Business & Technology Strategies

TechSurveillance

Wind Turbine Operation & Maintenance Issues

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This is the third in a series of NRECA TechSurveillance *articles about the status of the wind generation market and its impact on cooperatives. The* ***first article*** *provided an overview of how much wind generation capacity electric cooperatives currently own and purchase, and how they do it. The* ***second article*** *focused on current and advanced wind technologies, and this third article examines failure and maintenance issues. Visit* ***cooperative.com*** *for the* ***entire series****, as well as other helpful resources from NRECA.*

ARTICLE SNAPSHOT:

What has changed in the industry?
Despite very high availability overall, wind turbines have some major components that may fail before the typical 20-year rated lifetime of the entire turbine. The U.S. Department of Energy (DOE) laboratories, manufacturers, wind farm owners and operators, and other research organizations are working together and separately to develop solutions. In the meantime, operations and maintenance (O&M) best practices combined with sensor data from throughout the wind turbine can identify many preventative maintenance needs before components fail catastrophically.

What is the impact on cooperatives?
Some wind farm owners, including some electric cooperatives, have experienced premature failures of major components. In general, O&M costs for new wind farms are trending downward, but unplanned failures can be very time consuming (thus, losing the wind generation that would have been produced during the outage) and expensive, especially

if the repair requires a large crane.[1] These failures may reduce system reliability, increase O&M costs, and slightly increase the need for more spinning reserves and other generation. The good news is that, according to Sandia National Labs, unplanned failure and maintenance account for only about 2 percent of time overall, with scheduled maintenance at just 0.3 percent of time (Hines, Ogilvie, & Bond, 2013).

What do co-ops need to know or do about it?
Co-ops that own wind farms should ensure that they or their service contractors use O&M best practices and condition monitoring systems (CMS). Co-ops considering wind farm ownership should be aware of these potential issues and how to manage them. When purchasing or repowering wind turbines, owners can work with manufacturers and developers to specify components that have the best performance records, and to ensure sufficient sensors are included to monitor temperature, pressure, vibration, etc. and diagnose potential issues. Existing wind turbines that do not have CMS may be able to have this installed as a retrofit. In addition, the electric cooperative family has several highly-experienced wind turbine experts and excellent industry partnerships that can be leveraged for new and existing cooperative-owned wind farms.

While a portion of premature failures are caused by design flaws or defects, preventive O&M can extend component lifetimes.

INTRODUCTION

Today's wind turbines have expected lifetimes of 20 years or more with system-wide availability at 95 percent or more[2] (Lantz, 2013; Hines, et al., 2013), but some major components can fail prematurely.

While a portion of premature failures are caused by design flaws or defects, preventive O&M can extend component lifetimes. CMSs that include vibration sensors, SCADA data, and new analytics tools that use artificial intelligence (e.g. SparkCognition) can identify low cost maintenance needs before they become catastrophic failures. This allows for less expensive uptower repairs or early delivery of cranes before the failure occurs.

PREMATURE FAILURES OF MAJOR COMPONENTS

U.S. fleet data analyzed by National Wind Technology Center (NWTC) at the National Renewable Energy Laboratory (NREL) shows wind turbine major component replacements within the first 10 years of operation are:

- **Gearbox:** ~5 percent average replacement rate
- **Generator:** ~3.5 percent average eplacement rate
- **Blades:** ~2 percent average replacement rate (Lantz, 2013)

Figure 1 illustrates the major components of a wind turbine.

See Figure 2 for a yearly compairson on gearbox and generator replacements during the first 10 years of operation.

NWTC's findings are similar to other research from the U.S. and abroad for a similar time period.[3] However, it is important to note that CMS and other data analytics tools can now identify maintenance needs well in advance of a major component failure.

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[1] Large cranes can take a month or more to deliver, causing a very long outage and resulting in rental fees of $150,000 to $400,000 depending upon the remoteness of the location, as per GE staff presentation to NRECA, May 2017, Greenville, SC.

[2] Or about 93 percent with curtailment of wind turbine output due to transmission system congestion and constraints.

