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Wind Turbine Reliability: Understanding and Minimizing Wind Turbine Operation and Maintenance Costs

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Abstract

Wind turbine system reliability is a critical factor in the success of a wind energy project. Poor reliability directly affects both the project's revenue stream through increased operation and maintenance (O&M) costs and reduced availability to generate power due to turbine downtime. Indirectly, the acceptance of wind-generated power by the financial and developer communities as a viable enterprise is influenced by the risk associated with the capital equipment reliability; increased risk, or at least the perception of increased risk, is generally accompanied by increased financing fees or interest rates. This paper outlines the issues relevant to wind turbine reliability for wind turbine power generation projects. The first sections describe the current state of the industry, identify the cost elements associated with wind farm O&M and availability and discuss the causes of uncertainty in estimating wind turbine component reliability. The latter sections discuss the means for reducing O&M costs and propose O&M related research and development efforts that could be pursued by the wind energy research community to reduce cost of energy.

Introduction

Wind turbine system reliability is a critical factor in the success of a wind energy project. Poor reliability directly affects both the project's revenue stream through increased operation and maintenance (O&M) costs and reduced availability to generate power due to turbine downtime. Indirectly, the acceptance of wind-generated power by the financial and developer communities as a viable enterprise is influenced by the risk associated with the capital equipment reliability; increased risk, or at least the perception of increased risk, is generally accompanied by increased financing fees or interest rates.

Cost of energy (COE) is a key project evaluation metric, both in commercial applications and in the U.S. federal wind energy program. To reflect this commercial reality, the wind energy research community has adopted COE as a decision-making and technology evaluation metric. The COE metric accounts for the effects of reliability through levelized replacement cost and unscheduled maintenance cost parameters. However, unlike the other cost contributors, such as initial capital investment and scheduled maintenance and operating expenses, costs associated with component failures are necessarily speculative. They are based on assumptions about the reliability of components that in many cases have not been operated for a complete life cycle. Due to the logistical and practical difficulty of replacing major components in a wind turbine, unanticipated failures (especially serial failures) can have a large impact on the economics of a project. The uncertainty associated with long-term component reliability has direct bearing on the confidence level associated with COE projections.

In addition, wind turbine technology is evolving. New materials and designs are being incorporated in contemporary wind turbines with the ultimate goal of reducing weight, controlling loads, and improving energy capture. While the goal of these innovations is reduction in the COE, there is a potential impact on reliability whenever new technologies are introduced. While some of these innovations may ultimately improve reliability, in the short term, the technology risks and the perception of risk will increase. The COE metric used by researchers to evaluate technologies does not address this issue.

This paper outlines the issues relevant to wind turbine reliability for wind turbine power generation projects. The first sections describe the current state of the industry, identify the cost elements associated with wind farm O&M and availability and discuss the causes of uncertainty in estimating wind turbine component reliability. The latter sections discuss the means for reducing O&M costs and propose O&M related research and development efforts that could be pursued by the wind energy research community to reduce COE.

Current Industry Status

A wind turbine's reliability is dependent largely on the particular machine model, how well it is designed, and the quality of manufacture. Reliability also varies with operating environment, as it is the machine's reaction to the wind environment that determines the loading imposed on the components. The variety of potential component failures - gearbox bearings, generator bearings and windings, power electronics, gearbox torque arms, pitch drive electronics – indicate that the operating conditions and load conditions for a large wind turbine and not completely understood.

The number of wind turbine models and the wide range of operating wind regimes make it difficult to distill useful reliability numbers that can be globally applied. However, attempts have been made by several researchers using selected historical data. These efforts are summarized in the following sections.

Reliability and the Cost of Energy

In the wind energy research community, the accepted COE calculation for a wind turbine system is as follows [1]:

$$COE = \frac{ICC * FCR + LRC}{AEP_{NET}} + O\,\&\,M$$

$$AEP_{NET} = AEP_{GROSS} * Availability * (1 - Loss)$$

COE	Cost of Energy ($/kWh)
ICC	Initial Capital Cost ($)
FCR	Fixed Charge Rate (%/year)
LRC	Levelized Replacement Cost ($/year)
O&M	Operations and Maintenance Costs ($/kWh)
AEP	Annual Energy Production (kWh/year)

This calculation method has been adopted by the Department of Energy in the Low Speed Wind Turbine (LWST) program. It provides a reasonable approximation of the COE that would be estimated by a potential investor and takes equipment reliability into account when determining the AEP, O&M, and LRC terms. AEP is affected by equipment reliability through turbine downtime associated with both scheduled and unscheduled maintenance. O&M consists of both scheduled (preventive) and unscheduled (repair) maintenance costs, including expenditures for replacement parts, consumables, manpower and equipment.

