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Sandia National Laboratories

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

Large Offshore Rotor Development:

THE SANDIA 100-METER SERIES OF BLADE DESIGNS

Abstract

Design and development of large blades is very challenging due to economic, logistical, and technical barriers. This is a very challenging design problem, and one that becomes more challenging to do cost-effectively as blades grow even longer. Addressing these challenges is a major motivation behind this research. Sandia National Laboratories [Ref. 1] has been researching large blades at 100-meter length for several years and has documented several key design challenges [Ref. 2] for large blades in the course of this work, which include gravitational fatigue loading, panel buckling, and aero-elastic stability. Through a series of design studies for 100-meter blades, the goal has been to mitigate the technical challenges in order to achieve a *light-weight, cost-effective, manufacturable, and aero-elastically stable* large blade design. The final study focused on the effects of flatback airfoils and blade slenderness with respect to these challenges.

Background on Sandia 100-meter Design Studies

This research began with an all-glass baseline 100-meter blade design study that produced the SNL100-00 baseline design [Ref. 2]. The baseline design was heavy and not cost-effective due to elevated design pressures on structural requirements for fatigue, buckling, and deflection. Thus a series of follow-on studies and improvements were pursued to evaluate pathways to achieve:

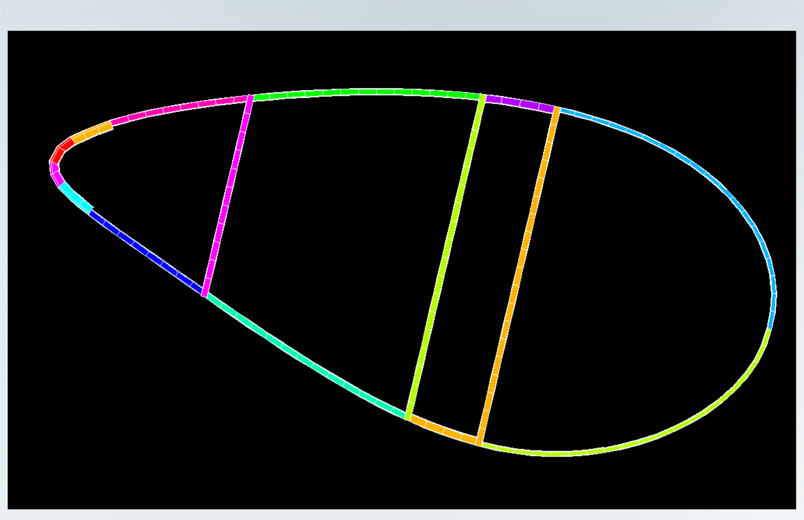
a light-weight, cost-effective, manufacturable, and aero-elastically stable 100-meter blade design.

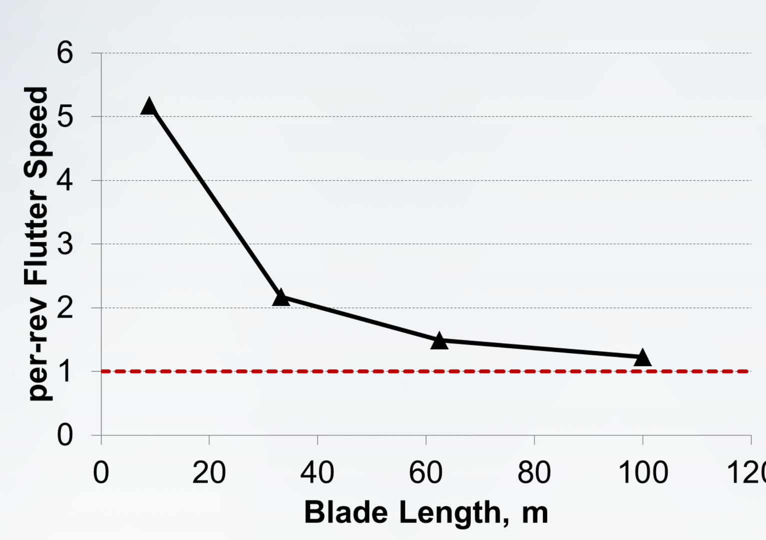
THE FOLLOW-ON STUDIES INCLUDING THE CURRENT STUDY ARE SUMMARIZED AS FOLLOWS:

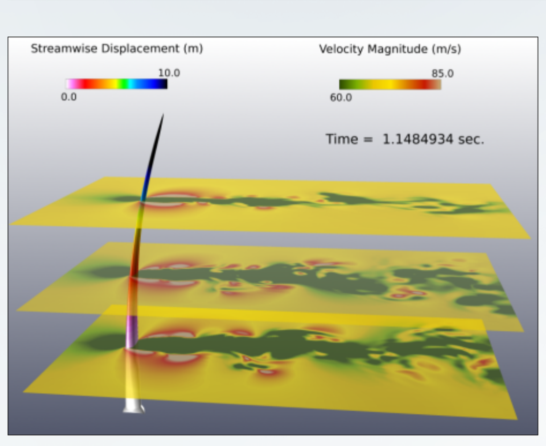
1. Flutter parametric study and flutter tool improvements [Ref. 3],
2. CFD analysis of the baseline design [Ref. 4],
3. Blade manufacturing cost modeling and trends analysis [Ref. 5],
4. SNL100-01 blade: carbon fiber study [Ref. 6],
5. SNL100-02: blade: advanced core material study [Ref. 7], and
6. SNL100-03: improved geometry with flatback airfoils.

The focus of the most recent study is design of blades with varying slenderness using flatback airfoils with attention to aerodynamic, structural, manufacturing, and economic trade-offs.

All-glass Baseline Blade:	SNL100-00	114 ton weight	Reference 2
Carbon Design Studies:	SNL100-01	74 ton weight	Reference 6
Advanced Core Material:	SNL100-02	59 ton weight	Reference 7
Advanced Geometry:	SNL100-03	<50 ton weight	Present Study

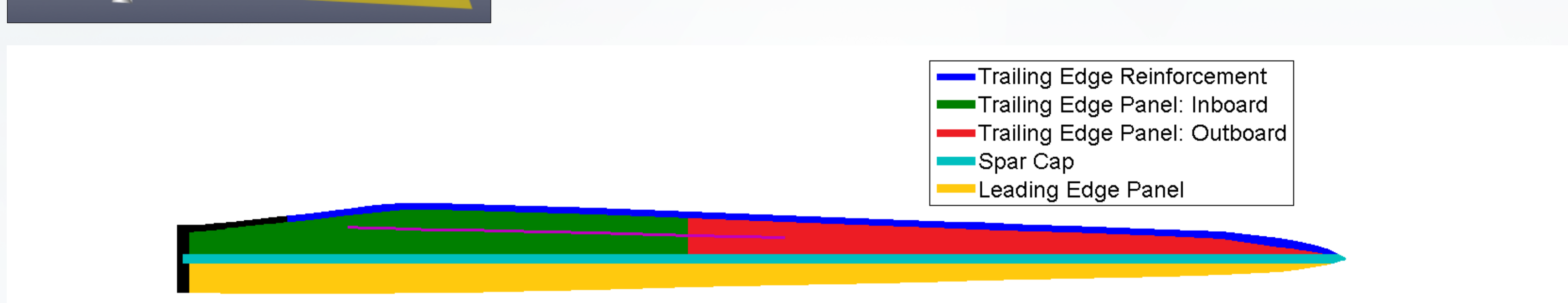






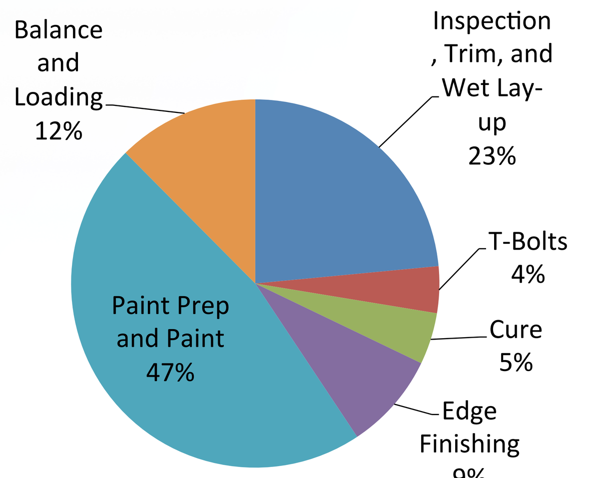
SEVERAL OF THE 100-M DESIGN STUDY RESULTS ARE SHOWN HERE:

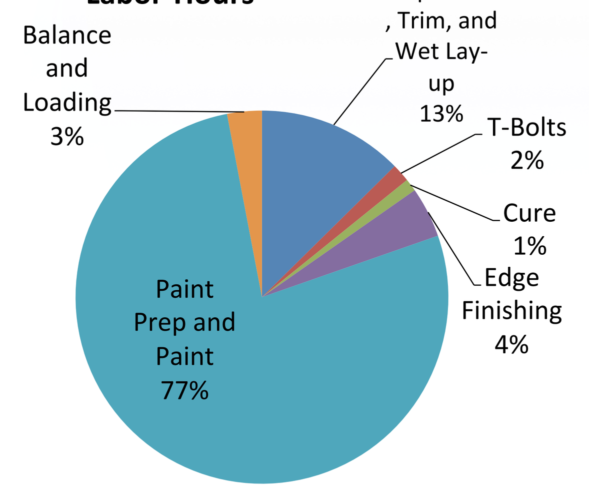
a) Panel buckling addressed using 3rd shear web
b) Flutter speed margin reduced for larger blades
c) High-fidelity CFD for design codes evaluation
d) Advanced core placement strategies



Manufacturing Cost Analysis

One example: An analysis of labor costs shows the growth in labor hours for area-driven manufacturing tasks such as paint prep and paint as blades grow longer [Ref. 5].



