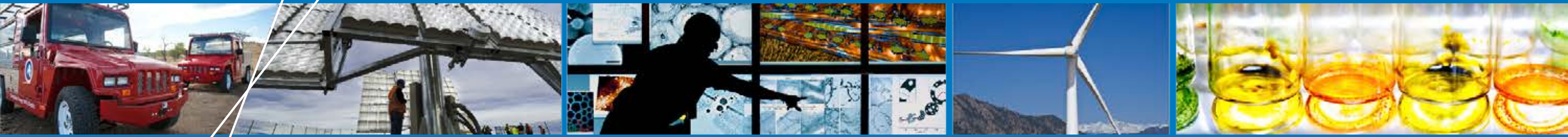
Wind Turbine Drivetrain Testing and Research at the National Renewable Energy Laboratory



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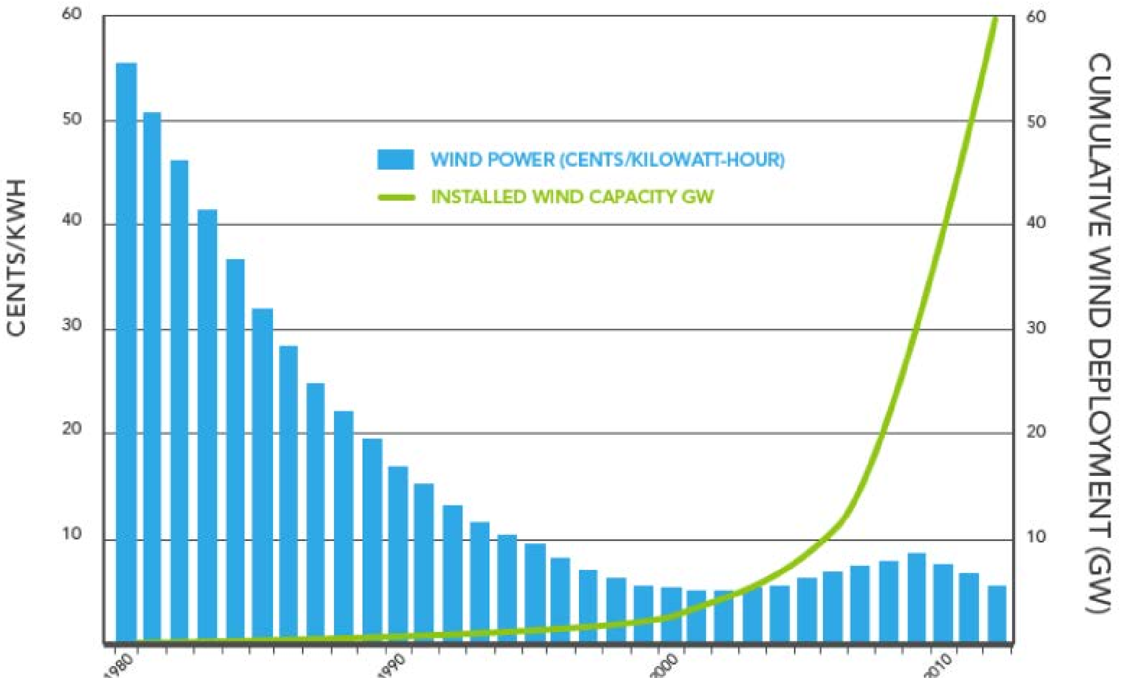
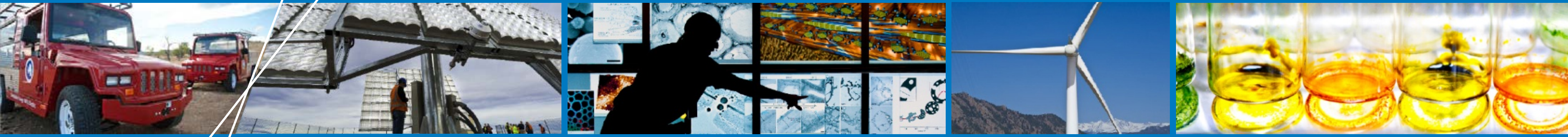
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Wind Power Industry Overview

- **Wind energy today…**
  - Multibillion dollar industry with multinational corporations
  - 60+ gigawatts (GW) deployed (~5% of U.S. electricity)
  - Land-based wind @ 7-8 ₵/kilowatt-hour (kWh); beating coal
  - Leads all renewable technology deployment.
- **Tremendous opportunity remains…**
  - Achieve parity with natural gas at 5–6 ₵/kWh
  - Establish offshore wind
  - Provide research and development (R&D) to achieve 30% wind.



Source: AWEA



National Wind Technology Center Overview

U.S. Department of Energy National Wind Technology Center

- Turbine testing since 1977
- Leader in development of design and analysis codes
- Pioneers in component testing
- Modern utility-scale turbines
- Unique test facilities:
  - Megawatt-scale turbines and sites
  - Blade testing
  - Dynamometers
  - Controls research turbines

Photo by Dennis Schroeder, NREL 30764

- 130–160 personnel on-site
- Partnerships with industry, CRADAs, and work-for-others
- Leadership roles for international standards
- Offshore wind and marine and hydrokinetic technology development.

Current Test Facilities

- **Field**
  - Field test sites and infrastructure
  - DOE 1.5, industry megawatt (MW) turbines, small turbines
  - Controls Advanced Research Turbines (CARTs)
  - Research-grade inflow meteorological data.
- **Drivetrain**
  - 225-kW, 2.5-MW, and 5-MW dynamometers
  - Dynamic torque testing of fully integrated drivetrain systems (gearboxes, generators, PE)
  - Model-in-the-loop (to simulate turbulence).
  - Non-torque loading to simulate rotor loads
- **Blade**
  - Static testing and resonant fatigue testing to 50 meters (m)
  - Accredited (A2LA) fatigue (resonant) and static testing of blades to IEC standards, modal and blade property measurements, profiling
  - Innovative blade test methodology R&D
  - Massachusetts large blade test facility.
- **ISO 17025, A2LA-accredited to IEC Standards**
  - Power performance, power quality, acoustic emissions, structural loads, duration, and structural and fatigue testing.