LRC costs are associated with major overhauls and component replacements over the life of a wind turbine. Usually this category includes only major components and is based on components whose expected life is less than the wind turbine's design life. Although the replacement frequency will vary over the equipment life, especially in the case of campaign rebuilds, the total assumed cost is spread over the machine lifetime.

Equipment reliability directly affects the LRC in that the LRC figure is only as accurate as the component life estimates. Wind turbines are commonly designed so that the major component design lives are equal to the turbine's design life. However, there are numerous examples where the design life for major components is not realized in practice [2]. The reasons for this discrepancy include inappropriate design assumptions, inadequate knowledge about the true operating environment and manufacturing quality control issues. The difficulty in assigning accurate useful-life figures to turbine components makes the LRC cost component less predictable than the O&M component.

Relative Cost of O&M

O&M costs can account for 10 – 20% of the total COE for a wind project, based on current COE figures of 3.5-6 cents/kWh. Because there is significant uncertainty in future O&M costs, when projects are financed, sensitivities are frequently done on O&M costs. The difference between typical low and high estimates can impact the COE and after tax return on investment approximately 10%. At present, the tax benefits associated with wind energy contribute significantly to a project's economics. As these benefits reduce over time, the significance of uncertainty in O&M will increase. For example, while the difference between low and high O&M estimates impacts after tax return approximately 10%, it impacts pretax returns on the order of 20%. Thus, the uncertainly in O&M costs will become more important to the industry as the tax credits available to the commercial industry decline. From the research community's perspective, confidence in the O&M costs numbers is desirable to ensure that the COE metrics being used to evaluate technology are appropriate.

Several published O&M estimates are shown in Figure 1. Both Vashon [3] and Lemming and Morthorst [4] give similar COE estimates of approximately $0.005 to $0.006/kWh for new turbines, escalating to approximately $0.018 to $0.022/kWh after 20 years of operation. As a reference, the National Renewable Energy Laboratory [5] currently uses a levelized COE of $0.007/kWh for calculations in all of its Low Wind Speed Technology (LWST) projects. The U.S. Department of Energy [6] estimates the total COE for new wind turbine projects to be $0.005 to $0.006/kWh.

