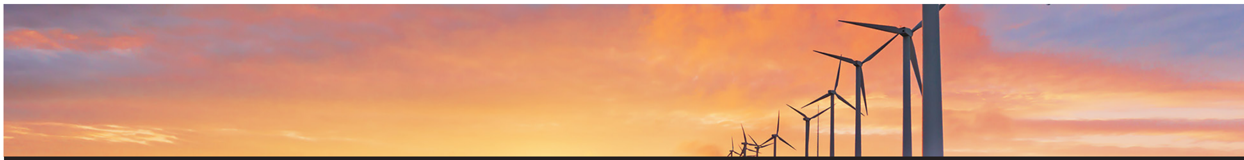
WIND TURBINE GEARBOX RELIABILITY ASSESSMENT

Value of Increased Reliability and Reduced Operations and Maintenance Costs

December 2021



Abstract

Reliability tracking of wind turbine major systems and components (including blades, pitch, main bearing, gearbox, and generator) is key for future failure rate predictions and operations and maintenance (O&M) optimization. The premature failures of these major systems are one of the primary reasons for a significant increase in O&M costs, turbine downtime, and lost revenue. Wind turbine gearboxes are manufactured by multiple suppliers, resulting in variability and uncertainty in quality and reliability. It is important for operators to know the impact of this variability and unreliability on their O&M costs. To address these industry needs, the Electric Power Research Institute (EPRI) and National Renewable Energy Laboratory (NREL) collaborated with wind turbine operators/utilities on reliability data specifications and standards for an industrywide effective reliability analysis. In this report, gearbox reliability, critical components, and the impact of design and operating conditions are discussed in detail. Also, the report includes details on the digitalization of wind assets enabling implementation of reliability tracking, benchmarking, and O&M budget forecasting techniques.

Business Needs for Gearbox Reliability—Industrywide Collaboration

Wind energy technology continues to develop at a rapid pace. Turbine ratings have doubled every 10 years since becoming economically viable in the 1990s. Additionally, turbines are being deployed at lower wind speeds (wind class) with a dramatic increase in the average capacity factor (efficiency of capturing wind energy). As the renewable energy industry heads toward a higher percentage of total power generation, reliability and predictability of O&M costs are a top priorities and, at least, a tremendous opportunity.

Wind turbine O&M costs have increased with usage due to major system (such as gearbox) failures and replacements. Unscheduled, fault-driven events and the associated downtime can drive more than 60% of land-based turbine O&M costs, which equate to about a third of the overall operational expenses [1]. Hence, operators have been focusing on exploring and implementing new technologies to track and forecast reliability and O&M costs and allot optimum budgets.

Duke Energy is using advanced analytics to improve its commercial renewables availability and reliability. EPRI's research and input have enabled optimization of our assets performance for our company and our customers.

— James Bezner, Director, Performance Services

Duke Energy Sustainable Solutions

The following are the key questions that operators need to address specifically to wind turbine gearbox reliability and O&M budget forecasting:

- What are the data specifications and standards for tracking wind turbine reliability?
- What are the impacts of design, supplier quality, and operating conditions on system life and reliability?
- What are the critical components in a gearbox? How can I extend the life of a gearbox?
- Do I have statistically significant reliability data to make accurate reliability predictions?

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This white paper was prepared by Raja V. Pulikollu (EPRI), Shawn Sheng (NREL), Jeff Mclaughlin (Machine Building Specialists), Brandon Fitchett (EPRI), and Andrew Han (EPRI).

To address these industry concerns, EPRI developed [Wind Network for Enhanced Reliability](#) (WinNER; Figure 1), a web-based tool [2], by leveraging industry data for benchmarking at the fleet level, turbine level, and system level and to demonstrate reliability forecasting methods. NREL supported this effort in developing reliability data specifications and standards, and shared gearbox reliability data and their expertise. WinNER helps wind operators to effectively compare their fleet reliability with the rest of the industry's anonymized data and identify opportunities for O&M improvements and forecast an optimum O&M budget.

Gearbox Reliability Assessment

EPRI has been collecting wind turbine reliability data on a biannual basis from over 25 utilities/operators for benchmarking and performing reliability assessments at the fleet level, turbine level, and system level. This includes identifying critical wind farms, critical wind turbines, gearbox issues, and providing mitigating strategies. EPRI and NREL developed reliability data standards and specifications for tracking healthy and failed assets and addressing wind industry digitalization technical and business needs. These reliability data are used to identify critical components, conduct a failure root cause analysis, and implement life extension strategies.