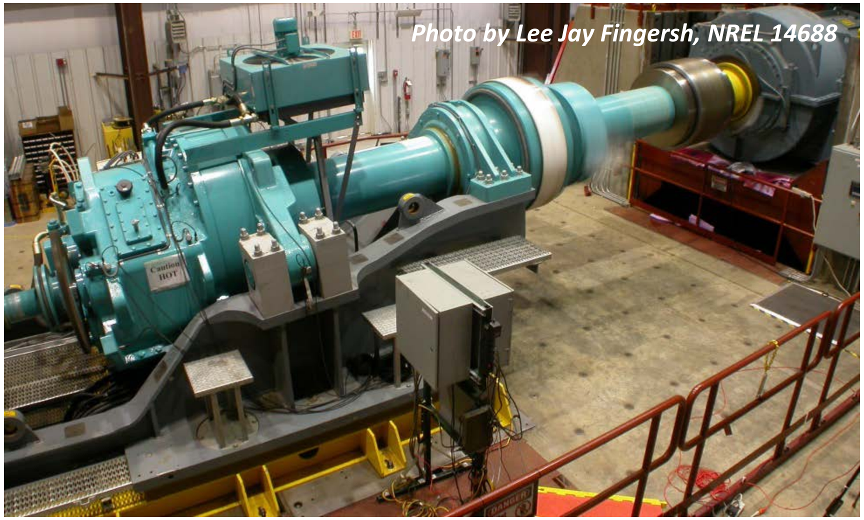


Photo by Lee Jay Fingersh, NREL 14688


Photo by Lee Jay Fingersh, NREL 16269


Photo by Dennis Schroeder, NREL 30780

Multimegawatt Turbines

Photo by Dennis Schroeder, NREL 30770

- **GE 1.5 MW**
  - Model: GE 1.5 SLE
  - Tower height: 80 m; rotor diameter: 77 m
  - DOE-owned; used for research and education
  - Turbine commissioned September 2009.
- **Siemens 2.3 MW**
  - Model: SWT-2.3-101
  - Tower height: 80 m; rotor diameter: 101 m.
- **Alstom 3 MW**
  - Model: ECO 110
  - Tower height: 90 m; rotor diameter: 110 m.
- **Gamesa 2 MW**
  - Model G97
  - Tower height: 90 m; rotor diameter: 97 m.

Dynamometer Facilities

Photo by Lee Jay Fingersh, NREL 16267

Photo by Robb Wallen, NREL 17400


Photo by Mark McDade, NREL 27249

2.5-MW Dynamometer

- 2.5 MW (low-speed shaft)
- 17–31 rpm (at full power)
- 1.64 MNm (1.2 M ft-lb) max torque
- Non-torque loads in 3 degrees of freedom (DOF)
- Single 50-ton crane
- 12.2 m x 15.2 m test bay
- 0–6 degree drive table tilt

New 5-MW Dynamometer

- 5.8 MW (low-speed shaft)
- 12–4 rpm (at full power)
- 4.6 MNm (3.4 M ft-lb) max torque
- Non-torque loads in 5 DOF
- Dual 75-ton cranes
- 20 m x 12 m test bay
- 5 degree drive table tilt

Designed to test entire integrated wind turbine drivetrain system

5-MW Dynamometer Non-Torque Loading System (NTL)

- **Emulate rotor loading on drivetrain**
- **Produce forces in 5 DOF on test article low-speed shaft while rotating**
  - Up to 7.2 MNm (5.5 M ft-lb) bending moment
  - Up to 3.5 MN (800,000 lb) axial force
- **Hydraulic force actuators**
- **High priority for stakeholders.**

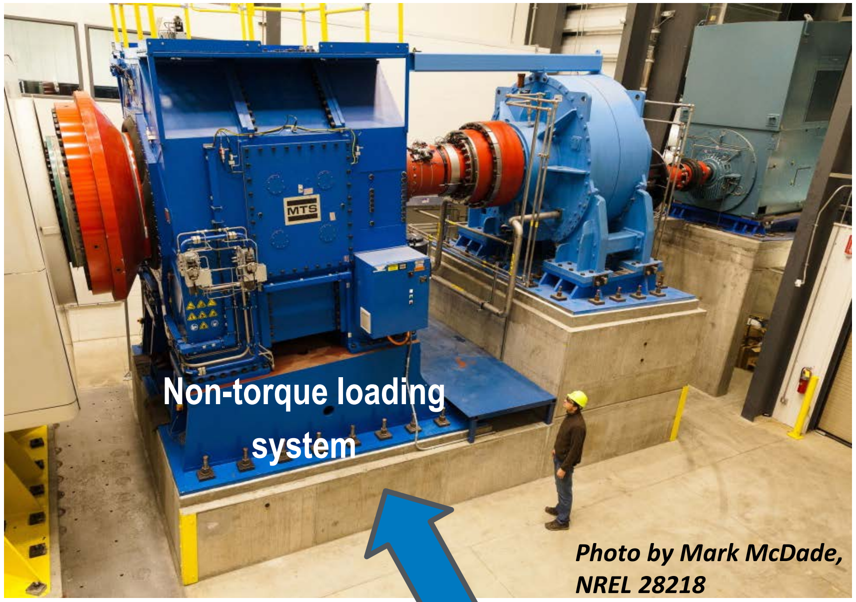


Photo by Mark McDade, NREL 28218

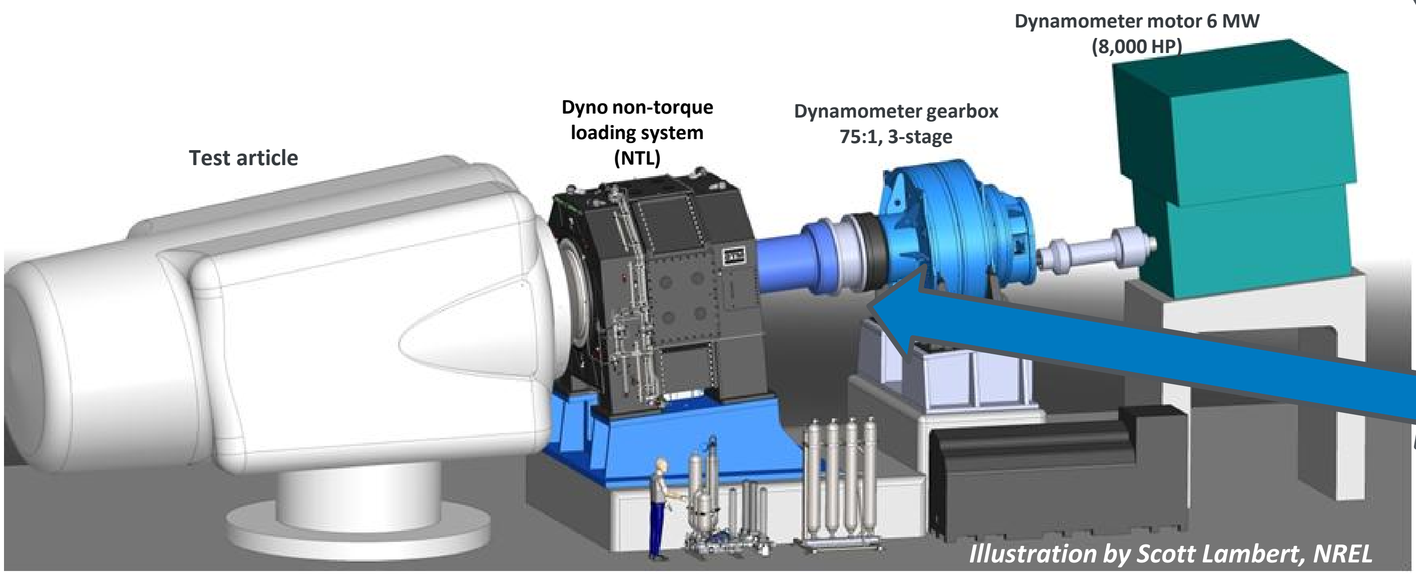
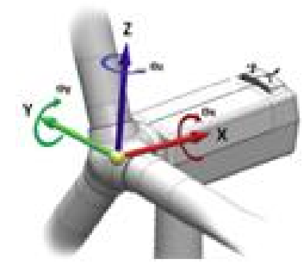