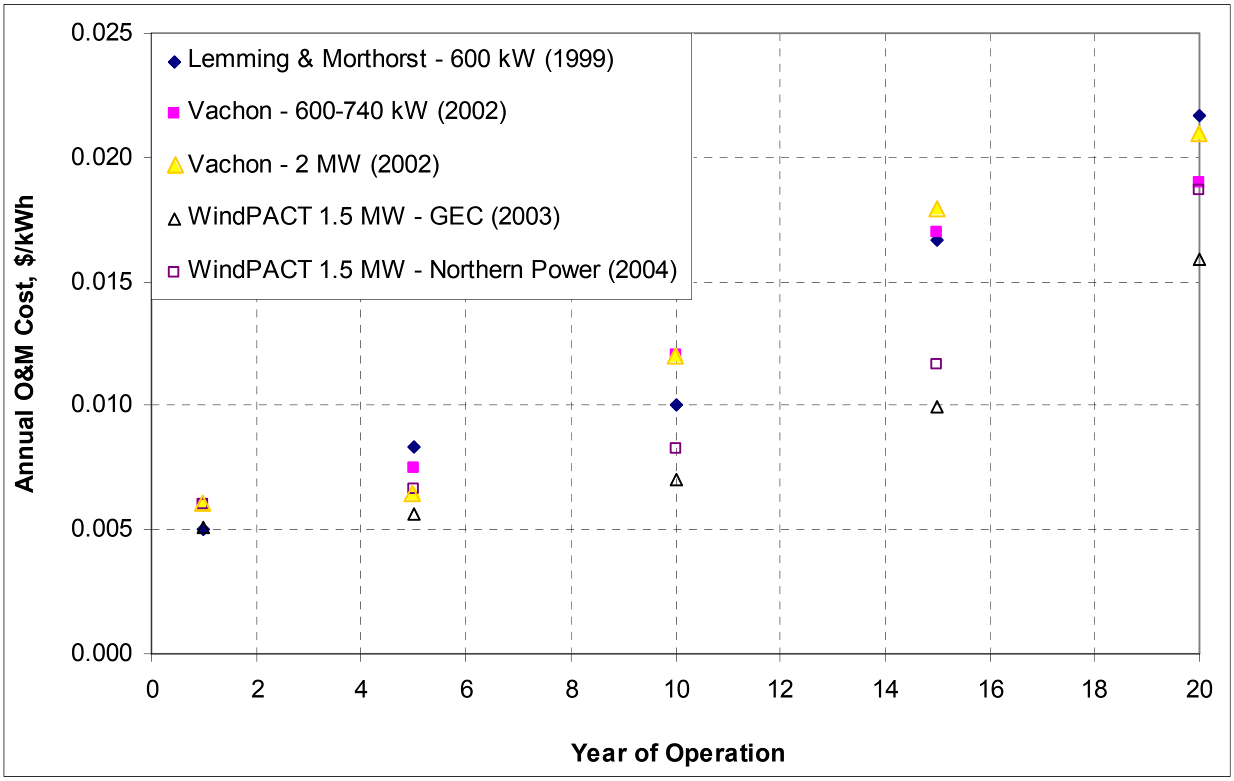

Figure 1. Estimated cost per unit energy production for O&M

Vachon has estimated that cumulative O&M costs can represent 75%-90% of a turbine's investment cost. This estimate is based on a 20-year life cycle for a 100 MW project populated with 600 750 kW size machines, and includes assumed crane costs and inflation rates. The model for these estimates is based on a statistical algorithm using cost and failure-rate data from North American installations. Lemming, et al, derives a slightly lower estimate of 65% for 600 kW machines, based on data from the Danish fleet over the past 20 years. However, the difference between these estimates can be easily explained by the sensitivity to assumptions.

O&M costs are also presented normalized to the rated power of the wind turbine. Reported values of this metric show the general trend toward a reduction in O&M costs for larger machines. Hahn [7], for example, reviewed 10 years of data for the German fleet and reports that in the sixth year of operation, when premature failures and initial problems are assumed to have been resolved, average O&M costs for machines under 500 kW size are $40/kW, while for 500 kW and 600 kW machines, the cost is $20/kW. This significant drop in the normalized O&M cost as machine size increases is related to the fact that the tasks associated with maintaining and operating a single machine are the same irrespective of wind turbine capacity, while the size of the machine and its components impose only a very small penalty.

The normalized costs for O&M in general escalate over the project's life. Vachon estimates that for a 100 MW project consisting of 600 750 kW machines, costs may escalate from $15 to $55/kW per year over a 20-year period; Lemming, et al., propose similar ranges. These projections assume that the operating costs will escalate only slightly, primarily due to inflation, while the maintenance and replacement costs will increase as parts wear and begin to fail. Note that the cost to the operator during the first few years when the equipment is under warranty will be primarily preventive (scheduled) maintenance and routine operations.

The overriding assumption in all of the above-mentioned studies is that the technology remains essentially the same and the components are scaled for capacity. Certainly this is true for the majority of the initial wind turbine fleet installed in the 1980s and 1990s, when the basic configuration of the machines was established and the designs reached a level of maturity where only incremental changes were applied to newer models. Vachon has relied on this consistency to develop mean-time-between-failure (MTBF) estimates for common subsystems employed in kW size wind turbines with conventional configuration. Using these estimates to predict future failure rates for a standard existing project is predicated on similar operating conditions and failure mechanisms.

In the late 1990s, manufacturers began to introduce wind turbines in much larger sizes. While the larger kW size machines are still being produced by many manufacturers, the new 'MW' size machines are being installed in significant numbers. Most major vendors offer turbines in the 1.5 MW range and are actively developing and installing first versions of 2 MW to 3 MW machines. Most of these larger machines employ technologies that are sufficiently new that the validity of extrapolating data from the 'standard' machines of the 1990s is questionable. An example of the dramatic difference in technology is the trend toward direct-drive turbines that eliminate the gearbox entirely and employ a low-speed, large-diameter synchronous generator. While the move away from conventional gearing is a promising step for many who have dealt with the numerous gearbox failures of the past several years, there are scant data on the reliability and failure modes of these large diameter generators, and their performance in a variety of wind environments is limited. The Dutch Offshore Wind Energy Concepts (DOWEC) study [8] in the Netherlands compared projected reliability for six design strategies for 5 MW machines and concludes that the failure rates will increase by approximately 20% for innovative variable-speed and direct-drive designs. Northern Power Systems [9], in their design study for an innovative direct drive wind turbine, reach the opposite conclusion and estimate that unscheduled maintenance costs will decrease by 60% with their design due to the elimination of the gearbox.

Even ignoring the questions surrounding innovation, there is reason to doubt that extrapolating standard, proven designs to larger size machines is a straightforward exercise. Although Vachon projected that the O&M costs for a project consisting of 2 MW machines might be 12% less than the cost for an equivalent project of 750 kW machines, the track record of ‘up-sized’ machines does not bear this out. The German insurance industry has estimated that the additional O&M cost for a MW size machine may be $125,000 every five years (approximately $.01/kWh per year, assuming a 30% capacity factor) [10].