To date, EPRI's WinNER database includes data collected from 7,358 turbines, a total capacity of 16 gigawatts (GW) with data spanning from turbine installation year to 20 years of operational life. EPRI's database consists of 819 gearbox failure data points which are mainly used for the development of reliability and health monitoring models. WinNER data include reliability data corresponding to those in the NREL gearbox reliability database (1,321 turbines, 1.9 GW). Over 150 wind farms covering seven major turbine original equipment manufacturers (OEMs)—Gamesa, GE, Mitsubishi, Nordex, Siemens, Suzlon, Vestas—with 29 different turbine types/ratings ranging from 1.0 to 4.5 megawatts (MW) are included in the WinNER database. These

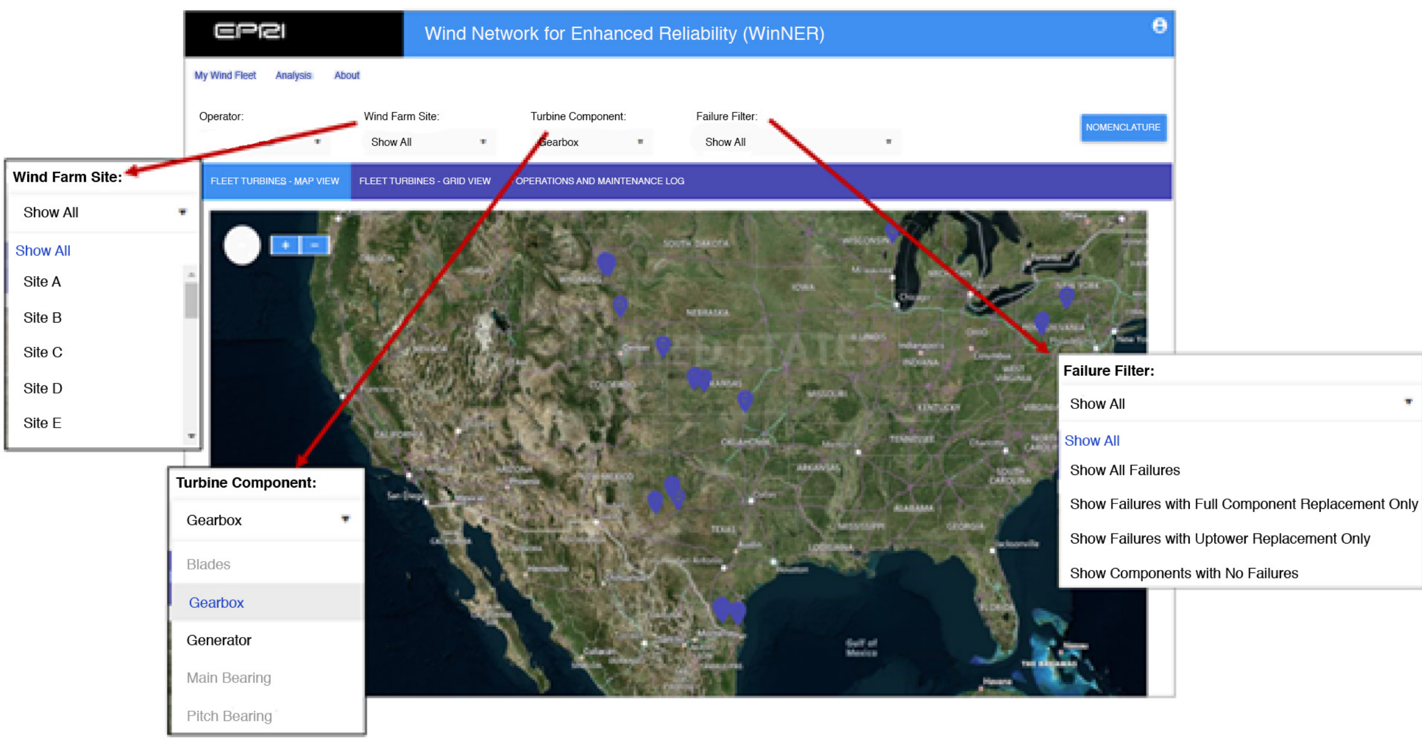


Figure 1. Wind Network for Enhanced Reliability (WinNER), web-based tool for benchmarking and O&M optimization

