Condition Monitoring of Wind Turbines

CONDITION MONITORING OF WIND TURBINES

- UP00195/R/0001
- Version 2
- 11 August 2006

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CONDITION MONITORING OF WIND TURBINES

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1. Executive Summary

Over the last two decades, on-shore wind energy technology has seen a ten-fold reduction in cost and although not competitive with fossil fuels for electric power generation, is one of the more cost effective technologies for the generation of Renewable Obligation (RO) certified electricity (landfill gas and co-fired biomass being amongst the most cost effective). While onshore wind technology is maturing rapidly, the need for further technology development still remains, such as better controllability, dispatchability, intelligent interaction with the grid, and output power condition monitoring. In addition, as wind energy penetrates further into the grid and becomes a more significant part of the energy mix, industry growth, dispatchability, controllability and infrastructure barriers will become critical long term issues.

Over 14 GW of new on- and off-shore wind projects are under construction of going through planned in UK, moving wind into mainstream generation.

The success of land based turbines can be attributed to the ability of designers to reduce the initial capital cost of turbine components while maintaining or improving overall reliability, coupled with generous subsidies and relative ease of maintenance resulting from good accessibility. The consequence of this is that added capital investment to reduce the long term O&M burden is not standard for on-shore systems due to the lack of a demonstrated life-cycle payback model and the desire to keep initial project costs low.

However, work at sea is significantly more costly and time consuming and the on-shore O&M model will not provide the best economic option. New off-shore strategies must be developed to minimise the work done at sea, requiring a shift in project design (e.g. through use of high specification components, introduction of automated condition monitoring systems) and operational implementation e.g. use of predictive or reliability centred maintenance techniques. Materials must be selected for durability and environmental tolerance. Design, starting with the preliminary concepts, must rigorously place a higher premium on reliability, construction and ease of operation and maintenance. Turbines equipped with intelligent turbine condition monitoring and self-diagnosis systems will help to manage Operation and Maintenance (O&M) weather windows, minimise down time and reduce the equipment needed for up-tower repairs. Ultimately, a new balance between initial capital investment and ongoing operating costs will be required to be established which will have in impact on all aspects of the industry.

The financial modelling and anecdotal evidence from practioners indicates the CBM is currently too expensive to be cost-effectively retrofitted to existing facilities. The price where CBM would become financially viable is dependent on the payback period required and the size of the wind turbines. The larger the wind turbine, the more likely it is that CBM could be cost effective.

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Current systems require a minimum turbine size of 3 MW to achieve an acceptable 6 year simple payback.

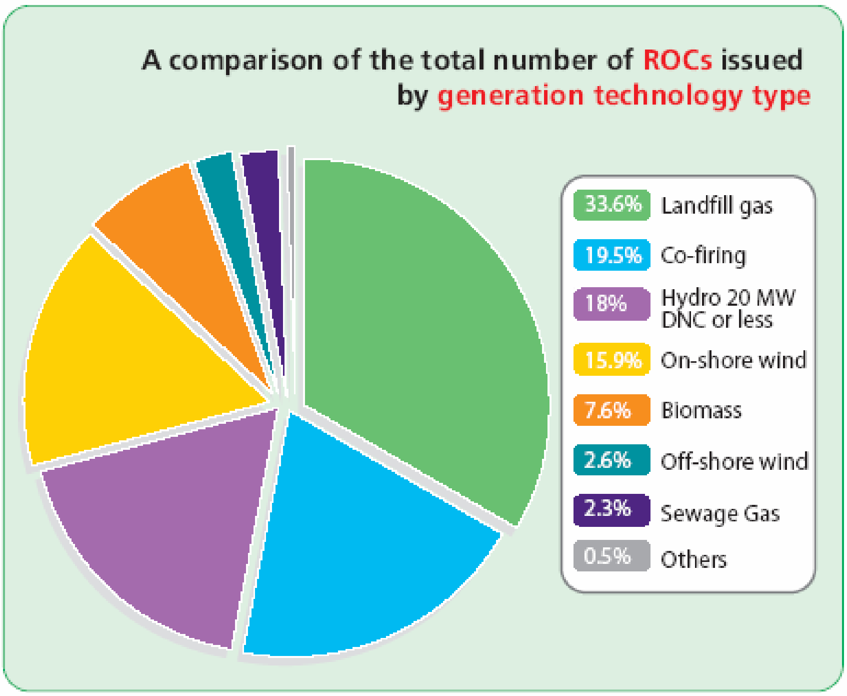
In order for there to be a viable retrofit marketplace then the cost of condition monitoring equipment needs to be reduced significantly and given the relatively low volumes of wind turbines it is SKM's opinion that in order to develop this marketplace further cross-fertilisation with mass market technology (e.g. automobile industry) would be essential.

2. Introduction

Over the last two decades, on-shore wind energy technology has seen a ten-fold reduction in cost and although not competitive with fossil fuels for electric power generation, is one of the more cost effective technologies for the generation of Renewable Obligation (RO) certified electricity (landfill gas and co-fired biomass being amongst the most cost effective). The following market information can be used to place wind generation in the context of the wider renewable picture: Figure 1 shows the allocation of Renewables Obligation Certificates (ROCs) by generation technology; Figure 2 shows a comparison of the costs of different forms of electricity generation; and, Figure 3 shows potential market share in 2010-2011.

While onshore wind technology appears to be maturing rapidly, the need for further technology development still remains, such as better controllability, dispatchability, intelligent interaction with the grid, and output power condition monitoring. In addition, as wind energy penetrates further into the grid and becomes a more substantial part of the energy mix, industry growth, dispatchability, controllability and infrastructure barriers will become critical long term issues. Over 14 GW of new on- and off-shore wind projects are under construction ongoing through planning in UK, moving wind into mainstream generation.

- **Figure 1 ROCs by generation technology type (for 2004 – 2005)[1]**



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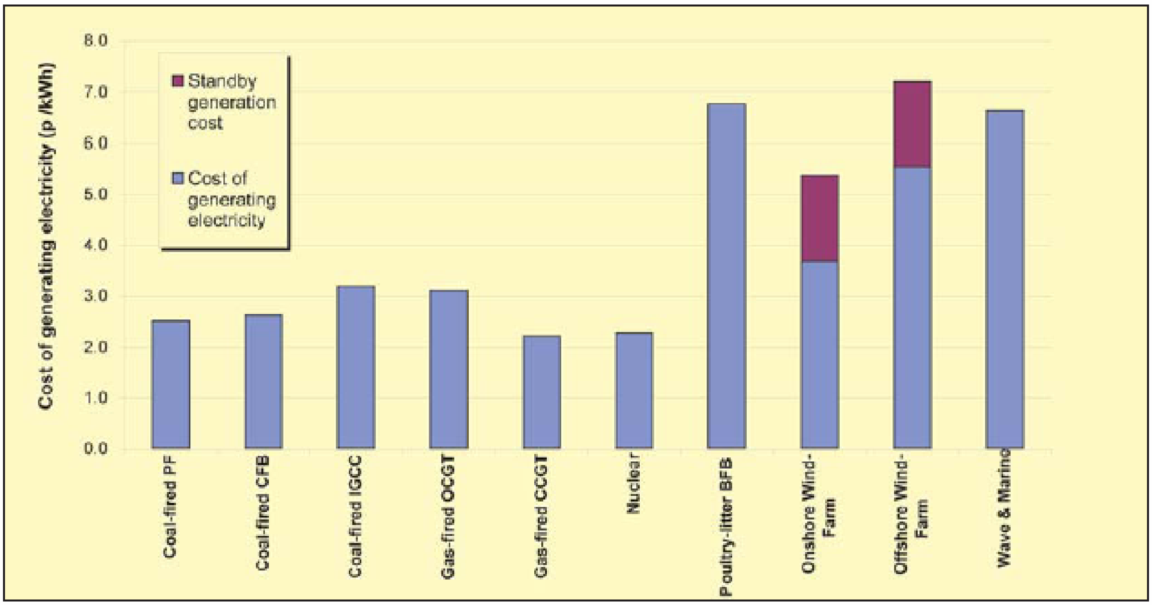
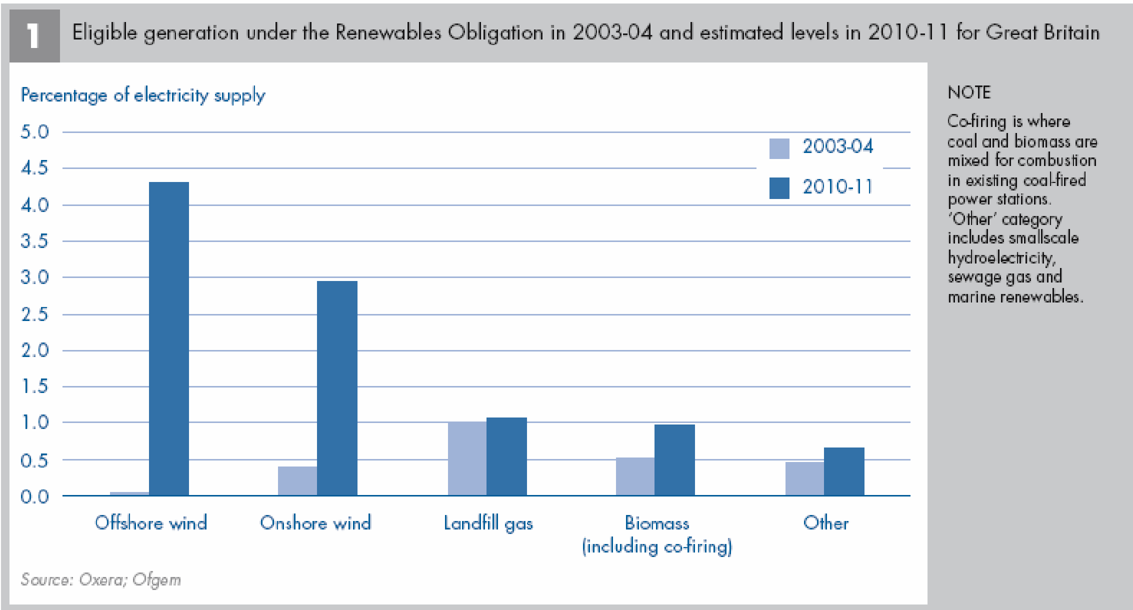
- **Figure 2 Electricity generation costs for different technologies[2]**