Cost Elements

A program to reduce O&M costs for wind energy projects must begin with an understanding of the cost elements associated with a wind farm operation. The costs can be separated into the broad categories of operations, scheduled maintenance and unscheduled maintenance. The portion of O&M costs associated with unscheduled maintenance – the area most difficult to predict – is between 30% and 60% of the total, and generally increases as the project matures and equipment failure rates increase.

Operations

This category comprises activities associated with day-to-day project operation such as scheduling site personnel, monitoring turbine operation, responding to turbine fault events, and coordinating with the utility to address curtailment or outage issues. In some cases, substation operation, including any power factor correction equipment, is part of operations. Most recently commissioned wind turbine sites include a Supervisory Control and Data Acquisition (SCADA) system to allow turbine monitoring and, in some instances starting, stopping and resetting individual machines from a central location. Control of power factor correction equipment is often integrated into the SCADA system.

Operations also include ongoing activities associated with inventory management, coordinating with sub-suppliers for site and maintenance services, administering power purchase agreements, and submitting and tracking warranty claims. Operations staff usually collect and interpret performance data for the project and generate periodic reports.

Costs associated with operations depend on the range of tasks assigned and on the size of the wind project. A reasonable estimate can be based on required staffing levels plus expenses for facilities and office overhead.

Scheduled (Preventive) Maintenance

The objective of preventive maintenance is to replace components and refurbish systems that have defined useful lives, usually much shorter than the projected life of the turbine. Tasks associated with scheduled maintenance fall into this category. These tasks include periodic inspections of the equipment, oil and filter changes, calibration and adjustment of sensors and actuators, and replacement of consumables such as brake pads and seals. Housekeeping and blade cleaning generally fall into this category. The specific tasks and their frequency are usually explicitly defined in the maintenance manuals supplied by the turbine manufacturer. Costs associated with planned maintenance can be estimated with reasonable accuracy, but can vary with local labor costs and the location and accessibility of the site. Scheduled maintenance costs are also dependent on the type and cost of consumables used.

Unscheduled (Failure Related) Maintenance

A certain amount of unscheduled maintenance must be anticipated with any project. Commercial wind turbines contain a variety of complex systems that must all function correctly for the turbine to perform; rarely are redundant components or systems incorporated. Failure or malfunction of a minor component will frequently shut down the turbine and require the attention of maintenance personnel.

Unscheduled costs can be separated into direct and indirect costs. The direct costs are associated with the labor and equipment required to repair or replace, with the component costs themselves, and with any consumables used in the process. The indirect costs result from lost revenue due to turbine downtime.

Labor costs are driven by the difficulty of accessing and working on the components. With the exception of some switchgear and power conversion equipment, most the turbine equipment is accessed by climbing the tower. For safety reasons, a two-person crew is generally required for any up-tower activity. In remote locations, access to the turbine itself may be difficult and limited by weather. Working conditions can be in extreme temperature conditions and may be curtailed by high winds. Some turbines are equipped with hoists and rigging equipment, but in general, all tools and equipment, in addition to spares, must be lifted into the nacelle. Space is limited inside the nacelle and working positions may be awkward. Work outside of the nacelle, including transitions into the hub on some turbines, requires working with a safety harness and lanyards.

Labor cost estimates for major component replacement are developed from experience. Although some major components may be reworked *in situ*, this is not generally the case, and replacement will require a crane to dismantle the drive train, and several personnel in addition to the crane operator. The equipment and procedures for disassembling the rotor or drive train are established during assembly. The actual cost, however, may vary due to accessibility to the turbine site, equipment availability, and wait time during high-wind conditions. The availability of cranes capable of lifting turbine components in the MW capacity range is limited in many of the remote locations where wind farms are being developed, and mobilization costs alone can make up a major portion of the repair cost.

As an example, the cost for replacing a gearbox in a 660 kW turbine, on a 65 meter tower, is on the order of $120,000, for a site with local hydraulic crane service. The bulk of this cost, perhaps 80%, is for procuring and overseas shipping the new gearbox, and the remainder is for crane, site labor and local shipping. Overhauling the gearbox at a local rebuild shop can reduce the total replacement cost to around $40,000 - $50,000; these facilities are occasionally being established in areas with high concentrations of wind power projects

Replacing a gearbox in a 1.5 MW turbine on an 80 meter tower is substantially more expensive, even on a pre-kW basis. A rebuilt gearbox will cost 3 to 4 times as much as for a rebuilt gearbox for a 660kW turbine, and most likely a lattice-boom crawler crane must be hired. Since each boom section – 10 to 12 sections in all – and counterweights must be shipped on a dedicated truck, the mobilization cost is high, and total crane costs can reach $50,000 to $70,000.