[3] See: Nivedh, 2014 and Wang, 2014

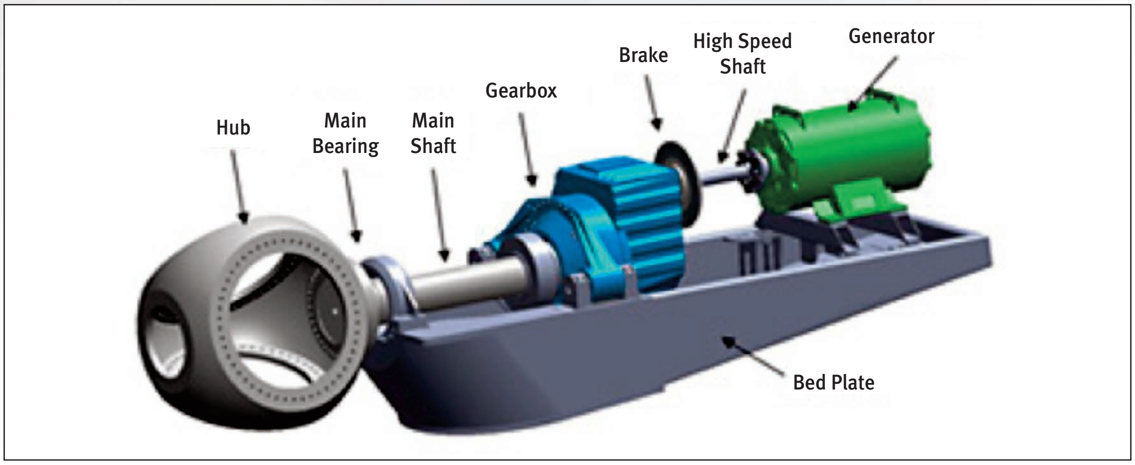

FIGURE 1: Wind turbine major components *(Source: NREL)*

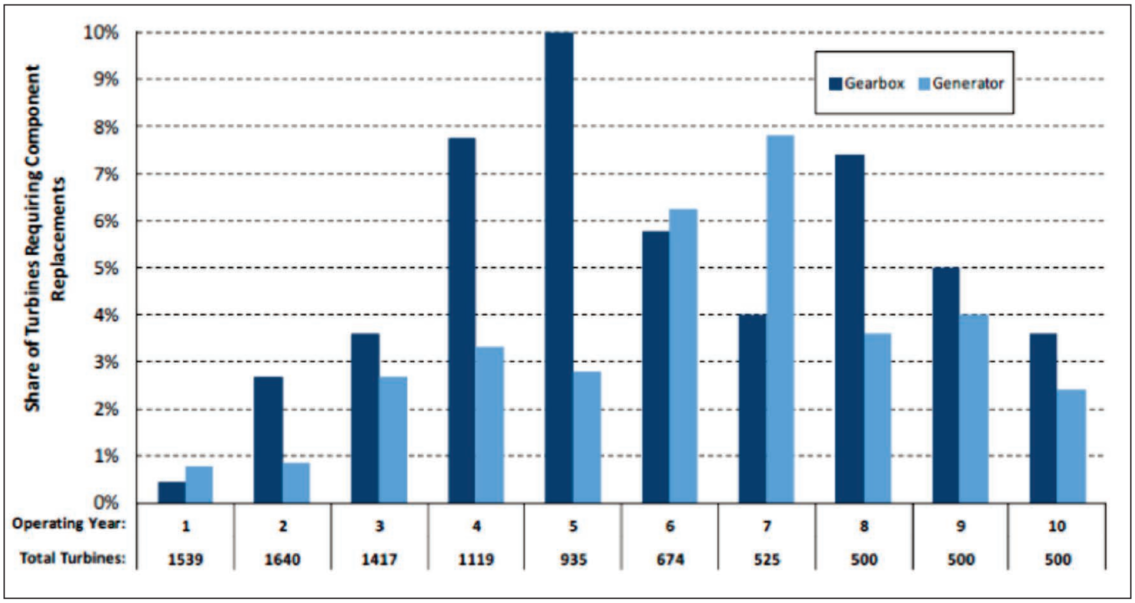

FIGURE 2: Percentage of Turbines Requiring Component Replacements in Years 1-10
(Source: Lantz, 2013, with data from DNV KEMA)

Gearboxes are the most common and most critical failure.

Gearboxes

Gearboxes, which are replaced at about a 5 percent rate during the first 10 years of operation (Lantz, 2013), are "the most common and most critical failure" (Chan & Mo, 2016). Gearbox failures (along with generator failures) cause the most downtime and greatest economic losses of all the failure types (Nivedh, 2014). A total gearbox failure requires significant replacement time and expenses, including rental of a large crane.