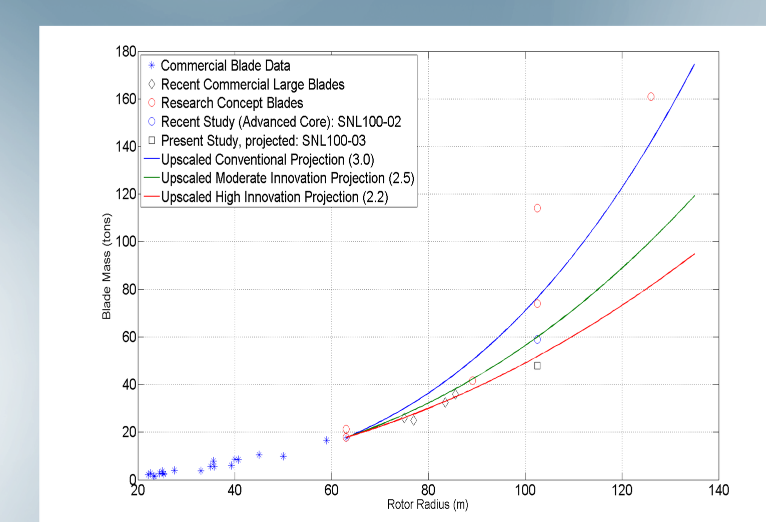


Large Blades: Survey of Industry and Research Concepts

The chart shows blade mass versus rotor radius including historical data for blades from 20 to 60 meters, recent commercial large prototype blades in the 70 to 80 meter range, and research concept blades of length 61.5, 86 [Ref. 9], 100, and 123 [Ref. 8] meters.

Mass projections from the 61.5 meter blade are plotted for three cases including conventional scaling (exponent of 3.0), moderate innovation (scaling of 2.5), and high innovation (scaling of 2.2).

The progress to higher innovation mass is shown for the Sandia 100-meter series at 102.5 meters radius.

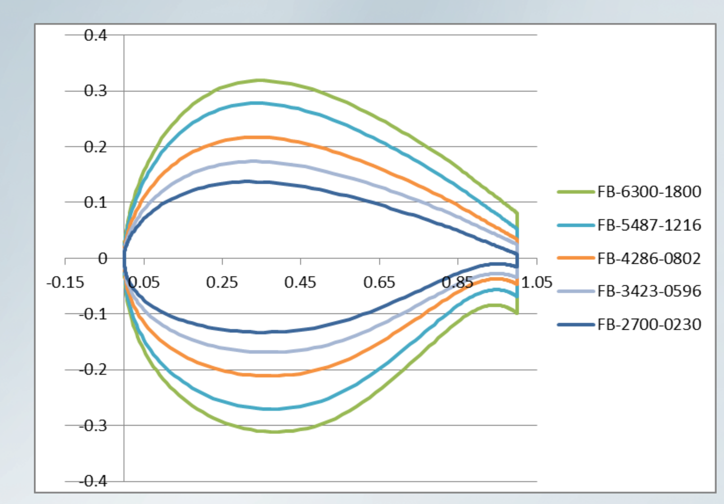


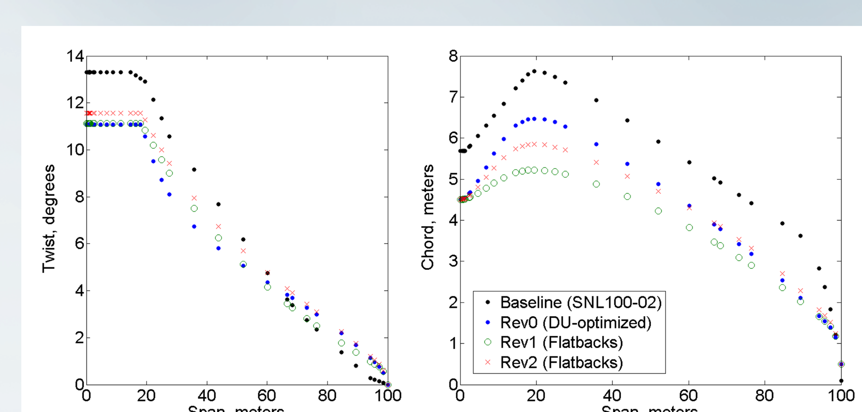
Pre-Design Geometry for the SNL100-03 100-meter Blade

The final design study is focused on the effects of flatback airfoils and blade slenderness for SNL100-03.