turbines contain gearboxes supplied by 17 different manufacturers (including Winergy, Moventas, Nanjing, ZF, Bosch Rexroth [L&S], Eickhoff, GETS, and Hansen). These gearboxes contain cylindrical and tapered roller bearings supplied by six manufacturers (SKF, FAG, INA, NSK, NTN, and Timken). Hence, digitalization of a gearbox is a very complicated task for operators/utilities due to the involvement of multiple OEMs, designs, and suppliers. As of today, there are no clear agreements in place among OEMs, suppliers, and utilities/operators for smooth data transfer supporting digitalization [3]. This is a critical gap in the wind industry that utilities/operators have been trying to address with EPRI and NREL support.

Figure 2 is an illustration of a representative three-stage gearbox, planetary stage (Stage I), intermediate stage (Stage II), and high-speed stage (Stage III) used for land-based applications. In the case of newer land-based wind turbines, there is a trend toward two-planetary stage gearboxes. For offshore wind turbines, two-planetary stages or a direct drive with no gearbox is preferred.

Figure 3 shows land-based turbine gearbox annual failure percentages (%) for various operational years. These failure rate data include both uptower replacements (45% of the failures) and full gearbox replacements (55% of the failures). Most of the uptower

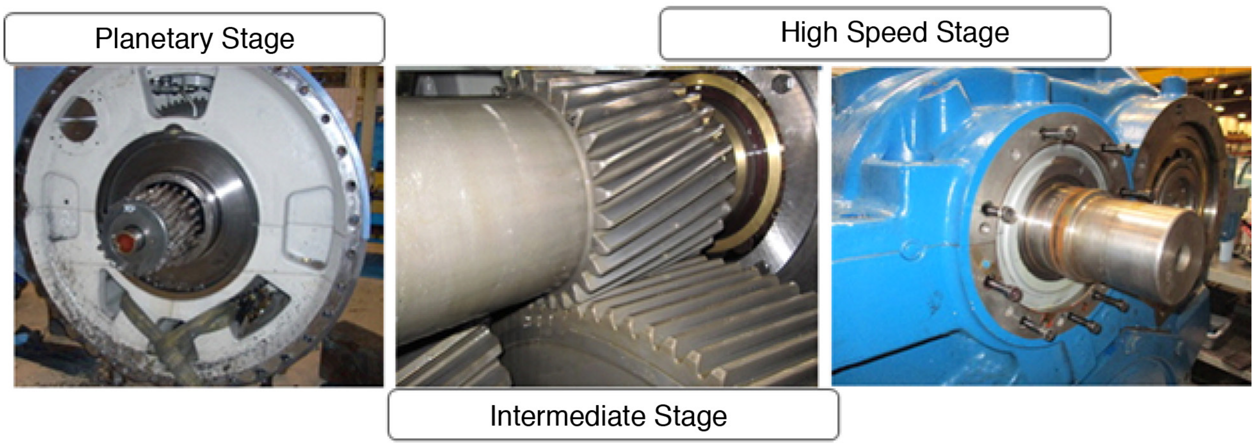


Figure 2. Wind turbine typical three-stage gearbox components (Courtesy of Jeff Mclaughlin, Machine Building Specialists)