To address this, the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) formed the **Gearbox Reliability Collaborative (GRC)** in 2007. One activity of the collaborative is the development of a database of gearbox failure statistics. Approximately 25 industry partners, including wind turbine and gearbox manufacturers, wind farm owners and operators, and independent O&M service providers, voluntarily participate to provide data to the GRC database. The GRC database contains information from more than 1,600 gearbox damage records from 84 wind plants, dating back to 2009. Using this data, researchers identify patterns and causes that contribute to gearbox failures. In addition, the GRC uses its own dynamometers and wind turbines at NREL's Boulder, Colorado National Wind Technology Center (NWTC) facility for drivetrain testing (NREL, 2015). Figure 3 provides a break-down of the causes of gearbox failure, as found by NREL's research.

Bearings are responsible for most gearbox failures — about 70 percent (Sheng, 2013). Axial cracks, also known as white-etching cracks (WECs), cause 70 percent of all bearing failures and most frequently occur in the high-speed section of the gearbox. However, the root causes of WECs are not yet well-understood. A related part of the GRC's current research program is exploring "the influence of skidding/sliding between the bearing rolling element and the raceway" (Keller, Gould & Greco, 2017).

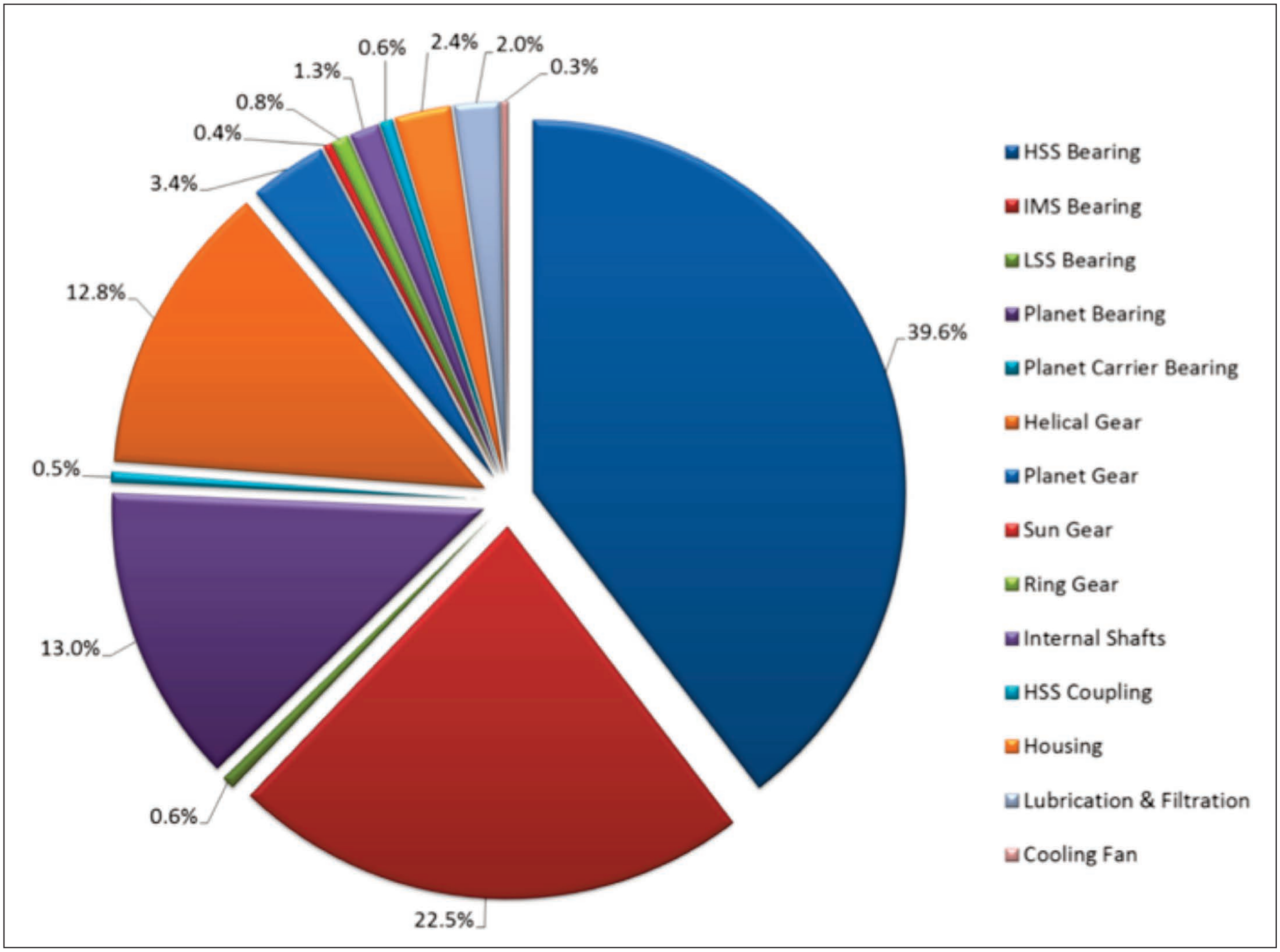

FIGURE 3: Causes of Gearbox Failures *(Source: NREL, 2016)*[4]

[4] HSS-high speed shaft, IMS-intermediate speed shaft, LSS-low speed shaft

Bearings account for the majority of failures of gearboxes and generators.

