NREL
Transforming ENERGY

Drivetrain Reliability from Inherent to Operational

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National Renewable Energy Laboratory

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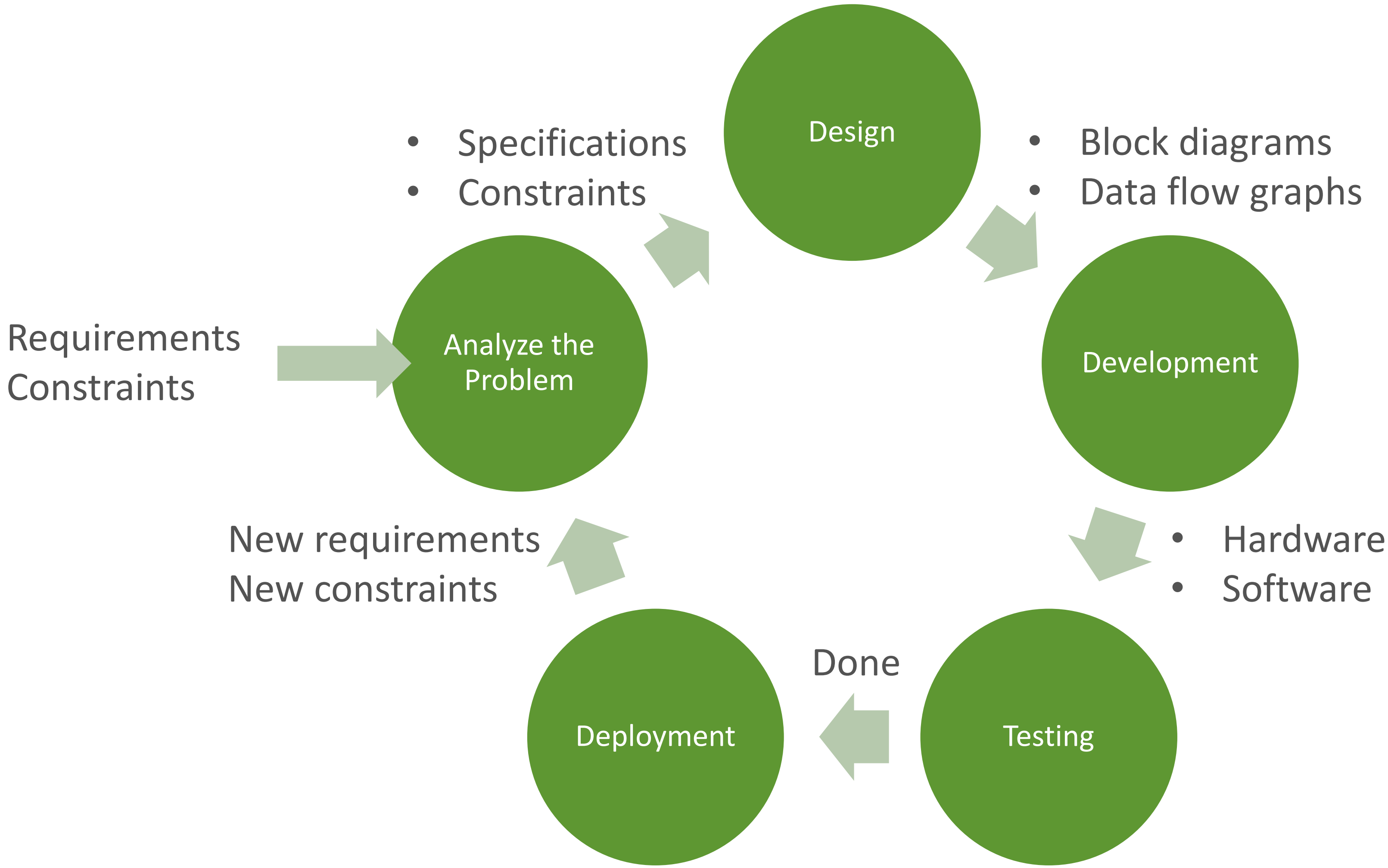
Outline

- Reliability from Two Angles
- Drivetrain Reliability Efforts at NREL
  - Inherent
  - Operational
- A Wishful List