- **Figure 3 Eligible generation under Renewables Obligation[3]**



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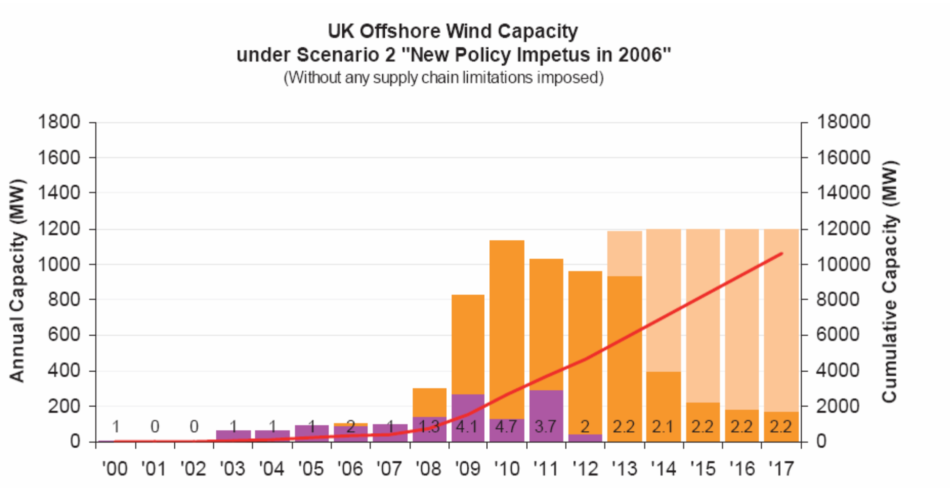
Offshore wind: current situation 2006

Off-shore wind energy started in the shallow waters of the North Sea where the abundance of sites and higher wind resources are more favourable by comparison with Europe's land-based alternatives. The first installation was in Sweden with a single 300 kW turbine in 1990 and the industry has grown slowly over the past 15 years. There are now 18 operating projects with an installed capacity of 804 MW. The majority of the capacity is now located in Denmark and the United Kingdom, using mostly Danish turbine technology.

Over 11 GW of new off-shore wind projects are planned before the year 2010 with most of the development taking place in Germany and the UK(5 GW).

A recent report[3] has examined the potential growth of offshore wind. A detailed critique of this report is beyond the scope of this document but Figure 4 shows an optimistic evaluation of the future market for offshore wind. The numbers represent the number of projects to be completed, the pink bars UK offshore round 1 projects, the orange bars UK round 2 and other projects and the tan bars UK offshore round 3 and later projects.

- **Figure 4 Predicted UK Offshore Wind Capacity[4]**



The largest offshore turbine installed to date sits in the Irish Sea at the 25 MW Arklow Banks wind farm. Each of the seven turbines has a rotor diameter of 104 m with a hub height of over 70 m. Each unit has an output capacity of 3.6 MW and can generate up to 15GWh per year based on a load factor (average wind conditions and availability) of 35%. Although this turbine model is unlikely to be installed in future projects it exemplifies the current trend which indicate that off-shore turbines will grow much larger than this in the future; there are several 5 MW to 6.5 MW class turbines in the prototype and early production

Photo GE Energy

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stage. Market indicators suggest that the 1.5MW to 3.6MW size of turbine will dominate the off-shore market going forward.

As off-shore wind turbines become larger the cost of downtime also increases – this is a positive driver for Condition Based Monitoring (CBM). Additionally, the situation of any turbine off-shore creates accessibility and maintenance issues. The opportunity to plan maintenance rather than simply react to failures and the access difficulties for regular manual inspections are also positive drivers for CBM.

The availability[1], and potential difficulty in accessing, of these machines will be key to the cost effectiveness of such turbines and therefore condition monitoring could play an important role. However, given the relatively high predicted availability there is limited scope for improving the available operating hours through application of CBM.

2.1. Wind Turbine Technology

Wind power has undergone significant development since the early '80s, when wind turbines were producing 50 kW_e, until now where turbines as large as 5 MW_e are being manufactured for electrical generation. Wind power is a mature technology with many years of commercial operational experience. Having said that, the designs of turbines are continually changing as manufacturers explore the limits of scaling up current technologies and introduce and develop the potential of new technologies.

All wind turbines rely on the conversion of kinetic energy within the wind to drive an electrical generator. There are two main types of wind turbine:

- horizontal axis wind turbines (HAWT);
- vertical axis wind turbines (VAWT).

There are a number of variations on both types of turbines. Furthermore, turbines are available over a wide range of sizes and can be as small as roof mounted schemes to turbines nearly 160 m to tip height. Generally speaking, the more capital intensive the plant and the greater the cost of lost production through unscheduled or unnecessary maintenance the more cost effective CBM is. As such, CBM is likely, as is discussed later in the report, to be more viable on larger scale devices located in inaccessible areas, such as offshore, than smaller devices that are easily accessible, such as roof-top mounted.

[1] A 1% decrease in availability equates to £1,500 per installed MW per year.

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2.1.1. Horizontal Axis Wind Turbines (HAWT)

The HAWT is the typical type of wind turbine installed world-wide. HAWTs have a number of advantages over VAWTs including for example:

- greater investment and operating experience;
- higher performance capability;
- access to higher wind speeds through rotor being raised off the ground;
- better blade control to adapt to differing wind conditions; and
- smaller footprint.

A typical commercially available HAWT consists of a steel tower with a three bladed rotor upwind of the generator. The rotor is usually connected via a gearbox to the generator, although versions without gearboxes are also available.

A wide range of commercially operational HAWTs are available and an optimal turbine type can often be selected for a given location. The cost for on-shore wind turbines in the UK is now of the order of £1m per MW installed.

2.1.2. Vertical Axis Wind Turbines (VAWT)

There are only a small number of VAWTs installed world-wide and operational experience is significantly less than that for HAWTs. The number of VAWTs in commercial operation is very small when compared with HAWTs.

VAWTS do however have a couple of advantages over HAWTs, including for example:

- the generator and gearbox is at the base of the tower, making maintenance easier; and
- VAWTs can accept wind from any direction without the need of a yaw system.

The simpler and more reliable the turbine the less scope there is for cost effective CBM.

2.2. Offshore

Off-shore wind has different factors to consider in comparison with on-shore:

- Unit size is generally larger.
- Individual unit failure will represent a larger percentage of the installed capacity of the farm and loss of revenue will consequently be larger.
- Gear boxes will be increasing in size and complexity as rotor diameters increase.
- Although the largest machines are currently being installed on-shore, the trend is the off-shore turbines will be generally larger.

- Access restricted to fewer weather windows.
- Availability of maintenance platforms / barges is restricted[2].
- Common systems, such as electrical connection and transformers, can be subject to the harshness of the marine environment.
- Plant designed for reduced maintenance.

2.3. The practitioners perspective

The general feeling from operators is condition monitoring is not an appropriate technology to be applied to wind turbines. This opinion is based on a number of factors:

- Maintenance staff are generally of automotive maintenance background. The emphasis is on reliability centred maintenance and active fault repair.
- On-shore wind farms benefit from continuous site presence. Many developing problems are identified early from review of logs and close proximity to problem machines.
- Unit sizes have, until recently, been small (sub 1 MW). The loss to the owner of one machine being unavailable was not great.
- Unit capital investment was small. Hence, the additional cost of monitoring equipment would be significant (up to 3%) and the potential cost savings low, due to the relatively low output of the devices.
- Access is not normally an issue for on-shore wind farms. Crane availability is not constrained (although for the larger turbines this is not true), sites can generally be accessed for most of the year, high winds will be an issue for short periods of time. In short, weather windows are not critical.
- Many failure modes are identified symptomatically and only through site visit or analysing general machine telemetry can the cause be identified.
- Many third party systems are available, all with all their associated claims to detect faults early and allow targeted preventative maintenance. However, most of the systems available have experienced limited uptake and the perception is suppliers can provide no real evidence as to the effectiveness of their products.
- The general perception of operators is unless costs come down and the technology becomes more proven practitioners will not wish to adopt.

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[2] However, it is noted that the market should respond to increased demand. New support vessels have been developed which mitigate this problem.

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2.4. Operation experience

Operators and manufacturers of wind turbines endeavour to obtain availabilities of more than 97%[3], which are contractually established and guaranteed. The lost value due to 3% unavailability will vary depending on prevalent weather conditions as the machine may not be capable of operating at Maximum Rated Capacity (MRC) at the time of the unscheduled outages. This availability level is commonly achieved if good operation and maintenance practices are followed such as the use of experienced maintenance staff; adopting a reliability centred maintenance regime; adopting incentive based maintenance contracts; and planning outages to correspond with weather windows.

Equally high reliability guarantees are required for off-shore wind turbines as for on-shore wind turbines, although the difficult access in the off-shore area implies significant down-times in the case of complicated repairs.

Anecdotal evidence suggests that if a typical on-shore turbine, with an availability of 97%, were installed in the off-shore environment the resulting machine availability would reduce to 85%. The reduction in availability can be attributed to the harsher operating environment and the difficulty of accessing the machine to conduct routing maintenance and repairs. Hence, a turbine specifically designed for the off-shore environment are configured differently to reduce ingress of salt saturated air, material selection is driven by corrosion resistance and would be designed for reduced maintenance. It likely that turbines designed specifically for off-shore use will achieve similar reliabilities to those enjoyed by on-shore turbines given the significant investment undertaken by the manufacturers in improving the robustness of the technologies.