According to Al Zeitz, a 25-year veteran of the wind industry who is now manager of renewable energy services at Iowa Lakes Electric Cooperative, gearboxes are lasting longer than they were eight to ten years ago. “It used to be they would last about five years. Now we’re seeing gearboxes last a lot longer, but we still have gearbox issues as a fleet; usually it’s the bearings that fail.”

While Zeitz says there is no way to totally prevent gearbox failures at this point, ILEC is testing a new technology from **Aero Torque** that dampens torque spikes and torque reversals that go through the drive train of the turbine. “Some studies have drawn a correlation between those torque spikes / reversals and the damage caused in some of the bearings in the gearboxes, possibly even the main bearing and generators, but primarily in the gearbox,” he explained.

Generators

A second major wind turbine component that can fail prematurely is the generator. Over 10 years, generator replacement rate is about 3.5 percent, peaking in years six and seven (Lantz, 2013). Again, bearings account for the majority of generator failures. Bearing fatigue can result from poor lubrication and the sometimes-extreme fluctuations of mechanical power from changing wind speeds (Nivedh, 2014).

Kevin Alewine, director of marketing at **Shermco Industries**, provided observations based on generator failure data from more than 3,000 wind turbines from 2005 through 2016 (see Figure 4). Shermco Industries, based in Dallas, Texas, “is a provider of testing, maintenance, repair, commissioning, engineering, and training services for electrical infrastructure including substations, switchgear, transformers, motors, and generators.” Their work includes up-tower work and re-manufacture of turbine generators.

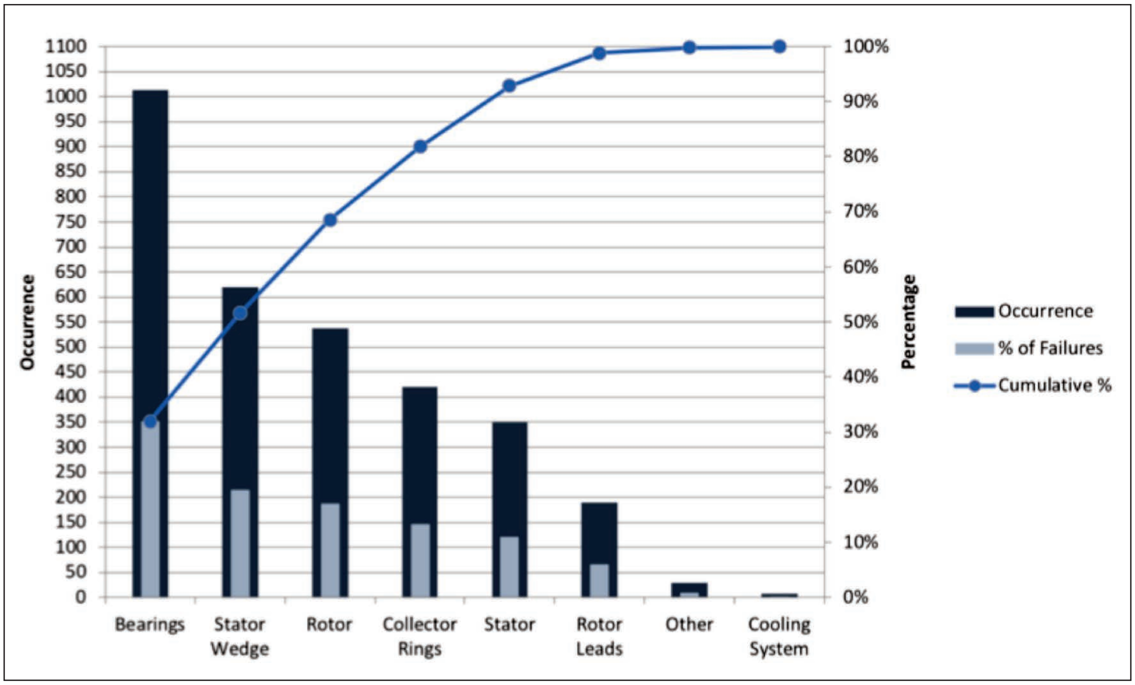

FIGURE 4: Generator failures 660kW to 3MW, 2005 – 2015 (3165 total in study) *(Source: Alewine, 2016)*

In some cases, design modifications to European models have not been robust enough to accommodate the increased stress from U.S. wind conditions.