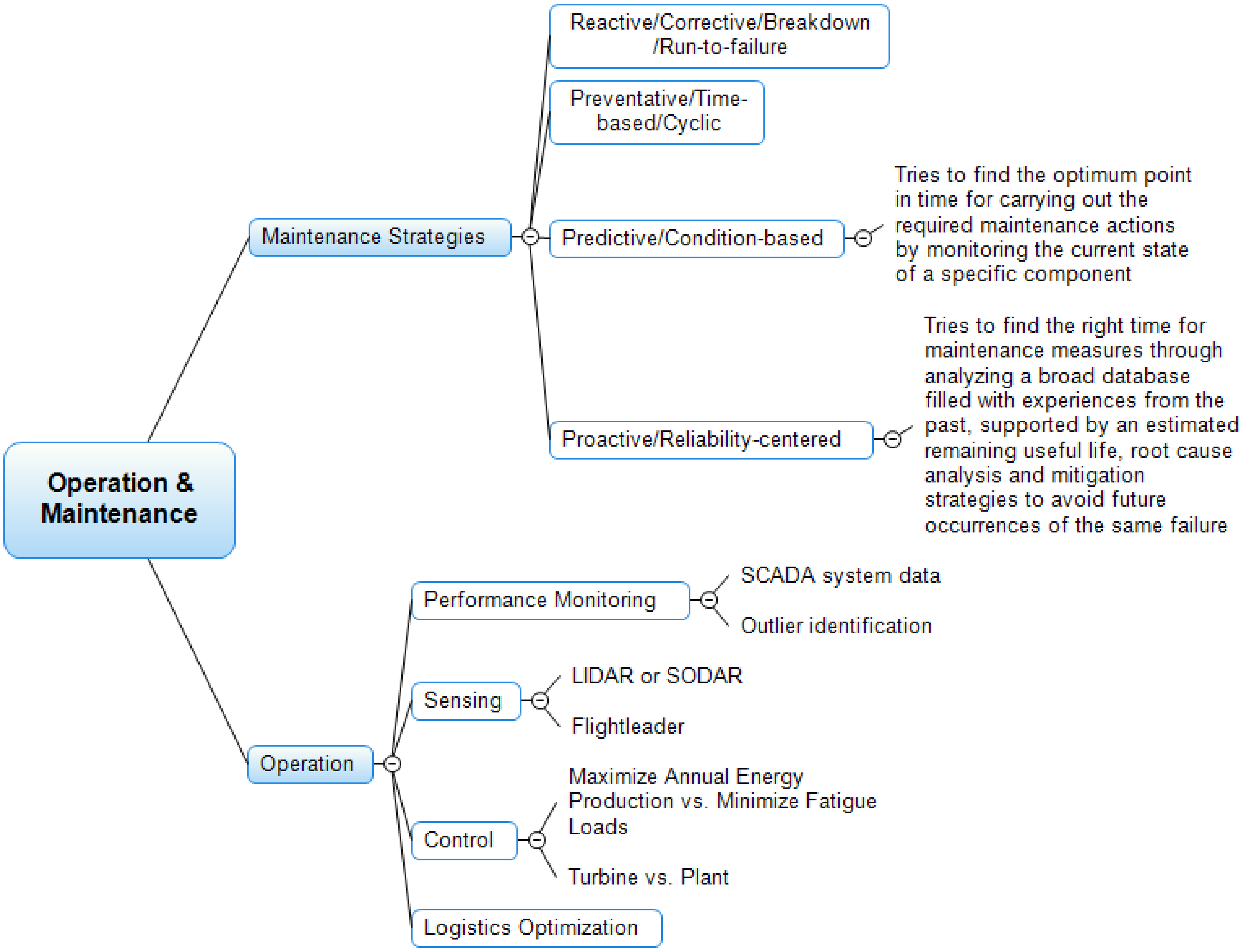
Photo by Lee Jay Fingersh, NREL 17245

Product Development: Inherent Reliability As the Focus



Source: Valvano, Jonathan, and Ramesh Yerraballi. 2014. *Embedded Systems: Introduction to ARM Cortex-M Microcontrollers.* Austin: The University of Texas. http://users.ece.utexas.edu/~valvano/Volume1/E-Book/C7_DesignDevelopment.htm.

Wind Turbine Operation and Maintenance: Operational Reliability As the Focus



Inherent Reliability

- Gearbox loads:
  - Planet bearings
- Operational conditions:
  - High-speed shaft and main bearings
- Dynamic modeling approaches and recommended practice.

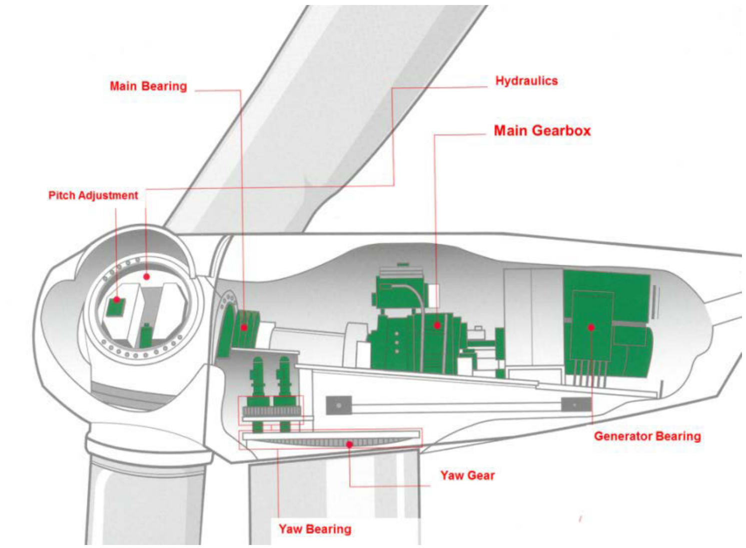


Illustration from Jon Leather, Castrol

Illustration by Cisco Oyague, NREL

Gearbox Loads Investigation: Planet Bearings

- Compare planet bearing load-sharing characteristics
  - Preloaded tapered roller bearings versus cylindrical roller bearings in clearance.