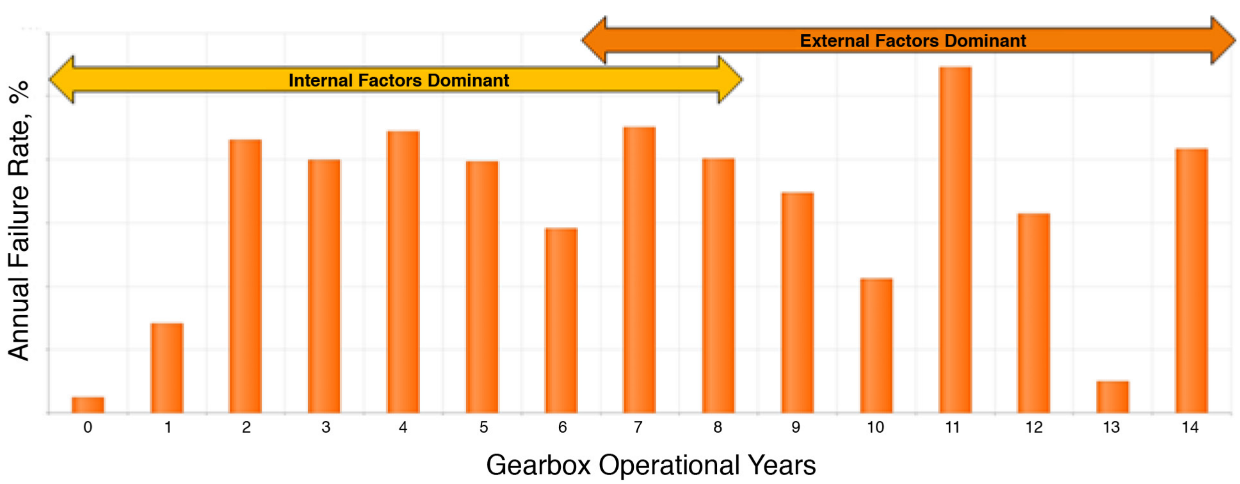
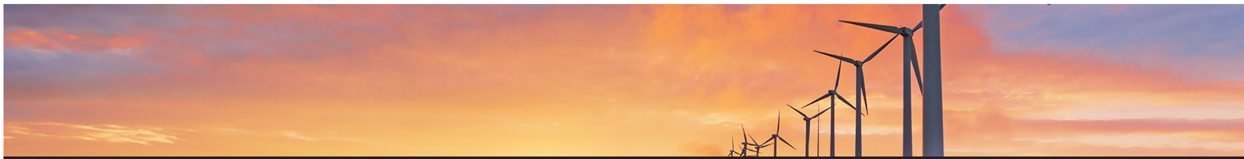


Figure 3. Wind turbine gearbox annual failure rate versus operational years (data obtained from WinNER)



replacements were related to intermediate stage (Stage II) and high-speed stage (Stage III) repairs that typically cost approximately $15,000–$70,000. Whereas most of the full gearbox replacements are due to planetary stage (Stage I) failures. Planetary failures are relatively hard to detect using traditional monitoring technologies [1]. Also, these failures cannot be easily fixed uptower [1]. Hence, in most cases, operators have to replace an entire gearbox if planetary damage is not detected early. This leads to production revenue loss due to prolonged downtime, and a full gearbox replacement may cost approximately $350,000 [2].

Gearbox failures during the first seven to eight years of operation are mainly due to internal factors (design, assembly, and manufacturing/serial defect issues). The failure rate can be higher during five to six years of operation due to end-of-warranty inspections and repairs. Gearbox failures after seven to eight years of operation are mainly due to external factors (site conditions, turbine operations, and grid events). Overall, wind turbine gearbox failures are significantly impacting operators' O&M budgets.

Figure 4 shows the wind turbine gearbox cumulative failure rate percentages versus number of operational years. The cumulative gearbox failure rate is categorized based on commission/installation year, ranging from 2009–2017. This analysis has shown an interesting trend of higher gearbox failure rates for the turbines installed during 2013–2016. These higher failure rates are mainly attributed to: 1) change in gearbox manufacturing locations, poor material quality, and design issues; and 2) increase in turbine ratings with larger blades led to higher loads on the gearboxes.

