate filters in order to increase the lifetime of gearboxes.

The schematic in figure 27 shows the modular definition of a gearbox and its main subcomponents.
Onshore wind farm availability has increased substantially in recent years reaching 95-98% on average. However, for offshore wind farms much lower availabilities are recorded which reduce the overall average to as low as 80-85% [26]. Wind turbines at the Scroby Sands, North Hoyle, Kentish Flats and Barrow had all gearbox bearing or full gearbox replacements within the first 3 years of operation.

There is evidence from several European wind farm operators that the quality of repairs can influence by a noteworthy margin the Mean Time Between Failures (MTBF) and thus the requirement for further maintenance. Also the way maintenance is carried out can influence the extent that damage may evolve and how it will affect the overall wind turbine operation in the future.

There have been a number of studies that have investigated the reliability of industrial scale wind turbines. RELIAWIND, an FP7 project (Grant Agreement Number FP7-212966, www.reliawind.eu) which was concluded relatively recently considered 35,000 downtime events associated with 350 pitch-controlled variable speed wind turbines from four different manufacturers [27].

The graph in figure 28 shows the percentage contribution to overall failure rate for the wind turbines considered in the study. The highest failure rates have been experienced by the power converter.

The pitch system has also experienced relatively high failure rates. Very surprisingly the study revealed a higher failure rate for the yaw system than the gearbox.

The sample of wind turbines considered in the RELIAWIND study is relatively small over a relatively small period of time.

Also the age of the wind turbines has not been revealed thus it is very difficult to draw safe conclusions regarding the gearbox failure rate which seems generally lower in comparison to the information gathered from other sources.
The graph in Figure 29 shows the percentage contribution to the overall downtime caused by failure of various components for the wind turbines considered during RELIAWIND.

**Figure 28:** Graph showing the percentage contribution to overall failure rate for 350 wind turbines considered in RELIAWIND

**Figure 29:** Graph showing the percentage contribution to overall downtime for 350 wind turbines considered in RELIAWIND

Figure 30 shows results from the WS D, LWK D and WS DK studies for the period 1993-2004. However, it is difficult to relate these results to the findings of the RELIAWIND
project as the wind turbines considered are likely to be of older technology and most likely improvements in the gearbox design have taken place in the meantime.

In general there is significant scatter of data from study to study and this is due to several reasons including wind quality, maintenance practice, types of turbine used, etc.

![Graph showing survey failure rate comparison from 1993 to 2004](image)

**Figure 30:** Results from the WSD, LWK D and WS DK studies for 1993 to 2004 [Source: SUPERGEN Consortium Presentation].

Figure 31 shows the hours lost per failure for different component faults according to the results of the LWK study from 1993 to 2004. Gearbox failures were determined to cause the highest downtime.

Figure 32 shows the average failure rate per wind turbine based on the results of the LWK study from 1993 to 2004.
Figure 31: LWK survey on hours lost per failure for 1993-2004. [Source: SUPERGEN Consortium Presentation].

Figure 32: LWK average failure for different wind turbines for 1993-2004 [Source: SUPERGEN Consortium Presentation].

The average failure rates for WT components from various studies (Bussel G J W van, Zaaijer M B., EWEC, 2001; Ribrant J, Bertling L. M., IEEE Transactions on Energy Conversion, 2007; Ribrant J. Master’s thesis, KTH School of Electrical Engineering,
Stockholm, 2006; Spinato F, Tavner P J, Bussel G J W van, Koutoulakos E., Renewable Power Generation, IET, 2009) is shown in figure 33.

Considering the cumulative failure rate of each component, the control system has the highest value, followed by the blades/pitch and then the electric system.

Gears, yaw system, hydraulic, brake, generator, sensor and others form a group with medium cumulative failure rate. Hubs, drive trains and structures all have low rates.

![Figure 33: Average rate of failure for various wind turbine components](source)

Another study carried out by ECN considered a wind farm of 9 multi-MW turbines with two different types of gearboxes and generators.