Photo by Mark McDade, NREL 40432

Project Summary Report

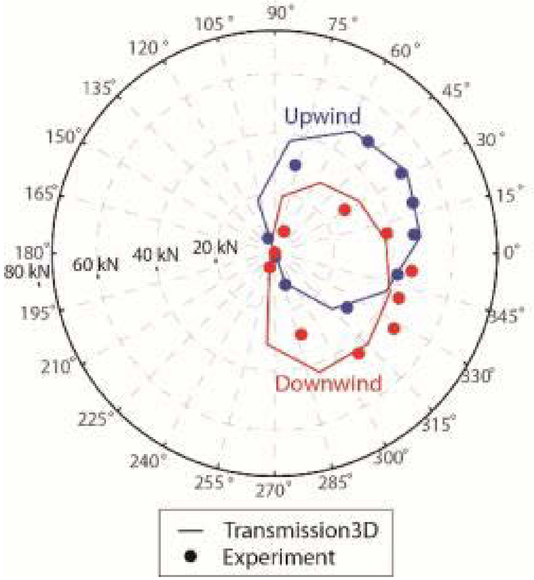


Photo by Jon Keller, NREL 36521

Industry partners: Romax Technology, Powertrain Engineers, Timken, and Brad Foote Gearing

Operational Conditions: High-Speed Shaft Bearings

- Determine turbine operations conducive to crack formation
  - Torque, loads, bearing roller sliding
  - Tribological conditions: temp, moisture, current.

Photo by Jonathan Keller, NREL 49044

Instrumentation Details

Photo by Jonathan Keller, NREL 40979

Photo by Jonathan Keller, NREL 40981

Industry partners: Argonne, SKF GmbH, and Winergy

Operational Conditions: Main Shaft Bearings

- Instrument and install a SKF SRB-Wind main bearing
  - Bearing strain (load), temperature, acoustic emission, vibration
  - Electric current across bearing, axial movement, misalignment
  - Auto-lube system with routine grease sampling.

Industry Partners: SKF USA

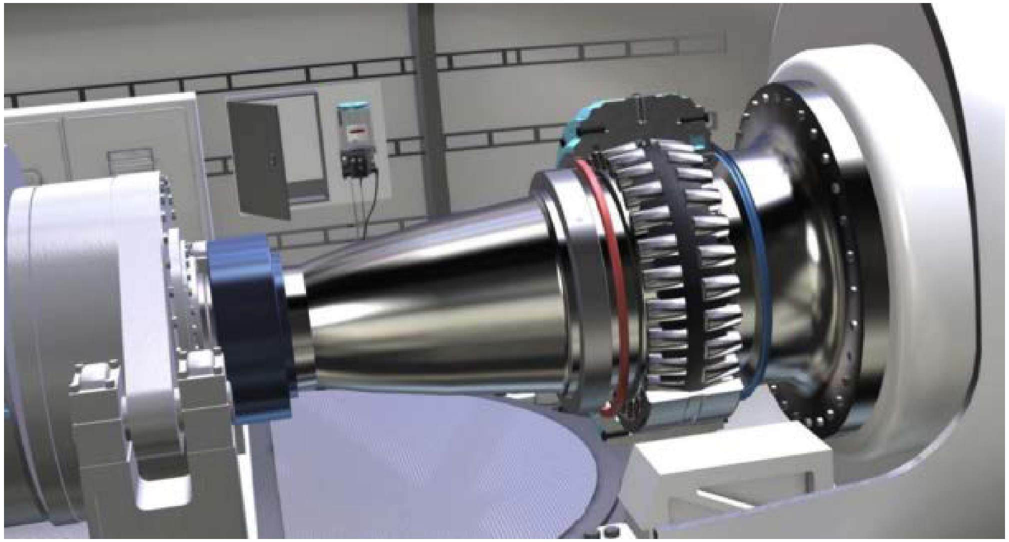


Photo from SKF

Uptower Drivetrain Testing

Photo by Jonathan Keller, NREL 49379

Dynamic Modeling Approaches

Gear Contact Analysis

- Gear tooth loading
- Time-varying stiffness
- Tooth contact stress

Structure Finite Element (FE) Analysis

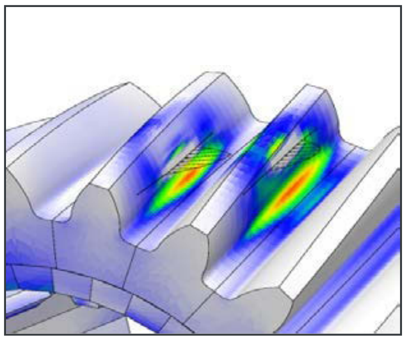
- Torsional windup
- Pin misalignment
- Carrier/pin fit