Illustration by Scott Lambert, NREL



NWTC Controllable Grid Interface (CGI) Facility

Photo by Dennis Schroeder, NREL 25890

- CGI connected to both dynos and some turbines
- Command voltage profiles to emulate real power-line faults
- 7 megavolts-ampere (MVA) continuous with 28 MVA short circuit capacity

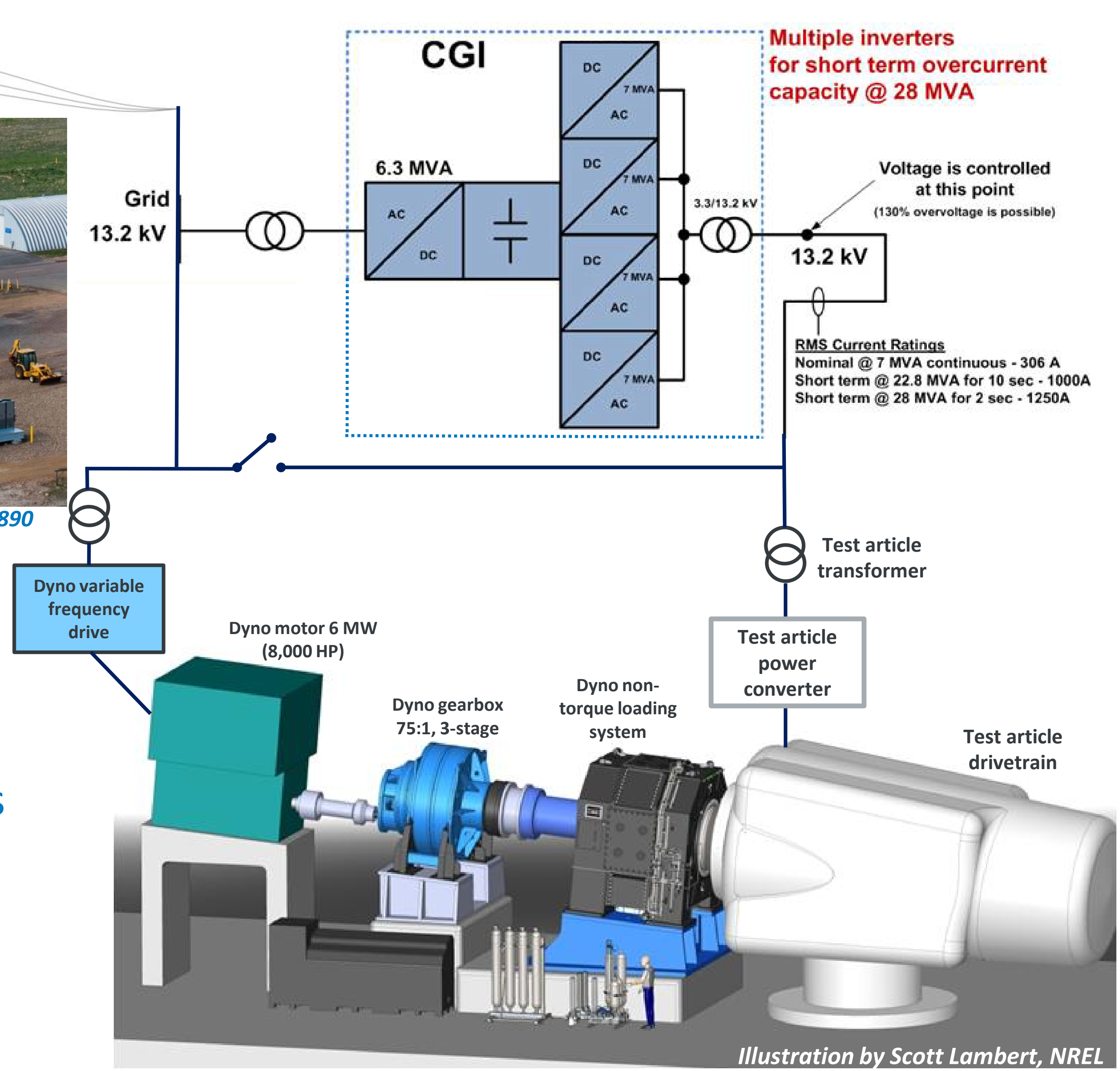
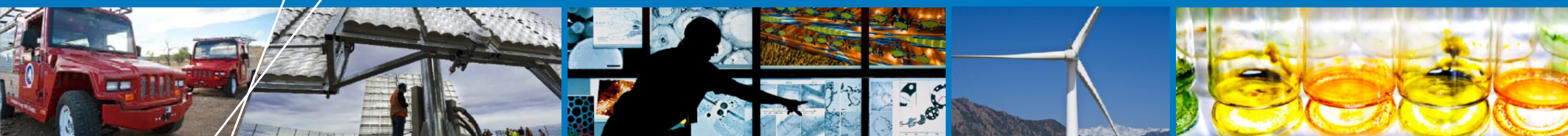


