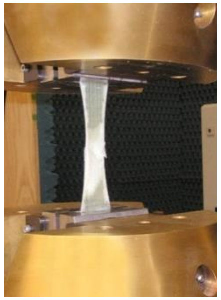

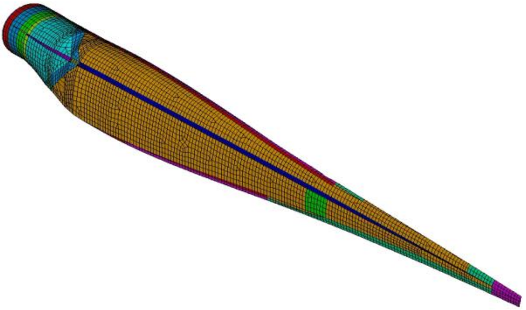

Sandia Rotor Research

SMART Wind Composites Subgroup Meeting

February 17th, 2015

Brian Naughton

Sandia National Laboratories

Exceptional service in the national interest

Document Number: SAND2015-1011 C

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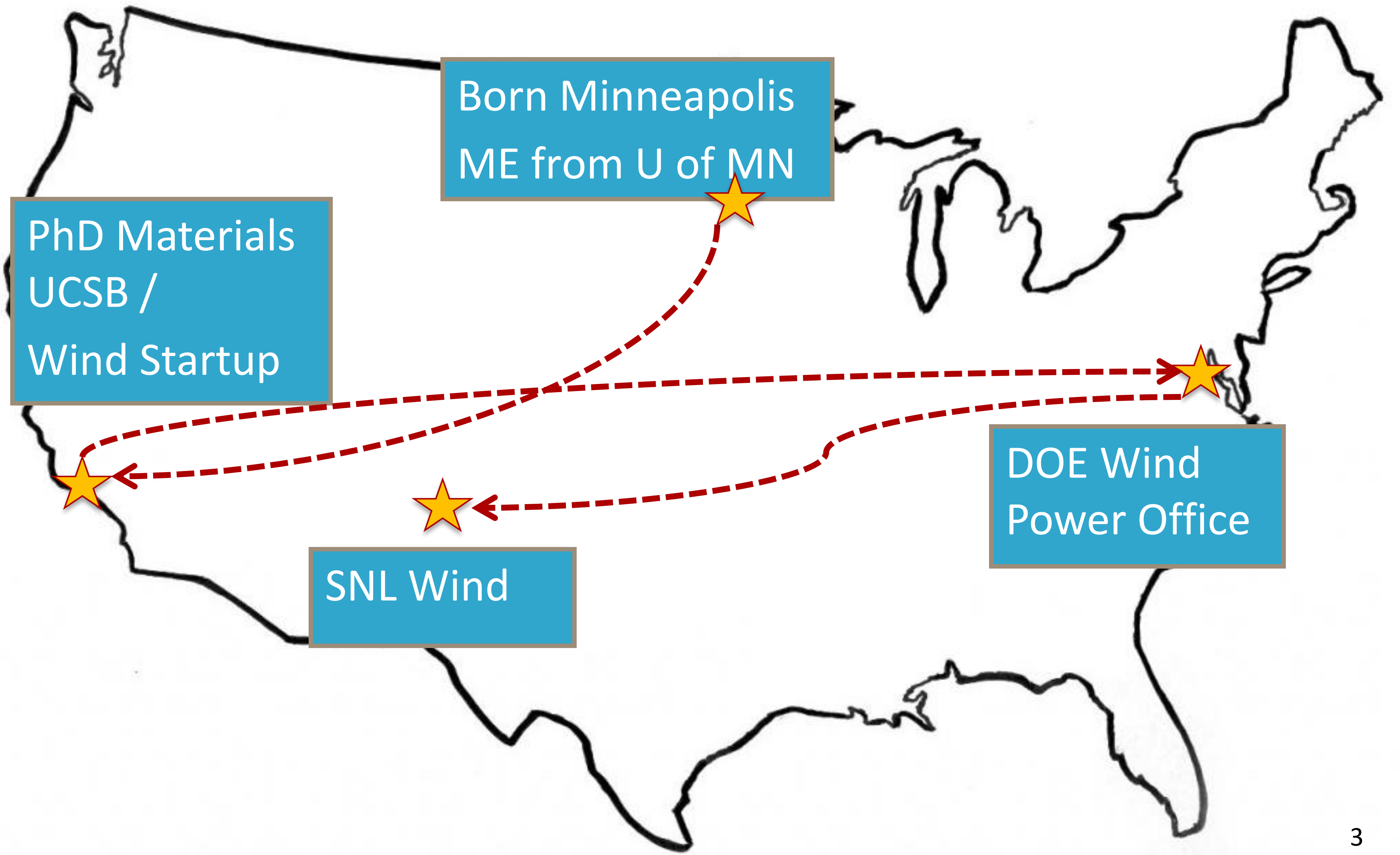
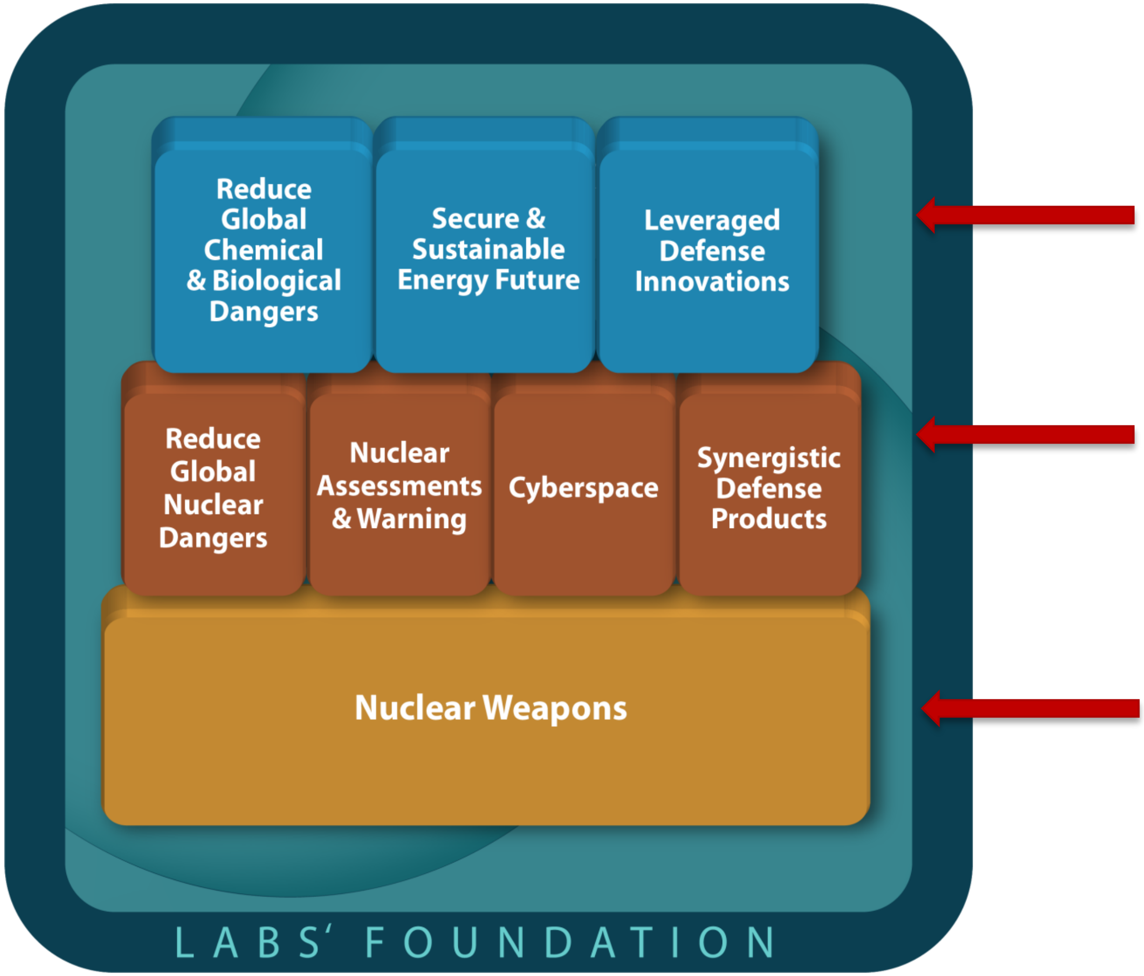
Outline

- Background: Personal & Sandia National Laboratories
- Wind Energy Market Trends
- Current Blade Technology Overview
- Blade Technology R&D Opportunities and Sandia Projects
  - Historical rotor programs
  - SWiFT test site
  - Blade materials and structural reliability projects
  - Advanced Manufacturing Initiative
  - Public design tools
  - Radar friendly blade
- Funding and partnerships

Personal Background



Sandia Mission Areas



- Top row: Critical to our national security, these three mission areas leverage, enhance, and advance our capabilities.
- Middle row: Strongly interdependent with NW, these four mission areas are essential to sustaining Sandia's ability to fulfill its NW core mission.
- Bottom row: Our core mission, nuclear weapons (NW), is enabled by a strong scientific and engineering foundation.

Energy & Climate PMU

Energy Research

ARPAe, BES Chem Sciences, ASCR, CINT, Geo Bio Science, BES Material Science

Climate & Environment

Measurement & Modeling, Carbon Management, Water & Environment, and Biofuels

Nuclear Energy & Fuel Cycle

Commercial Nuclear Power & Fuel, Nuclear Energy Safety & Security, DOE Managed Nuclear Waste Disposal

Renewable Systems & Energy Infrastructure

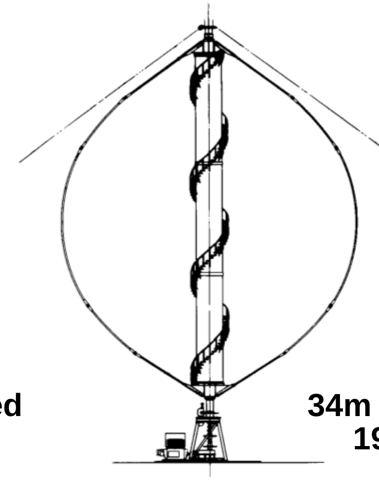
Renewable Energy, Energy Efficiency,
Grid and Storage Systems