100-METER DESIGN VARIANTS IN THIS STUDY:

- "Baseline": SNL100-02 blade; up-scaled DOWEC chord
- "Rev0": With same DU foils but with updated geometry
- "Rev1": With flatback airfoils (more slender than Rev2)
- "Rev2": With flatback airfoils (less slender than Rev1)





Structural and aerodynamic performance constraints were included in the design process to produce these blade geometries.

AEP was constrained to be the same for all four design variants.

Pre-Design Geometry for the SNL100-03 100-meter Blade

The three new geometries were compared with respect to *blade weight, loads, deflection, fatigue, buckling, flutter speed, and surface area labor operations*. It should be stressed that neither the Rev0, Rev1, nor Rev2 designs are final designs as the tabulated data is intended to focus on the effects of airfoils and slenderness effects for similar layups (identical for Rev1 & Rev2). Systematically optimized designs will be the focus of the subsequent work that leads to a final SNL100-03 design that meets the stated design objectives.

	SNL100-02	SNL100-03: Rev0	SNL100-03: Rev1	SNL100-03: Rev2
Geometry Description	Baseline	DU-Optimized	More slender	Less Slender
Airfoil Family	DU	DU	Flatbacks	Flatbacks
Mass (kg)	59,047	53,146	50,530	53,671
Flap RBM (max) (kN-m)	111,900	87,410	74,930	92,600
Tip Deflection (m)	10.51	10.62	13.37	11.02
Spar Fatigue @ 15% (years)	646	4004	340	2641
Trailing Edge Fatigue @ 15% (years)	352	31.6	0.3	2.7
Lowest Panel Buckling Freq.	2.10	--	3.60	3.15
Flutter Speed Ratio	1.65	1.67	1.54	1.62
Surface Area (sq. meters)	1262	1021	886	979

References

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2. Griffith, D.T. and Ashwill, T.D., "The Sandia 100-meter All-glass Baseline Wind Turbine Blade: SNL100-00," Sandia National Laboratories Technical Report, SAND2011-3779, June 2011.
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9. Bak, Christian et al. "Light Rotor: The 10-MW reference wind turbine". Proceedings of EWEA 2012 - European Wind Energy Conference & Exhibition. EWEA - The European Wind Energy Association. 2012.

Acknowledgement

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Project Website: http://largeoffshorerotor.sandia.gov

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Blade Reliability Collaborative

Blade reliability issues related to manufacturing, transportation, installation, and operation can have large effects on COE as blade failures can cause extensive down time and lead to expensive repairs.

The Blade Reliability Collaborative will improve the reliability of blades delivered to the field so that remediation work before operation can be eliminated and the service lifetimes can achieve the 20 year targets that are expected by wind plant operators and financiers.

Core Areas of Research

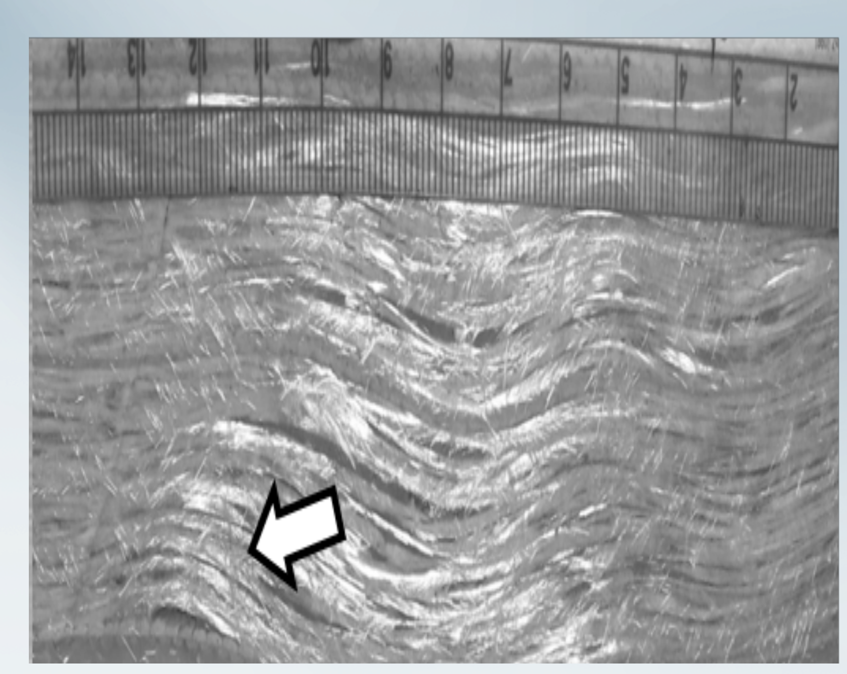
INSPECTION TECHNOLOGIES
Evaluate the ability of inspection techniques to accurately characterize blade defects and damage in manufacturing plants and in the field