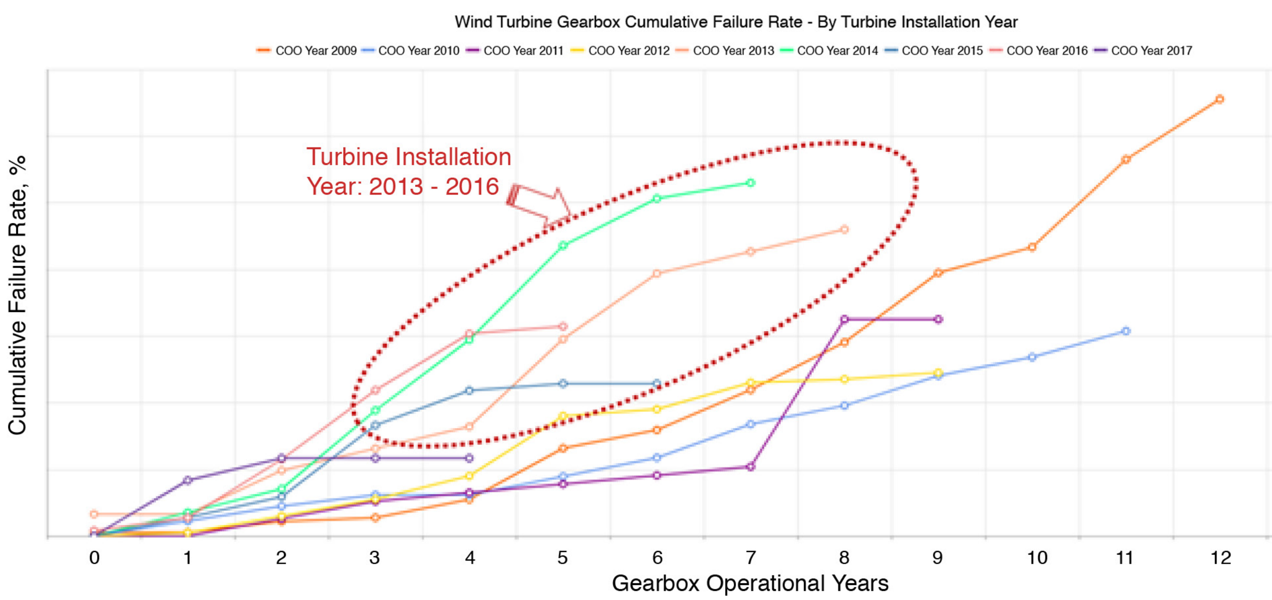
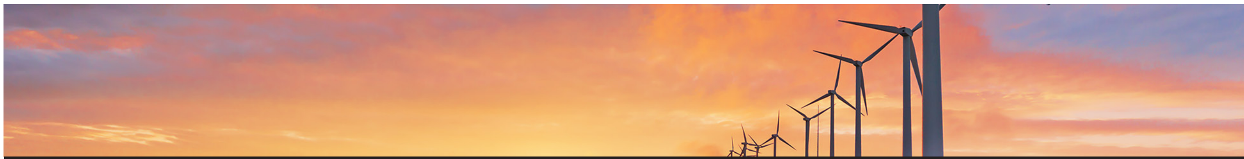


Figure 4. Gearbox cumulative failure rate by turbine installation year (data generated by WinNER)



Below are the top five gearbox critical components based on the failure events data in the WinNER database (Figure 5). The critical component ranking order may vary depending on the turbine model, gearbox supplier, bearing supplier, manufacturing year, and wind farm O&M.

- High-speed intermediate shaft generator side (HSIS GS) bearing
- Planet gear
- High-speed shaft rotor side (HSS RS) bearing
- Planet shaft bearing (both generator side and rotor side, PS GS/RS)
- High-speed shaft (HSS) pinion