Illustration by Scott Lambert, NREL

Gearbox Reliability Collaborative

http://www.nrel.gov/wind/grc/index.html

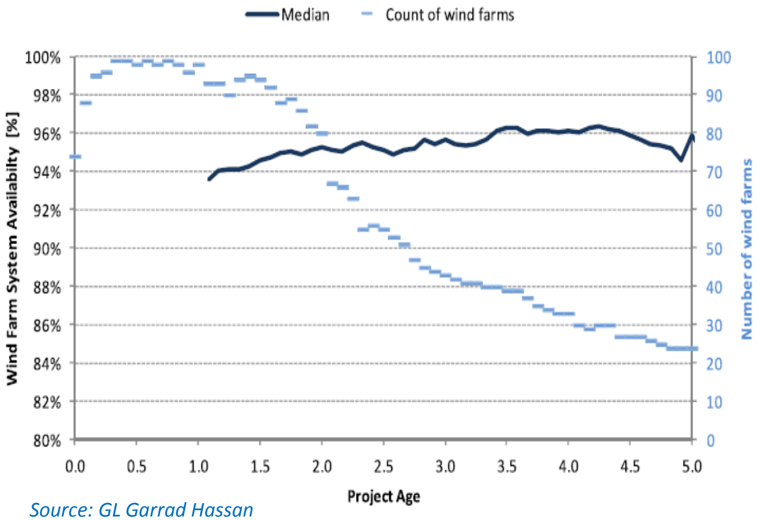


Sponsor: DOE EERE Wind

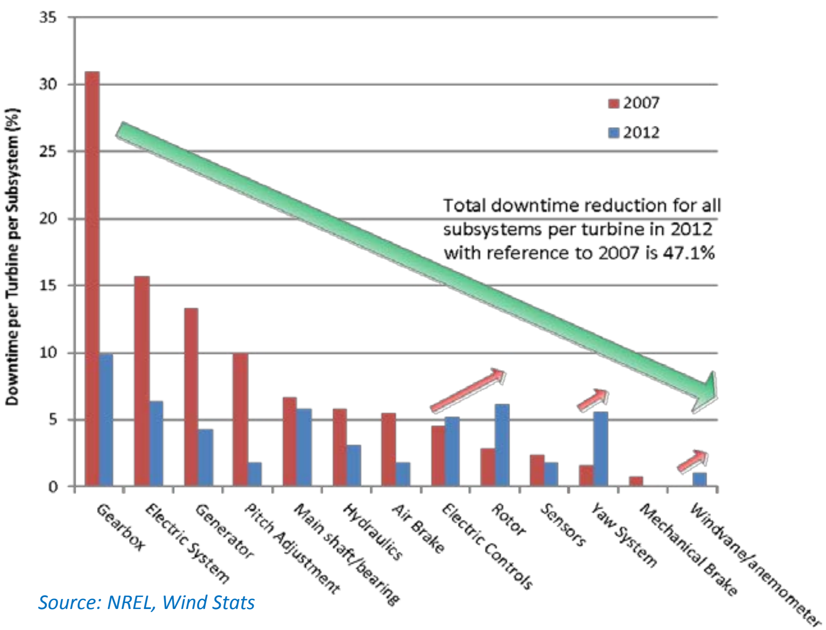
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Wind Turbine Reliability

- **Plant availability often 95%+**
  - Adjusted for curtailment
- **Subsystem reliability improving, but still an operation and maintenance (O&M) cost driver**
  - Decrease in downtime of gearbox, generator, and electrical system
  - Gearboxes continue to be the largest source of downtime
  - Generator, power conversion, and main bearing not far behind
- **Need to maintain availability with less cost and effort.**



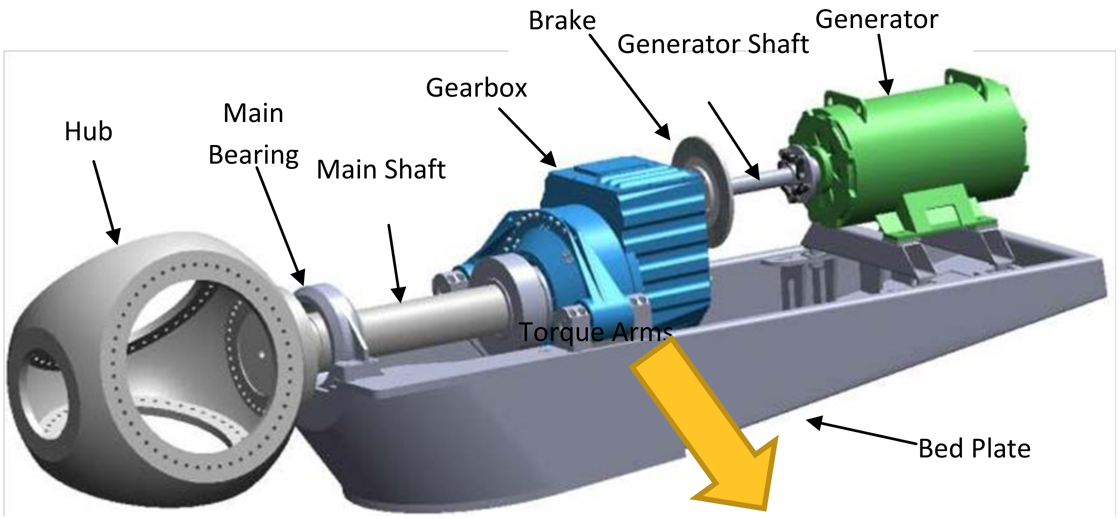
Source: GL Garrad Hassan



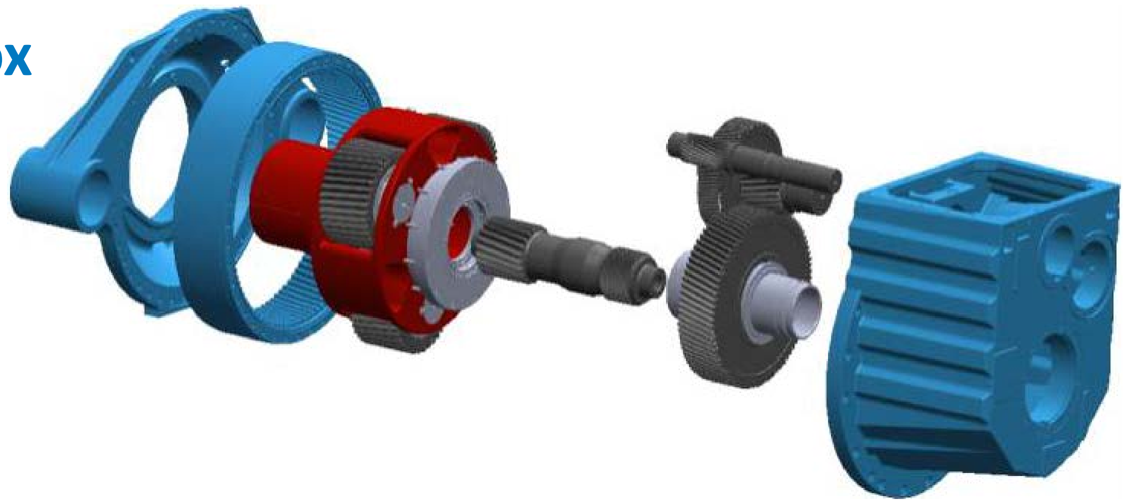
Source: NREL, Wind Stats

Typical Wind Turbine Drivetrain Architecture

- **Modular, three-point mounting system**
  - Main bearing and gearbox torque arms