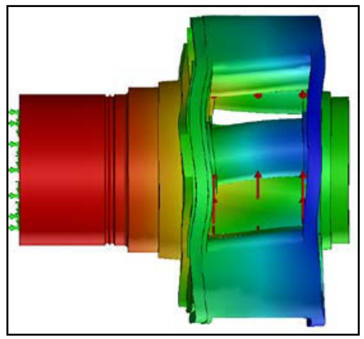
Bearing Analysis

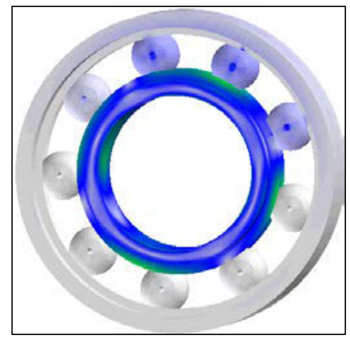
- Nonlinear stiffness
- Load distribution
- Bearing life

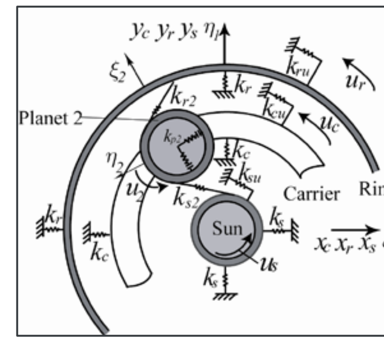
In-House Program

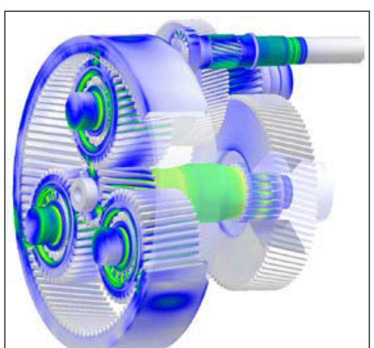
- Gravity/trans-mission error
- Clearance
- Tooth wedging





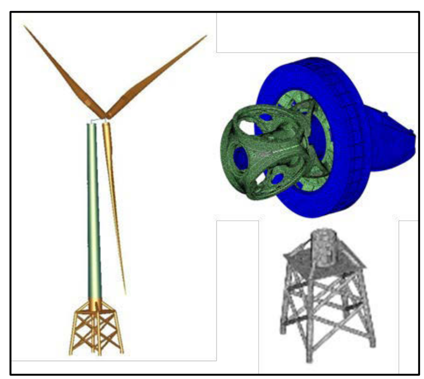






Gearbox Analysis

- Deflections
- Misalignment
- Clearance
- Vibration
- Dynamics



Full Turbine Analysis

- International Electrotechnical Commission (IEC) load cases
- Turbulent wind
- Aerodynamics
- Drivetrain dynamics
- Hydrodynamics
- Structural dynamics

Recommended Modeling Practice

Recommended Minimum Model Fidelity

Major Drivetrain Components	Recommended Modeling Approach	Requirements for Degrees of Freedom (DOF)
Rotor/Hub	Rigid body with lumped weight	N/A
Main shaft	Flexible, FE beams	Six DOF
Main bearing	Stiffness matrices	Five DOF
Gearbox housing	Flexible, condensed FE	N/A
Planetary carrier	Flexible, condensed FE	N/A
Gearbox shafts	Rigid shaft with correct bearing locations	N/A
Gearbox support	Stiffness matrices	Six DOF
Gears	Rigid body with contact stiffness	Six DOF
Gearbox bearings	Stiffness matrices	Five DOF (except rotation)
Spline	Stiffness matrices	Two DOF (tilting)
Bedplate	Rigid body or condensed FE	N/A
Generator coupling	Stiffness matrices	Five DOF (except rotation)

Recommended Factors to Consider

Other Factors	Effects	Priority
Manufacturing tolerance	Affects component motions but has limited effects on loads	Medium
Bearing clearance or preload	Affects component motion and loads. Operational values w/operating temperature are recommended	High
Gear tooth micro-geometry	Affects frequency spectrum of component motions and gear tooth load distribution	Low
Bedplate tilting angle	Causes gearbox axial loads due to gravity	Medium
Gravity	Affects component motion and loads	High
Nontorque loads	Affects component motion and loads	High
Gear mesh stiffness or transmission error	Affects frequency spectrum of component motions	Medium

Source: Guo, Y. et al. 2014. "Gearbox System Modeling Practice, Preprint." Golden, CO: National Renewable Energy Laboratory. NREL/CP-5000-63444. https://www.nrel.gov/docs/fy15osti/63444.pdf.