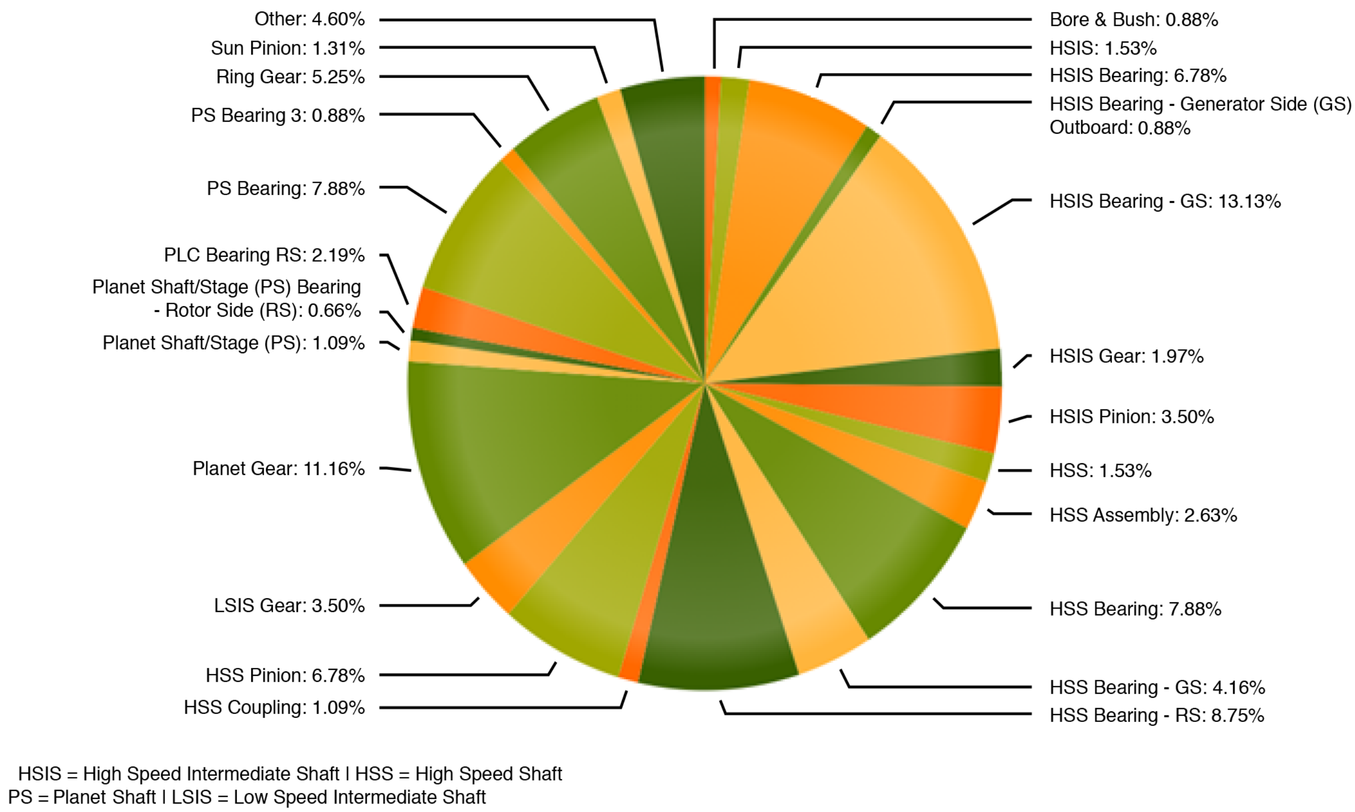


Figure 5. WinNER, wind turbine gearbox critical components leading to premature failures

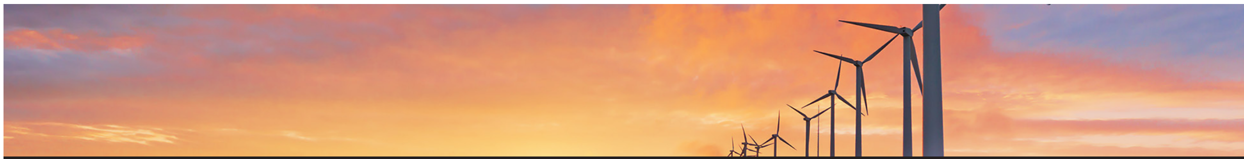


Table 1 lists gearbox critical components and their typical damage/failure modes observed in the wind industry. Most of the bearing failures are due to the following reasons:

- High contact stresses leading to pitting/spalling
- Bearing race slippage
- Macro-pitting due to skidding, bearing slippage
- Wear due to inadequate lubrication
- Race cracking due to white etch formation
- Low-quality materials and material defects/inclusions
- Improper bearing design leading to nonuniform loads/stresses

Other damage modes, not listed in Table 1, include scuffing, corrosion, and false brinelling. Bearing damage can affect the shaft alignment causing higher contact and bending stresses on the neighboring gears. These higher stresses due to misalignment may