Failures occurring in the wind farm were recorded and analysed for three consecutive years. It can be seen in figure 34 that failures were evenly distributed among the nine turbines.

Figure 35 shows the distribution of the failure causes.
It is evident that the gearbox-related failures are the dominant fault for all turbines with the power converter experiencing far less faults [26].

The graph in figure 36 shows the failure distribution per cause recorded in Sweden between 2000 and 2004. Figure 37 shows the associated downtime per mode of failure.

Table 1 summarises the statistical findings of the study carried out in Sweden [19]. Gearbox failures are summarised in Table 2. The important findings of the Swedish study are summarised in Table 3.
Figure 36: Distribution of number of failures for Swedish wind power plants between 2000-2004 [19].

Figure 37: Distribution of downtime per failure mode.
### Table 1: Summary of statistical findings for Sweden, Finland and Germany between 2000 and 2004 [19].

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average number of failures per turbine</td>
<td>0.402 times a year</td>
<td>1.38 times a year</td>
<td>2.38 times a year</td>
</tr>
<tr>
<td>Average downtime per year</td>
<td>52 hours per year</td>
<td>237 hours per year</td>
<td>149 hours per year</td>
</tr>
<tr>
<td>Average downtime per failure</td>
<td>170 hours per failure</td>
<td>172 hours per failure</td>
<td>62.6 hours per failure</td>
</tr>
</tbody>
</table>

### Table 2: Type of gearbox failure [19].

<table>
<thead>
<tr>
<th>Type of reported failure code</th>
<th>Component</th>
<th>Number of failures</th>
<th>Average downtime (hours)</th>
<th>Number of failures, Cause: B1</th>
<th>Average downtime, Cause: B1 (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-1</td>
<td>Bearings</td>
<td>41</td>
<td>562</td>
<td>36</td>
<td>359</td>
</tr>
<tr>
<td>L-2</td>
<td>Gearwheels</td>
<td>3</td>
<td>272</td>
<td>2</td>
<td>172</td>
</tr>
<tr>
<td>L-3</td>
<td>Shaft</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>L-4</td>
<td>Sealing</td>
<td>8</td>
<td>52</td>
<td>4</td>
<td>30</td>
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<tr>
<td>L-5</td>
<td>Oil system</td>
<td>13</td>
<td>26</td>
<td>5</td>
<td>36</td>
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<tr>
<td>L-others</td>
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<td>44</td>
<td>230</td>
<td>19</td>
<td>299</td>
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</tbody>
</table>

### Table 3: Result of statistical findings for Sweden [19].

<table>
<thead>
<tr>
<th>Country</th>
<th>Sweden</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average number of failures</td>
<td>0.402 times a year</td>
</tr>
<tr>
<td>Average downtime per year</td>
<td>52 hours per year; 170 hours per failure</td>
</tr>
<tr>
<td>Most number of failures</td>
<td>Electrical system; Sensors; Blades/Pitch</td>
</tr>
<tr>
<td>Most amount of downtime</td>
<td>Gears; Control system; Electrical system</td>
</tr>
<tr>
<td>Longest downtime per failure</td>
<td>Drive train; Yaw system; Gears</td>
</tr>
</tbody>
</table>

**Important findings from the failures statistics**
- Turbines below 1MW show similar failure rate trends, with a small increase for the first three years of operations and after five years it decreases.
- Turbines above 1MW show an increasing failure rate over the operational years.

**Important findings concerning gears**
- The amount of failures has decreased for the most recent years.
- The downtime for gearbox failures has increased in recent years.
- The majority of the gearbox failures are caused by wear.
- No link between brand of turbine and amount of gearbox failures can be proved since the amount of available data is small, but two types of turbines stand out compared to the others.
Onshore and offshore wind turbines seem to experience similar failure rates in the power electronics according to a study carried out by Vattenfall recently as shown in Table 4.

However, experience of other wind farm operators point out that power electronics suffer a substantially higher failure rate in offshore wind turbines in comparison to onshore.

**Table 4:** Average failure event rate per year for two different types of multi-MW turbines for offshore and onshore wind farms [Source: T. Stalin, Vattenfall Presentation, 2013].