SKM is aware of improvements in off-shore support vessel design which, through dramatically increasing crew access to the turbines, facilitate availability figures approaching that of on-shore farms. Off-shore maintenance is likely to be modelled on techniques employed in the floating platform arena which represents a more logistical approach to that employed in the on-shore wind turbine environment.

2.5. Insurance considerations

There is an increasing trend with German and Danish insurance companies to stipulate in their policy terms and conditions requirements for maintenance / overhaul activities. This would typically involve the requirement to overhaul the turbine major components every 40,000 hours

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[3] Unavailability is typically calculated based solely on the time when the turbine is not able to run when it is required to. The figure does not account for the down time due to scheduled maintenance, low or high wind limits or network outages etc which typically account for an additional 1.5% downtime.

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operation or 5 years whichever occurs earlier. The policy would also contain a clause describing a relaxation in this maintenance regime if a condition monitoring system were installed. Indeed, as the investment market in Germany and Denmark is lead by insurance companies designers have no choice but to install condition monitoring systems.

Hence the requirement of insurers becomes a factor for consideration when developing the turbine technology and any associated condition monitoring system would need to meet certain standards in order to satisfy the requirements of the insurer.

The insurance industry accepted guideline for the development of condition monitoring systems is “Guidance for the certification of Condition Monitoring Systems for Wind Turbines” produced by Germanischer Lloyd WindEnergie GmbH

The guideline describes the requirements for the certification of condition monitoring systems for wind turbines and control centres. It establishes a basis for the development and installation of condition monitoring systems in wind turbines and establishes rules for the application of the measured values, for example, for the evaluation, interpretation and storage, as well as procedures to be carried out when the determined threshold values are exceeded.

SKM considers this to be a pragmatic overview of the minimum requirements for CBM in that it states that the system must :

- work to established rules ;
- specify the values and parameters to which measured components must adhere ;
- store and, more particularly, interpret the data arising ;
- report activities to be undertaken in the event that certain measured parameters exceed the prescribed thresholds.

However, as discussed elsewhere in the report, the key driver for CBM will always be whether it is cost effective or not.

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3. Condition monitoring systems

3.1. Incentives

Critical factors in respect of availability are mean time between failures (MTBF) of individual components and the systems as a whole and the mean time to repair (MTTR). Because of easier access on-shore wind turbines have a shorter MTTR that off-shore wind farms. However, there are a number of long-lead time spares items where failure prediction and proactive manufacture through condition monitoring may be an advantage – indicative MTTR is provided in Figure 8 in section 4.2.1.

Condition monitoring systems are not yet widely available from machine manufacturers, the major players either do not have any systems commercially available or they are in the process of releasing their first system. That is not to say the manufacturers do not conduct condition monitoring of their machines. Indeed, some manufacturers have been conducting extensive studies into plant reliability and condition monitoring for many years. Thus, manufacturers have been developing systems to bring to market, but have been holding off product release until meaningful data has been gathered and system effectiveness has been demonstrated. One such manufacturer is Vestas, who have been installing condition monitoring in many of their machines for some years and are now planning to release a condition monitoring package towards the end of 2006.

Other organisations involved in driving the development of condition monitoring systems have been 3rd party equipment suppliers (the specialist condition monitoring organisations) and the owner/operator/developer. To date uptake of such systems has been slow. Further details are provided in section 3.4.

Condition monitoring of wind turbines comes in many formats. Importantly, there are many machine parameters which, if monitored correctly, can provide valuable information in assessing the condition of the machine. Condition monitoring should not, therefore, be limited to looking at gear box vibration.

3.2. Condition Monitoring Techniques

The following techniques, available from different applications, which are possibly applicable for wind turbines, have been identified[4]:

1) Vibration analysis
2) Oil analysis

[4] This list may not be exhaustive, but represents technologies where information is readily available.

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3) Thermography
4) Physical condition of materials
5) Strain measurement
6) Acoustic measurements
7) Electrical effects
8) Process parameters
9) Visual inspection
10) Performance monitoring
11) Self diagnostic sensors

The above techniques are applied widely in many industries (aviation, conventional power generation, heavy industry (e.g. steel and aluminium production), oil and gas, paper and wood product production etc.). That is generally where the cost of lost production is significant, often running into tens of thousands of pounds per hour or alternatively in safety critical systems. Prices vary from a few thousand pounds (e.g. oil analysis in a large scale diesel generator plant) through to tens of thousands of pounds (e.g. acoustic crack detection on a continuous press in wood product manufacture).

3.2.1. Vibration Analysis

Vibration analysis is the most known technology applied for condition monitoring, especially for rotating equipment. The type of sensors used depends more or less on the frequency range relevant for the monitoring:

- Position transducers for the low frequency range i.e. Rotor
- Velocity sensors in the middle frequency area i.e. Drive train
- Accelerometers in the high frequency range i.e. Gearbox
- SEE sensors (Spectral Emitted Energy) for very high frequencies (acoustic vibrations)

Examples in general industry can be found for condition monitoring of:

1) Shafts
2) Bearings
3) Gearboxes
4) Compressors
5) Motors
6) Turbines

7) Pumps

For wind turbines this type of monitoring is applicable for monitoring the wheels and bearings of the gearbox, bearings of the generator and the main bearing.

Signal analysis requires specialised knowledge. Suppliers of the system offer mostly complete systems which include signal analysis and diagnostics. The monitoring itself is also often executed by specialised suppliers who can also perform the maintenance of the components.

Application of vibration monitoring techniques and working methods for wind turbines differ from other applications with respect to:

- The dynamic load characteristics and low rotational speeds
- In other applications, loads and speed are often constant during longer periods, which simplifies the signal analysis. For more dynamic applications, like wind turbines, the industry experience is very limited.
- The high investment costs in relation to costs of production losses.

3.2.2. Oil analysis

Oil analysis may have two purposes:

- Monitoring the oil quality (contamination by parts, moisture)
- Monitoring the components involved (characterisation of parts)

Oil analysis is mostly executed off line, by taking samples. However, application of online sensors is increasing for monitoring the oil quality. Sensors are available, at an acceptable price level, for particle counting and moisture. Monitoring the condition of the oil filter (pressure loss over the filter) is regularly applied for hydraulic and lubrication oil systems.

3.2.3. Thermography

Thermography is often applied for monitoring and failure identification of electronic and electric components. Hot spots, due to degeneration of components or poor electrical contact can be identified quickly and simply. The technique is only applied for off line usage and interpretation of the results is always visual. At this moment the technique is not generally available for on-line condition monitoring. However, cameras and diagnostic software are entering the market which are suitable for on-line process monitoring. In the longer term, this might have application for the generator and power electronics.

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3.2.4. Physical condition of materials

This type of monitoring is mainly focused on crack detection and growth. Methods are normally off line and not suitable for on line condition monitoring. An exception to this might be the usage of optical fuses in the blades and acoustic monitoring of structures.

3.2.5. Strain measurement

Strain measurement by strain gauges is a common technique, however it is not often applied for condition monitoring. Where it is applied to wind turbines, strain measurement is used for life time prediction and monitoring of the stress level, especially for the blades. More robust sensors might open a reliable application in this area. Optical fibre sensors show some promise, however they are possibly too expensive and not yet fully developed. Availability of cost effective systems, based on fibre optics can be expected within the next 5 years. Strain measurement as condition monitoring input will then be of growing importance.

3.2.6. Acoustic monitoring

Acoustic monitoring has a strong relationship with vibration monitoring, with one principle difference. While vibration sensors are rigid mounted on the component involved, and register the local motion, the acoustic sensors 'listen' to the component. They are attached to the component by flexible glue with low attenuation. These sensors are applied successfully for monitoring bearing and gearboxes.

There are two types of acoustic monitoring. One method is the passive type, where the excitation is performed by the component itself. In the second type, the excitation is externally applied.

3.2.7. Electrical effects

For monitoring electrical machines MCSA (Machine Current Analysis) is used to detect unusual phenomena. For batteries the impedance can be measured to establish the condition and capacity.

Medium and high voltage grids, transformers and switchgear, can be monitored by a number of techniques:

- Discharge measurements
- Velocity measurements for switches
- Contact force measurements for switches
- Oil analysis for transformers

Cabling isolation faults can be detected by imposing electromagnetic pulses on the system and measuring the reflection. These types of inspection measurements do not directly influence the operation of the wind turbines.

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3.2.8. Process parameters

For wind turbines, condition monitoring based on process parameters is common practice. The control systems are becoming more sophisticated and the diagnostic capabilities are improving. However, condition monitoring is still largely based on level detection or comparison of signals, which directly result in an alarm when the signals increase beyond predefined limit values. At present, more intelligent usage of the signals based on parameter estimation and trending is not common practice in wind turbines.

- **Figure 5 Modern SCADA systems for Wind Farms**

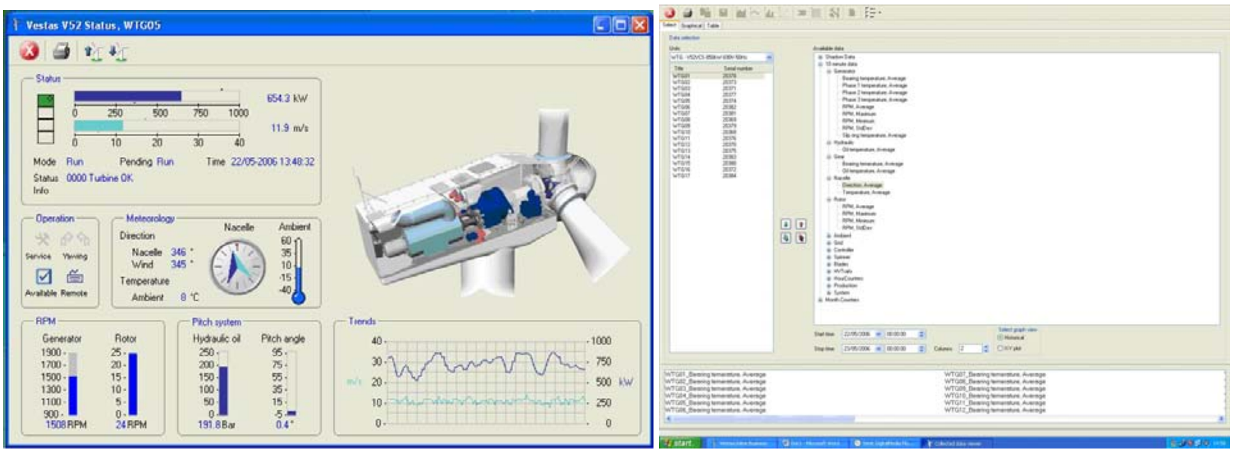

Figure 5 above gives an indication of the process parameters monitored in a modern wind turbine SCADA system.