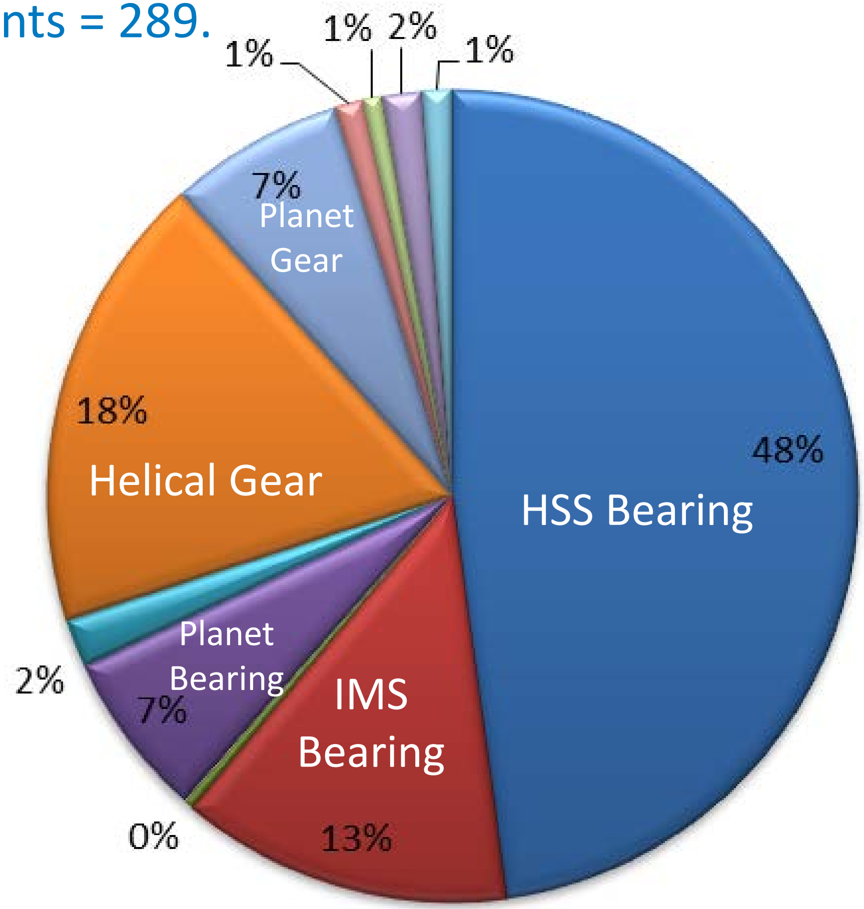


- **Three-stage gearbox**
  - Ratio of 80 or 100:1
  - Three-planet stage(s)
  - Floating sun
  - Parallel stage(s).



NREL Gearbox Failure Database

- **Gearbox failure event data highlighting damaged components, failure modes, and possible root causes**
  - Twenty partners involved in operating ~30% of the U.S. capacity
  - Number of gearbox failure incidents = 289.
- **Observations**
  - Bearings 70%
  - Gears 26%
  - Parallel section faults most common
  - High-speed and intermediate-speed stage (HSS and IMS) bearing axial cracking most common failure mode.



Gearbox Reliability Collaborative

- **Potential causes:**
  - Underspecified loads?
  - Inaccurate design tools?
  - Inadequate design practice?
  - Insufficient testing?
- **Solution process:**
  - Conduct field and dynamometer testing to measure responses (150+ signals)
  - Validate modeling approaches (multibody, finite element analysis)
  - Analyze design deficiencies (cylindrical roller bearing [CRB] clearance)
  - Redesign gearbox to correct (preloaded tapered roller bearings [TRBs])
  - Propagate lessons learned to industry and standards.

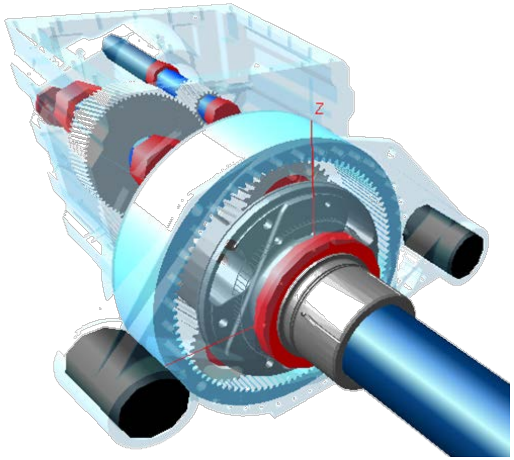
Test → Validate → Analyze → Redesign → Propagate

Photo by Jeroen van Dam, NREL 19257

Dynamometer test

NREL dynamometer. *Photo by Lee Jay Fingersh, NREL 16913*

Analysis
- Load cases
- System loads
- Internal loads

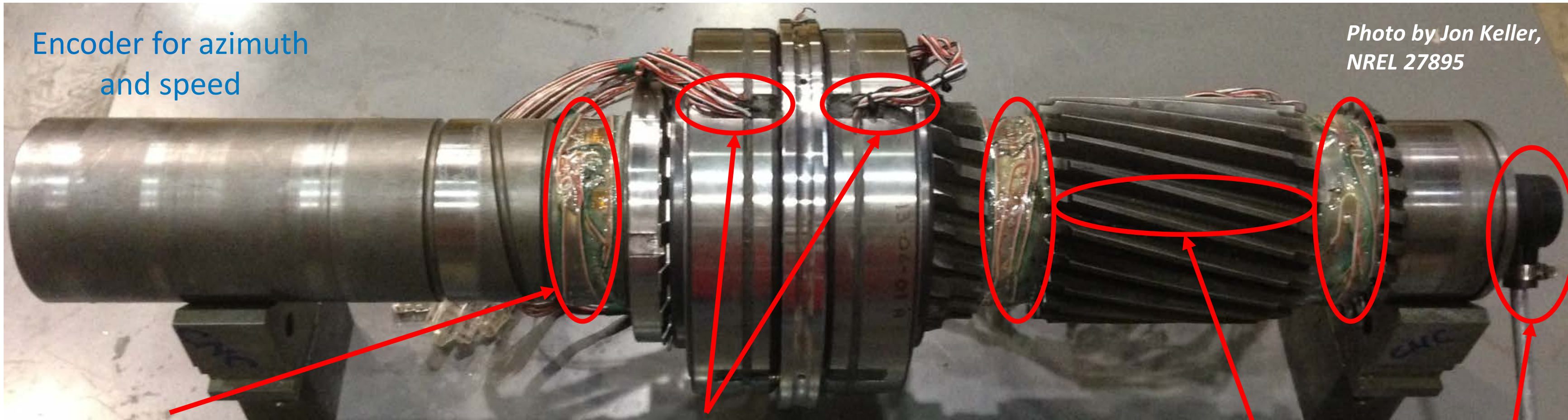


GRC Implementation

- **Use smaller 750-kW drivetrain to control costs**
- **Lack of public models → re-design/re-build commercial gearbox (GB)**
  - First iteration (GB 1&2) brings to state of the art circa 2007
  - Second iteration (GB 3) brings to state of the art circa 2012.
- **Significant internal and external instrumentation**
  - Main shaft, gearbox, coupling, and generator displacements
  - Planetary section loads, motions, and temperatures
  - HSS, pinion, and bearing loads recently added.