Labor for minor repairs (those associated with sensors, actuators or control components that fail or function intermittently) is generally accounted for by assigning a number of turbines to each technician. Due to the difficulty in accessing the equipment, travel and climbing time may be much higher than the actual time required to diagnose and repair. Intermittent malfunctions that are difficult to diagnose may require multiple trips.

Most replacement parts used on a project are supplied by the turbine manufacturer. Many smaller components, such as electronic and hydraulic parts, are stock items that are available from multiple sources. But the bulk of the power-transmission and rotor components, and most of the controller and power conversion equipment, are purpose-built items that are sourced by the turbine vendor. Turbine models that have been in existence for more than ten years and are large in number have spawned an after-market in blades and in generator and gearbox rebuild services.

Indirect costs due to lost revenue depend on the total repair downtime, including acknowledgement, access, diagnosis, labor and part mobilization, and replace or repair activity, and also on the wind resource during the repair time. Commonly, the statistic reported is the downtime associated with the repair, although modern SCADA system calculate and record the projected revenue that would have been captured during the downtime, in which case ‘downtime‘ is reported as lost kWh.

Reducing O&M Costs

Most of the approaches to reducing the O&M costs for wind power projects are common to any industrial plant, and techniques from the general body of knowledge associated with maintenance engineering can be applied to wind turbines as well. Cost reduction efforts in general will focus on improving component reliability and on reducing the cost to perform maintenance. However, the unique nature of the wind power environment places constraints on what is practical and favors certain aspects of a standard O&M cost reduction program.

Improving System Reliability

- **Identify Critical Components**
  Within any complex system, certain components will stand out as high-risk items, either because they are ‘weak points’ that are demonstrated to be failure prone, are absolutely essential to turbine operation, or are expensive and time-consuming to diagnose and repair.

Identifying the critical components allows the O&M staff to direct their monitoring, training, inventory, and logistics efforts on areas that will provide the most benefit. Although to some extent the critical components depend on the manufacturer, configuration, and operating environment, certain candidates for attention (gearboxes, generators, and power converters, for example) are well known throughout the industry. Minor components, though perhaps less costly to replace or repair, may be elevated to a critical status if their frequency of failure is high.

- **Characterize Failure Modes**
  Understanding the failure mode allows the maintenance staff to focus monitoring efforts and potentially delay or prevent catastrophic failures. A generator short may be difficult to predict, but gearbox bearing or gear wear may be detected early with scrupulous lubricant monitoring and/or "condition" monitoring, and the progression of damage possibly mitigated with more frequent oil changes or better filtering. An understanding of the way in which a failure progresses is essential to ensuring that staff avoid consequential damage due to unanticipated breakage.

- **Determine the Root Cause**
  Although the wind plant operator may be primarily interested in replacing a failed component and getting their machine back on-line, a failure always represents an opportunity for improvement. Most wind turbine manufacturers include failure analysis as an essential part of their continuous quality improvement process. Evaluating the root cause of a major component failure is essential to determining if the failure is due to manufacturing quality, product misapplication, design error, or inappropriate design assumptions. This information, in turn, assists the manufacturer in determining if the problem is an isolated instance or a systemic problem that is likely to result in serial failures. In the latter case, retrofits or redesigns will be required and a field replacement plan will be developed.

Reducing Maintenance Costs

- **Develop Logistics Plan**
  A comprehensive logistics plan allows O&M staff to efficiently deal with breakdown problems when they occur and minimize turbine downtime. At a minimum, a logistics plan will identify major failure events and list the tasks required for effecting a repair. A thorough plan will anticipate likely failures and prepare a spares inventory, manpower, and equipment.

- **Identify Opportunities for Redundancy**
  Currently, redundant systems in commercial wind turbines are limited to those required to ensure turbine safety, such as uninterruptible power supplies for the control system and backup power for pitch systems. Potentially there are other areas where redundancy (especially in the ancillary fluid, cooling, and sensor control systems) may reduce labor costs with minimal additional expense. The attractiveness of backup systems will increase with the inaccessibility of the equipment, especially as turbines are installed in more remote or offshore locations.

- **Improve Training**
  Thorough personnel training is essential for proper maintenance and for effective fault and failure diagnosis. Most turbine manufacturers offer comprehensive training for their own technicians, as well for the site owner's personnel. Frequently seasoned wind site personnel will have worked either alongside the manufacturer's staff during the warranty period, or will have worked as technicians themselves.

  As new technologies are being introduced to the latest generation of wind turbines, the skills required of maintenance technicians have increased in scope. While the mechanical and hydraulic systems have remained relatively consistent, the diagnostic, control and power electronic systems have become increasingly complex. Operators must make strategic decisions regarding the depth of expertise that they want to invest in their staff as opposed to pulling in from consultants and service providers when the need arises. If the wind farm is large enough, trade specialization may be an option.