SCADA systems are generally improving for modern wind farm sites however, SCADA is not appropriate for gathering spectrum information produced by vibration monitoring equipment as this requires high volume, high scan rate local data acquisition and analysis.

Wind turbine control systems incorporate increasing functionality. Some of the functions come very close to condition monitoring. With relatively low costs, some more intelligence can be added, which makes early fault detection based on trend analysis possible. Apart from condition monitoring, trending of wind turbine main parameters (power, pitch angle, rotational speed, wind velocity, yaw angle) can give global insight in the operation in the turbine. It may be possible to detect that “something might be wrong”. The SKF Windcon system discussed in section 3.4.4 provides this sort of functionality and is claimed to be effective. Operational experience from the Scottish Power wind farms also suggests that predictive trending can be effective for early fault identification.

3.2.9. Performance monitoring

For condition monitoring purposes, the relationship between power, wind velocity, rotor speed and blade angle can be used and in case of large deviations, an alarms generated. The detection margins are large in order to prevent for false alarms.

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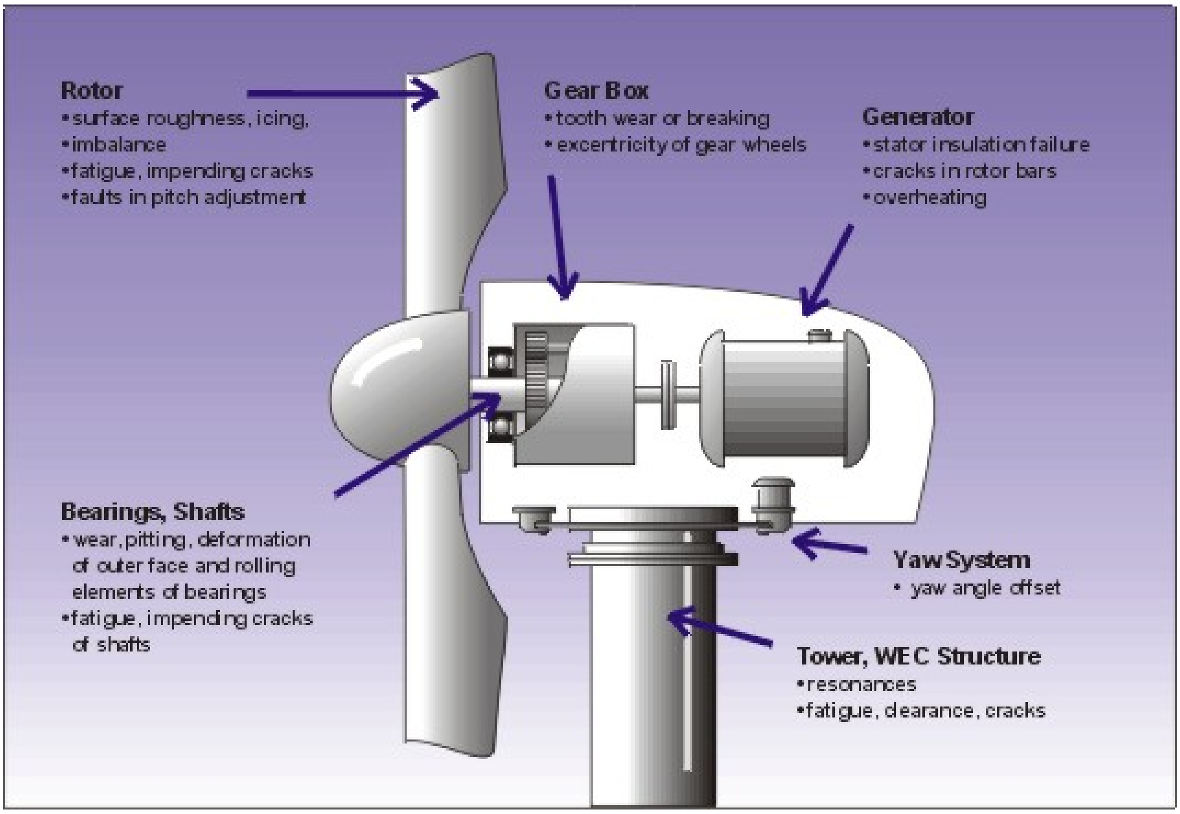
3.3. Possibilities of application in wind turbines

Of the techniques identified previously a number are adaptable to the wind turbine platform. Figure 6 shows some of the key components and how they could be monitored.

- **Figure 6 Wind Turbine Components**



3.3.1. Rotor

Strain monitoring can be used for blade life time prediction. Methods are not yet well developed but there certainly is potential for condition monitoring based on strain measurement. The measurement techniques and the necessary rotating interfaces, which push up the CBM investment cost, are reasons that this type of monitoring is not often used. Techniques based on optical fibres are in development and will be suitable for commercial application within the next few years. Several parties are working on this subject (Smart Fibers, FOS, Risoe, ECN, and some manufacturers.).

Vibration monitoring and acoustic emission are also relevant to condition monitoring of the blades. Acoustic emission can be used to detect failures in the blade.

3.3.2. Pitch mechanism

Large turbines often have independent pitch control. Condition monitoring is realised by current measurement, time measurement and pitch angle differences. Trend analysis based on parameter estimation is not generally applied, but has potential for condition monitoring.

3.3.3. Nacelle

Gearbox and main bearing:

Gearboxes are widely applied components in many branches of industry. As such, condition monitoring of gearboxes is reasonably common practice. Despite significant design effort, wind turbines often had, and still have, problems with gearboxes. Therefore condition monitoring is of growing interest, because the costs of gearbox replacement are high.

Condition monitoring techniques for gearboxes are:

1) Vibration analysis based on different sensors
2) Acoustic emission
3) Oil analysis

For vibration analysis, different types of sensors can be used. Most commonly used are acceleration sensors. Displacement sensors can be used for application with bearings operating at a low speed, i.e. main bearing.

Acoustic emission is another technique, based on higher frequencies. For vibration analysis the frequencies relate to the rotational speeds of the components are monitored. For acoustic emission higher frequencies are considered, which give an indication of starting defects. The effects normally attenuate after short period.

Oil analysis becomes significant when defects are identified, based on one of the previous techniques, and is of use for further diagnostics. Based on characterisation of parts and component data, diagnosis can be approved. This simplifies the repair action.

Degradation of the oil itself can also be a source for increasing wear. There exist a strong relationship between the size and number of particulate contaminants and the component life time. Also moisture has a strong reducing effect on the lubrication properties. Condition monitoring of the filters and on line particle counting and moisture detection can help to keep the oil in an optimal condition by signalling a time for appropriate corrective action. Costs arising from oil replacement as well as from wear of the components can be reduced by optimal oil management.

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3.3.4. Generator

The generator bearing can be monitored by vibration analysis techniques, similar to the gearbox. The condition of the rotor and stator windings can be monitored by a combination of temperature, short circuit and discharge monitoring. Due to the changing loads, trend analysis based on parameter estimation techniques will be necessary for early detection of failures.

3.3.5. Hydraulic system

The hydraulic system for pitch adjustment is the most critical (not relevant for machines with electrical pitch adjustment). Condition monitoring of hydraulic systems is very similar to other applications because intermittent usage is common practice.

3.3.6. Yaw system

Although the yaw system is historically failure prone as it can be subject to significant forces, condition monitoring is difficult because of the intermittent usage. The system is only operating for long periods during start up and re-twisting. Newer designs of turbines have addressed the historical failure mode problems with the yaw system and the likelihood is the frequency of failure from this system will be reduced.

3.4. Currently available systems

3.4.1. Acceleration Enveloping

GE Energy has recently produced a study[5] looking at acceleration enveloping for CBM on wind turbines.

Wind turbines are generally instrumented with externally mounted accelerometers or velocity transducers and a Keyphasor probe which provides a once-per-turn speed reference. Frequency analysis based on direct vibration monitoring can be carried out but is a complicated task due to the combination of mesh frequencies, harmonics and bearing defect frequencies.

Acceleration enveloping uses a high-pass filter on the raw accelerometer waveform before rectifying, enveloping and processing through a Fast Fourier Transform (FFT) algorithm. The resulting envelope spectrum reveals the defect repetition frequencies, which can then be compared to known bearing defect frequencies.

The technique was tested by Bentley Nevada who found that enveloping provided superior sensitivity to bearing defect frequencies in wind turbine applications. The key advantage was found to be that enveloping provided good visibility of bearing defect frequencies without the visual interference of gear mesh frequencies in the same spectrum. GE Energy has now included acceleration enveloping as part of their Trendmaster Pro System.