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A</td>
<td>WT1</td>
<td>Offshore</td>
<td>0.13</td>
<td>0.026</td>
<td>0.9</td>
</tr>
<tr>
<td>Site B</td>
<td>WT1</td>
<td>Onshore</td>
<td>n.a.</td>
<td>n.a.</td>
<td>46.5</td>
</tr>
<tr>
<td>Site C</td>
<td>WT1 WT1*</td>
<td>Offshore</td>
<td>0.15</td>
<td>0.025</td>
<td>5.4</td>
</tr>
<tr>
<td>Site D</td>
<td>WT2</td>
<td>Offshore</td>
<td>0.39</td>
<td>0.021</td>
<td>6.1</td>
</tr>
<tr>
<td>Site E</td>
<td>WT2</td>
<td>Onshore</td>
<td>n.a.</td>
<td>n.a.</td>
<td>2.5</td>
</tr>
<tr>
<td>Site F</td>
<td>WT2</td>
<td>Onshore</td>
<td>n.a.</td>
<td>n.a.</td>
<td>2.0</td>
</tr>
<tr>
<td>Site G</td>
<td>WT2</td>
<td>Onshore</td>
<td>n.a.</td>
<td>n.a.</td>
<td>1.7</td>
</tr>
</tbody>
</table>

There is serious evidence that gearbox failures are the main reason of downtime in offshore wind farms. The Alpha Ventus offshore wind farm experienced serious problems with a number of gearboxes in 5 MW wind turbines.

The problems were associated with overheating of bearings which were attributed to a combination of materials selection (aluminium alloy instead of steel) and lubrication.

The gearboxes of these turbines needed to be refurbished shortly after they were initially commissioned.

The annual service time for this particular wind farm has been indicated to be 450 hours per wind turbine.

Significant problems with the gearbox have been experienced in the offshore wind farms of Kentish Flats, Egmond, Barrow, Thanet and Horns Rev.

Figure 38 shows the annual availability of several offshore wind farms in comparison to normal average availability of onshore wind farms.

It is evident that in some cases the availability of offshore wind farms is reduced dramatically predominantly due to gearbox related problems.
Figure 38: Annual availability of selected offshore wind farms compared to the average availability of onshore wind farms [Source: Paavo Blåfield].

Figure 39 shows the number of failures associated with planetary bearing faults at the Horns Rev 1 wind farm reported by Vattenfall.

It is expected that repair requirements of offshore wind turbine gearboxes will increase as the number of wind turbines installed also increases potentially making resource planning more complicated and costly.

According to Wind Power Monthly (Sara Knight, 2011) in 2010 there were approximately 16,000 wind turbines installed globally with about 30% of them installed in Europe. It is expected that by 2017-2020 there will be 5,500 gear boxes that were installed in 2010 which will need to be refurbished in Europe alone.

This number does not include the gearboxes of wind turbines that are already in service from previous years.

The price for a new gearbox for a 2MW turbine is in the range of €160,000-190,000. The standard cost of bearing replacement, gear teeth overhaul and regrinding and component measurement in this type of gearbox is in the range of €90,000-105,000 according to Wind Power Monthly.

This does not include the logistics of the repair operation which can cost a further €20,000-40,000 if the whole operation takes place within one day.

This cost can be doubled if the gearbox needs to be removed, repaired and replaced at a later date. If damage such as a broken shaft has to be rectified, the cost can rise up to €130,000.
damaged gearbox may be cost-effective to repair up to a cost of €150,000-160,000, after that a wind farm operator will normally opt for a replacement gearbox instead [Source: Sara Knight, Wind Power Monthly, 2011].

The above scenario refers to an onshore wind turbine. The costs can be much higher for an offshore wind farm.

O&M costs for offshore wind farms can thus be two to seven times higher than the average of onshore wind turbines [29].

![Figure 39: Planetary bearing failures at Horns Rev 1 offshore wind farm reported by Vattenfall [Source: R&D Examples Presentation, May 2012].](image)

Significant gearbox problems have been reported in other wind farms where some of the wind turbines had to have their gearboxes replaced several times.