According to Alewine, typical root causes of wind turbine generator failure are:

- **Design issues** — materials and processing, rarely basic mechanical design
- **Operations issues** — alignment, vibration, voltage irregularities, improper grounding, over-speed, transit damage, etc.
- **Maintenance practices** — collector systems,[5] lubrication procedures, etc.
- **Environmental conditions** — weather extremes, lightning strikes, etc. (Alewine, 2011)

Generator bearing failures are attributable to too much or not enough lubrication, Alewine explained.[6] Alignment and vibration issues are the next most common reasons for generator failure.

Shermco has observed many generators that are simply under-designed for their applications. For example, wind generators can cycle 20 times per day, which is much more than a natural gas generator. In addition, specifications for some generators used in the U.S. were based on conditions in Europe, where wind speeds are typically lower. Similarly, some generator models used in the U.S. have been adapted European generators. Models originally developed for 50 Hz that have been partially modified for 60 Hz applications experience more stress than they were originally designed for, since 60 Hz yields 18 percent more rotations per minute than 50 Hz, or 18 percent more stress. In some cases, these design modifications have not been robust enough to accommodate the increased stress (see Figure 5).

Golden Spread Electric Cooperative, headquartered in Amarillo, Texas, had to replace nearly 80 percent of the generators in the 34 wind turbines at their Golden Spread Panhandle Wind Ranch, commissioned in September of 2011. A manufacturing issue with the generator model in the Siemens Mark II (2.3 MW) wind turbines

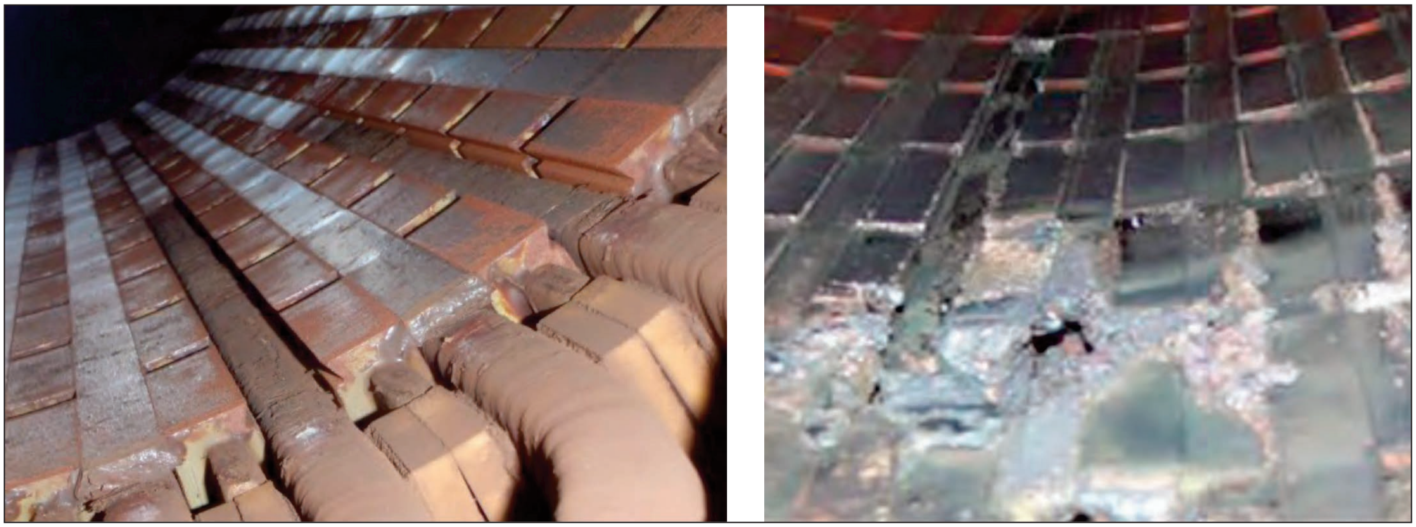

FIGURE 5: Missing and damaged magnetic wedges *(Source: Alewine, 2016)*

[5] Collector system, in this case, is the slip ring, carbon brushes and brush holder assembly (along with its enclosure and ventilation system) that provides power to the rotating element in many popular generator designs.