- **Improve Maintainability**
  Maintainability refers to the relative ease and efficiency of performing tasks associated with machine maintenance, including both routine service and unplanned repairs. Maintenance personnel are very good at finding efficient ways to perform routine tasks, and often have an understanding of the equipment that can only be gained from hands-on experience. Their suggestions and comments should be routinely incorporated in the continuous improvement process.

  Staff ability to diagnose problems and select the appropriate corrective action is a major contributor to equipment breakdown response time. Turbine manufacturers are well aware of this and generally include extensive troubleshooting charts to assist the staff in isolating problems. Most turbine control systems include some diagnostics information on the status of the various subsystems, and often a history buffer is available to allow a review of events leading up to a fault. Some manufacturers are incorporating remote turbine/project monitoring at a central location that is staffed with resident experts, who then contact on-site staff with recommendations for fixing a problem. This concentration of expertise and experience is fertile ground for developing expert systems to diagnose problems, and also for rapidly closing the loop between field experience and design improvements.

  Another aspect of maintainability that has gained increased attention in recent years is the advantage of modularity. Several turbine configurations are being developed that utilize multiple generators and gear units in the drive train instead of one larger unit. The primary argument for this arrangement is that it is possible to remove and replace the units using the rigging that is permanently installed in the nacelle, thus avoiding the high costs of bringing in a mobile crane. Secondary advantages are the possibility of running at reduced power if only one modular unit fails, and the reduced inventory cost for smaller units.

  At the same time, direct-drive turbine configurations are promoted that use fully integrated drive trains, with the main shaft, bearings, and generator designed into one structure. In this case, a failure of any one component within the drive train may require dismantling of the entire drive train and rotor. In between these extremes are configurations that combine the drive train components but allow disassembly and, in some cases, refurbishment inside the nacelle without the need to dismantle.

The maintainability advantages of modular configurations must be weighed against the increased potential for failures due to increased part count. However, an argument can also be made that the risk associated with smaller units using ‘stock’ parts and conventional manufacturing methods is cumulatively less than the risk associated with very large custom components and manufacturing techniques that may not be fully developed. Incorporating modularity must also be weighed against the added complexity inherent with multiple interfaces and the added fixture cost required for *in situ* disassembly.

- **Implement Condition Monitoring**
  Condition monitoring is an essential component of an effective maintenance program. A comprehensive monitoring program provides diagnostic information on the health of the various turbine subsystems and alerts the maintenance staff to trends that may be developing into failures or critical malfunctions. This information can be used to schedule maintenance tasks or repairs before the problem escalates and results in a major failure or consequential damage with the resultant downtime and lost revenue. In some cases, remedial action can be planned to mitigate the problem. An example is filtering gearbox oil if monitoring indicates unacceptable contamination levels. In other cases, such as the indication of a structural crack, measures can be implemented to track the problem’s progression. In the worst case of an impending major failure, condition monitoring can assist maintenance staff in logistics planning to optimize manpower and equipment usage and to minimize the cost of a repair or replacement.

  Condition monitoring falls into two broad categories: off-line and on-line monitoring. Off-line monitoring requires that the machinery be taken out of service to allow inspection by maintenance personnel. Generally these off-line inspections are scheduled at regular intervals and consist of routine procedures. Off-line monitoring is standard practice on commercial wind turbines. Scheduled maintenance generally includes verification of fluid levels and quality; inspection of structural joints and fasteners; measurement of wear items such as brake pads, bushings and seals; and functional checks of the safety and control systems. Special diagnostic techniques, such a thermography for switchgear or NTD methods for crack detection, may be used as required.

  On-line monitoring offers several advantages over off-line monitoring. First, on-line observation provides deeper insight into how well the turbine subsystems are performing while rotating under load and can alert the maintenance staff to both long-term trends and short-term events that may not be obvious with a ‘spot check.’ Second, on-line monitoring can be incorporated into SCADA systems to automatically trigger appropriate alarms and alert staff when a problem occurs. This feature is essential for unattended turbine operation, especially in remote or inaccessible locations.

All commercial turbines incorporate basic on-line monitoring. Generally the control system includes sensors to monitor machine parameters such as temperatures, speeds, fluid levels, line phase imbalance, voltage levels, and tower vibration. This level of monitoring is used to confirm that the turbine is operating correctly, that the lubrication and cooling systems are functional, and that an unsafe condition has not occurred. Since maintenance personnel normally do not have access to the turbine nacelle while the turbine is in operation, they do not have the advantage of being able to use their senses to observe the equipment or to make spot-check measurements. This basic level of monitoring is usually the only means for observing the turbine during operation.