NREL dynamometer. *Photo by Lee Jay Fingersh, NREL 16913*

New HSS Instrumentation

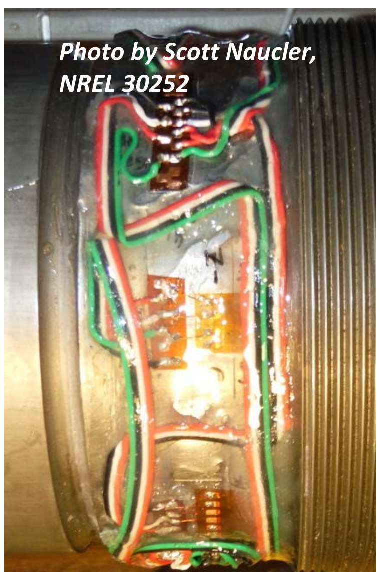


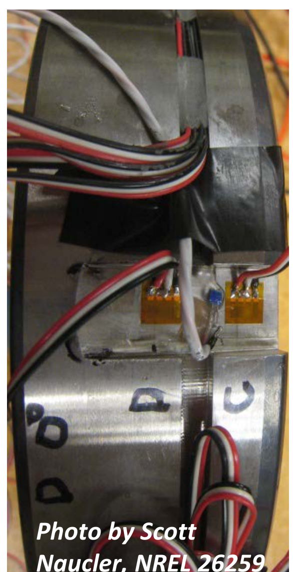
Shaft bending strain
(two axes, three axial locations,)
and shaft torsion for torque

Bearing strain for relative loading
(four axial slots, two Poisson gauges per slot,)
and temperature (both bearings)

Pinion tooth toot
strain for Gear $K_{h\beta}$

Slip rings





Test Summary

- **Phase 1 (300+ hours of data)**
  - GB 1 field load test
    - Oil loss event led to GB damage
- **Phase 2 (700+ hours of data)**
  - GB 2 dynamometer static load test
  - GB 1 dynamometer test
    - Condition monitoring and GB teardown
- **Phase 3 (underway)**
  - GB 2 dyno re-test
    - HSS loads, dynamic field loads, and generator misalignment
  - Improved GB 3 test.


Ponnequin Wind Farm. Photo by Jeroen van Dam, NREL 19257

Apr 2009

Oct 2009

July 2010

Nov 2010

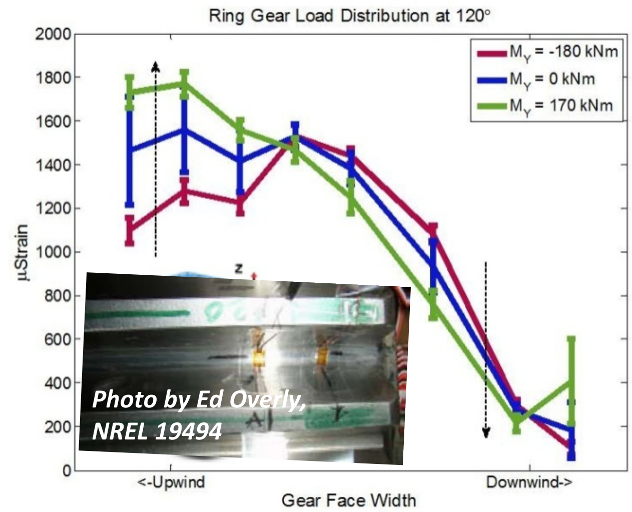
Jan 2011

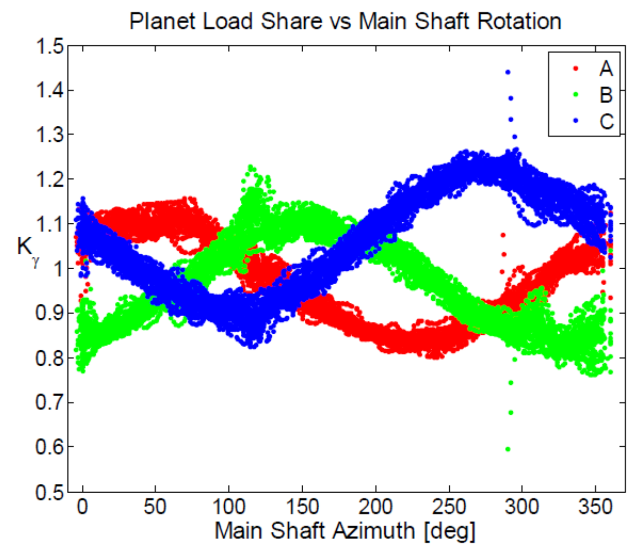
Jan 2013

Jan 2015

Gearbox 1 & 2 Design Deficiencies

- **Non-Torque and Planetary Loads**
  - Significant effect in three-point configuration
  - Cause edge loading on planetary gear teeth
    - Misalignment between carrier and ring gear because of operating radial clearance in carrier bearings
  - Cause poor load share between planets and upwind and downwind planetary bearings
    - Carrier wind-up and planetary pin deflection with operating radial clearance in the CRBs
    - High bearing skidding risks at low torque.