[6] Over-full bearings will run hot, which can create tolerance issues and damage lubricants prematurely. Excess grease can also leak both inside of the generator, encouraging contamination of the electrical windings, as well as outside of the housing, creating environmental contamination. One of the problems experienced with auto lubrication systems is that exit ports and grease traps are often not cleaned and maintained properly, resulting in old, drying grease clogging the exit system and contributing to the over-filled phenomena. (Alewine, personal communication, December 6, 2017).

Early detection of generator problems is critical.

Lightning strikes are the most common reason for blade failure; however, the industry has made great strides in lightning protection.

was responsible for the failures. Due to the known design flaw and the fact that the turbines were still under warranty, Siemens covered costs for these replacements. Kevin Defoor, site manager, explained, “Generally, this is what I would expect, having worked directly with a manufacturer. The manufacturer receives a warranty on the gearboxes from whomever they purchased them from. The wind turbine manufacturer extends that warranty to the customer. If there is an issue with the part, the wind turbine manufacturer can go back to component supplier to get credit, especially if it’s a known serial fault.” The generator manufacturer has since changed a manufacturing technique, as well as corrected the design flaw.

Early detection of generator problems is critical. Many issues can be repaired up-tower, eliminating the need for costly, large cranes. However, according to Zeitz, “If a bearing fails and causes the rotor to touch the stator while it’s spinning, it would damage the winding and the generator would have to be re-wound. There’s no way you could put that back in service up-tower.”

Blades

Wind Power Monthly reported that worldwide, blades fail at a rate of 0.54 percent per year.[7] On average, 1 to 3 percent of turbines require blade replacements per year in the first 10 years of operation. During the first few years of operations, blade replacements may be the result of manufacturing defects or damage during transport and construction. However, lightning strikes are the most common reason overall (Lantz, 2013).

Sandia National Laboratory (SNL) conducts research and testing on blade materials and failure as part of their blade reliability program.[8] According to Joshua Paquette, Blade Reliability project lead, key operational causes are lightning strikes and leading-edge erosion due to rain.[9] Manufacturing defects, transportation damage, and occasionally hail are responsible for other issues.

Blade tips can travel at 200 mph, and rain drops may fall at 50 mph. Therefore, blades can collide with rain drops at 250 mph, which eventually creates defects on blade edges. In addition to structural damage, explained Paquette, leading edge erosion can reduce energy production by up to 5 percent. A variety of tapes and coatings are available to protect against erosion. Some are applied at the factory when the blade is manufactured; others can be applied in the field.

ILEC has a blade maintenance program. Annually, they address leading edges of blades with a protective coating to prevent erosion. In addition, crews inspect all blades when they apply the coating. By doing so, “we have found some minor discrepancies that we were able to take care of. It’s very important to take a look at your blades regularly and maintain them,” said Zeitz.

Zeitz also noted that damage from lightning strikes is not as common as it used to be. “The industry has made great strides in lightning protection for blades,” he said. Modern blades have conductors inside them and receptors on the outside. The receptors and conductors create a path to ground which helps reduce potential damage from a lightning strike.

Defects imposed during blade manufacture and transport can also lead to failures, according to Paquette. Because of their scale, blades are manufactured manually. Imperfections can occur in material applications and surface irregularities. SNL actively researches this area

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[7] https://www.windpowermonthly.com/article/1347145/annual-blade-failures-estimated-around-3800

[8] http://energy.sandia.gov/energy/renewable-energy/wind-power/blade-reliability

[9] Icing is less of an issue for reliability; however, in some cases wind turbines have to be shut down during an ice storm.

Many total failures can be prevented if identified early.

and is working to improve blade inspection processes.

Paquette pointed out that identifying blade issues is different from processes used for gearbox and generators. Blades do not have the same kind of condition monitoring sensors as other components. A sensor in one area would not necessarily flag an issue in another area, and covering blades with sensors is impractical. Like Zeitz, he stressed that regular blade inspection is important. Also, because blades used on a single make and model of wind turbine can come from many factories, ask where blades on any wind turbines you purchase are coming from. A blade coming from China, for example, will have been subject to many more crane lifts and potential transport damage than one manufactured closer to the site.

Main Shaft Bearings

Root causes of main shaft bearing failure have not yet been well-documented; this is a new focus area for NREL. According to Jon Keller, principal investigator of NREL's GRC, "As far as pure dollars, main bearing failures are even more problematic than gearbox failures right now." The reason: High speed shaft bearings are small and typically can be replaced up tower with a service crane. The rotor and gearbox do not need to be removed for these repairs. A main bearing failure requires a large crane and removal of the rotor, which can cost hundreds of thousands of dollars. Because these repairs are so costly, some operators will also preventatively replace the gearbox at this time, or vice versa, since they already have the large crane on site.