Transportation Energy & Systems

Vehicle Technologies, Biomass, Fuel Cells & Hydrogen Technology

SNL Wind Program History

28 Years of wind turbine rotor development

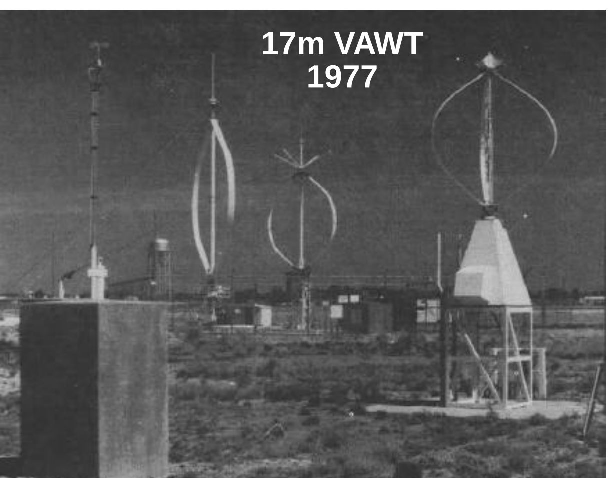


Wind Program Established 1975

34m VAWT 1984

Blade Program 1994

SWiFT Facility 2013



17m VAWT 1977

Composite Materials Database 1988

Advanced Manufacturing Initiative 2008

Wind Energy Market Trends

Cost of Energy Reduction

$$COE = \frac{CAPEX(75\%) + OPEX\ (25\%)}{AEP}$$

US Wind Resource Quality Drop

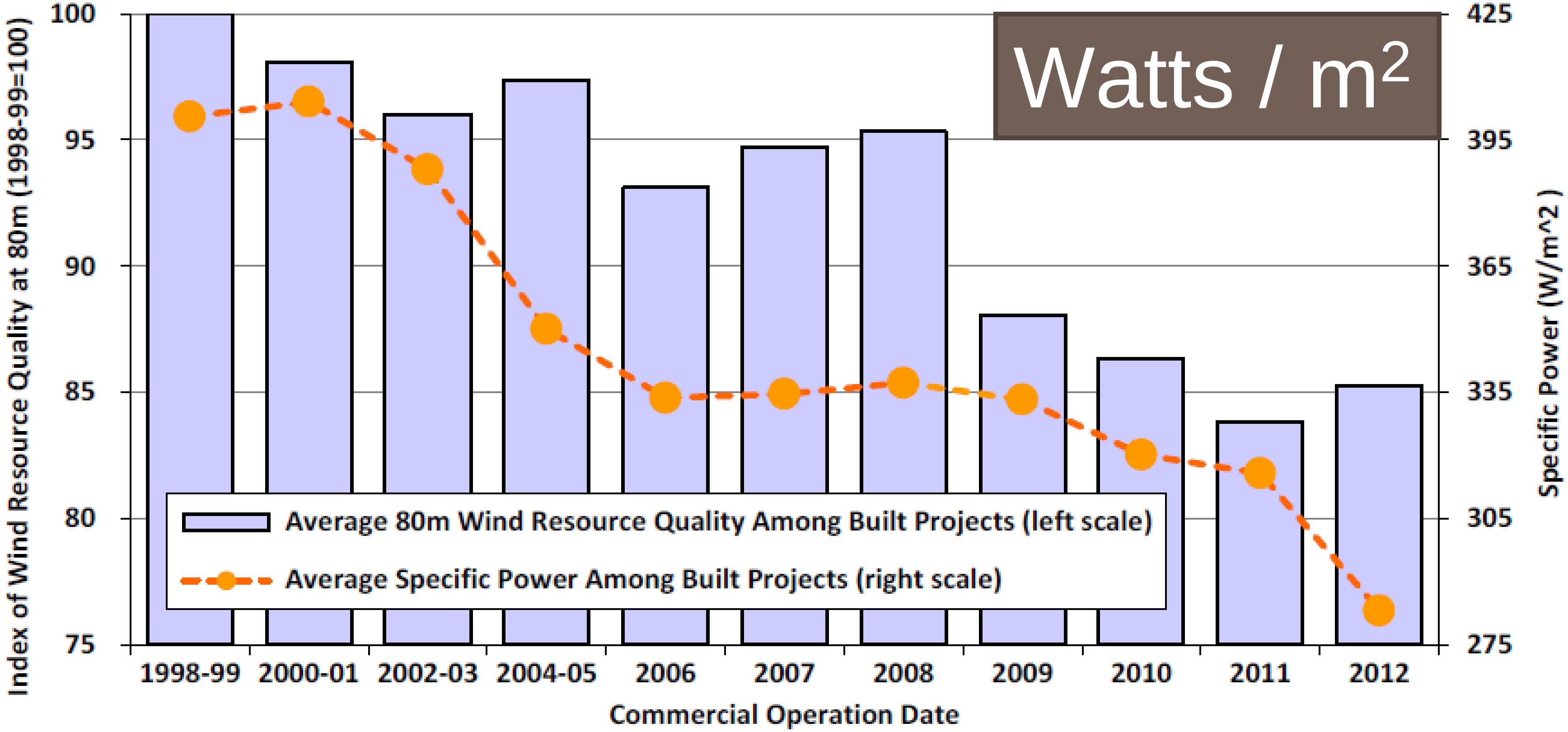
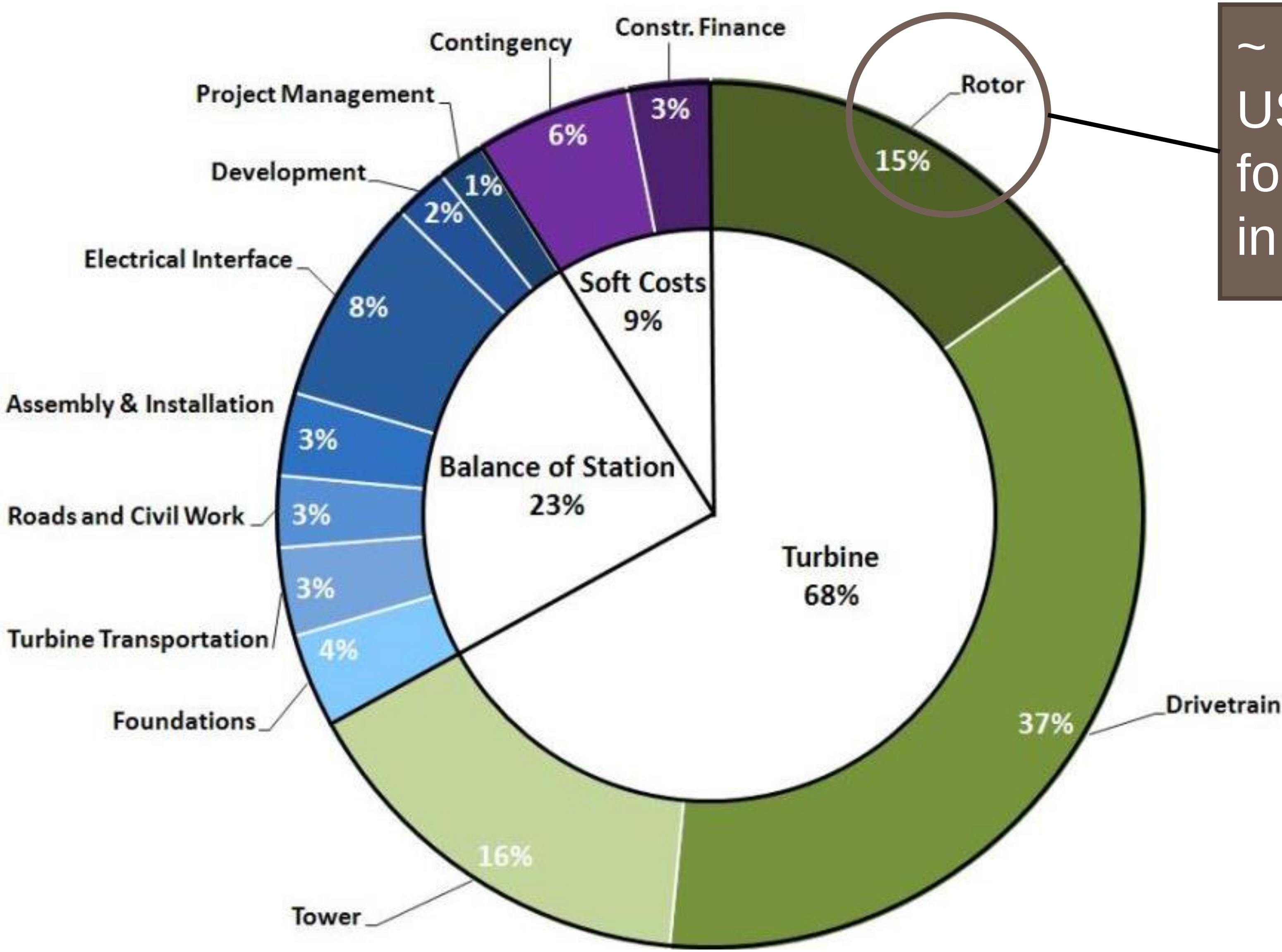