In recent years, more sophisticated on-line monitoring systems have been introduced to wind turbines. These systems use technologies that were initially developed for other industries, such as marine propulsion and power generation, and have now reached a level of maturity where they are useful in a production environment. The most common are vibration monitors and the fluid contamination monitors.

Vibration monitoring is used to detect faults in the bearings and gearing. Two categories are used, but both are distinct from the common low-frequency vibration monitoring included in the turbine control and safety systems. The first category uses sensors mounted to the bearing housing or gear case to detect characteristic vibration signatures for each component. The signature for each gear mesh or rolling-element bearing is unique and depends on the geometry, load, and speed of the components. The monitoring system then compares the signature during operation with the characteristic signature and flags any anomalies. The second category includes the ‘shock-pulse’ or acoustic systems that use high-frequency, narrow-band vibration sensors to detect structure-borne pulses that occur when a rolling contact or gear mesh encounters a discontinuity in the surface, indicative of wear or debris particles. Both systems are component-specific, and require a significant investment in up-front engineering time to select the optimum sensor configuration and to develop algorithms (‘rules’) for interpreting the data collected from the sensors.

On-line contamination monitoring technology takes several forms. One system type applies a magnetic field to a contained fluid stream to detect the presence of ferro-magnetic debris, which is indicative of wear particles from rolling or rubbing contacts. Another type was originally developed for evaluating the cleanliness of fluids used in process industries, and has recently been adapted to hydraulic and lubricant fluids. These systems use a laser light source and target arrangement to count the particles, seen as obstructions, in a fluid stream. The more sophisticated systems can detect particle size and quantity and convert these into a standard metric for cleanliness, such as the ISO 4406 contamination code. A third system passes fluid over a fine mesh screen and detects the pressure drop as an indicator of accumulated contamination.

The question to ask when evaluating any of these condition monitoring systems is whether the cost of installing and commissioning these systems is justified by the usefulness of the information. The answer may prove to be turbine-specific, as it easier to justify a $10,000 monitoring system for one 1.5 MW turbine than it is to justify twice the expenditure for two 750 kW machines. But in both instances, the case must be made that the information gained from the monitoring system is both timely and unique. The candidate system must provide early enough warning of an impending problem to allow for remediation or at least convenient scheduling of repairs, but it must also provide insight that cannot be gleaned from routine visual inspection or oil sample analysis. It must also be considered that on-line systems, once they are verified and trusted, can potentially reduce the labor cost for off-line inspections. These costs are in turn dependent on the turbine's height and accessibility.

Causes of Uncertainty

As discussed previously, the uncertainty associated with component life has direct bearing on the risk associated with a wind turbine project. The factors that affect the level of certainty are numerous and to some extent unique to the wind industry. First and foremost is the lack of data relating to component reliability. Turbine manufacturers maintain records of failures and wind farm operators maintain records of warranty claims and associated downtime, but this information is proprietary and is not accessible to the public. Even assuming that these data were accessible, one cannot expect that the format will be consistent or that the information will include enough detail to allow a systematic evaluation.

It must also be appreciated that although operators will have general information on the number of failures and general type, they may not have information on the root cause of the failure. This is especially true during the warranty period when, unless a serial defect is declared, the turbine manufacturer may not be obligated to disclose this information in any detail. The same argument may apply to the turbine manufacturer in the case of sub-supplier components, although the manufacturer will generally require this information as part of their sub-supplier agreement.

Several institutions record turbine production and availability data; these are TrustPower Limited (New Zealand), Global Energy Concepts (USA), Energimyndighet (Sweden), Kema (The Netherlands), Betrieber-Databasis/IWET (Germany), and Windturbinepark Zeebrugge (Belgium). The *WindStats Newsletter* collates and publishes this information periodically, and also includes more comprehensive data for turbines operating in Denmark, with comments describing reasons for downtime. In most cases, the data are self-reported and the format is inconsistent between sources. *WindStats* also publishes a summary of component failures for Danish production sites, broken down into broad subsystem categories.

The difficulty in obtaining useful component failure data is compounded by the rapid pace of development in wind turbine technology. There exist large fleets of similar model turbines, but in many cases detailed changes and revisions have been implemented, often in response to serial defects. Many turbine manufacturers source components from several sub-suppliers, and although the interface may be identical, the details of design and manufacturing process are frequently specific to the manufacturer. In turn, the sub-supplier may incorporate internal revisions and model variations.