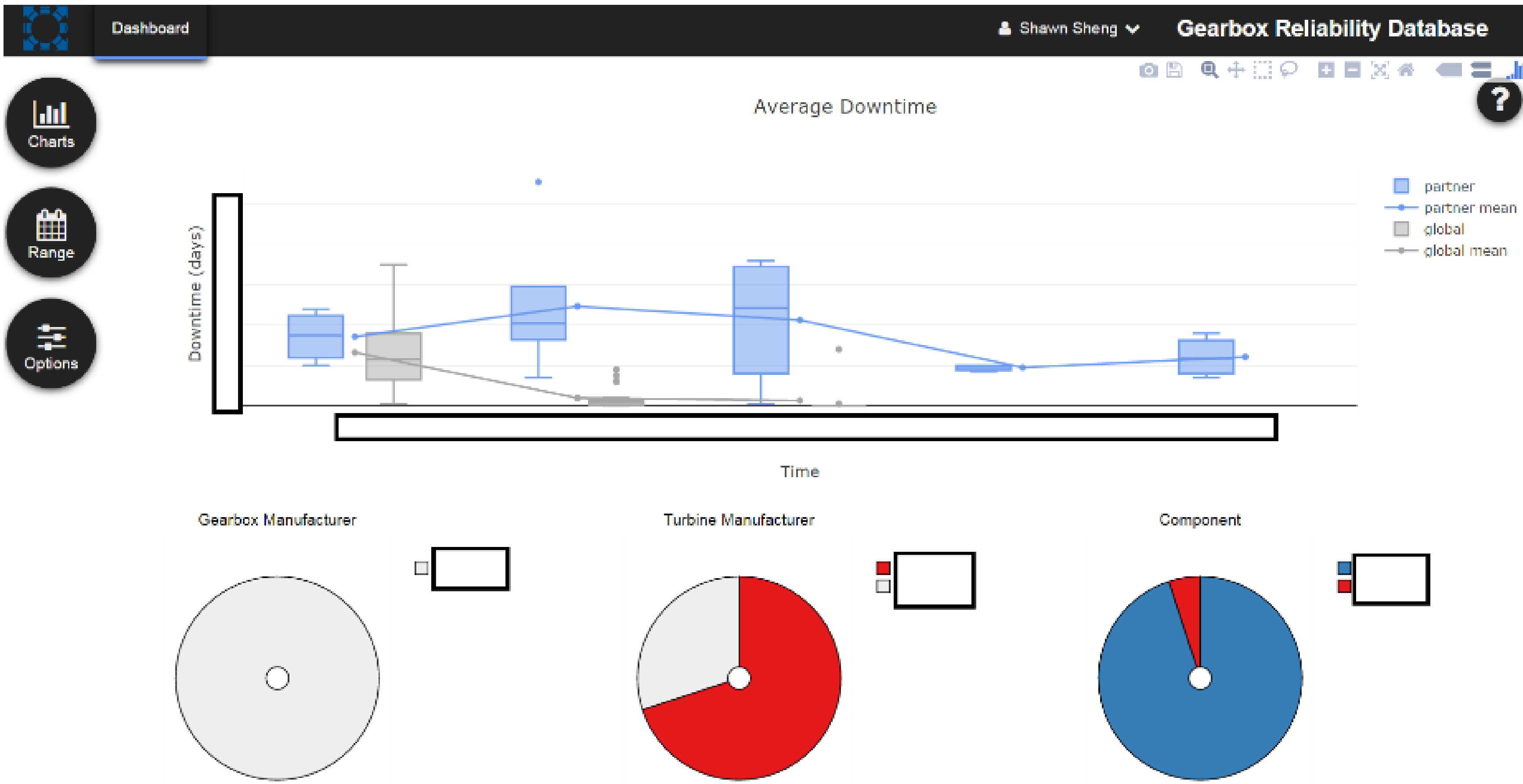
Operational Reliability

- Benchmarking
- Performance monitoring
- Condition monitoring
- Remaining useful life prediction