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3.4.2. High frequency sound-based Stress Wave Analysis (SWAN)

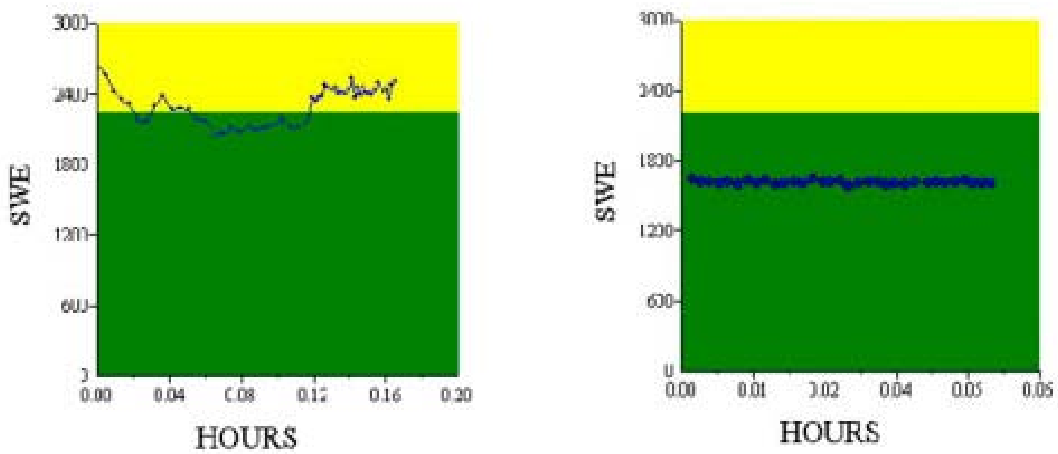
Swantech has developed a sound based monitoring system[6] that claims to avoid the inherent limitations of vibration analysis. It measures sound and provides direct measurement and comparison of the amount of friction and impact occurring within the machine.

When a failure occurs in a wind turbine it starts as a small discrepancy and then develops into a larger discrepancy which can result in secondary damage, unacceptable operating conditions or catastrophic failure. By measuring the stress waves the incipient failure can be detected whilst it is still only a small discrepancy.

The technology is based on the premise that healthy drivetrains produce low stress wave energy in comparison to damaged machines. Therefore, it is possible not only to identify a problem but also to estimate the extent of the problem based on the stress wave energy. The SWAN system permits trending and failure prediction to be undertaken, helping to plan maintenance activities and avoid equipment failures.

An example trace is provided in Figure 7 below that shows how the trending system operates. The graph on the left shows an erratic trace from a damaged drive system whilst the figure on the right shows a healthy drive system.

- **Figure 7 SWAN CBM system trending**



3.4.3. On-line oil debris sensor

An alternative means of detecting potential faults in a gearbox is to sample the oil rather than monitor for vibration. In this methodology the oil is monitored for metallic particles with an increase in metallic particle concentration being indicative of damage to the gearbox. GasTOPS[7] has developed a system specifically for wind turbine gearboxes that is based on the same technology successfully employed on gas turbines and aircraft engines.

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3.4.4. SKF WindCon

SKF offers a remote monitoring system called WindCon. This system allows an operator to monitor a single turbine or an entire wind farm from a remote location. The system consists of a number of sensors connected to flash memory in an Intelligent Monitoring Unit (IMU) located in each wind turbine. The IMU can be configured remotely using a graphical interface and the signals and measurements can also be analysed and trended from a remote location. Some of the measurements that can be taken include :-

- Main bearing;
- Transmission;
- Generator;
- Tachometer;
- Tower / structure vibration;
- Blade vibration;
- Oil temperature;
- Oil pressure;
- Oil quality;
- Generator temperature.

The SKF WindCon system provides a comprehensive and flexible approach to CBM but due to its complexity and cost is most likely to find application only on larger, off-shore turbines.

3.5. Current research projects

DTI Project No. PP211: Improved performance of wind turbines using fibre optic structural monitoring

Photo : LM Glasfiber A/S

This project recognises that manufacturers of utility class wind turbines have started to deploy condition monitoring systems in their latest wind turbine designs. It is noted that the CBM systems in the wind turbines typically monitor the drive shaft, gearbox and drive bearings but do not monitor the turbine blades and turbine hub. The project aims to develop a complete fibre optic structural monitoring system for wind turbine blades and the hub structure.

Optical fibres have been shown to effectively monitor the strain in a structure but current systems are expensive, circa £50,000, as well as being large, demanding on power and insufficiently rugged for turbine operation. This project is being carried out by Invensys Limited in collaboration with WindForce GmbH to attempt to solve these technology difficulties. The project has been running since December 2004 and is due to conclude in September 2006.

EPRI: Field assessment of wind turbine condition monitoring technology

This project recognises the trend for larger wind turbines (1.5 MW or greater) compared with the wind farm developments in the 1990s that typically consisted of turbines rated 750 kW or less. It is noted that the larger units have the potential to reduce the overall O&M costs for a facility but will mean that any single failure will be more costly. CBM is a possible means of reducing these costs.

Acoustic sensor mounted on gearbox of Vestas V47 turbine. Picture : Caithness Energy

The project consists of a field assessment of on-line wind turbine condition monitoring technology on three 600 kW Vestas V47 wind turbines at the TVA Buffalo Mountain wind project near Oak Ridge, Tennessee. The turbines are reaching an age when problems are thought to be likely to start to appear. The project aims to test CMB systems from a number of vendors and the results will be compared and analysed.

The project commenced in the final quarter of 2005 and is scheduled to complete by the end of 2007.

Energy Research Centre of the Netherlands: Condition monitoring and measurement techniques

This project is being conducted by Energy Research Centre of the Netherlands (ECN). This organisation has stated aims of increasing the long term value-cost ratio of wind energy and removing technical barriers for the implementation of wind power. In accordance with these aims this project looks at new measurement techniques for wind turbines. Of relevance to the development of CBM techniques new methods for blade monitoring are being investigated. At the moment, a prototype for load measurements in the blades by means of optical strain gauges is being tested.

Picture : ECN

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3.6. Conclusions on available technology

Based on the review of existing CBM systems and discussions with practitioners a number of conclusions can be drawn:

- The critical components requiring monitoring include the generator, gearbox and drive train. The existing CBM technology for these units works reasonably well;
- The relatively small number of CBM installations on existing wind turbines limits the available information to a few organisations. Data in the effectiveness of CBM is not yet widely available.
- Additional components where CBM would be beneficial include turbine blades but the condition monitoring of these is still a novel technology and is expensive;
- CBM technology has the capability to prevent catastrophic failures by permitting early detection of equipment failure;
- The benefits of installing condition monitoring as a retrofit are that it can reduce down time and prevent catastrophic failure. However, the small size of existing turbines makes the financial argument for retrofit unattractive at the current prices for CBM;
- A possible retrofit solution would be a basic sensor to detect a general fault fitted to each turbine with a portable unit that would be used to investigate in more detail should a general fault be flagged;
- The results from vibration frequency monitoring are not easy for the layperson to interpret and require specialist analysis;
- Vibration analysis is the dominant technology at the present time;
- Oil analysis is developing but is expensive;
- Condition monitoring of turbine blades is still novel technology and is expensive.

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4. Cost / benefit

4.1. Financial benefits

4.1.1. Financial benefits of Condition Monitoring

To be effective condition monitoring needs to deliver information to operators on the status of the turbine and, in particular, the condition of individual components within the turbine (eg: gearbox, bearings, couplings, semi-conductor devices) and give advance warning of likely failure/loss of performance. It should also provide predictive information on the likelihood of failure of components, so that preventative maintenance systems can be established.

The main objective of installing condition monitoring is to improve the understanding of the machine condition such that maintenance can be undertaken in advance of component failure and hence improve the overall availability of the turbine. If condition monitoring is effective unscheduled maintenance will be significantly reduced. Also, preventative maintenance techniques may be used potentially reducing the equipment for scheduled maintenance. Assessing the financial effectiveness of installing condition monitoring requires an understanding of a range of costs and maintenance issues, such as:

- How much annual revenue is lost due to unscheduled maintenance and extended down time due to failure of long lead time components;
- What additional costs are associated with unscheduled maintenance activities;
- What are the financial benefits of predictive failures and implications of various lead times for these predictions? (one week, one month or three months in advance failure);
- What are the differences in on-shore and off-shore wind turbine installations?

4.1.2. Effectiveness vs cost of condition monitoring equipment

The technical advantages of an effective condition monitoring system to an operator are that it delivers a better understanding of the machinery condition enabling better scheduling of maintenance activities. Ultimately the justification for installing condition monitoring needs to be made on financial grounds, with the cost of installation being fully recovered by revenue from the increased output resulting from increased availability during critical high wind periods. The rate of return of the installation is determined by the investment costs, the relevant failure characteristics, the cost savings of reduced maintenance and damage avoidance and the reduction of production loss. For off shore wind applications, the cost savings due to reduction in site attendance to conduct corrective maintenance will be the most important factor. When unnecessary visits can be avoided or postponed to a regular visit, or when more damage can be prevented, considerable amounts of money can be saved. Ultimately this will also contribute to increased availability.

4.1.3. Factors for consideration

When considering the economic case for installing condition monitoring systems on wind turbines a number of factors need to be quantified or qualified in order to reach a meaningful conclusion.

The most important aspect, which will be the result of the interaction of a number of factors, is the unscheduled down time avoided, and hence increased energy sale revenue achieved, by installing the condition monitoring system. There are grounds for argument that if a problem is spotted early then the operator will have enough time to organise remedial work before the defect accelerates to failure. Typically the lead time prior to repair includes sourcing / procurement of large components (if not held on site) and site mobilisation. Further discussion, derived from the experience of windfarm operations personnel, is provided in section 2.3.

A further significant consideration is the potential for avoidance of secondary damage as the defect develops into a failure. For example, a bearing defect within a gearbox can, if identified early, be repaired with minimal machine down time. If the bearing defect is not detected and seizes, the secondary damage to the gearbox can be catastrophic, requiring a complete gearbox replacement and additional machine down time. As an example, a new gearbox may cost upwards of £60,000 whilst reconditioning the same gearbox, should a defect be found in time, may cost just £15,000. Aside from the generator, all other major components have significantly smaller cost implications, typically at least an order of magnitude less.