Figure 29. Index of Wind Resource Quality at 80 Meters vs. Specific Power

Source: LBNL Wind Technology Market Report 2012

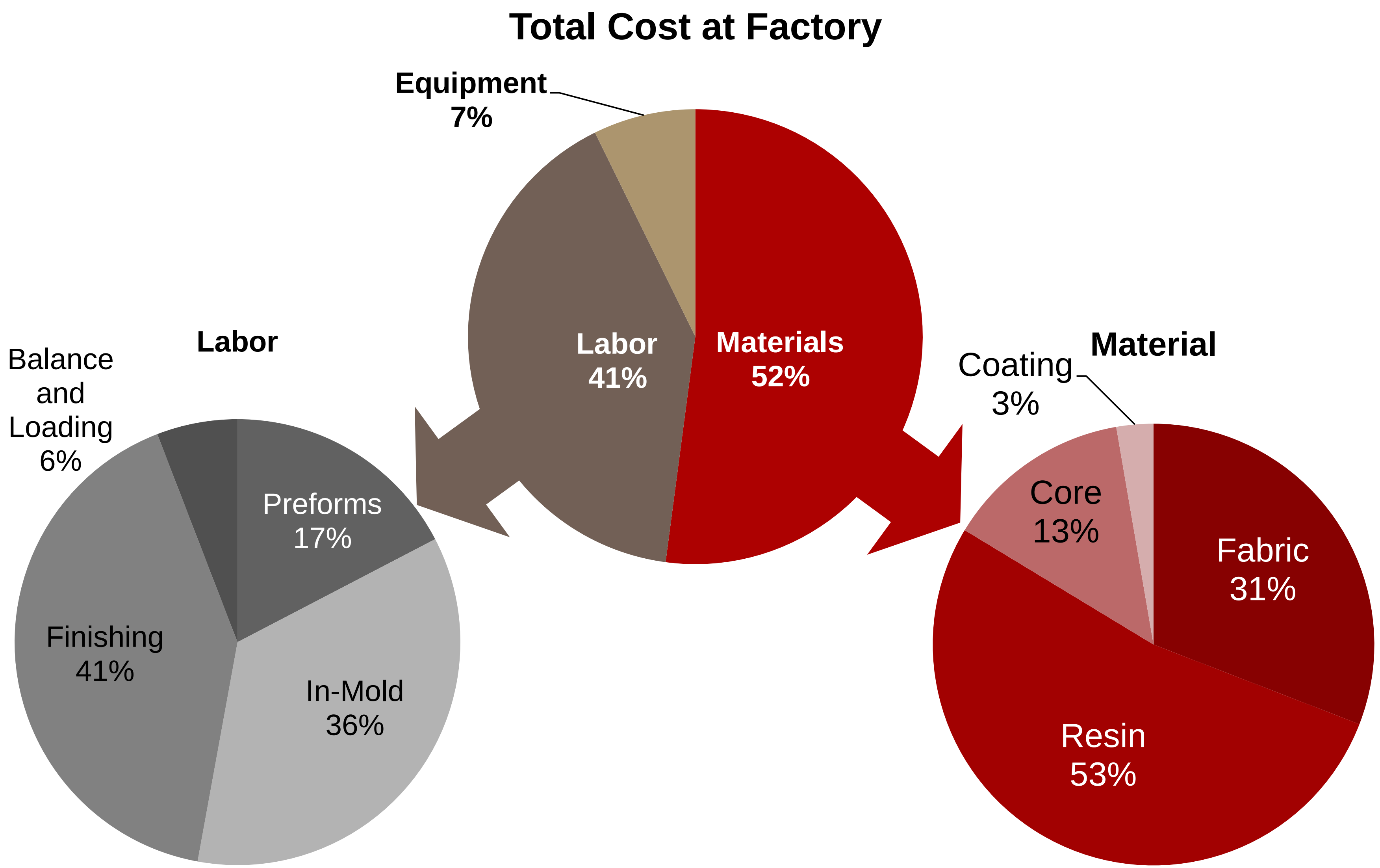
Capital Cost by Component



~ $2.5B US market for blades in 2012

Source: NREL Cost of Wind Energy Review 2011

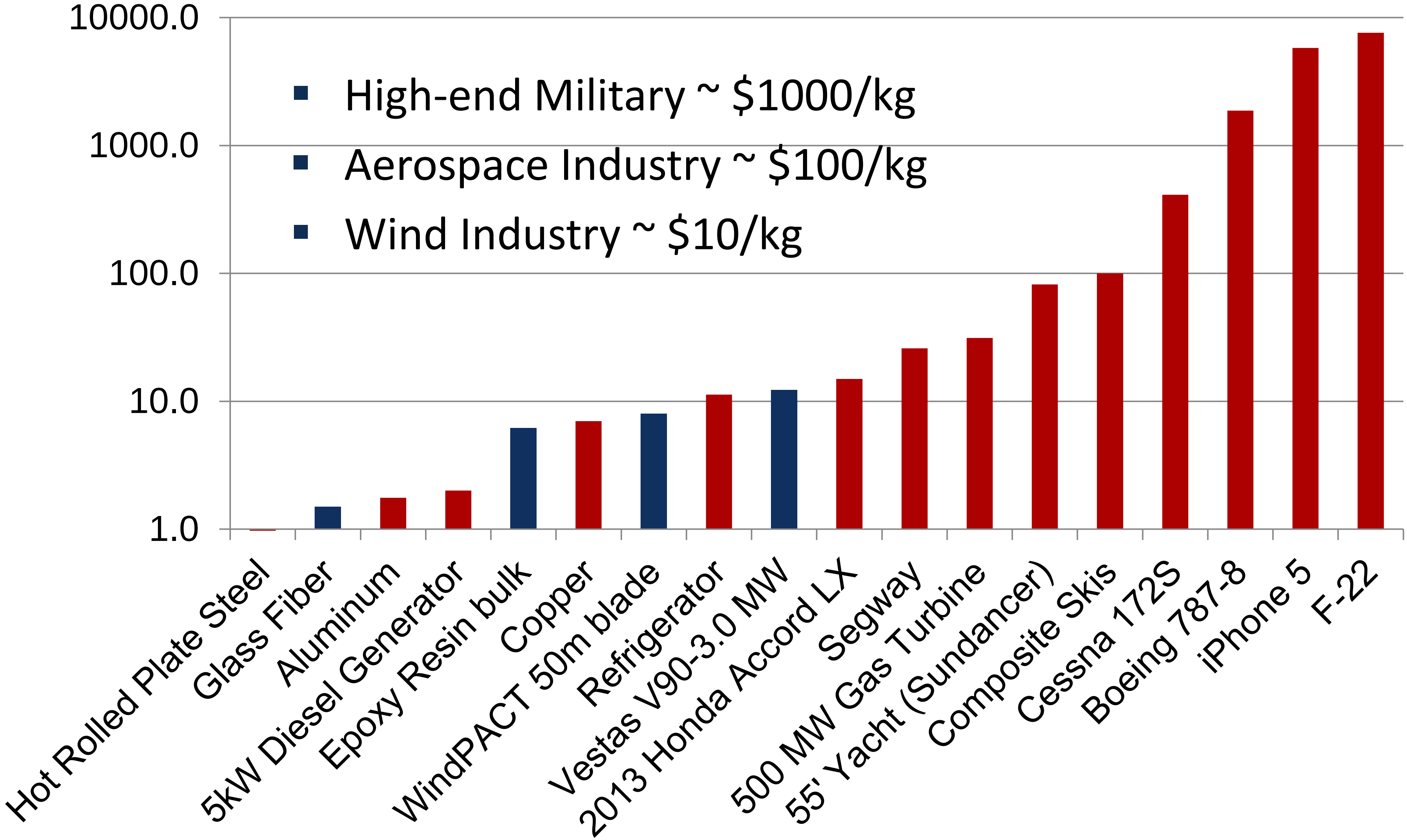
Blade Cost – 40 m Blade



Source: Blade Cost Model – SNL Report: SAND2013-2734

Materials Cost $/kg

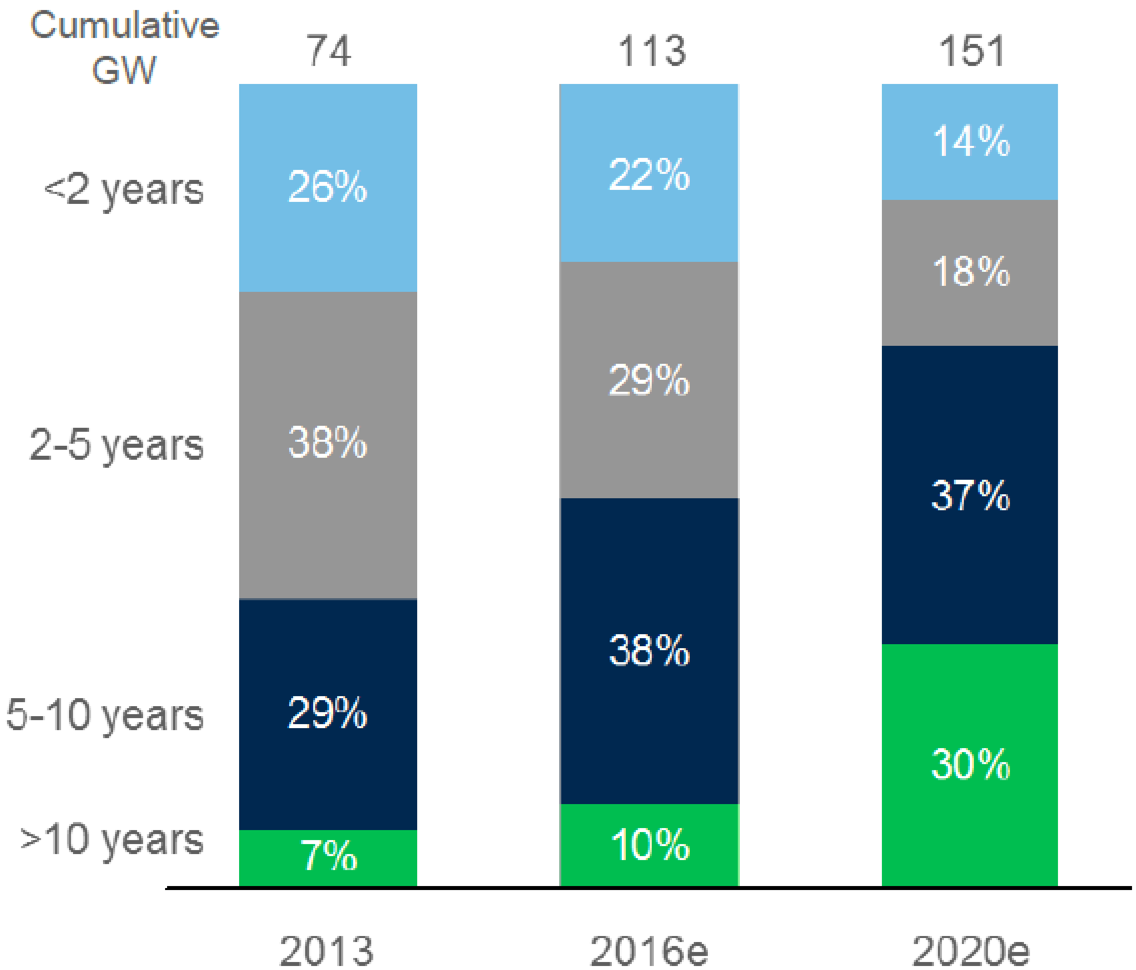
- High-end Military ~ $1000/kg
- Aerospace Industry ~ $100/kg
- Wind Industry ~ $10/kg



Source: Various product sheets from manufacturer websites

Aging Turbine Fleet

Turbine Age Distribution (North and Latin America regions)



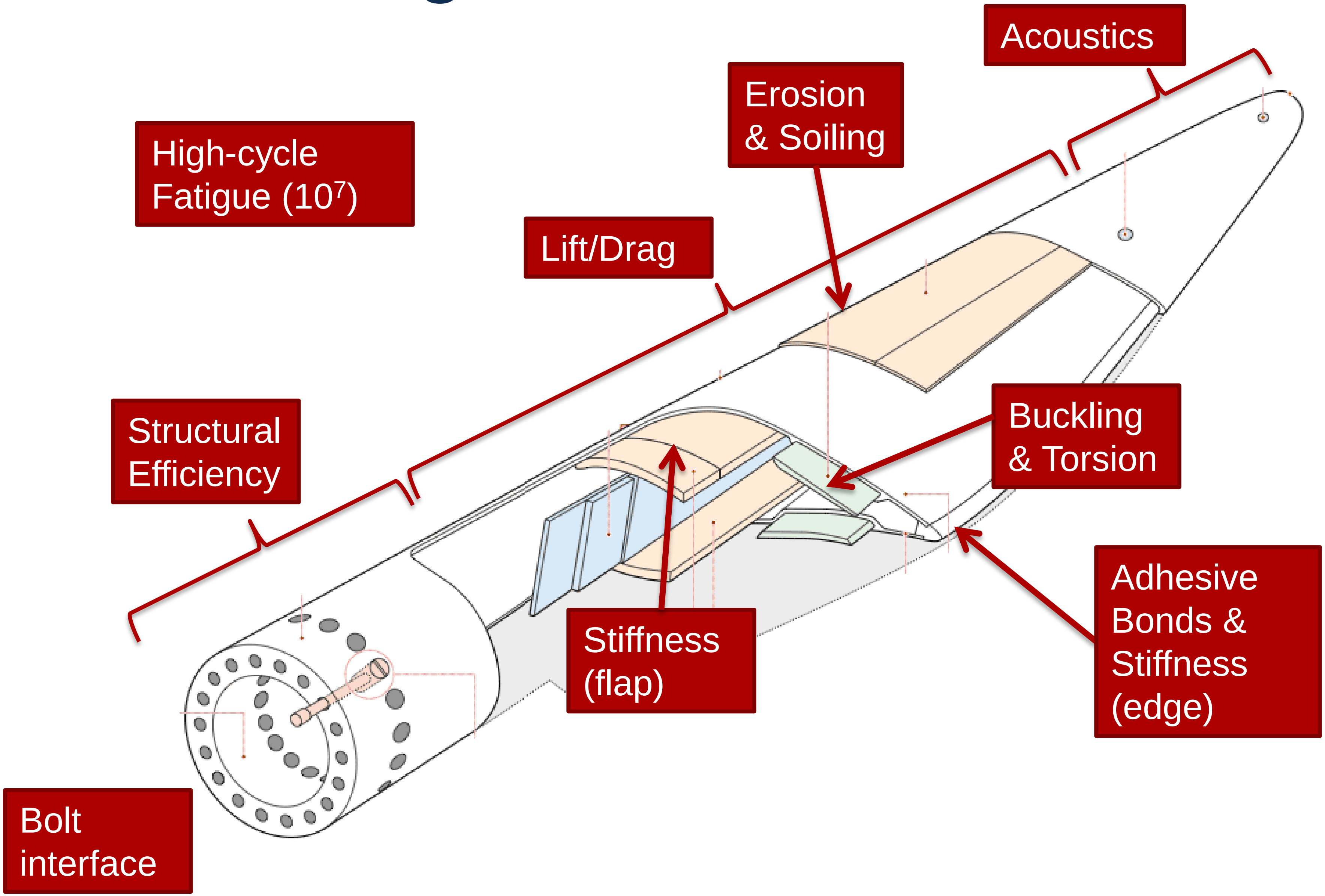
Source: MAKE Consulting, O&M Report 2014

Market Trends Summary

- As resource quality drops, rotors have increased
- Blade Capex is 50-50 materials and labor. Materials are already inexpensive and hard to automate
- Blade Opex – aging fleet presents repair/repowering opportunities