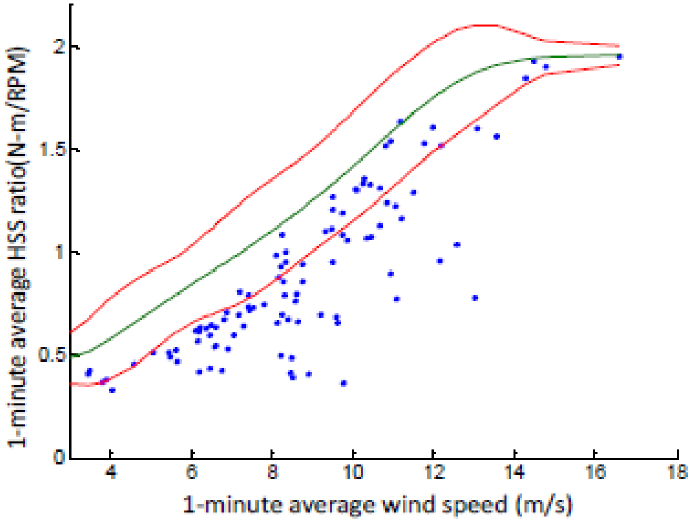
Photo by Gary Norton/DOE, NREL 27358

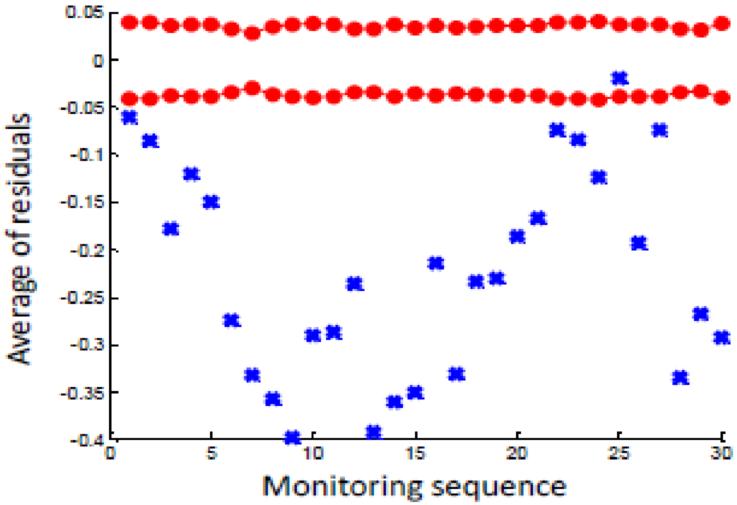
Benchmarking To Identify Gaps

- Performance and reliability based on industry standardized key performance indicators
- Gearbox reliability database as an example: partner-owned data compared with global data.



Performance Monitoring Using Supervisory Control and Data Acquisition Data

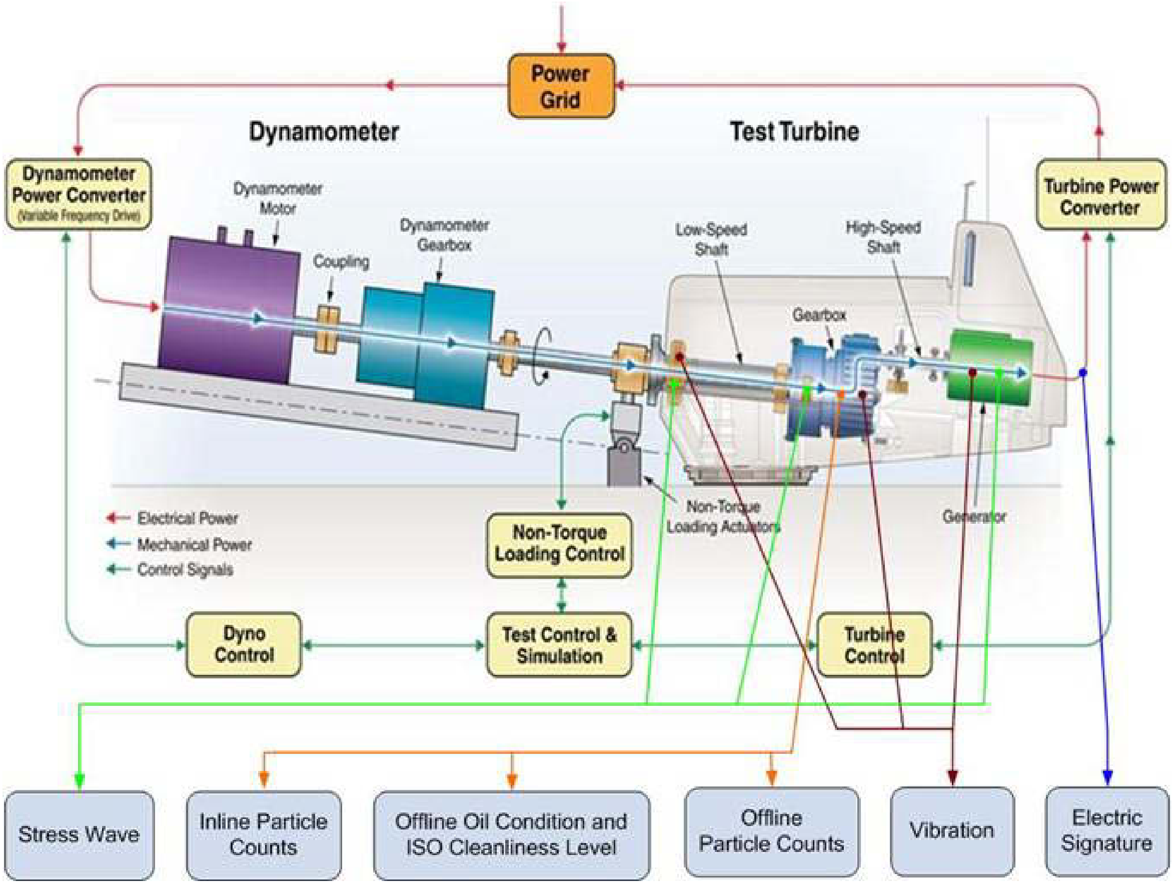




- High-speed shaft (HSS) ratio: HSS torque to HSS rpm
- Model developed based on normal operation
- Thresholds established based on a certain allowable false alarm rate
- Two angles: response and residual
- Abnormal: outside of the established thresholds.

Source: N. Yampikulsakul, E. Byon, S. Huang, S. Sheng, M. You. "Condition Monitoring of Wind Power System With Nonparametric Regression Analysis." *IEEE Transactions on Energy Conversion*, Vol. 29 (2014): pp. 288-299. https://dx.doi.org/10.1109/TEC.2013.2295301.

Condition Monitoring via Dedicated Instrumentation



*Round robin testing of wind turbine drivetrain condition monitoring techniques.**

- Stress wave analysis
- Vibration analysis
- Main filter loop particle counting
- Offline filter loop particle counting and oil condition monitoring
- Electric signature monitoring
- Periodic oil sample analysis.