The graph in Figure 40 shows the availability for different offshore wind farms. In the aforementioned wind farms problems recorded included generator bearing failure and planetary bearing failures which was also the main cause of downtime.

Some of the problems were revealed using endoscopy.

The photograph in Figure 41 shows a typical endoscope device used to assess the gearbox components.
Figure 40: Availability at four different offshore wind farms between July 2004 to December 2007 [Source: Y. Feng et al., Durham University, December 2010].

Table 5 summarises the typical design characteristics of a generic gearbox.

<table>
<thead>
<tr>
<th>Gear Stage</th>
<th>Module (mm)</th>
<th>Helix Angle (°)</th>
<th>Face Width (mm)</th>
<th>Number of Tooth</th>
<th>Pitting Resistance Safety Factor</th>
<th>Bending Strength Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1 (epicyclic)</td>
<td>Sun Planet Gear</td>
<td>25</td>
<td>20</td>
<td>750</td>
<td>29</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>58</td>
<td>1.41</td>
<td>2.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 2 (parallel)</td>
<td>Pinion Gear</td>
<td>16</td>
<td>10</td>
<td>500</td>
<td>27</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>108</td>
<td>1.42</td>
<td>2.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 3 (parallel)</td>
<td>Pinion Gear</td>
<td>12</td>
<td>20</td>
<td>220</td>
<td>25</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>105</td>
<td>1.39</td>
<td>2.65</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6 shows the main faults associated with the power converter of wind turbines and the average downtime caused by different types of failure. The downtime has been classified for wind turbines rated below and above 1 MW.

<table>
<thead>
<tr>
<th>Failure type</th>
<th>WT&lt;1MW average downtime in hours</th>
<th>WT&gt;1MW average downtime in hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter IGBT</td>
<td>15.5</td>
<td>8.9</td>
</tr>
<tr>
<td>Rectifier IGBT</td>
<td>5.8</td>
<td>7.9</td>
</tr>
<tr>
<td>Relays</td>
<td>1.9</td>
<td>3.8</td>
</tr>
<tr>
<td>Capacitors</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td>Measurement Items</td>
<td>5.8</td>
<td>3.4</td>
</tr>
</tbody>
</table>

The availability of specialised equipment and personnel is far more difficult and costly in the case of offshore wind farms as shown in the photographs in figure 42.
Figure 42: Equipment for construction and maintenance of offshore wind turbines.

The photograph in Figure 43 shows the typical arrangement of an offshore wind farm.

Figure 43: Wind turbine arrangement in a typical offshore wind farm.

The graph in Figure 44 shows the typical failure rates from various wind turbines. The data have been acquired from the LWK study (2006-2009).
Figure 44: Typical failure rates from various wind turbines [Source: LWK 2006-2009].
3. Conclusions

This deliverable report presented the data collected with the help of the industrial partners of the consortium about the failure modes that affect wind turbines and from the literature. The importance of failures associated with power converters and gearboxes has been highlighted. There seems to be a consistency in the failure rates of power converters recorded for both onshore and offshore wind farms. However, in the case of gearboxes problems encountered seem to be significantly higher in offshore wind farms. In general the planetary bearing are a major consideration followed from high speed shaft bearings.
4. References

5. Source: EUROSTAT Website
27. Source: www.reliawind.eu
OPTIMUS Acknowledgement

OPTIMUS (Demonstration of methods and tools for optimisation of operational reliability of large-scale industrial wind turbines) is a cooperation between the following organisations: NAREC, INGETEAM Service, The University of Birmingham, ACCIONA ENERGIA, Instituto de Soldadura E Qualidade, INDRA Sistemas, Feldman Enterprises, Universidad de Castilla-La Mancha, Dynamics, Structures and Systems International, The University of Sheffield, Romax Technology and TERNNA Energy. The Project is managed by NAREC and is a partly funded project by the EC under the FP7 framework programme. Grant Agreement Number: 322430