Current Blade Technology Overview

Blade Design Drivers

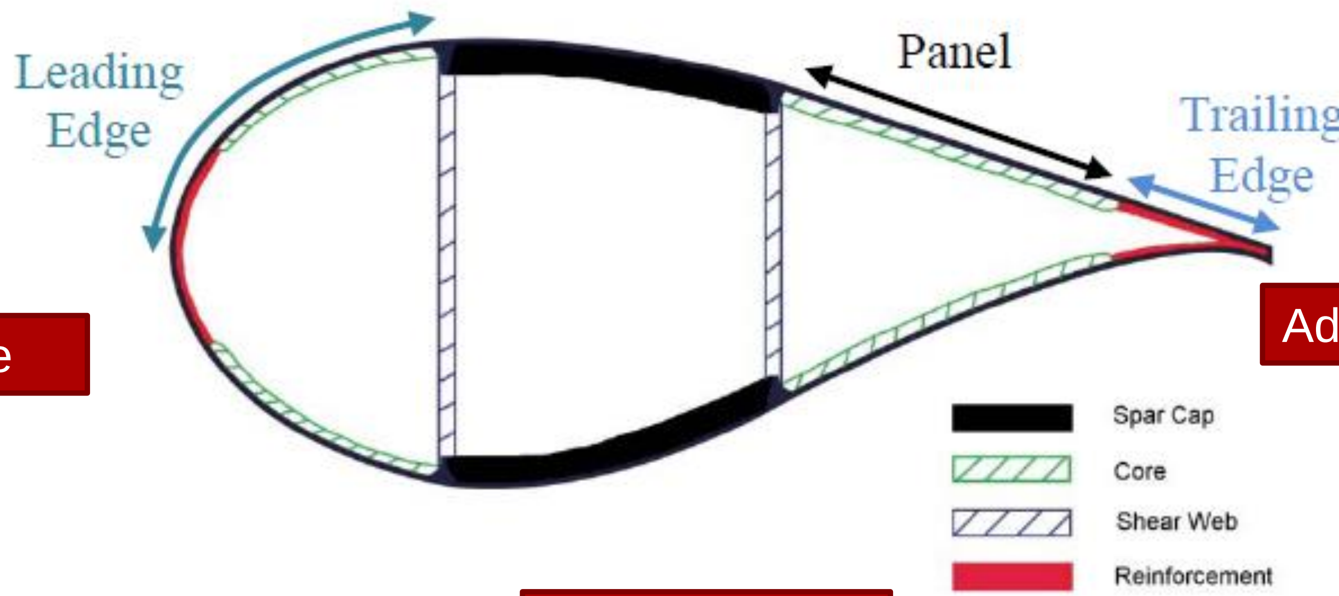


Source: Windpower Monthly July 2012

Material Selection

Biaxial fabric - core sandwich

Uni-directional fiber



Adhesive

Adhesive

High-shear modulus core

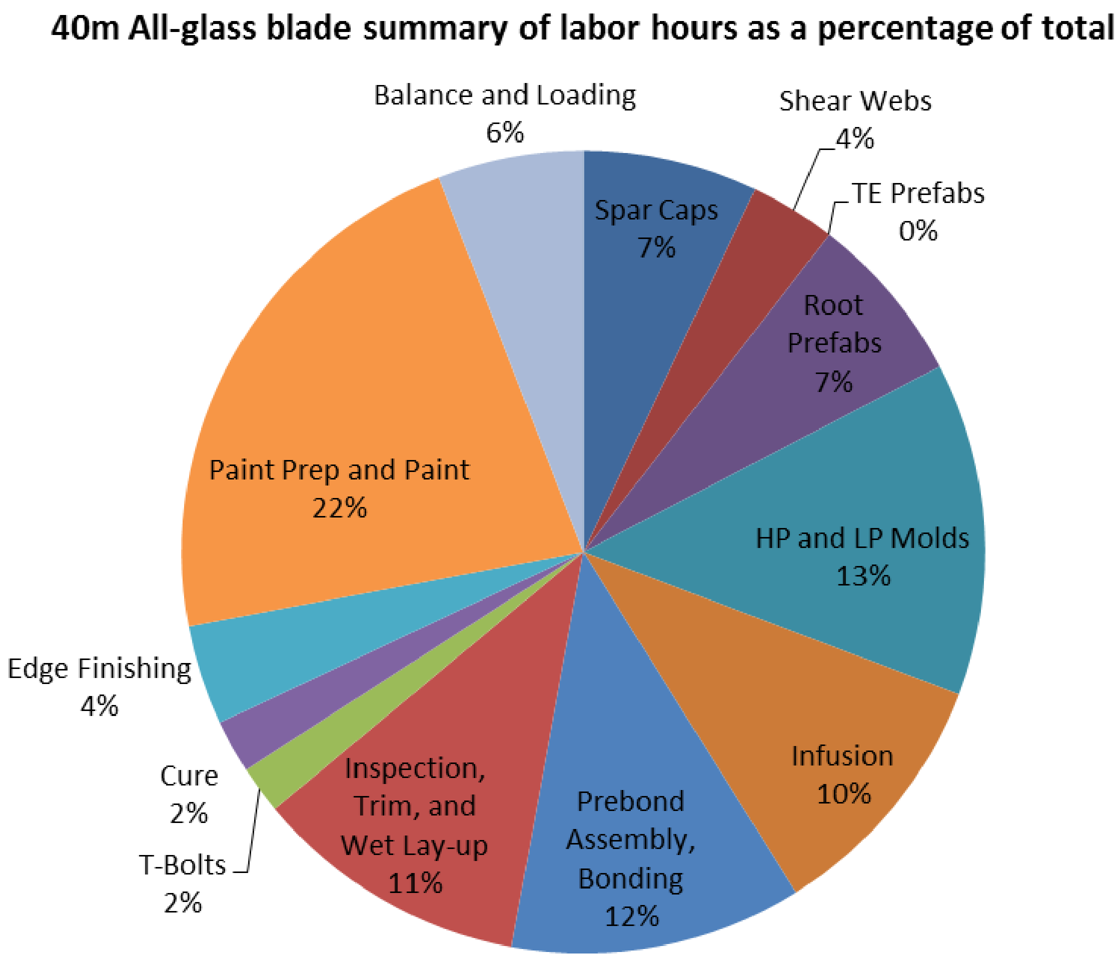
Source: 100m Glass Blade – SNL Report: SAND2011-3779

Manufacturing Technology

Varies from hands on to hands off depending on the process

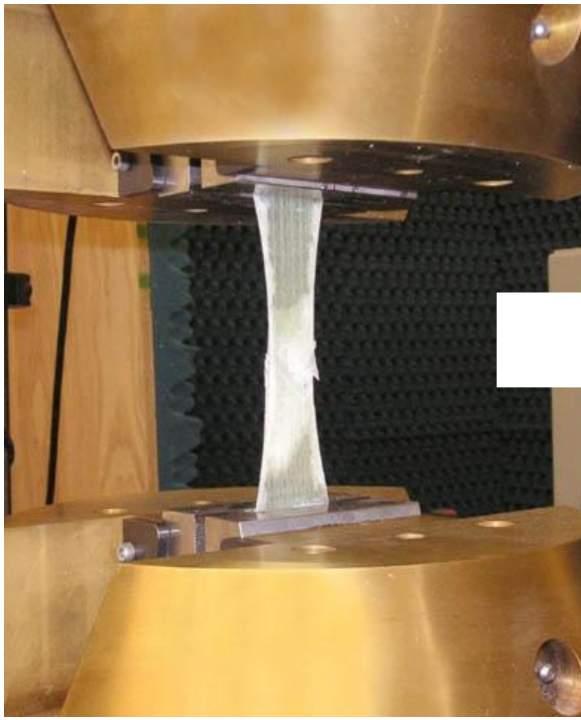
Source: Wind Systems Magazine, Bloomberg

Manufacturing Processes



Source: Blade Cost Model – SNL Report: SAND2013-2734

Current Testing Approach



Coupon testing → characteristic value → partial factors→ design allowable

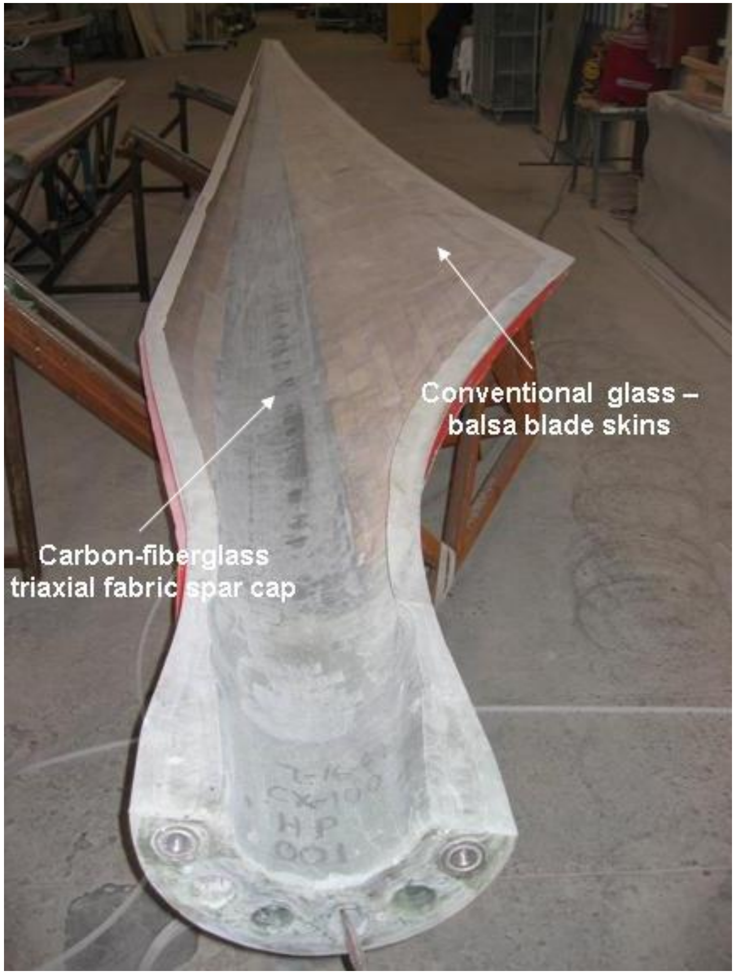
Tooling (molds) manufactured → 2 full-scale blades fabricated → 1 blade tested to ultimate loads → 1 blade tested for fatigue loads

Source: Montana State University Composites Group, NREL National Wind Technology Center

Blade Technology R&D Opportunities and Sandia Projects

Carbon Fiber Spars

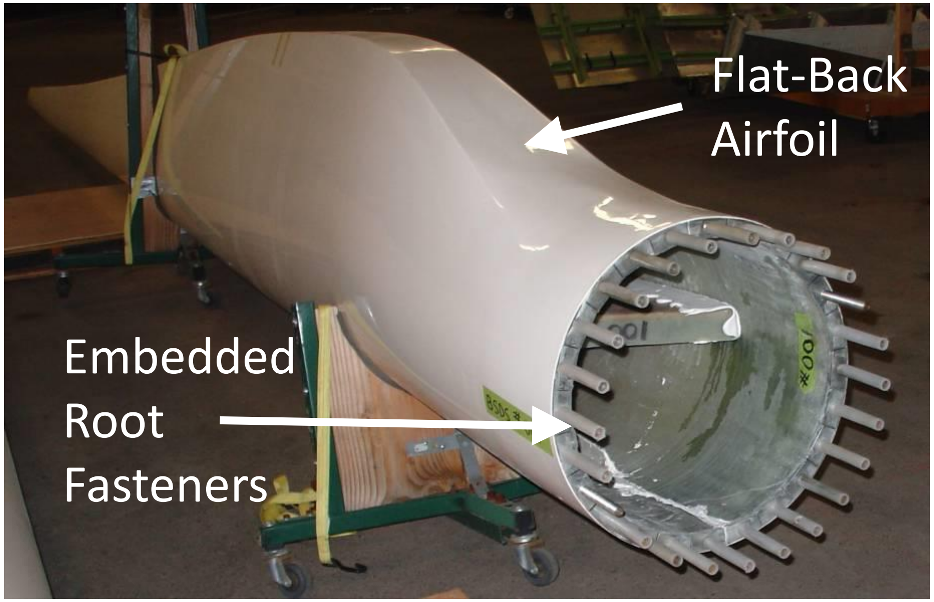
- Advantages:
  - High stiffness/strength
  - Low weight
- Challenges:
  - Higher cost
  - Difficult to infuse
  - Sensitive to flaws
- Sandia Research:
  - CX-100 Blade: Demonstrated method for producing infused carbon spar
- Industry Impact: Carbon spars widely used on large blades



Carbon Experimental 100kW (CX-100) Blade Skin

Aero-Structural Optimization

- Flat-Back Airfoils
  - Lower Weight
  - Increased Stiffness
  - Easier Manufacturing
  - Reduced sensitivity to surface soiling
- Embedded Root Fasteners
  - Reduced root laminate thickness
  - Allows for more fasteners, critical for large blades
- Sandia Research:
  - BSDS Project (industrial collaboration): Demonstrated aero and structural benefit
- Industry Impact: Common in current production blades