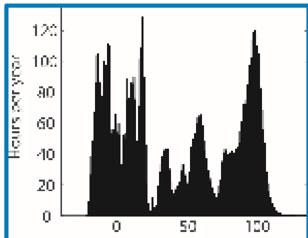
***Source:** Sheng, S. et al. 2011. *Wind Turbine Drivetrain Condition Monitoring During GRC Phase 1 and Phase 2 Testing*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-52748. https://www.nrel.gov/docs/fy12osti/52748.pdf.

Frictional Energy Loss-Based Component Remaining Useful Life Prediction

- High-speed-stage-bearing axial cracking
- Frictional energy loss under both normal and transient operations:

$$E = E_{np} + E_{tt}$$

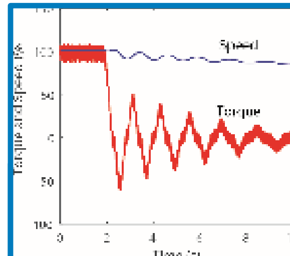
Operation



$$E_{np} = f(\mu, N, F, \Delta v)$$

- μ: friction coefficient
- N: number of cycles (roller)
- F: load
- Δv: sliding velocity between roller/raceway

Transient



$$E_{tt} = f(\mu, t, F, \Delta v)$$

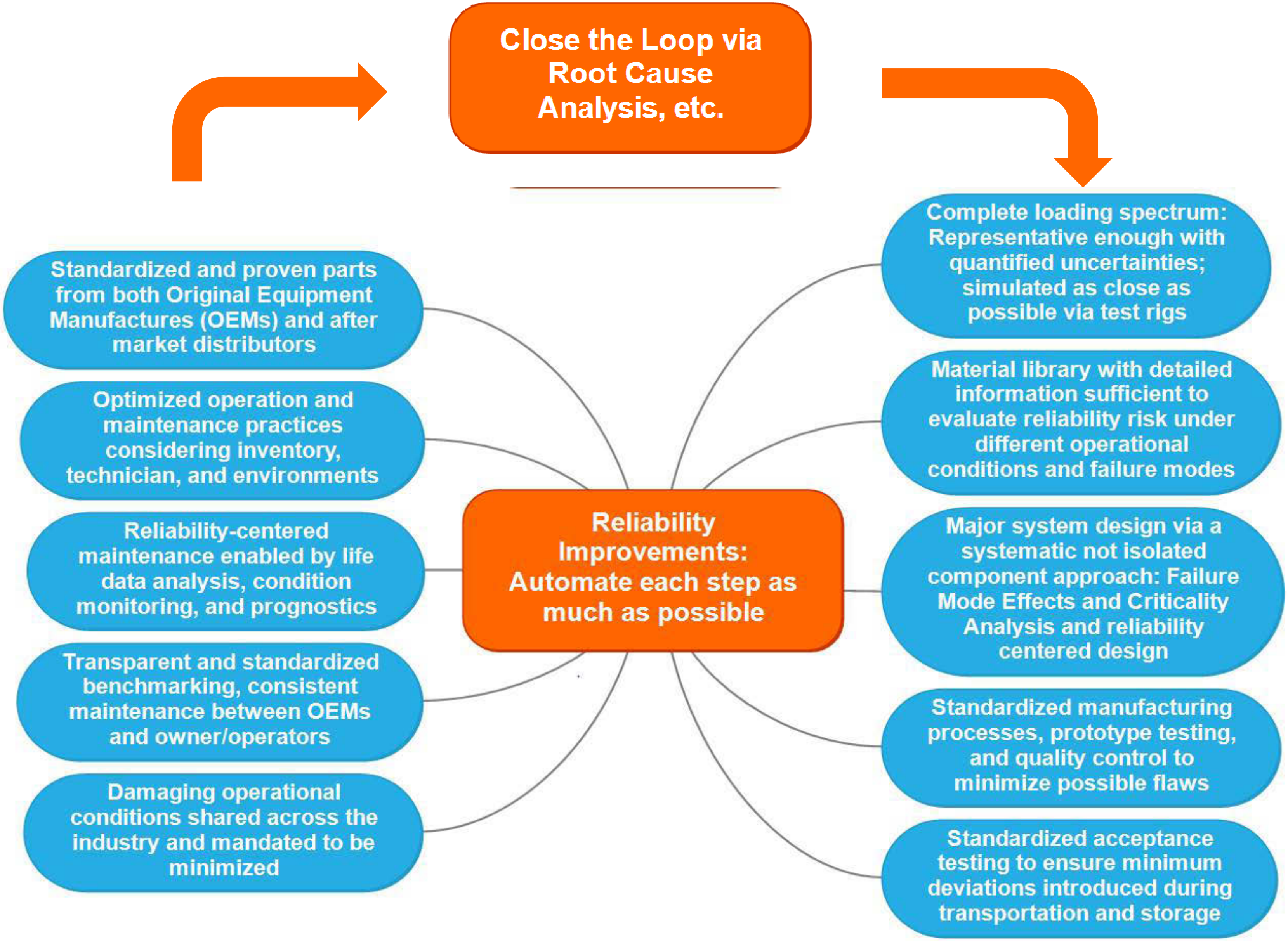
- μ: friction coefficient
- t: time
- F: load
- Δv: sliding velocity between roller/raceway