Table 1. Gearbox critical components and their typical damage/failure modes

Gearbox Stage	Gearbox Component	Location	Typical Damage/Failure Mode
Planet Stage	Carrier Bearings	Carrier RS Bearing	No Known Issues
		Carrier GS Bearing	GS (DW) Bearings (Unusual)
	Planets	Planet 1 (PS Gear 1)	Tooth Failures (Pitting, Spalling, Wear)
		Planet 2 (PS Gear 2)	Tooth Failures (Pitting, Spalling, Wear)
		Planet 3 (PS Gear 3)	Tooth Failures (Pitting, Spalling, Wear)
	Planet Bearings	PS1 RS Bearing	Macro Pitting Due to Skidding, Spalling of Races and Rollers
		PS2 RS Bearing	Macro Pitting Due to Skidding, Spalling of Races and Rollers
		PS3 RS Bearing	Macro Pitting Due to Skidding, Spalling of Races and Rollers
		PS1 GS Bearing	Macro Pitting Due to Skidding, Spalling of Races and Rollers
		PS2 GS Bearing	Macro Pitting Due to Skidding, Spalling of Races and Rollers
		PS3 GS Bearing	Macro Pitting Due to Skidding, Spalling of Races and Rollers
	Ring Gear	Ring Gear	Micro and Macro Pitting, Tooth Failures, Rim Cracking
	Sun Pinion	Sun Pinion	Tooth Failures (Pitting, Spalling, Wear)
Low Speed Intermediate Stage (LSIS)	Low Speed Intermediate Hollow Shaft	LSIS	No Known Issues
	Low Speed Hollow Shaft Bearings	LSIS RS Bearing	Race Cracks
		LSIS GS Bearing	Race Cracks, GS (DW) Bearing Severe Pitting, Thrust Overload
		LSIS GS Thrust Bearing	No Known Issues
	Low Speed Intermediate Shaft Gear	LSIS Gear	No Known Issues
High Speed Intermediate Stage (HSIS)	Intermediate Pinion Shaft	HSIS Pinion	Tooth Failures (Pitting, Spalling, Wear)
	Intermediate Pinion (Integral with Shaft)		Tooth Failures (Pitting, Spalling, Wear)
	Intermediate Shaft Bearings	HSIS RS Bearing	No Known Issues
		HSIS GS Bearing	Race Cracks, GS Bearing, Inner Race Cracks
		HSIS GS Thrust Bearing	No Known Issues
		HSIS Gear	No Known Issues
High Speed Stage (HSS)	HS Shaft	HSS Pinion	Tooth Failures (Pitting, Spalling, Wear)
	HS Shaft Pinion Teeth (Integral with HSS)		Tooth Failures (Pitting, Spalling, Wear)
	HS Shaft Bearings	HSS RS Bearing	Race Cracks, Bearing Slippage, Inner Race Cracks
		HSS GS Bearing	Race Cracks
		HSS GS Thrust Bearing	No Known Issues
	Pitch or Utility Tube		Leaks, GS Pitch Tube Bushing Failure (Leads to Planet Bearing Failure)

eventually cause multiple tooth loss affecting overall health state and resulting in a full gearbox replacement. So, bearing damage detection in its early stages can assist in avoiding catastrophic gearbox failure. Addressing this specific industry need, EPRI has been developing and implementing physics-based health monitoring models at operators' sites for early damage detection and turbine life extension [4, 5].

Reliability Analysis—Applications

Turbine reliability and O&M budget forecasting are important for wind farm maintenance planning as this information can be used to improve accuracy of maintenance cost and resource projections. For instance, specific turbines are susceptible to repetitive failures due to design and manufacturing flaws. This information is helpful for planning preventive maintenance and budgets for wind farm with similar turbines. This is especially insightful for future wind farm owners and maintenance personnel who plan to deploy these types of turbines.

Gearbox failure rates (Figure 6) and O&M budgets for the next 12 months and beyond can be predicted based on the following factors:

- Fleet configuration, and turbine size and rating
- Wind farm conditions (such as turbulence intensity, wind wake, and wind shear)
- Statistically significant historical gearbox failure data
- Individual turbine configurations (including gearbox supplier, model quality, and reliability)