Gearbox 3 Design Improvements

Illustration by Romax Technology

Ring Gear

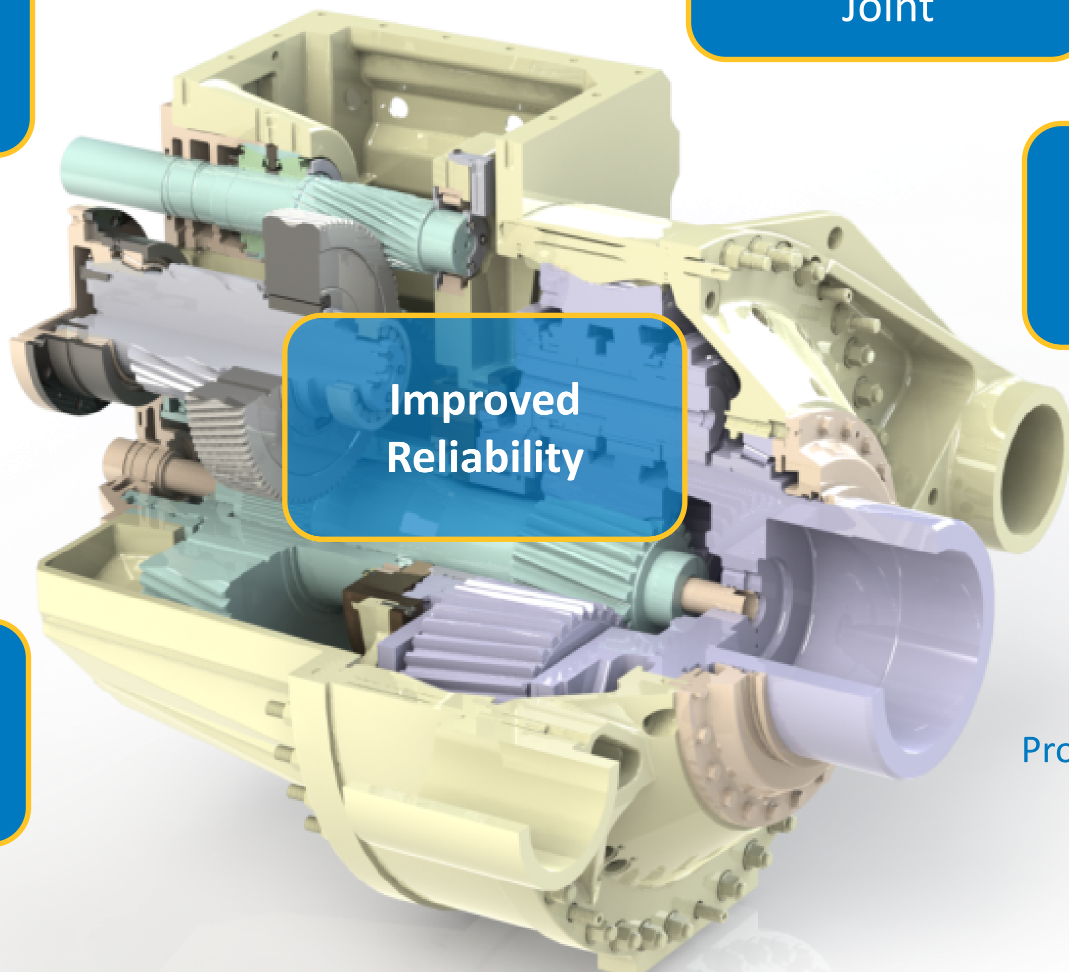
Ring/Torque Arm/Housing Joint

Planet Bearings

Carrier Bearings

Hollow Shaft Bearings

Lubrication

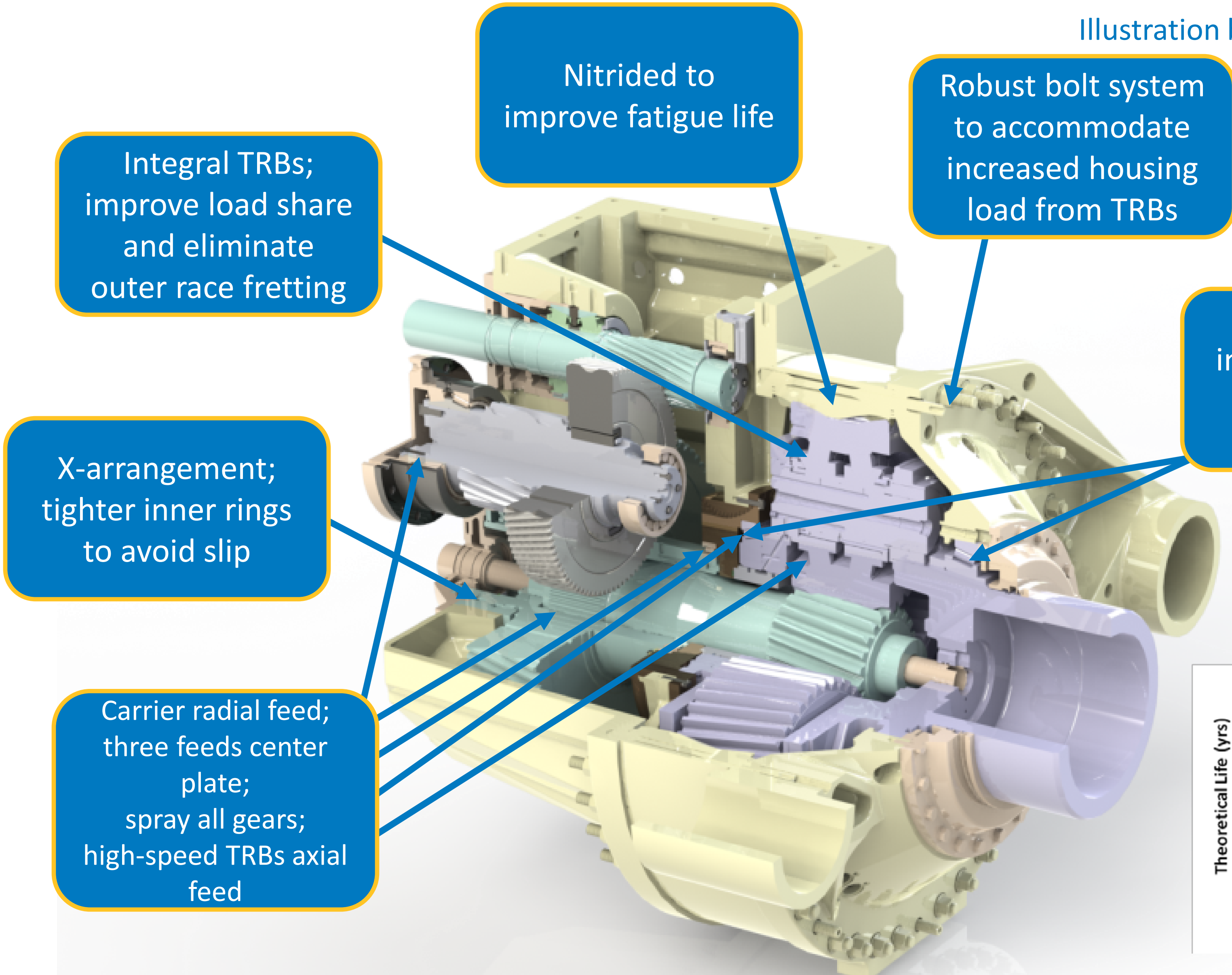


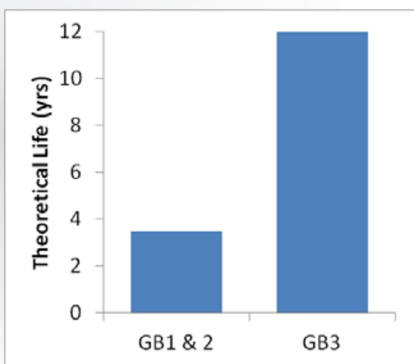
Improved Reliability

Project Team:
- Romax Technology
- Powertrain Engineers
- Timken
- Brad Foote Gearing

Gearbox 3 Design Improvements

Illustration by Romax Technology





NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Next Generation Drivetrain

http://apps1.eere.energy.gov/wind/newsletter/detail.cfm/articleId=189

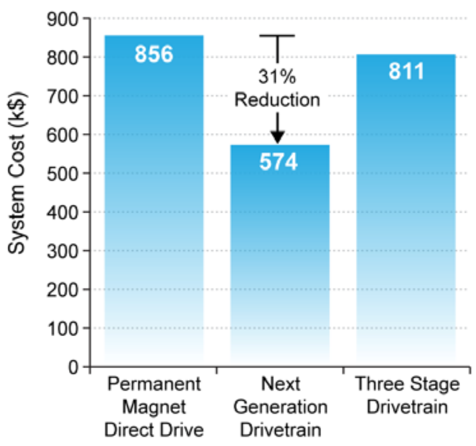
Sponsor: DOE EERE Wind

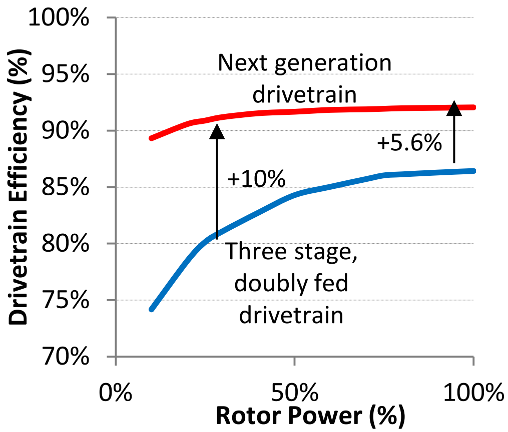
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Project Team: NREL
CREE
DNV KEMA
Romax Technology
Vattenfall Windpower

Next Generation Drivetrain

- **Project Concept**
  - Medium-speed, medium-voltage drivetrain incorporating advances in the gearbox and power converter that increase efficiency, reliability, and annual energy production (AEP); and reduce O&M costs and cost of energy (COE) from wind
  - Paper study proved the benefits and led to competitively selected funding for testing of key technologies
    - 5% increase in AEP and 13% decrease in COE at 5 MW.