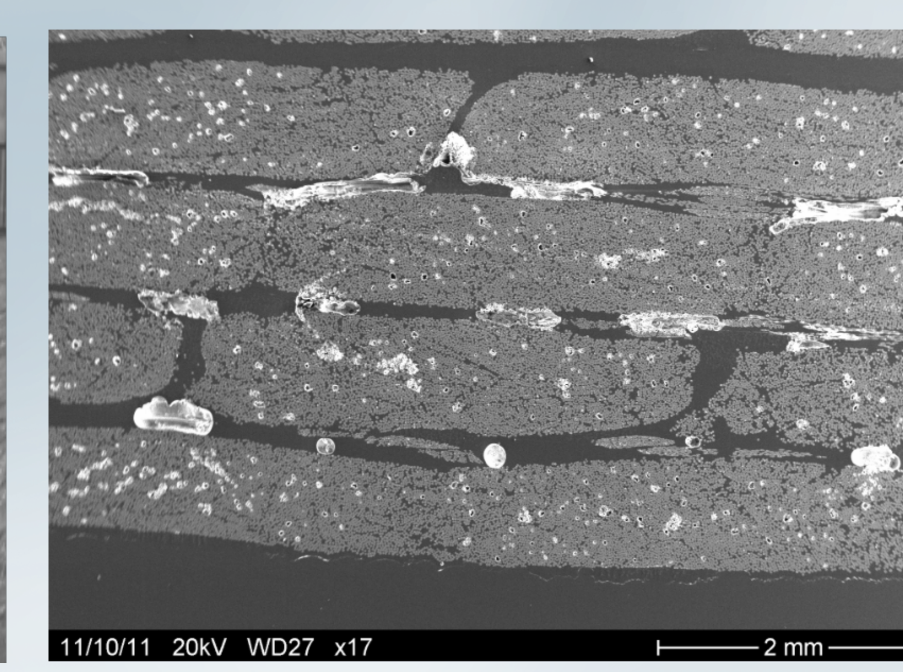
EFFECTS OF DEFECTS
Determine how common manufacturing defects affect blade strength and service life

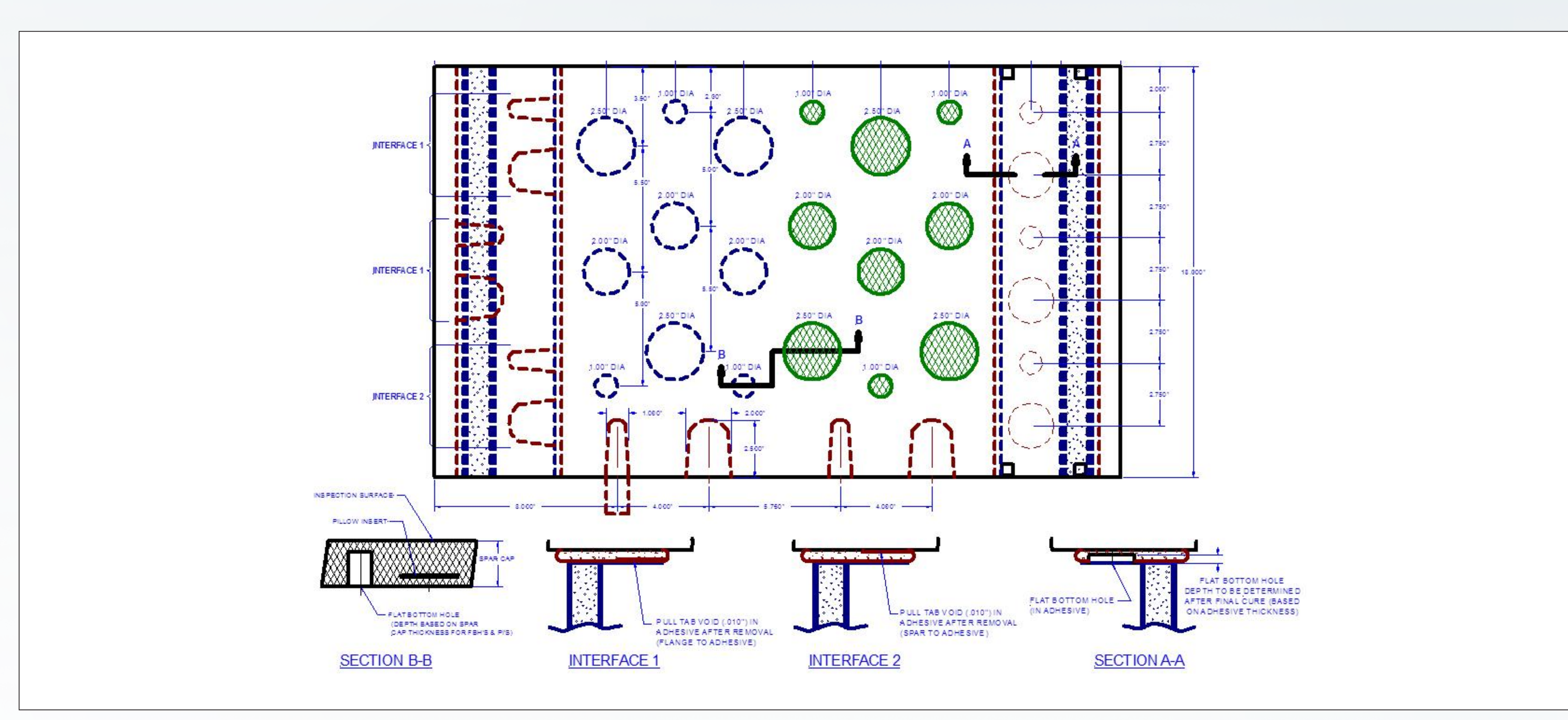
LEADING EDGE EROSION
Assess the impact and causes of erosion on blades