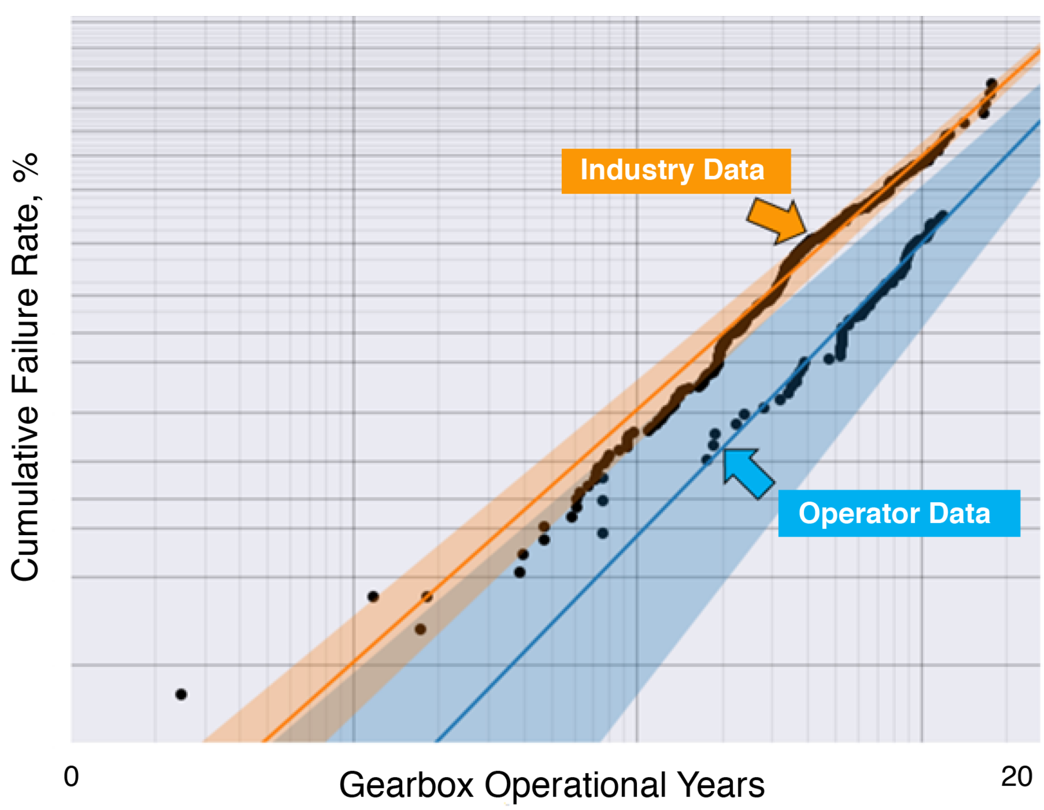
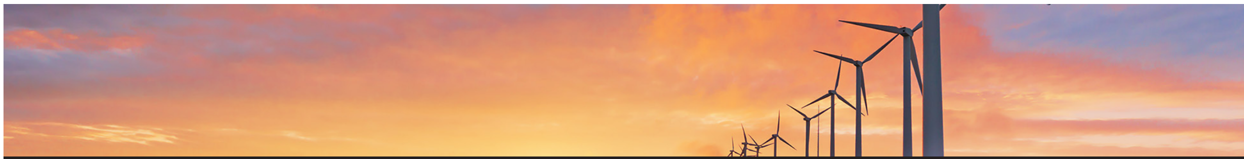


Figure 6. Wind turbine gearbox reliability benchmarking assists in identifying O&M areas for further improvement



The benefits and applications of a data standardization and gearbox reliability analysis include:

- Reduce O&M costs through wind asset digitalization
- Track, predict, and improve wind turbine reliability
- Optimum O&M budgeting and forecasting, warranty valuation, contracting versus self-operation decisions
- Reliability benchmarking (see Figure 6), inventory management, and OEM/supplier quality assessments

Summary and Next Steps

A detailed review of wind turbine reliability at the fleet level, turbine level, and system level uncovers opportunities to optimize and reduce O&M costs and increase revenue. This analysis also assists operators in making informed decisions for preventive maintenance operations and on contracting versus self-operation. These analytical techniques, when applied, may result in a public benefit through more efficient operating land-based and offshore wind farms.

In addition to the gearbox analysis, EPRI and NREL have already developed reliability data standards and specifications for generators, main bearings, and blades, and are in the process of collecting these data from utilities/operators. To date, with wind industry support, EPRI and NREL combined WinNER database includes a total capacity of 16 GW with data spanning from turbine installation year to 20 years of operational life. Wind operators/utilities have been adapting and implementing these reliability data standards to track their fleet performance. Also, utilities/operators are using the industry-level reliability data to forecast their fleet failure rate and optimum O&M budget. Wind turbine reliability findings specific to generators, blades, and main bearings will be included in future reports.

EPRI's WinNER reliability projections assisted our 2021 O&M strategy. We plan to expand this technique to other major wind turbine failure modes impacting availability and operational costs. Reliability projections will enable us to prioritize optimized maintenance efforts and better estimate the future costs.

— Alex Triplett (Wind Performance Engineer, Portland General Electric Co.)

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Note

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Wind Generation

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