Another consideration in analysing the economic case is the specific machine parts which can be reasonably monitored. Items of plant that will exhibit a physical sign of failure prior to failure such as those that exhibit heightened levels of vibration (gearbox and bearings), physical signs of wear (particles within oil, thickness of break pads), electrical particle discharge (generators, transformers and other heavy electrical items). For the purposes of this report the components monitored are those which can be reasonably said to exhibit signs of developing failure, which are capable of being monitored by reasonable extrapolation of existing techniques and which represent items with the most significant mean time to repair (MTTR), as outlined above and in section 4.2.1. The counter point to significant MTTR is the frequency of failure, which is generally infrequent (expressed as the mean time between failures, MTBF, i.e. the likelihood of each machine or sub component failing in each year).

Next, empirical data on failure modes, and associated consequences on down time, needs to be assessed and used as the basis of potential saved down time. The assessment can only be done as a qualified exercise using operational experience as a basis. Following on from the previous point, the MTTR and annual failure rate of each component are used to estimate annual down time for each failure mode.

Finally, the load factor and selling price of electricity generated provide a value for the avoided down time. It can be argued that if the operator knows a problem is developing in a component then the plant could be operated (perhaps under a restricted operating regime) until such time as a weather window presents itself and the maintenance can be carried out at a time where the machine would be generating at reduced load. In practice, however, the operator is likely to organise spares and mobilise as soon as the fault is identified and proceed to repair as soon as he is able. Confidence in the monitoring system would need to be high, or the defect well understood, in order for the operator to delay an immediate repair.

The answers to these questions are then used to derive the required maintenance strategy in terms of what corrective and proactive (predictive and preventive) maintenance is required. A detailed Reliability Centred Maintenance (RCM) for a wind farm is outwith the scope of this current study but SKM has spoken to ScottishPower who recently carried out such an exercise on the Hagshaw Hill wind farm. The outcomes from the initial study are at the stage of being implemented and therefore it is too early to determine whether this exercise will bring sufficient benefit to the on-going O&M to merit the cost of undertaking the study. However, the practioners whom SKM spoke to were positive about the process and believed that a useful outcome would be obtained.

Avoided repair costs will, by their nature, be installation specific but an illustration is provided earlier in this section for a gear box. Data from other industries is likely to be available but an analysis of this information is beyond the scope of this current exercise.

Notwithstanding the above, it is important to note that adequate condition monitoring can prevent secondary damage caused by failure and this should be considered when interpreting the cost / benefit results.

4.2. Cost / benefit model inputs

4.2.1. Failure frequency and MTTR

Assumptions on the frequency of failure and the mean time to repair have been gathered from a number of sources:

1) Empirical data available publicly from German and Danish national statistics databases.
2) Empirical data from SKM’s operational experience,
3) Anecdotal evidence from interviews with operations staff, subject matter experts, machine suppliers and equipment suppliers.

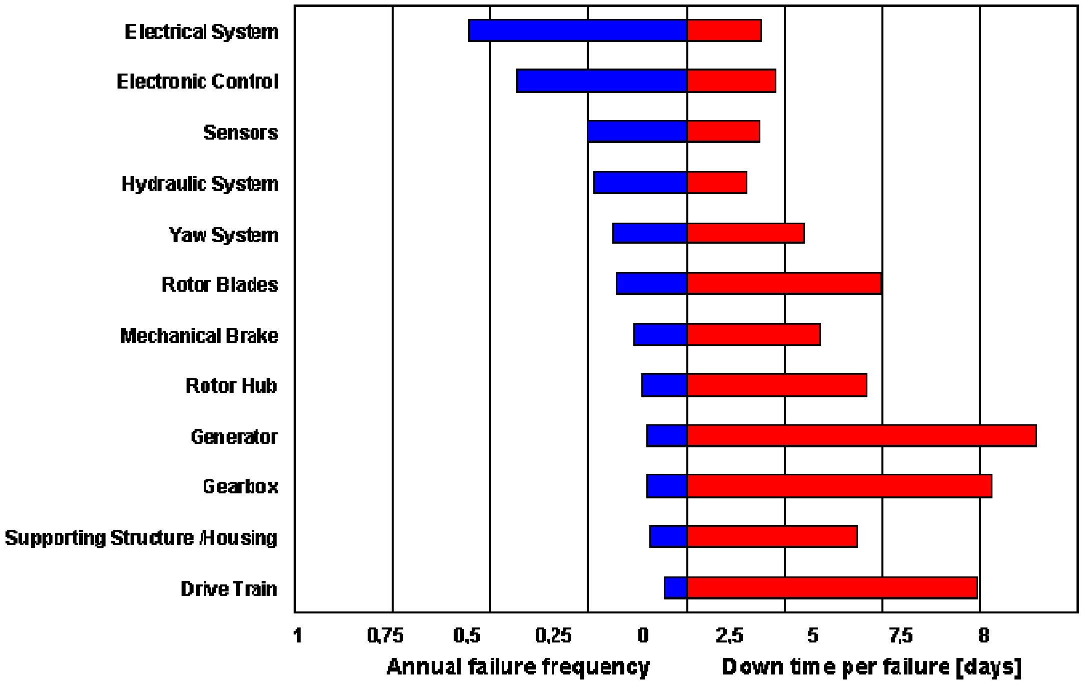
Data from REISI

The Renewable Energy Information System on Internet (REISI) provides product information and operational results from 1500 operational wind turbines currently operating in Germany and

Denmark which are under 10 years old, along with some additional data from wind farms greater than 10 years old.

Figure 8 shows the average annual failure frequency for a number of wind turbine components. This data was gathered

- **Figure 8 Average down time**



The reliability of wind turbines and components is measured by a combination of downtime (i.e. the time required to make the component available again following a failure) and the frequency of failure. Of course, since simultaneous repairs to a number of components are often necessary it is not always possible to determine the exact component that caused the down time. This must be taken into account when interpreting the data.

The information in Figure 8 shows that a failure of the drive train does not result in long periods of downtime. It also shows that the electrical and control systems have quite high incidences of failure although these are alleviated by the short downtime resulting.

It is interesting to look at the causes for component failures. A pie chart showing reported events is presented as Figure 9. It can be seen that the most significant cause of failures were defective parts. Loose parts also accounted for a number of failures. From the CBM viewpoint the potential downtime that could be avoided would be that due to defect of parts and loose parts. This accounts for almost 50% of the total failures.

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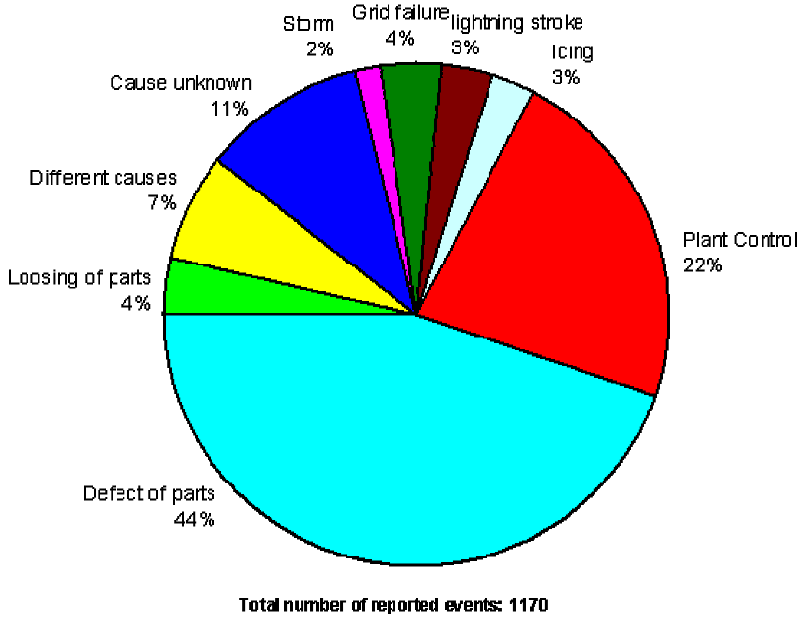
- **Figure 9 Causes of failure**



Another interesting statistic is the result of the failures. From the point of view of the potential savings offered by CBM there is a greater cost saving potential from obviating a failure that causes follow-up damage than a failure that simply causes a plant stoppage. The consequences of the failure events are shown in Figure 10.

In Figure 10 above defect parts and loosing parts can be taken to mean deterioration of components. Different causes is a loose catch all for inconsistencies in collected data or where the reasons for failure does not fall into a recorded category.

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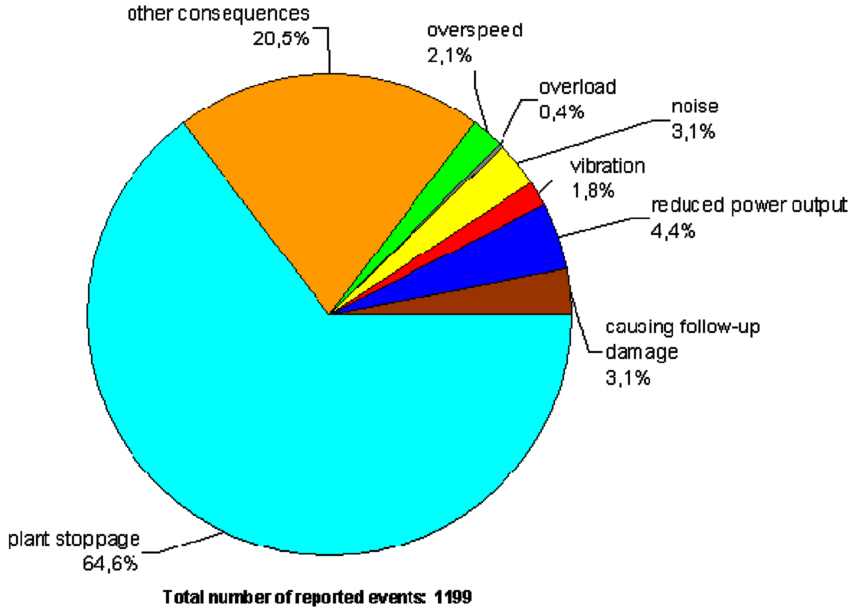
- **Figure 10 Consequence of failure**



It can be seen that the majority of failures resulted in plant stoppages with only 3.1% causing secondary damage to other plant items. Unfortunately, there is no quantification of what follow-up damage was caused and therefore it is not possible to put a cost estimate on it.