BLADE REPAIRS
Define best practices to repair damaged blades to regain structural and aerodynamic performance

STANDARDS AND PARTNERSHIPS
Interface with international standards committees and industrial partners to identify pathways to implementing improved design, manufacture, and inspection

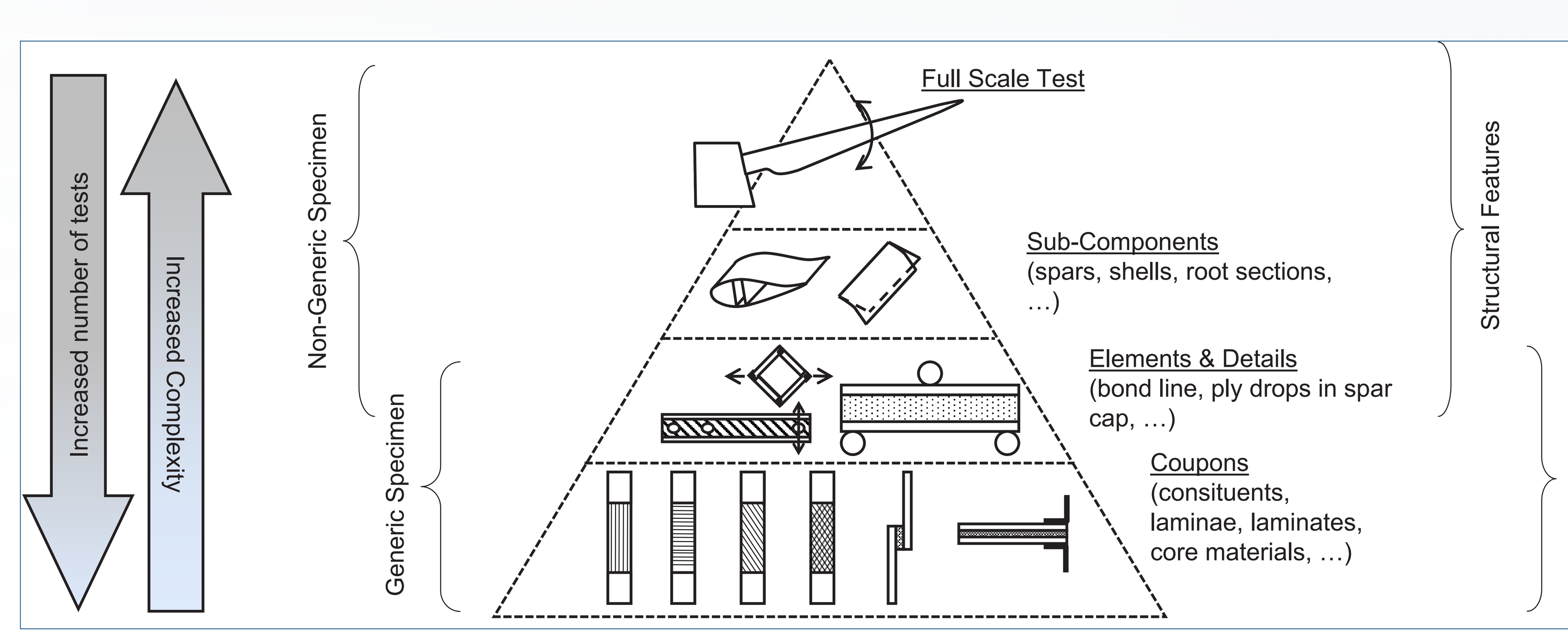






Partners

- National Renewable Energy Laboratory, Montana State University, Electric Power Research Institute: Jon Lindberg
- TPI Composites, MFG, Rope Partners, GE, Vestas, Gamesa, Iberdrola, EDPR, Laser Technology, Dantec Dynamics, and over 20 other NDI suppliers.