Blade System Design Study (BSDS) Blade

Passive Load Alleviation

- Passively sheds gust loads
- Allows for longer blades and higher energy capture
- Sandia Research:
  - TX-100 Blade: Off-axis fiber in skins to couple bend/twist
  - STAR Blade (industrial collaboration): Swept geometry to couple bend/twist
- Industry impact: Several current production and concept blades use this technology

Twist-Bend Coupled Experimental 100kW (TX-100) Blade Skin Blade Skin

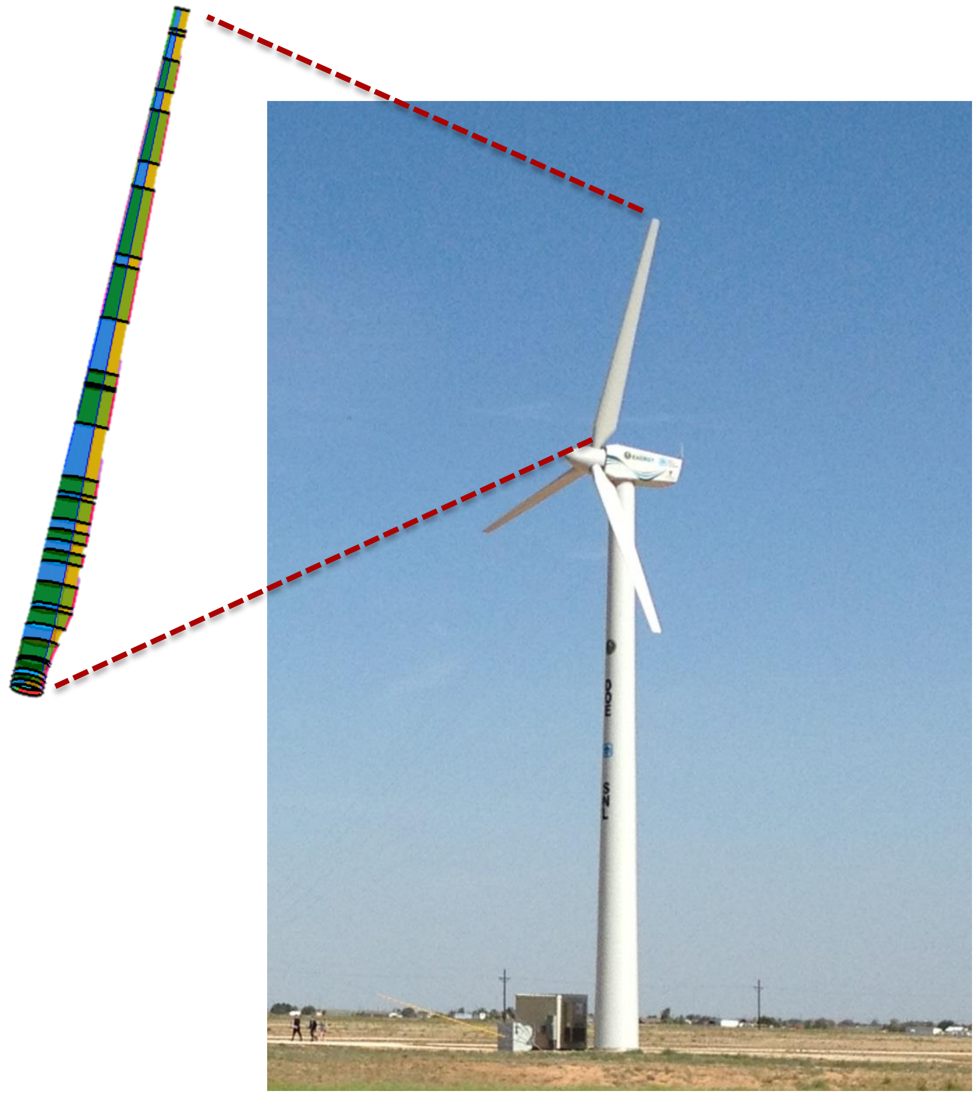
Sweep Twist Adaptive Rotor (STAR) Blade

Active Aerodynamic Control

- Quicker, more controllable response to shed gust loads
- Allows for longer blades and higher energy capture
- Possible performance enhancement
- Sandia Research:
  - SMART Blade: first full rotor with active controls
  - Utilized ailerons and patented blade displacement sensing system
- Industry Impact: Consistent industry interest, but no blades built to date

National Rotor Testbed

- Design and manufacture sub-scale rotors for the SWiFT turbines to emulate a modern, megawatt scale rotor.
- Enables low-cost field testing of new rotor technologies.
- Public rotor design



SWIFT Test Site

Sandia National Laboratories

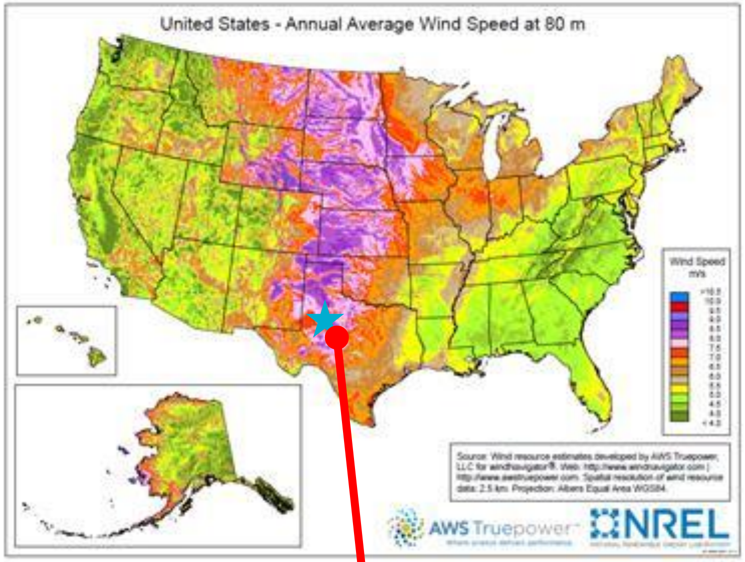
Scaled Wind Farm Test (SWiFT) Facility

Cost-effective wind plant testing facility to transition basic research to commercialization

- Lubbock, Texas
- 3 x 225 kW Turbines
- ~14 m blades
- Highly instrumented site and turbines
- Modern technology

TEXAS TECH UNIVERSITY

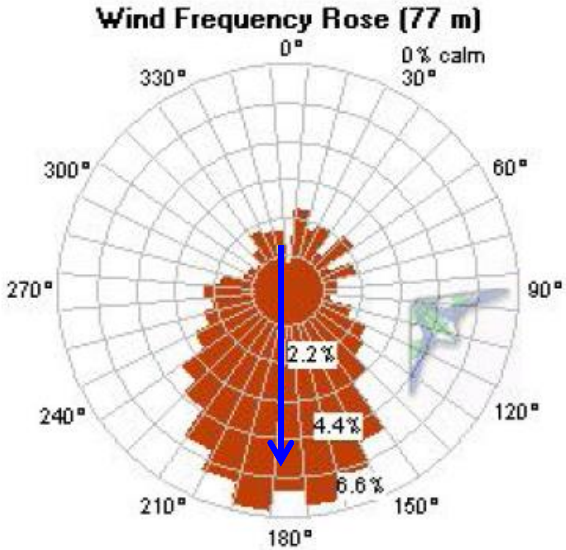
SWiFT: High, Consistent Wind



Location is in the best part of the US wind corridor—with favorable weather year-round and the most US wind installations: 12 GW and continued growth.

Consistent high data rate and efficient research execution due to:

- High winds (7.5 m/s at 50 m) with low variability
- Narrow wind rose, which provides consistent data for chosen array configuration
- Current and historical data from unique, site-adjacent 200 m meteorological mast
- Flat terrain, which allows reduced validation uncertainty and the opportunity to add man-made terrain effects in the future

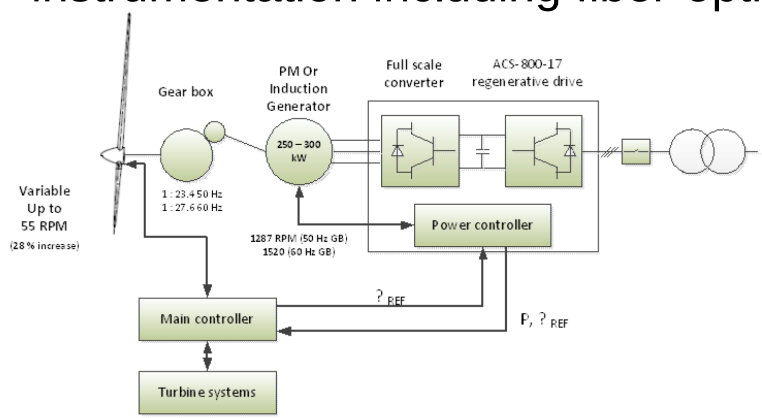


TEXAS TECH UNIVERSITY.

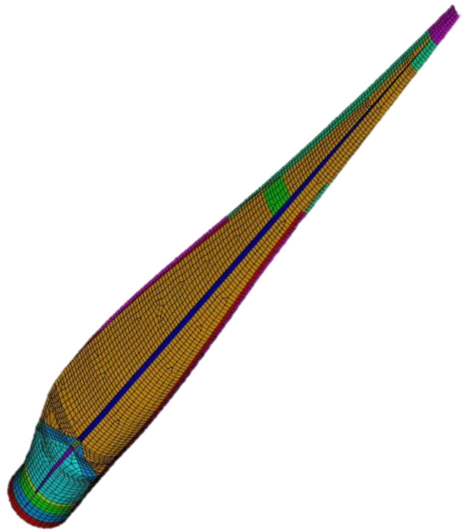
Open-Source Wind Turbines

Fully documented open source hardware, developed in collaboration with Vestas

- Solid, proven machines with collective-pitch system that allows almost any type of research to be performed
- 300 kW variable-speed generator
- AC-DC-AC full-scale convertor designed with ABB, Inc.
- Open-source controllers based on National Instruments
- Complete turbine/rotor state instrumentation including fiber-optics



Structural Reliability Program



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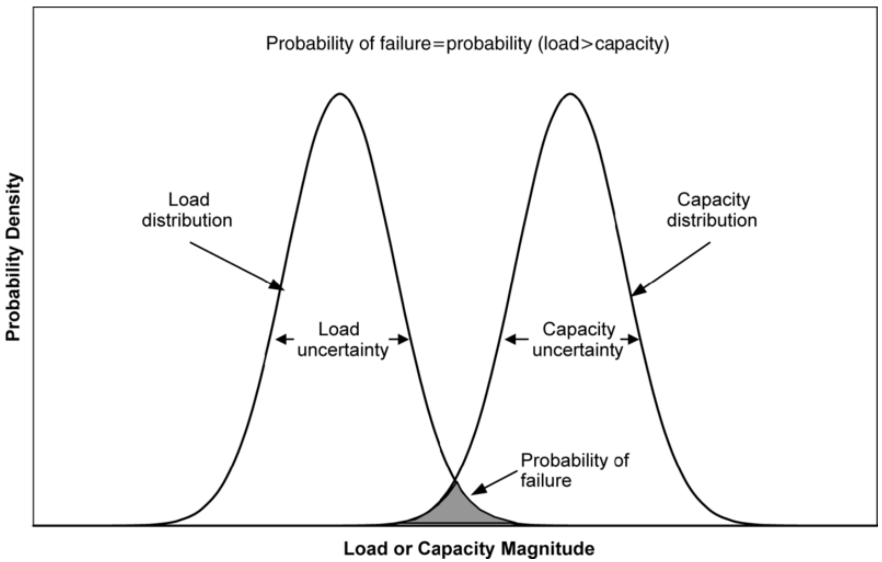