One of the other key decisions for CBM is to identify the components that are to be monitored. This decision should be based on the components that will have the largest penalty if they fail in combination with an assessment of which components are most likely to fail. Figure 11 shows the systems needing to be repaired as a percentage of overall repairs showing that, as with the identification of cause of failures, that the electric and control systems accounted for the majority of repairs. Most of the CBM that has been considered has been associated with the drive train which accounted for only 2% of the repairs.

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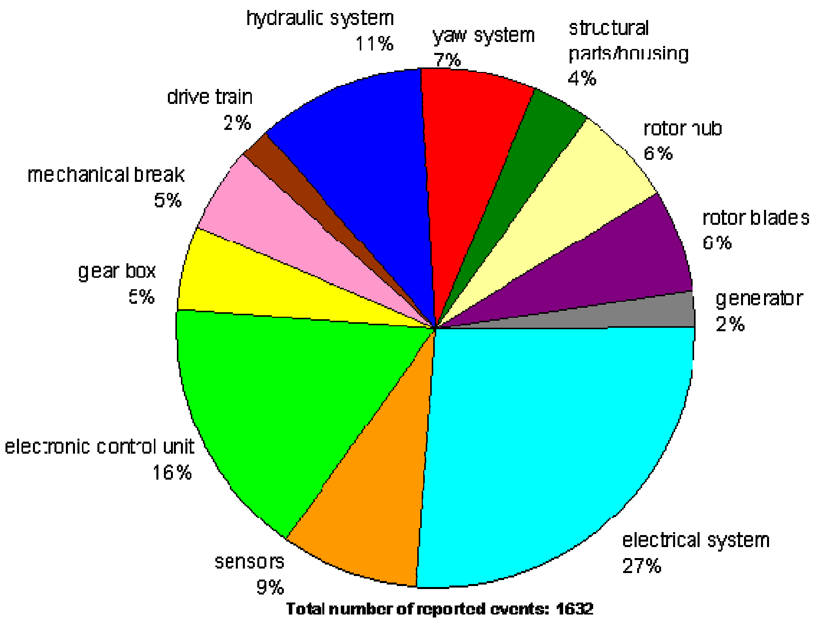
- **Figure 11 Systems repaired**



Data from SKM Operational Experience

SKM undertakes the operation and maintenance of the Penrhyddlan and Llidiartywaun (P&L) windfarm near Newton in Wales. This development consists of 103 Mitsibushi MWT-250G wind turbines rated at 300kW. The wind farm was commissioned in 1993 and has a capacity of 30.9MW. The age of this wind farm implies original commissioning related failures do not have a significant impact on the overall failure statistics.

P&L Windfarm – late evening. Picture : Landmarks of Britain

A large amount of data has been gathered during the operation of the site including information on component failures and plant down time. The data analysed from the P&L windfarm was collected over a 5 year period.

The data is summarised in Table 1 overleaf.

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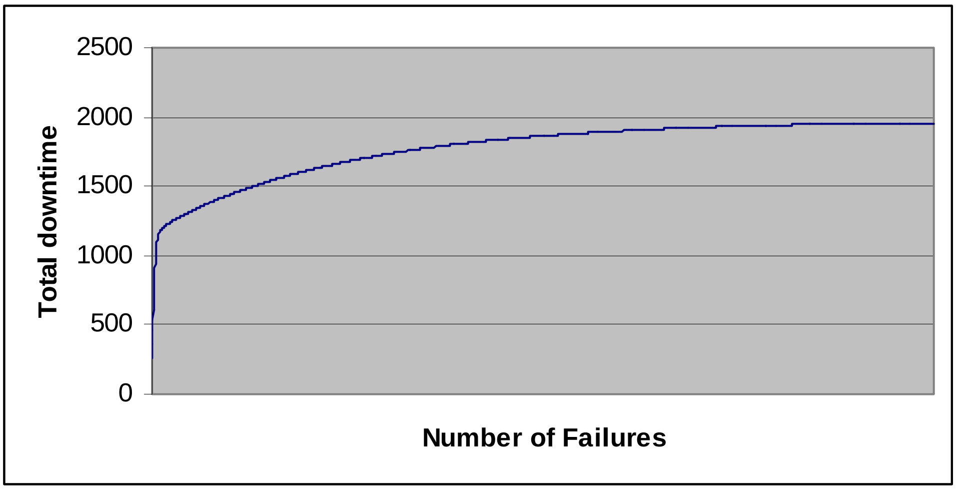
- **Table 1 – Summary of failure data from P&L**

Main Plant	Number of Failures	Downtime (days)
Anemometry	33	26.7
ASC System	72	20.2
Blades	278	78.0
Controller System	36	5.6
Electrical System	65	21.0
Gearbox	199	692.9
General Turbine	713	216.4
Generator	1	0.4
High Voltage System	205	300.7
Hydraulic System	121	31.7
Pitch System	864	204.4
VDM	4	0.2
Yaw System	921	357.1
Total	**3512**	**1955.1**

In total there were over 3500 failures but a relatively small number of failures account for the majority of the downtime. This is illustrated graphically in Figure 12.

- **Figure 12 Total downtime against number of failures**



In fact over 50% of the total downtime is accounted for by only 0.5% of the total number of failures and 80% of the total downtime is accounted for by 16.6% of the total number of failures. The skewed nature of the data has to be borne in mind when interpreting the information.

Turbine components which can reasonably said to be appropriate for condition monitoring are the Generator, Gearbox and Drive Train. These components have been selected as: they represent items which exhibit signs of failure prior to catastrophic failure; are rotating plant and where there is a body of knowledge and understanding in other branches of industry; are items where the significance of impact is great, in terms of component cost, lead time; and historically represent items with long repair times.

It can be seen from the data in Table 1 that there was only one failure of the generator and therefore there is little advantage in a detailed analysis for that component.

For the gearbox components there were 199 failures resulting in a total downtime of 693 days. 80% of the total downtime is accounted for by just 7 of the failures. A simplistic analysis to determine Mean Time Between Failures (MTBF) might suggest that for 103 turbines over a five year period then a total of 199 failures would give an annual MTBF for the gearbox of 0.39 per annum. This is higher than the data presented in Figure 8 because this site has specifically experienced problems with gearboxes.

The data in Table 1 can be translated into average number of failures per year and downtime per year and re-ordered to generally follow Figure 8, as follows:

- **Table 2 Summary of failure data from P&L - annualised**

Main Plant	Annual failure frequency per turbine	Downtime per failure (days)
Electrical System	0.13	0.3
High Voltage System	0.40	1.5
Controller System	0.07	0.2
Anemometry	0.06	0.8
ASC System	0.14	0.3
Hydraulic System	0.23	0.3
Yaw System	1.79	0.4
Blades	0.54	0.3
Pitch System	1.68	0.2
Generator	0.00	0.4
Gearbox	0.39	3.5
VDM	0.01	0.0
General Turbine	1.38	0.3

4.2.2. Financial impact of failures

A general analysis based on MTBF without weighting for the severity of the failure would result in a misleading result. A more representative analysis can be carried out by considering the average cost per failure in terms of lost revenue. A reasonable estimate for the value of electricity in the UK is £60 per MWh. The calculation is not quite as simple as multiplying the total downtime by the value of electricity as the turbines will not be required all of the time. Wind farms have a typical load factor of 25% to 40%[7] and this must be factored in to the calculation. A value of 30% will be used for the purposes of this analysis.

Therefore, the potential lost revenue for gearbox failures, on a per turbine basis can be determined by :-

$$Potential\_lost\_revenue = \frac{Value\_of\_Electricity \times Load\_Factor \times Total\_downtime}{Number\_of\_turbines}$$

This equation can be used to determine that the potential revenue that was lost through gearbox failures was approximately £2,900 per turbine over a 5 year period based on the P&L data.

If the condition monitoring system is sufficiently reliable and can predict an impending failure sufficiently before the failure occurs the operator can mobilise to site and perform corrective maintenance. The assumption is that the down time of the turbines with condition monitoring installed (for the turbine components which are monitored) is limited to the time necessary to conduct the repair, the down time associated with mobilisation of parts, equipment and personnel is eliminated. Based on operational experience the estimate has been made that the average repair time of the monitored components (gearbox, generator and drive train) is reduced by 50%.

4.2.3. Load factor and energy value

Load factor assumed for the typical UK wind farm is 30%. This figure will increase as the effect of off-shore developments filters through.

Average price for generation is assumed to be £60/MWHr. This figure is based on the typical long term investment criteria for a renewable energy project.

4.2.4. Summary of model inputs

The assumptions for load factor, average repair time saved for monitored components and electricity value are discussed above and are specifically applicable to the on-shore model. The model also makes a number of additional assumptions for MTBF and MTTR values for the components as well as estimates of the down days for each failure. These additional assumptions are based on the REISI data.

One of the most important assumptions is the value used for the average cost of condition based monitoring equipment. A value of £15,000 was chosen as this represents the middle to high end of the cost of the systems that were reviewed. Clearly, the cost of condition based monitoring equipment will require to be altered on a case by case basis depending on the technology being evaluated.

In order to provide some example analysis some arbitrary values have been used for the energy park configuration but these would of course be amended on a case by case basis.

A summary of the model inputs is provided in Table 3

Energy park configuration is very much an arbitrary input, but allows sensitivity of unit input to be modelled.

Resource and market represents reasonable load factors and energy values.

MTBF and MTTR values are taken from Figure 8 for the turbine components contemplated in Section 4.2.1.