Finally, wind turbine technology includes many variations on the basic horizontal-axis configuration. Although the majority of commercial turbines employ a three-bladed, upwind rotor with a gearbox and high-speed generator, there are several distinct variations on the type of mainshaft support, pitch mechanism, and power converter technologies. In addition, new technologies are being implemented on the next generation of MW-scale machines and many of these (for example, direct-drive permanent-magnet generators and carbon-fiber blades) are unproven in the wind turbine operating environment and employ subcomponents or manufacturing processes that are innovative.

Recommendations for Further Research

The effort to minimize wind turbine operations and maintenance costs must start with a better understanding of the current costs and of the factors that drive these costs. This first step will allow development of a sound cost model for evaluating the performance of existing projects and enable estimating the cost of proposed projects with reasonable certainty. Some of the factors that drive the costs will be common to wind power projects in general, but other factors will be site specific. Detailed information on the specific failure types, along with the operating conditions, will allow for an accurate model that can be adapted to different machine types and environments.

Additional effort is then required to identify opportunities for improving reliability. The information from the first step should provide a basis for selecting high-risk components that are candidates for research and development efforts. Innovative technologies that are currently being implemented in new machine versions should be reviewed as potential targets for component-level testing. Finally, maintenance techniques that have been proven in other industries, as well as innovative methods for improving maintainability, should be evaluated and demonstrated in the wind energy environment.

Some of this work is already being done by turbine manufacturers and their sub-suppliers, wind farm operators and maintenance service providers, and researchers in the public arena and academia. The challenge will be to establish a cooperative venture that will provide a practical benefit to the wind industry as a whole while respecting the proprietary concerns of the individual parties. Following are suggested tasks to support the general objectives identified above.

1. **Quantify O&M Costs Over Time**

   Both current operators and developers of potential projects would benefit from a reliable baseline for O&M costs. This baseline would rely on operating histories from wind farms with a variety of turbine types and environmental conditions. This information would allow current operators to gauge their performance with that of other wind farms with similar conditions, and would allow developers to more accurately estimate life-cycle O&M costs.

   The best source for these data resides with operators. Unfortunately, there is no standard reporting scheme among organizations, and many of the historical records may be viewed as proprietary. Possibly a voluntary ‘user group’ can be established to collect and evaluate on-going data, using a standard reporting format to ensure adequate depth and consistency. The information gathered should include the following:

   - Routine operations and maintenance tasks and associated costs
   - Unscheduled downtime associated with operating faults, environmental constraints, curtailments, retrofit activities and R&D activities
   - Component failure histories categorized by subsystem, with corresponding frequency, associated downtime, time to repair, replacement cost, and operating conditions.

All of the above information should be keyed to the equipment's size and complexity and the working environment. In the event that cost information is considered too sensitive, then component failure information and labor requirements would provide a good basis for comparison.

2. **Develop Component Reliability Model**
   A statistical reliability model of the major turbine components would be a useful planning tool for wind farm maintenance, assisting staff to budget spares, manpower, and equipment for the project's life. From a development point of view, a reliability model will identify the risks associated with component types, allowing planners to steer their equipment selection process toward lower-risk configurations. Trending the reliability data over time can validate the effectiveness of preventive maintenance strategies to improve component reliability.

   Ideally, the data required for the model could be taken from the information collected in recommendation 1 above. However, the usefulness of a reliability model depends on the breadth and depth of the data. Long-term data on failure rates, outage time, and time to repair are essential, but detailed information on common failure modes is also important. Quantifying the mean time to failure for a gearbox is useful for that item, and perhaps similar items, in similar conditions. Identifying the internal component that failed (e.g., planet bearing), along with the operating conditions preceding the failure, may allow a more accurate extrapolation of this metric to other types of gearboxes.

3. **Identify High-Risk Components and Understand Failure Modes**
   High risk components, those that incur significant cost and maintenance effort, should be identified based on historical data. Research should be conducted determine the causes of failure. These components may be targets for further research and development work and perhaps component laboratory testing. Although much of this work for production articles is being carried out by turbine manufacturers and their suppliers, there may be common components that would benefit from a dedicated and independent evaluation. This list may include new technologies and processes, for example permanent-magnet generators or carbon-fiber blades.

4. **Re-Evaluate Design Standards**
   The large number of load-carrying component failures has led to concerns about the applicability of the standards that are used for component design. Existing standards and design methods should be reviewed in light of experience to determine if the loading and response assumptions are justified and if the assumed operating conditions accurately reflect the wind turbine operating environment.

5. **Improve Maintainability**
   Techniques for improving maintainability, both from existing wind farms and from allied industries, should be explored and evaluated from a benefit-to-cost standpoint. These techniques include:

   - Using condition monitoring and expert systems to improve diagnostics
   - Developing tooling and on-board rigging to minimize crane costs
   - Applying redundant or more robust systems to minimize 'nuisance' faults

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