Blade Reliability Collaborative

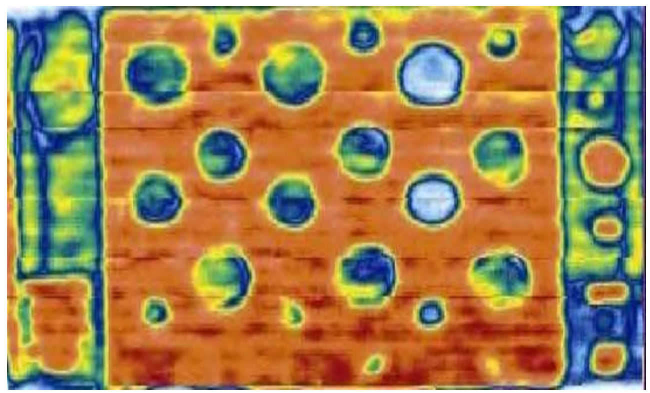
Sandia National Laboratories

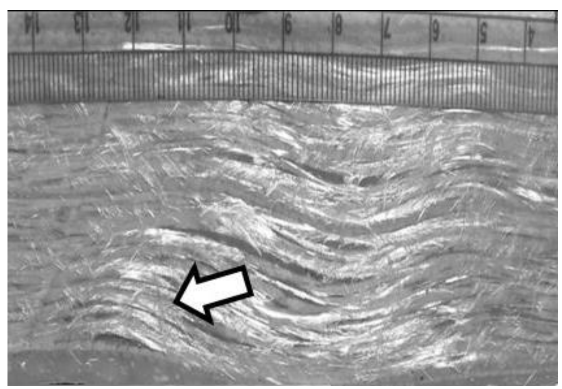
Improve the reliability of blades through field investigations, inspection technology, evaluating effects of defects, and improved design, analysis and certification

MONTANA STATE UNIVERSITY

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Many industry participants





Damage Tolerant Design

Sandia National Laboratories

Inspection Program

+

Progressive Damage Analysis (requires a damage growth model and accurate loads data

+

Residual Strength Analysis

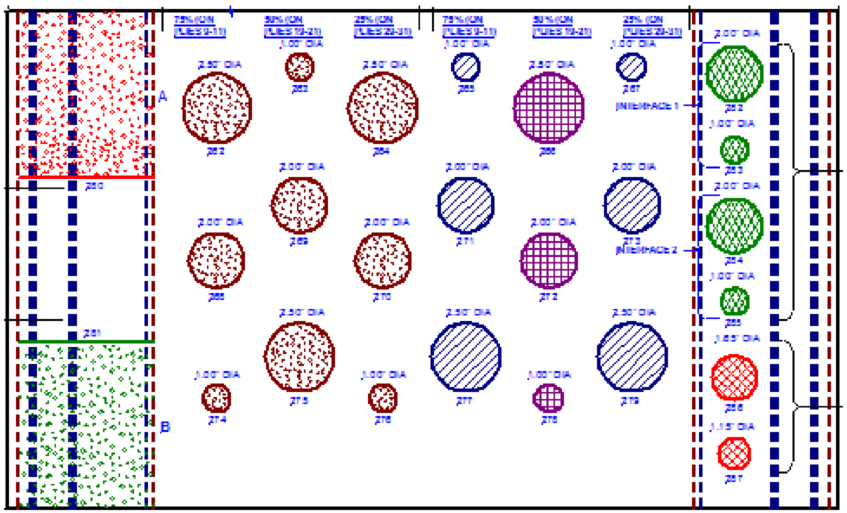
=

No in-service failures

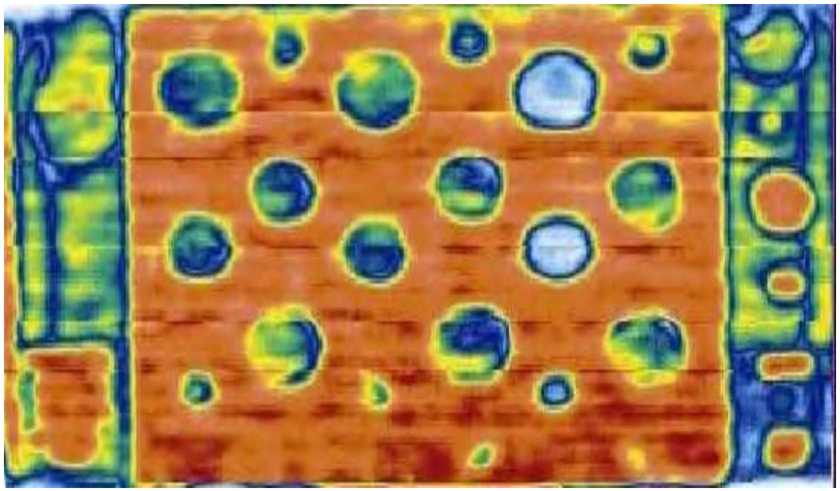
Inspection Technology

Inspection methods are need at the manufacturing plant and in the field to improve quality and reliability

- Test specimens with different flaw types and sizes
- Evaluation of non destructive inspection (NDI) methods to determine probability of flaw detection
- Operationalize methods for manufacturers and inspectors



Test Specimen of Known Flaws



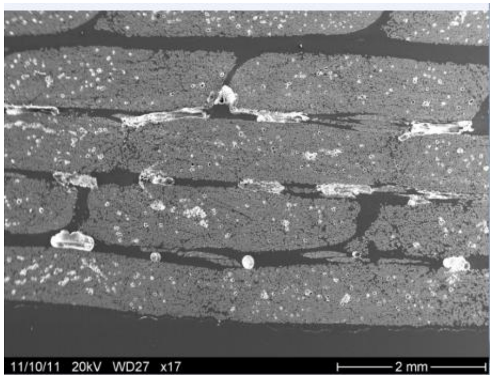
Ultrasonic Scan

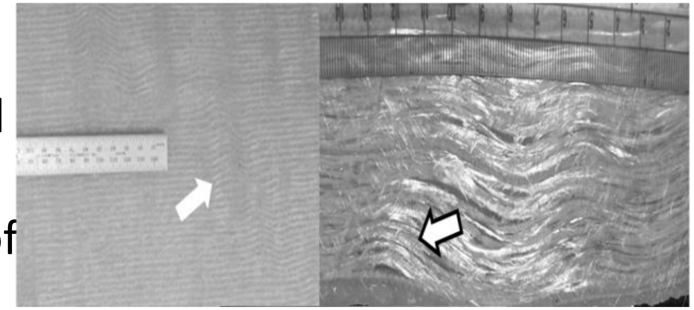
Source: SNL – Dennis Roach – Blade Reliability Collaborative

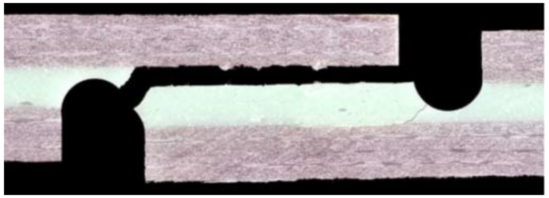
Effects of Manufacturing Defects

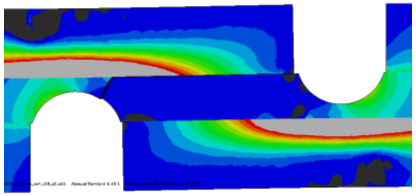
Sandia National Laboratories

- Defects in wind laminates are unique due to scale/manufacturing
- Current standards are possibly both over and under conservative in terms of flaws
- Sandia Research
  - Build, test, model coupons and sub-structures with defects
  - Develop probabilistic models of impact on blades
- Industry impact: Quantify effect on blade strength and reliability for improved standards