Continuous Reliability Enhancement for Wind (CREW) Database & Analysis Program

BENJAMIN KARLSON, JON WHITE, CHUCK CARTER, CARSTEN WESTERGAARD, SHAWN MARTIN

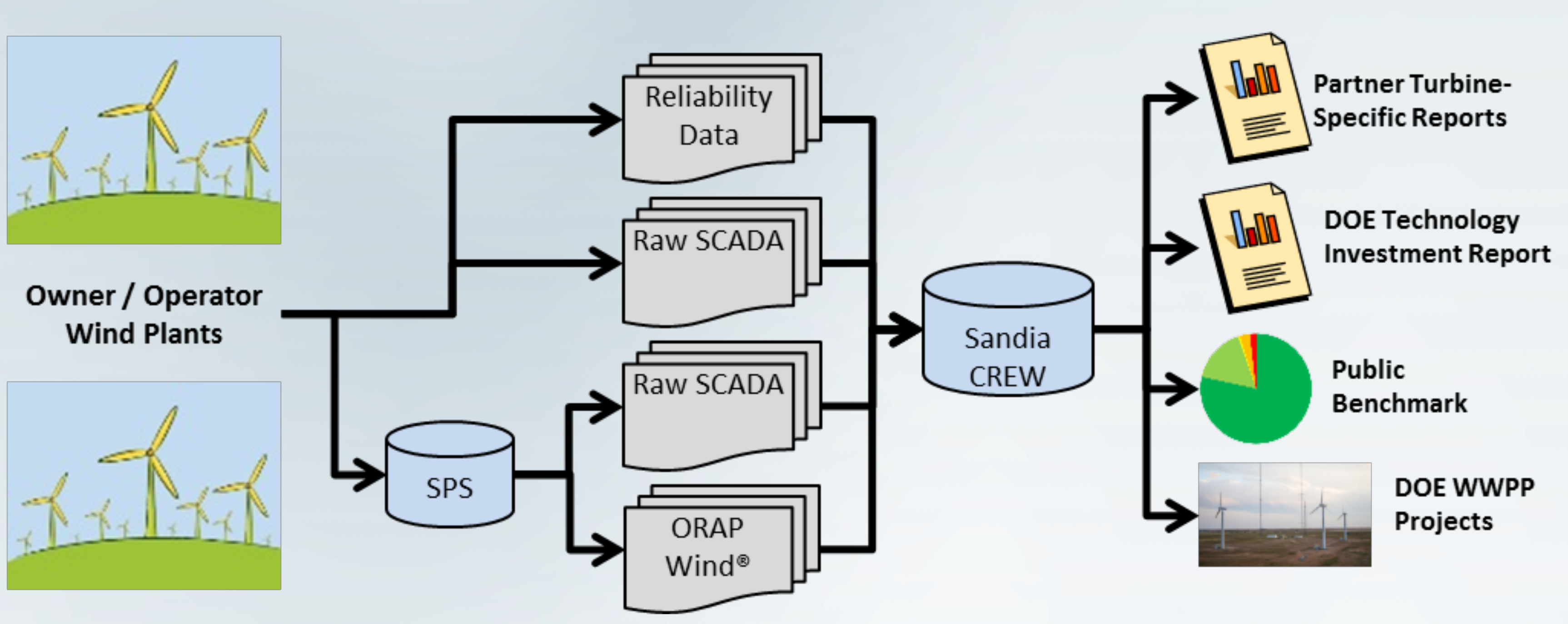
Sandia National Laboratories, Wind and Water Power Technologies

Introduction

The "20% Wind Energy by 2030" report (Department of Energy, 2008) specifically discusses financial risks from increasing Operations and Management (O&M) costs and the impact of lower-than-expected reliability. With the Department of Energy sponsorship, Sandia National Laboratories established the CREW (Continuous Reliability Enhancement for Wind) program to benchmark the U.S. wind turbine fleet's reliability and O&M performance, help prioritize technology improvement opportunities, and assess plant-level performance.

In 2013, an internal reassessment of the CREW effort was performed to identify the value of the benchmark, the gaps in the data, and opportunities to be better aligned with the wind industry. The reassessment found that wind plant owner/operators have been developing in-house reliability data collection tools with similar goals to the CREW project and that the original CREW strategy has been overtaken by a fast growing wind industry. However, a national reliability benchmark remains highly desirable for the wind industry to assist with their objectives of maximizing power performance yield, decreasing financial risk and uncertainty, and understanding reliability trends across turbine models, turbine components, geographical locations, and age.