NREL has formed industry partnerships to gather data on main bearing operational conditions in order to better understand and address them. Public data and research reports are forthcoming.

OPERATIONS AND MAINTENANCE SOLUTIONS

While some premature component failures in wind turbines are not related to O&M practices, many total failures can be prevented if identified early. Regular inspections and proper maintenance of all components is essential. CMSs, including vibration sensors, are also critical for catching problems early.

Preventative maintenance and early identification of problems

Based on his ten years in wind farm construction, O&M, and management, Golden Spread's Defoor advises:

- Ensure maintenance is completed correctly and in a timely fashion.
  - Technicians should address everything possible at each tower during regular maintenance visits.
  - Collect and test oil and grease samples at least annually for conditions including: high ferrous or non-ferrous metal content, moisture in gearbox, moisture in bearings, and level of oil additives. This provides a pre-indication of a failure and allows for up-tower repairs prior to bringing in a large crane.
- Have a robust vibration monitoring system.
  - This can identify a problem early and allow operators to schedule up tower maintenance instead of waiting for a total failure for which a crane is required.
  - Third-party companies can conduct a side-by-side vibration analysis of SCADA data to verify results, if desired.

TABLE 1: Summary of Condition Monitoring for Wind Turbines *(Source: Wang, 2014)*

Part of wind turbine	Fault	Technique	Sensor/monitoring quantity
Gearbox	Gear tooth damage, bearing faults	Vibration monitoring and spectrum analysis, supplemented with acoustic emission sensing detects pitting, cracking	Transducers, velocity sensors, accelerometers, spectral emitted energy sensors, acoustic emission sensors
		Oil analysis	Temperature, contamination, moisture
Generator	Stator, bearing, rotor inside	Signature analysis of generator current	Current measurement
Rotor blades	Creep & corrosion, fatigue, imbalance, roughness	Shearography, radiography, acoustic emission sensing	Acoustic emission sensors, strain gauges, Fiber Bragg Grating
Tower and blades	Ultrasonic testing techniques	Time-frequency techniques and wavelet transforms	Ultrasonic sensors, Fiber Bragg Grating
Pitch mechanism, yaw system, power electronics/electrical system	Voltage and current analysis, electrical resistance	Spectrum analysis, eddy current, thermography	Current and voltage measuring equipment

Predictive analytics offers significant savings opportunity on unplanned maintenance and repairs.

Table 1 shows the ways in which condition monitoring systems can identify issues throughout wind turbines.

CMSs are available from OEMs as well as third-parties. Data from them can be put online for remote monitoring or downloaded onsite. But, regardless of where it is retrieved, "This data allows operators to develop an effective predictive maintenance strategy, which can ultimately make room for considerable savings in time, resources and money."[10]

Typical O&M Costs

According to the DOE's latest Wind Technologies Market Report, typical O&M costs for wind farms developed in the 2000s is approximately $10/MWh, with a slight drop to $9/MWh for those developed post 2010 (Bollinger & Wiser, 2017). Interestingly, this is about half of the $20/MWh they cite as the average PPA cost (which includes the federal production tax credit of $24/MWh in existing and repowered wind turbines). Note that without the production tax credit, the average PPA cost would be $44/MWh and the typical O&M costs are still significant at 23 percent of total costs. However, the authors caution, "Operations and maintenance costs are an important component of the overall cost of wind energy and can vary substantially among projects. Unfortunately, publicly available market data on actual project-level O&M costs are not widely available. Even where data are available, care must be taken in extrapolating historical O&M costs given the dramatic changes in wind turbine technology that have occurred over the last two decades" (Wise & Bollinger, 2017, p. 53). An example of this discrepancy is *Wind Power Monthly*'s report of a median O&M cost of $19/MWh at an assumed wind speed of 7.5 meters/second compared to $9/MWh for wind turbines developed after 2010.[11]

[10] http://www.renewableenergyworld.com/articles/print/volume-20/issue-6/features/wind/eliminating-the-dreaded-downtime-in-wind-farm-operations.html?cmpid=enl_rew_wind_energy_news_2017-12-21&em

[11] http://www.windpowermonthly.com/article/1380738/global-costs-analysis-year-offshore-wind-costs-fell