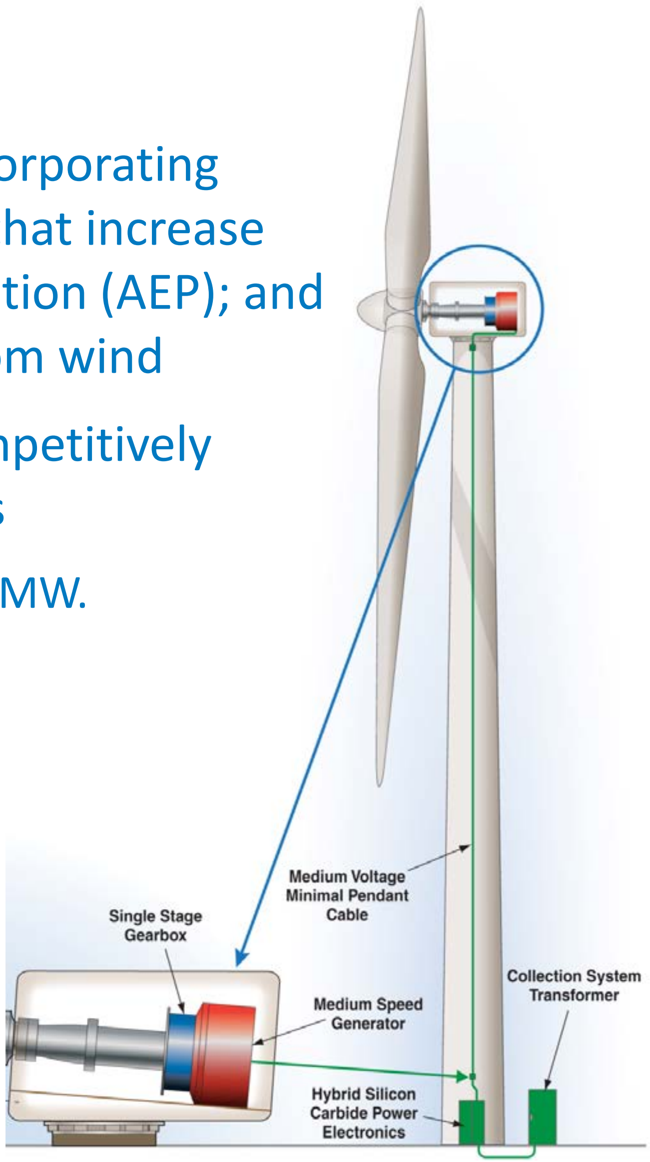
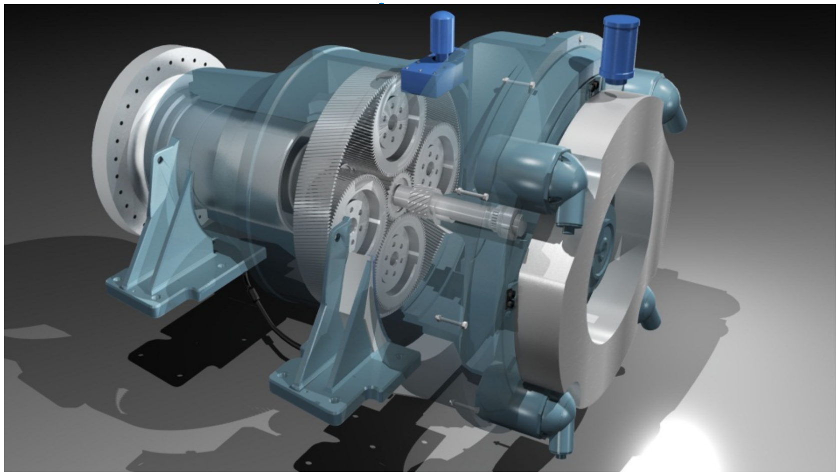


Illustration by Al Hicks, NREL

Technology Development and Testing

Dynamometer

- Gearbox journal bearing and flex pin robustness
  - Ferrium C61 explored on paper
- Converter grid fault control software effectiveness



650-kW drivetrain technology test bed

Power Converter Modules

- Medium voltage, hybrid Si/SiC module performance

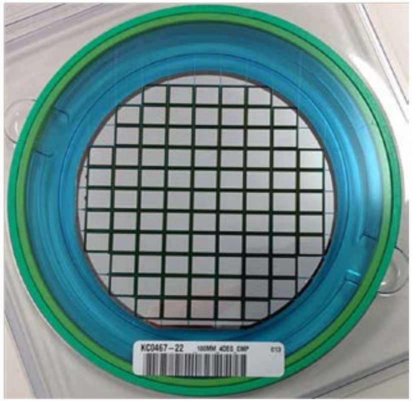


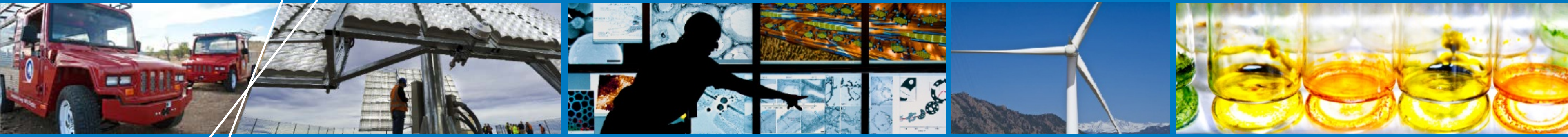
Photo by CREE

Medium voltage Hybrid Si/SiC Module test bed

Photo by DNV KEMA

Current Activities and Results

- **Gearbox in manufacture at Brad Foote Gearing**
- **Converter software in development at DNV**
  - NERC/FERC grid interconnectivity requirements emerging
- **Hybrid Si/SiC modules in manufacture at Powerex**
  - High-efficiency, medium-voltage power conversion a focus in many industries
- **Drivetrain and module testing complete early 2015.**



Wrap-Up

Opportunities for Researchers and Students

- **Researchers**
  - Research Participant Program (RPP)
    - http://www.nrel.gov/rpp/
    - https://www.youtube.com/watch?v=0TBeFWGU0T8
- **Students and Educators**
  - Science Undergraduate Laboratory Internships (SULI)
    - http://www.nrel.gov/education/suli_intern.html
    - https://www.youtube.com/watch?v=tAppljjGXLM
  - Graduate Fellowship Program
    - http://www.nrel.gov/education/scgsr.html
  - Visiting Faculty Program
    - http://www.nrel.gov/education/teachers.html#fast
- **Full-time Employment**
  - http://www.nrel.gov/employment/