Gearbox repair & replacement data is based on information gained from interviews with turbine operators. The gearbox base cost represents the cost of a new gearbox for a 300kW turbine. Incremental cost if a factor applied to scale up the cost of a new gearbox as the turbine size increases. This data is somewhat crude as it is only accurate for lower end of the turbine size range. Anecdotal evidence suggests the cost to recondition a gearbox will be half that of a new gearbox. Anecdotal evidence suggests half of the defective gearboxes could be repaired, this factor takes into account the background maintenance activities of on-shore maintenance staff. This factor will become more critical in the off-shore model.

Impact of condition monitoring system represents the time saved in lost production by having sufficient notice to prepare to repair an impending defect before machine failure.

Condition monitoring package is the cost of the complete condition monitoring package. The cost in the model is somewhat arbitrary as it represents an estimate of the cost of an expert system, not requiring outside data analysis, which covers the machine areas contemplated in Section 4.2.1.

Investment parameters is the typical discount rate applied investments of this type.

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Table 3 Model inputs

Parameter	Value
Energy park configuration	
MW/unit	3.6 MW
MW in park	100 MW
Units in park	27
Resource and Market	
Load factor	30%
Average electricity value	£60 /MWHr
MTBF and MTTR	
Generator failures per unit per year	0.1
Gearbox failures per unit per year	0.1
Drive Train failures per unit per year	0.05
Down days per generator failure	8.8
Down days per gearbox failure	8.2
Down days per drive train failure	7.9
Gearbox repair & replacement data	
Gearbox replacement cost base	£60,000
Gearbox replacement cost base - incremental / MW	£25,000
Gearbox repair cost - % of new	50%
Gearbox failures avoided	50%
Impact of condition monitoring system	
Time saved by predicting failure (fraction of MTTR)	50%
Condition monitoring package	
Cost of installing condition monitoring per unit	£15,000
Investment parameters	
Discount rate	10%

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4.3. Cost / benefit model calculation method

The method of calculation takes into account the MTBF and MTTR of the three machine components listed in Table 3 to calculate the number of down days per year per turbine. This number of down days is then multiplied by the factor for time saved by predicting failure. This is used to determine the potential time that could be saved by employing CBM for each turbine.

Multiplying this potential down time saving by the number of turbines in the park; the rated output for the turbines; the predicted load factor and the value of electricity gives an estimate of the potential additional revenue that could be generated from the installation of CBM.

The capital cost of installing the condition monitoring equipment is then calculated by looking at unit cost and number of turbines in the park. By comparing the investment cost to the annual additional revenue a simple payback can be derived and present value calculated.

4.4. Cost / benefit model results

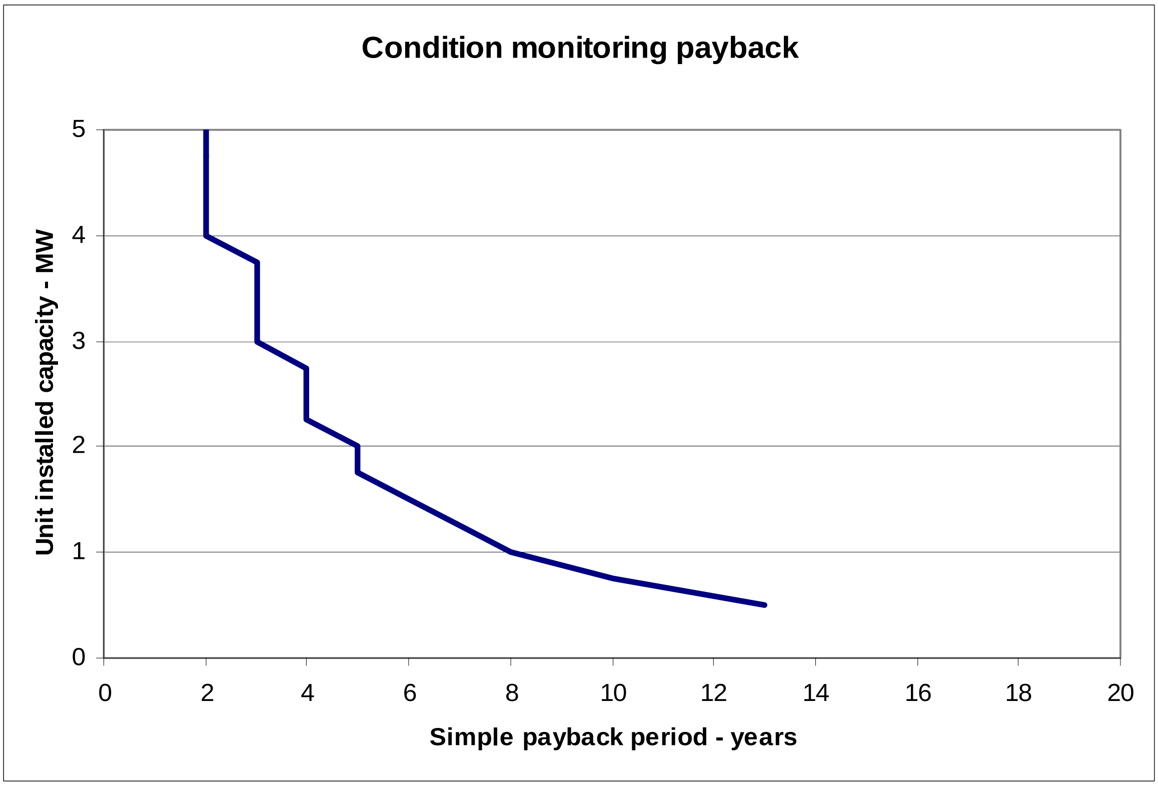
The model shows, as would be expected, that as the unit installed capacity increases so the simple payback period decreases. For the assumed condition monitoring installation cost of £15k / unit the simple payback approaches a reasonable level, 6 years, when the machine installed capacity approaches 1.5MW. The impact on availability is small; the model indicates each machine would be available for only one additional day per year, having a slight effect on annual availability figures.

The significant cost saving within the model is the avoided gearbox costs associated with repair and not replacement. The model assumes all gearbox defects can be identified early, allowing repair.

As the installed capacity increases so the payback period continues to reduce. Conversely, as the machine installed capacity decreases so the payback period increases at ever increasing steps.

If the condition monitoring installation cost were to, say, double a simple payback of 6 years coincides with a machine installed capacity of 4MW.

Figure 13 Condition monitoring payback



5. Conclusions

The general trend in the industry is towards ever larger turbines, located both on- and off-shore; multi-megawatt machines are now the norm. As this trend continues the impact that individual machine down time has on revenue and project viability increases. Adaptations in design which reduce component stress, i.e. variable speed, have a significant impact on component life but monitoring trends and early diagnosis of failure is becoming more critical in the effort to increase availability and reduce operating costs.

Condition monitoring systems have the potential to not only pay for its own installation but provide increased lifecycle earnings for the owners of wind farms through increased availability and decreased maintenance costs. The external influence of insurance premiums is also providing some incentive for operators to install condition monitoring systems; the insurance companies require a reduced maintenance effort if a certified condition monitoring system in operated.

In other industries, condition monitoring provisions are normally separate systems, removed from the machine control and safe guarding functions. The monitoring is often focused on a very limited number of parameters. For wind turbines however, the system to be monitored is rather complex, the margins for investments are small and the number of systems is high. So when existing systems are used, the adaptation should not only be focused on the dynamic load behaviour, but also on streamlining the system and integration.

A number of systems, from a variety of vendors, are available at present. Uptake of these systems has, to date, been slow. This, however, looks set to change; the manufacturers are starting to promote systems based on their considerable operational experience. On the back of this the industry may come to accept condition monitoring as normal and the opportunities for all parties may increase.

Cost / benefit analysis demonstrates the application of condition monitoring systems is extremely cost sensitive. The increased availability which should be achieved from installing a system will be in the order of one additional day of generation per machine per year. The benefits of installing a system must be fully recognised demonstrable to the potential client. Additional benefits of installing a system are two fold. Firstly, reduced requirement for insurance led overhaul and secondly, potential for avoidance of secondary damage from a catastrophic fault. In the second case the potential for avoidance of damage may valued at several tens of thousands of pounds but is difficult to quantify as off-line condition monitoring will be conducted routinely. If this is factored into the calculation the cost benefit model looks very much more favourable; more costly and functionally comprehensive systems begin to look feasible.

This model is based on data from mainly on-shore installations. Off-shore installations need to be designed to a consistently higher standard to achieve the same levels of availability. One key factor to off-shore operations is to reduce the requirement for a site presence, as access to site cannot be guaranteed. As would be expected, this is most critical during winter periods where, even with recent advances in support vessel design, accessibility is significantly reduced. Winter is also a time of generally higher wind speed and with that higher machine loads and increased incidence of failure.

The financial modelling and anecdotal evidence from practioners indicates the CBM is currently too expensive to be cost-effectively retrofitted to existing facilities. The price where CBM would become financially viable is dependent on the payback period required and the size of the wind turbines. The larger the wind turbine, the more likely it is that CBM could be cost effective.

Current systems require a minimum turbine size of 1.5 MW to achieve an acceptable 6 year simple payback.

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6. Recommendations for further work

The report suggests that there is merit in exploring further the benefits and advantages of CBM technologies and on the potential for a retrofit business activity based on novel, low cost CBM technologies. In order to evaluate this further regard is required in the following areas:

1) Greater in depth evaluation of CBM systems being developed by the major manufacturers in so far as commercial sensitivity allows;
2) Further in depth discussion with owner / operators that have evaluated CBM and analysis of conclusions;
3) Further in depth discussion and analysis of work being undertaken by independent plant technical services companies on the development of retrofit condition monitoring systems;
4) Evaluation of CBM applied in other industries, analysis of development of CBM in these areas and analysis of potential for transfer of technologies to the wind farm industry.

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7. References

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