Predictive analytics offer owners and operators a significant savings opportunity on unplanned maintenance and repairs. For example, "The data insight predicting a future gearbox failure led the owner of the turbine to perform a few hours of predictive maintenance that cost $5,000. In the end, that work saved the owner from having a more catastrophic, $250,000 problem and at least several days of down-time."[12] In some cases, crane delivery can take more than a month. While this technology is extremely beneficial for on-shore wind, it is essential for off-shore projects given their remote locations.[13]

Warranties and service agreements

Wind farm owners have a wide variety of options for warranties and service agreements that may cover many of the common premature failures. A typical warranty is two to three years; however, owners can purchase extended warranties. In addition, "most OEMs are now offering service contracts in the range of 7 to 10 years and also provide a guarantee on turbine availability."[14] Independent service providers offer plans that may be competitive with OEMs.[15] Wind farm owners can negotiate warranty periods and service agreements at the time of purchase and when original contracts expire.

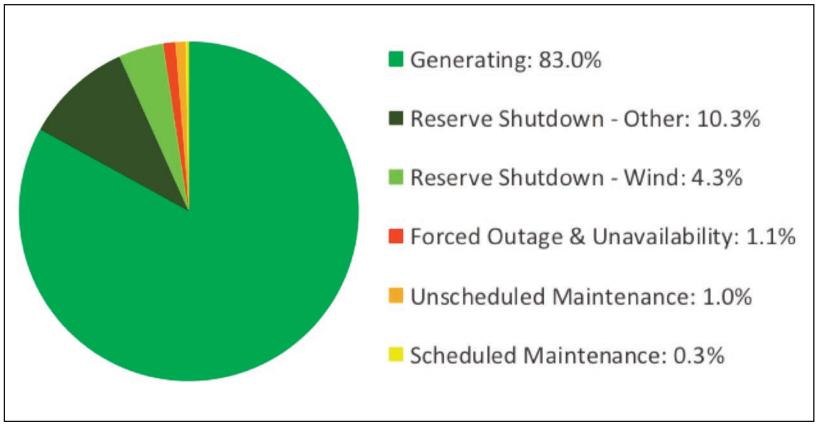

FIGURE 6: Wind Turbine Availability of Time Accounting, CREW database. *(Source: Hines et al, 2013, p. 8)*

CONCLUSION

Despite the premature failures that the industry has experienced, overall downtime for wind turbines is extremely low. According to SNL's Continuous Reliability Enhancement for Wind (CREW) database of approximately 900 U.S. wind turbines, forced outages account for only 1 percent of time; unscheduled maintenance accounts for another 1 percent. Scheduled maintenance requires 0.3 percent of time. For the remaining 97.6 percent, turbines were either generating electricity, or not generating (reserve shut-down)[16] due to factors including pre-generation run-up, curtailment, or non-favorable wind conditions (See Figure 6, Hines, et al, 2013).

U.S. federal laboratories and industry are working independently and together as partners to develop solutions to improve fleet reliability. Both NREL and SNL host public workshops on their wind turbine research. Concurrently, wind farm owners and operators can prevent many premature failures of major components by following O&M best practices and making sure CMS and SCADA data are being actively used to identify maintenance needs early. All major OEMs and some third-parties offer CMS for both new and repowered machines. ■

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[12] https://nawindpower.com/wind-operators-need-predictive-analytics-right-now

[13] http://www.owjonline.com/news/view,turbine-troubleshooter-uses-big-data-to-reduce-om-costs_49430.htm

[14] http://www.power-technology.com/research-reports/researchreportglobal-wind-turbine-operations-and-maintenance-market-expected-to-reach-274-billion-by-2025-5856565

[15] http://www.windpowerengineering.com/business-news-projects/oems-forecast-secure-50-growing-wind-om-market

[16] Reserve Shutdown – Wind: time when the turbine is NOT experiencing another event and the wind conditions are not appropriate for generation
Reserve Shutdown – Other: time when the turbine is experiencing a reserve event other than "Reserve Shutdown – Wind" (e.g., run-up before generation; cable unwind; curtailment)

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About the Author

Laura Moorefield consults for utilities, state and federal governments, and non-profits on lighting, energy efficiency, renewables, and program design. Since 2005, she has been influential in the development of innovative programs and policies to spur energy savings. In addition to her background in consulting, public speaking, technical writing and project management, Laura draws on industry experience from prior positions in manufacturing and product engineering. She founded Moorefield Research & Consulting in 2013 after holding positions with Ecova, Ecos Consulting and Rejuvenation. Laura is Lighting Certified by the NCQLP, and holds an MA in Renewable Energy from Appalachian State University (Boone, NC).

Questions or Comments

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