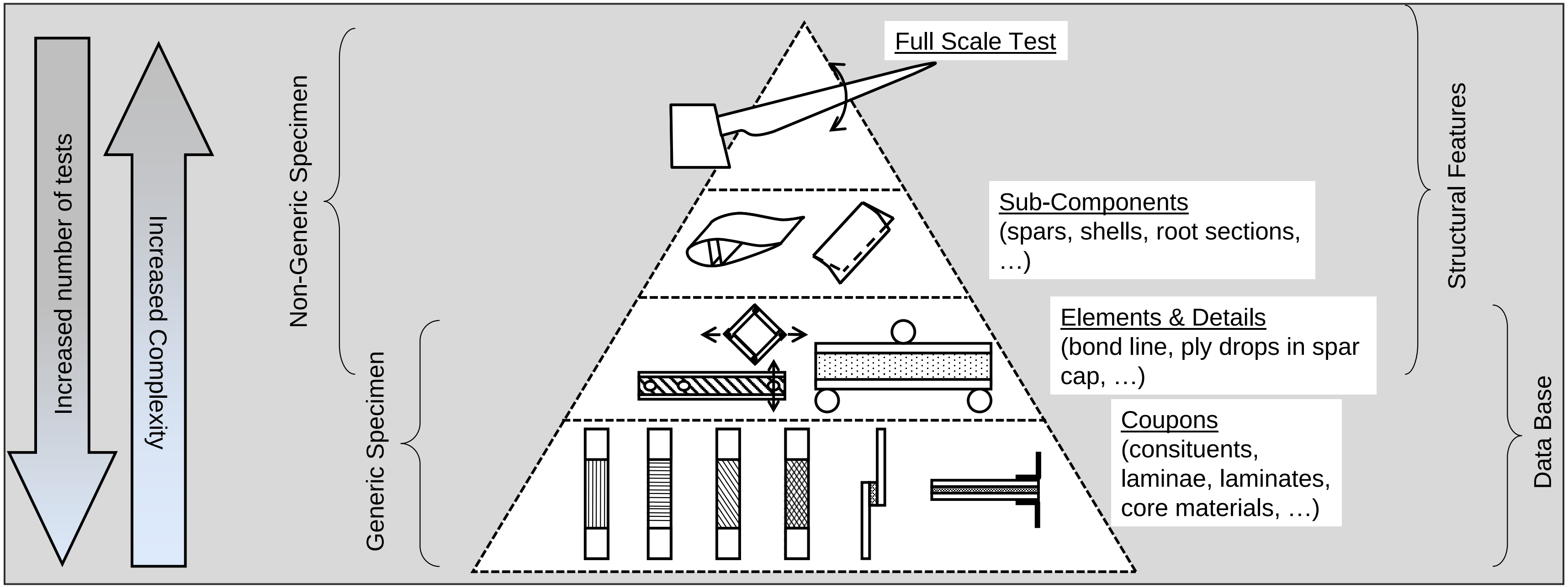






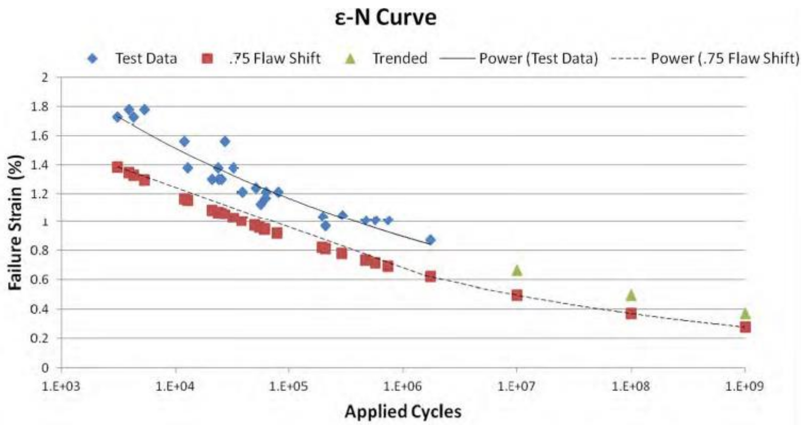


Testing Approach for Composites



Building Block Approach

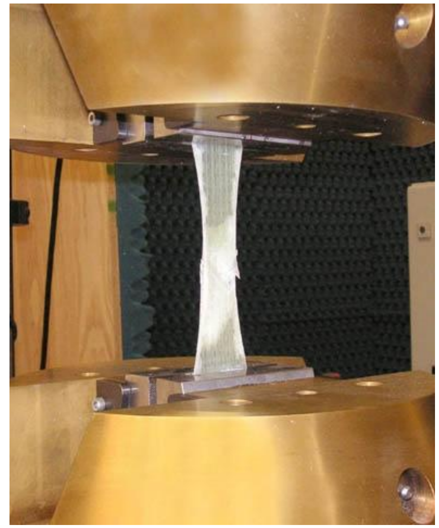
- Complex loads
- Structural Details

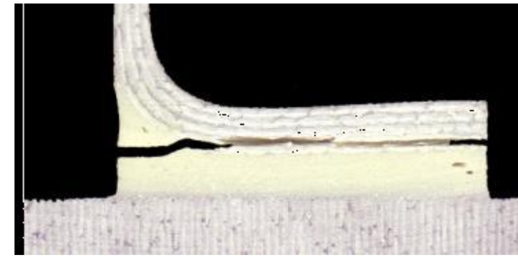


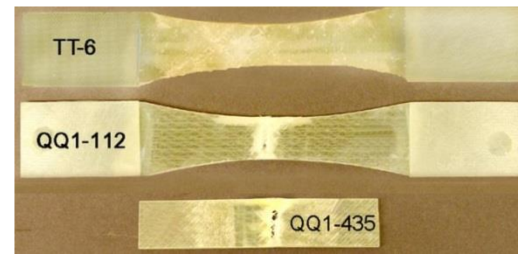
Coupon Testing

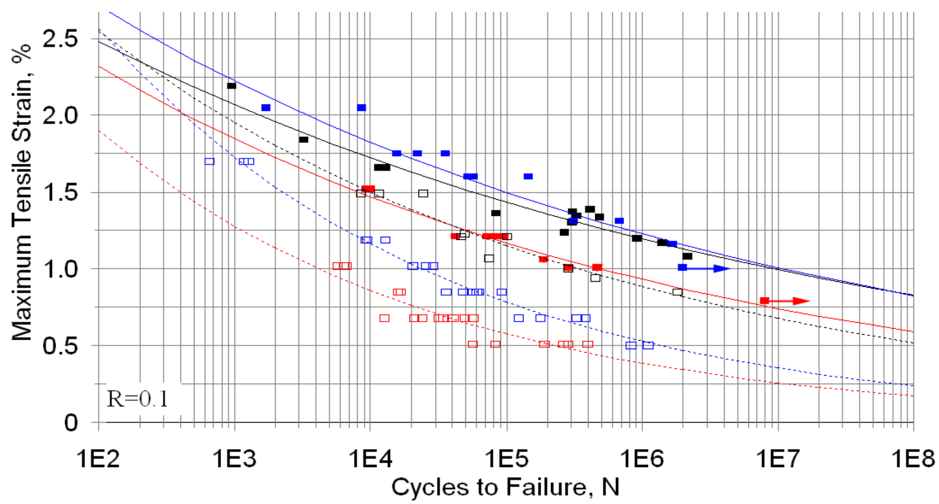
Characterize static and fatigue properties of blade materials from suppliers (resins, fabrics, adhesives, cores), and laminates and structural details from blade manufacturers.

Results published in Composite Materials Database since 1989

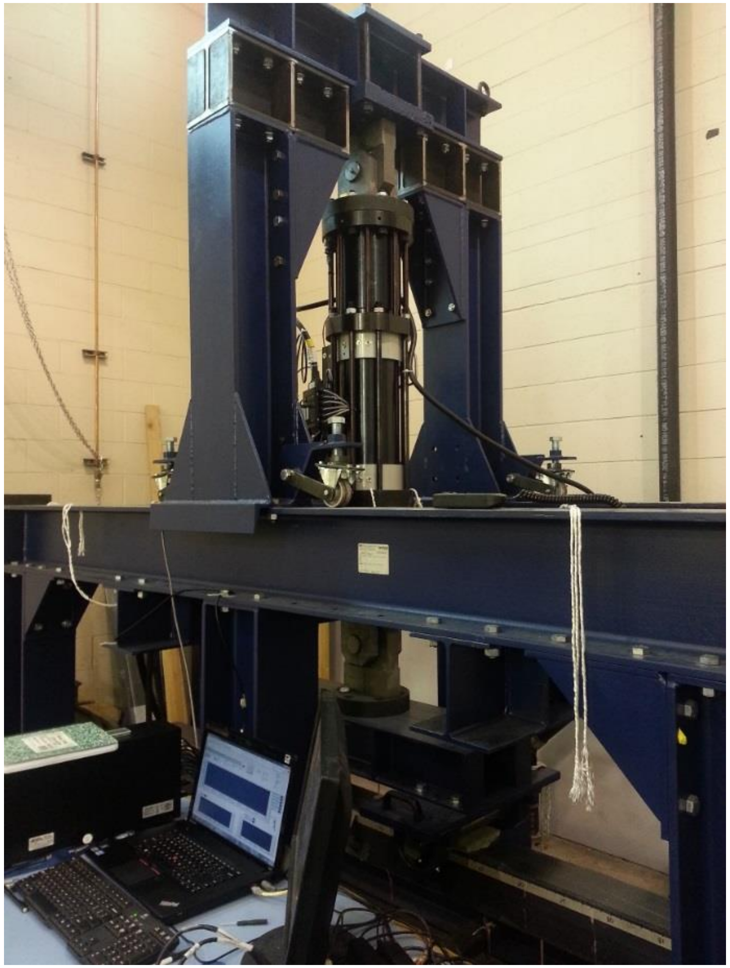


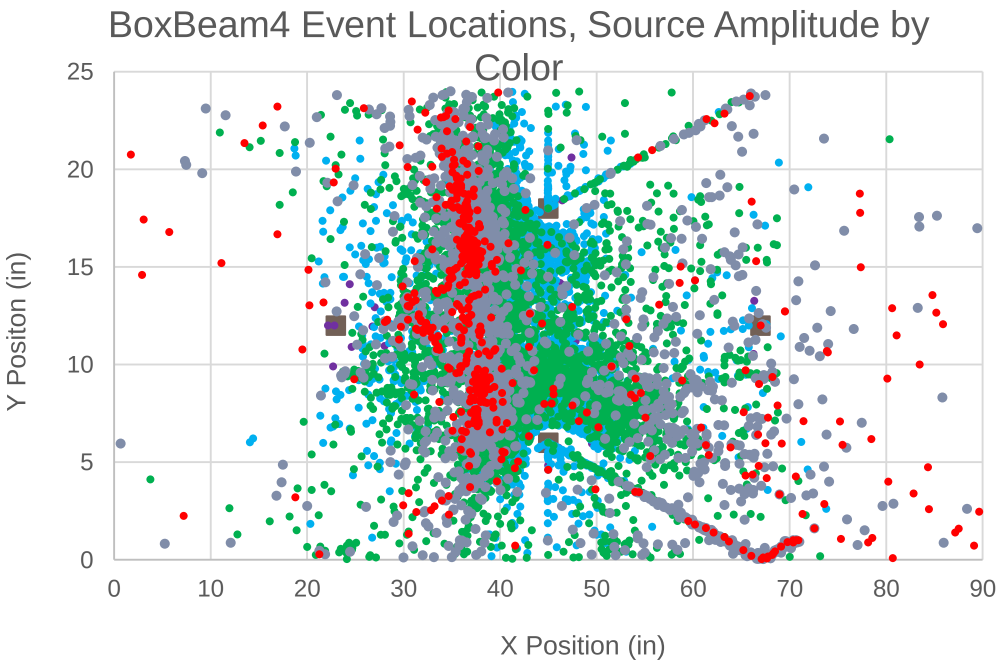






Sub-Structure Testing





Leading-Edge Erosion

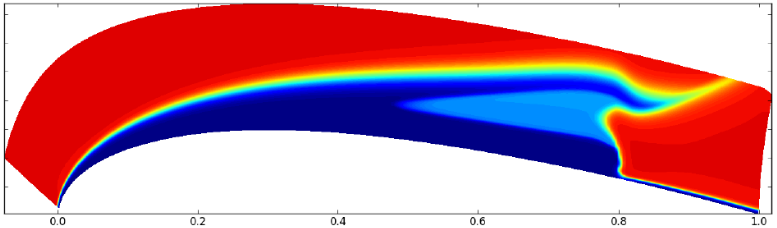
Characterization
Measurement
Modeling


Heavy blade erosion[2]

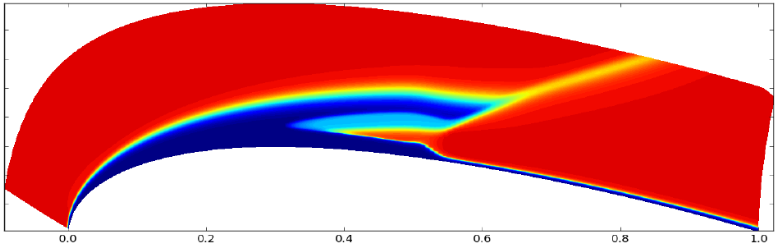

Insect roughness[3]


Leading edge blade erosion[4]


Oran W. Nicks Low Speed Wind Tunnel



No Roughness



k_s = 350 μm

Manufacturing Cost Reduction

Sandia National Laboratories

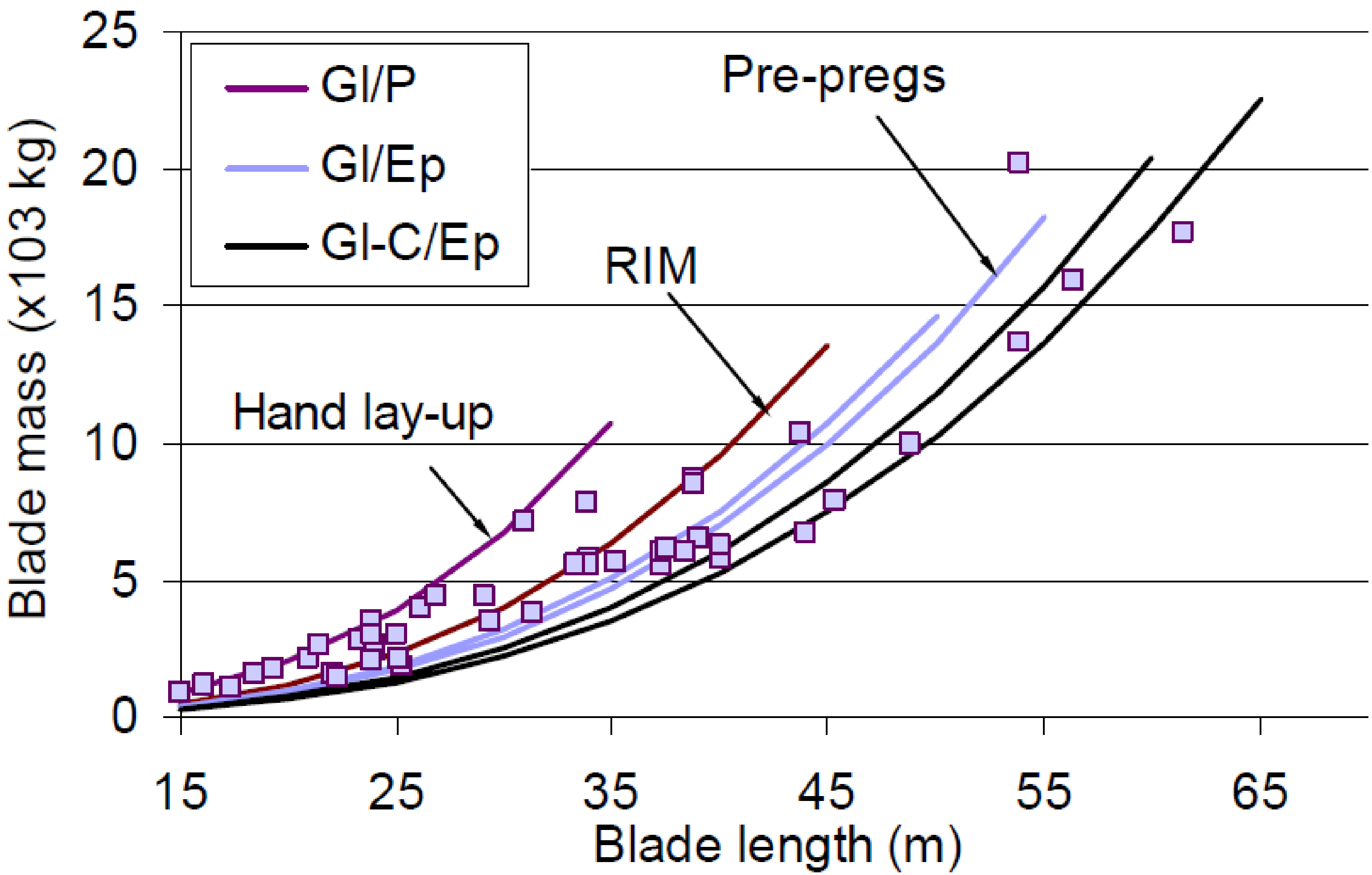
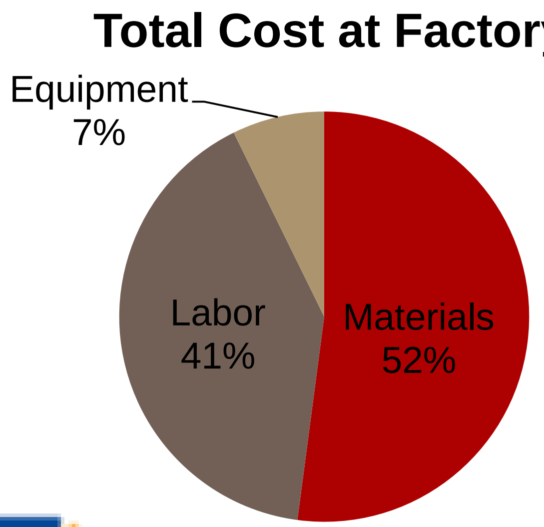