- First- and second-order reliability methods:

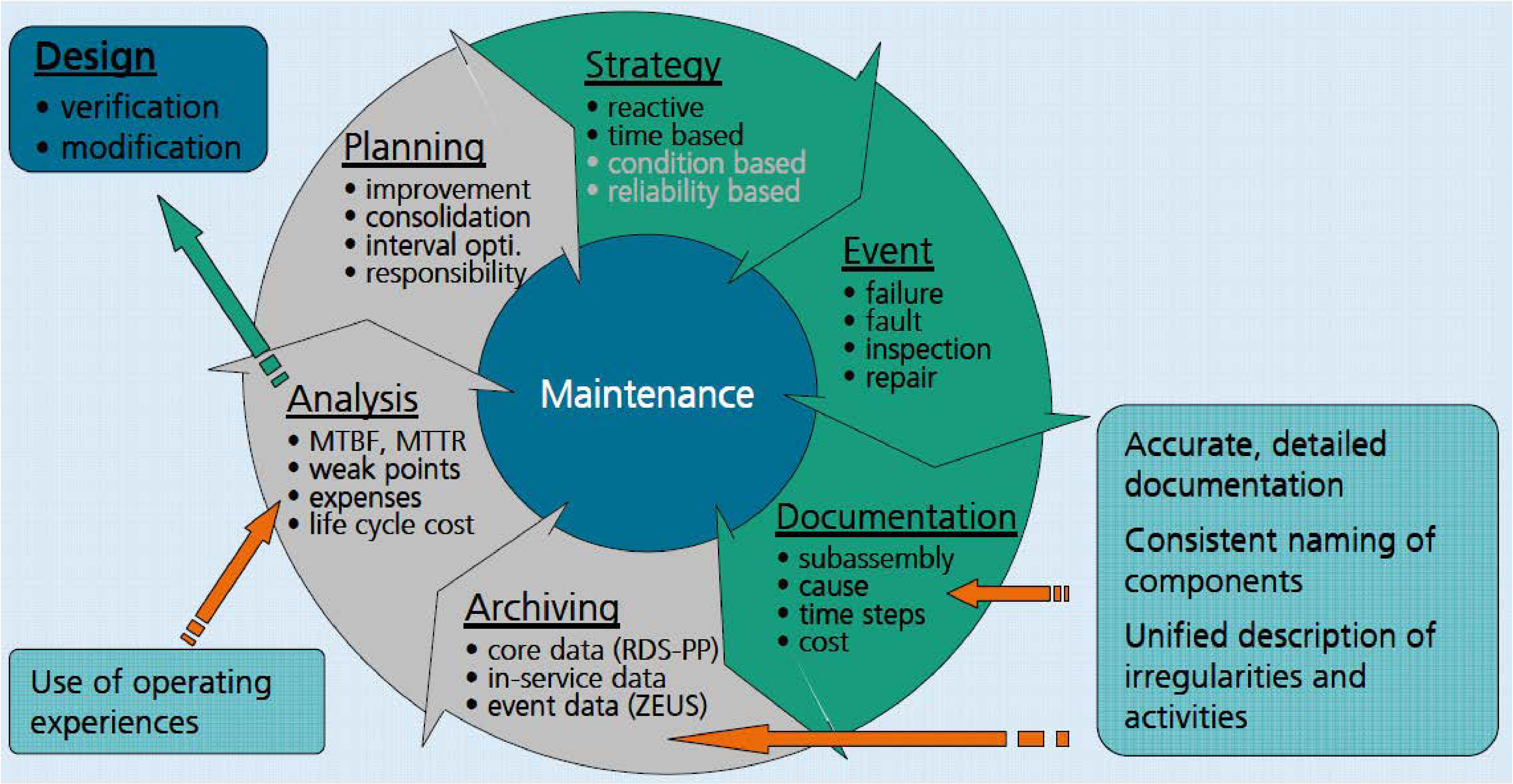
$$G = e^* - (E_{np} + E_{tt}) \qquad P_f = P\{G(U) < 0\}$$

Source: Guo, Yi and Shawn Sheng. 2018. *Probability of Failure for Gearbox High-Speed-Stage Bearings in Wind Turbines*. Golden CO: National Renewable Energy Laboratory. NREL/PR-5000-70972. https://www.nrel.gov/docs/fy18osti/70972.pdf.

Reliability Improvements: A Wishful List



A Recommended Maintenance Practice



Source: Kühn, P. et. al. "Standardization of Data Collection for Wind Turbine Reliability and Maintenance Analyses" (workshop, Dublin, Ireland, November 17, 2011).

Special thanks go to the U.S. Department of Energy, drivetrain reliability collaborative research partners!

The Block Island Wind Farm—the first offshore wind farm in the United States. *Photo by Dennis Schroeder, NREL 40389*

Thank You

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