Figure 6 Blade mass trend with respect to technology

Source: UPWIND SCALING LIMITS & COSTS REGARDING WT BLADES 2010

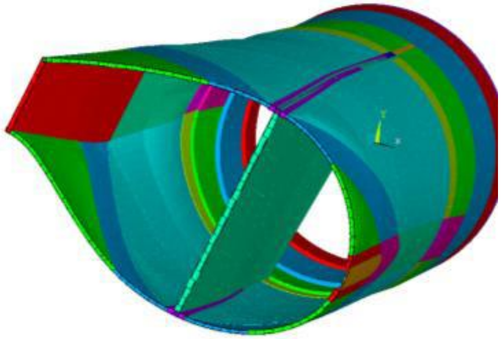
Advanced Manufacturing Initiative

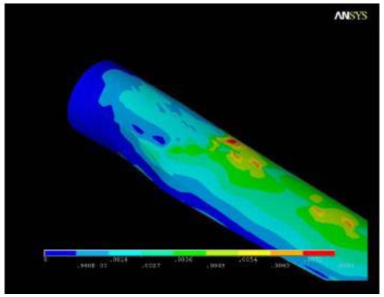
Increased labor productivity by ~14% and reduced cycle time by ~37% while maintaining or improving part quality (preliminary results).

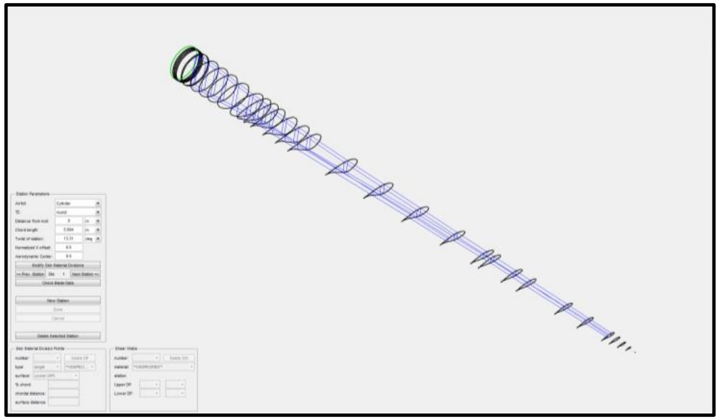


Blade Design Tools & System Modeling

- Design codes to analyze:
  - Structures
  - Aerodynamics
  - Control
  - Aero-servo-elastic stability
  - Manufacturing costs
- Public Tools:
  - NuMAD v.2
  - Structural blade models
  - Blade manufacturing cost model

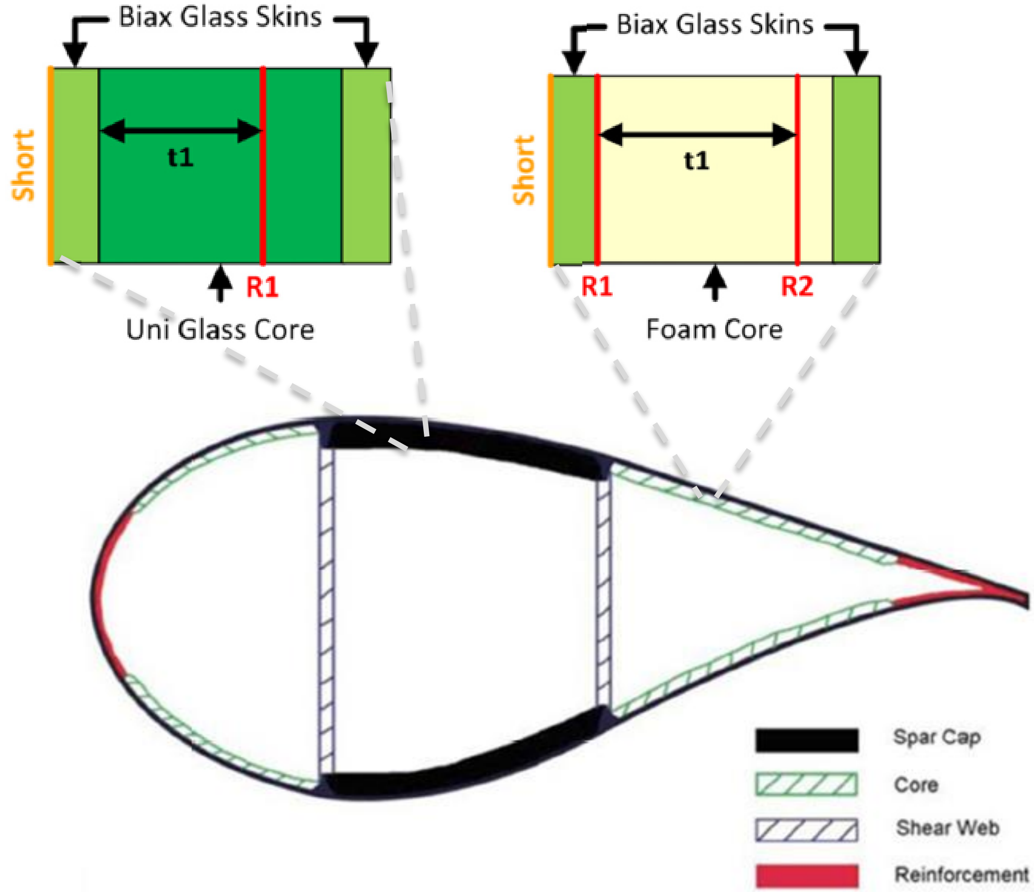


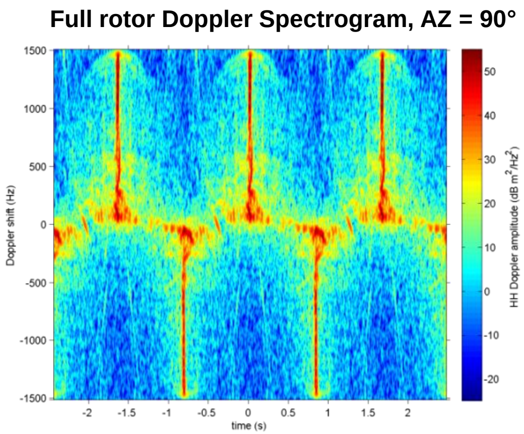


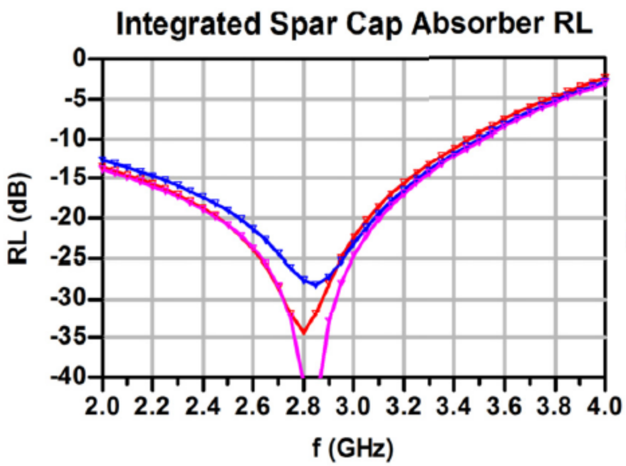


Radar friendly blade

Develop a low-cost material treatment compatible with current manufacturing processes that can reduce the RCS by 20 dB





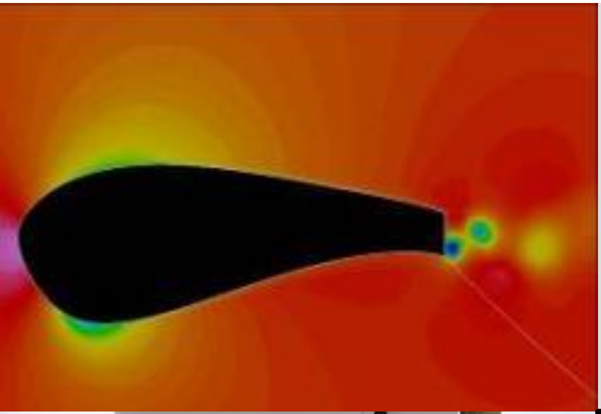


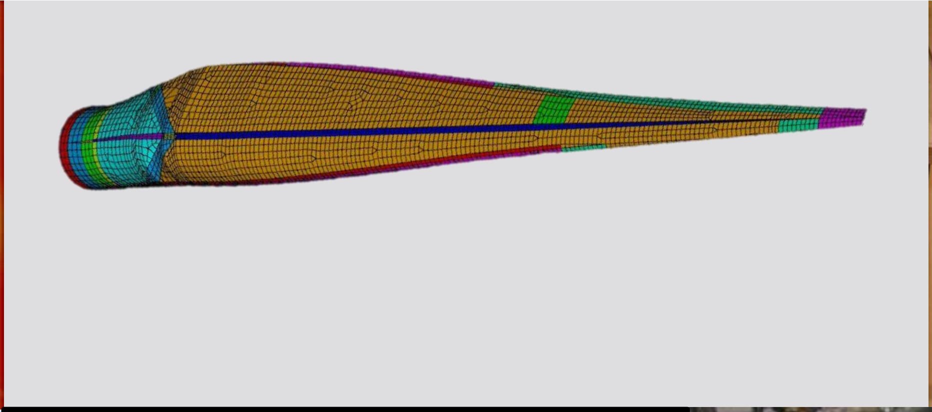
Source: Sandia National Laboratories

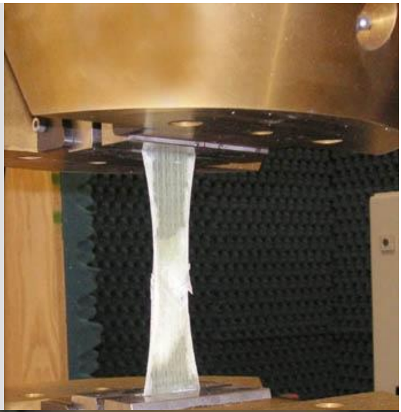
Funding and Partnerships

- Primary customer is Department of Energy Wind and Water Power Technologies Office
- Partnerships with industry and universities is common and instrumental to many research projects
- Various funding mechanisms exist to support partnerships as well as information sharing

Rotor Technology Integrators







Sandia National Laboratories

wind.sandia.gov