Methods



Data Collection

Sandia partnered with Strategic Power Systems (SPS), whose ORAPWind© (Operational Reliability Analysis Program) software collects real-time data from wind plant partners, including information from their Supervisory Control and Data Acquisition (SCADA) systems. In 2014, another data pathway was added, for summarized data directly from owners/operators.

Data Aggregation Steps

1. Gather sufficient data (duration, breadth) to aggregate without violating anonymity.
2. Create individual plants models and perform time accounting.
3. Create the aggregate reliability model with event frequencies and durations, by weighing individual plants models by their number of turbine-days. Also, create aggregate time accounting by summing turbine hours across plants.

Data Reporting Goals

PUBLIC BENCHMARK

- Provide public-domain reliability information

PARTNER REPORTS

- Create proprietary, plant-specific reports

DEPARTMENT OF ENERGY TECHNOLOGY INVESTMENT REPORTS

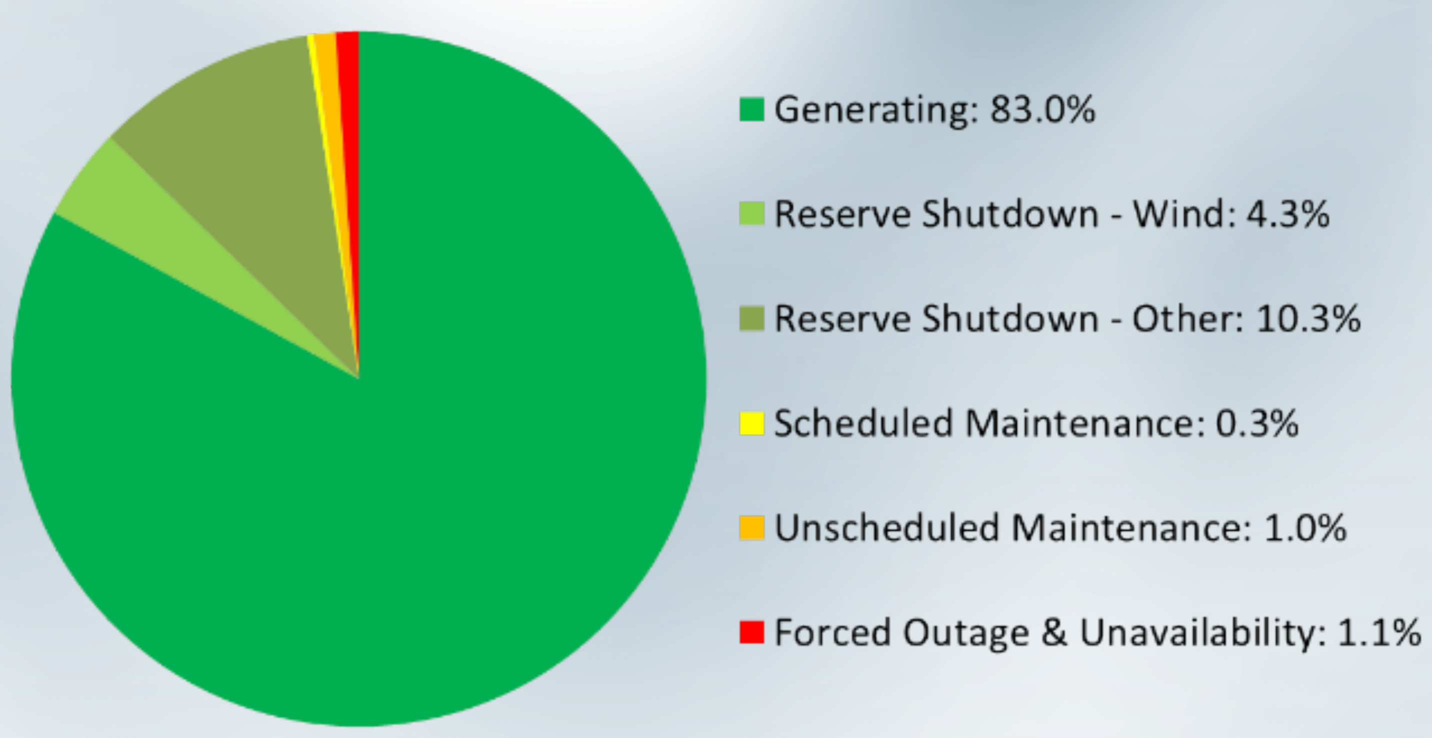
- Identify Technology Improvement Opportunities

TECHNOLOGY RESEARCH AND TOOL DEVELOPMENT

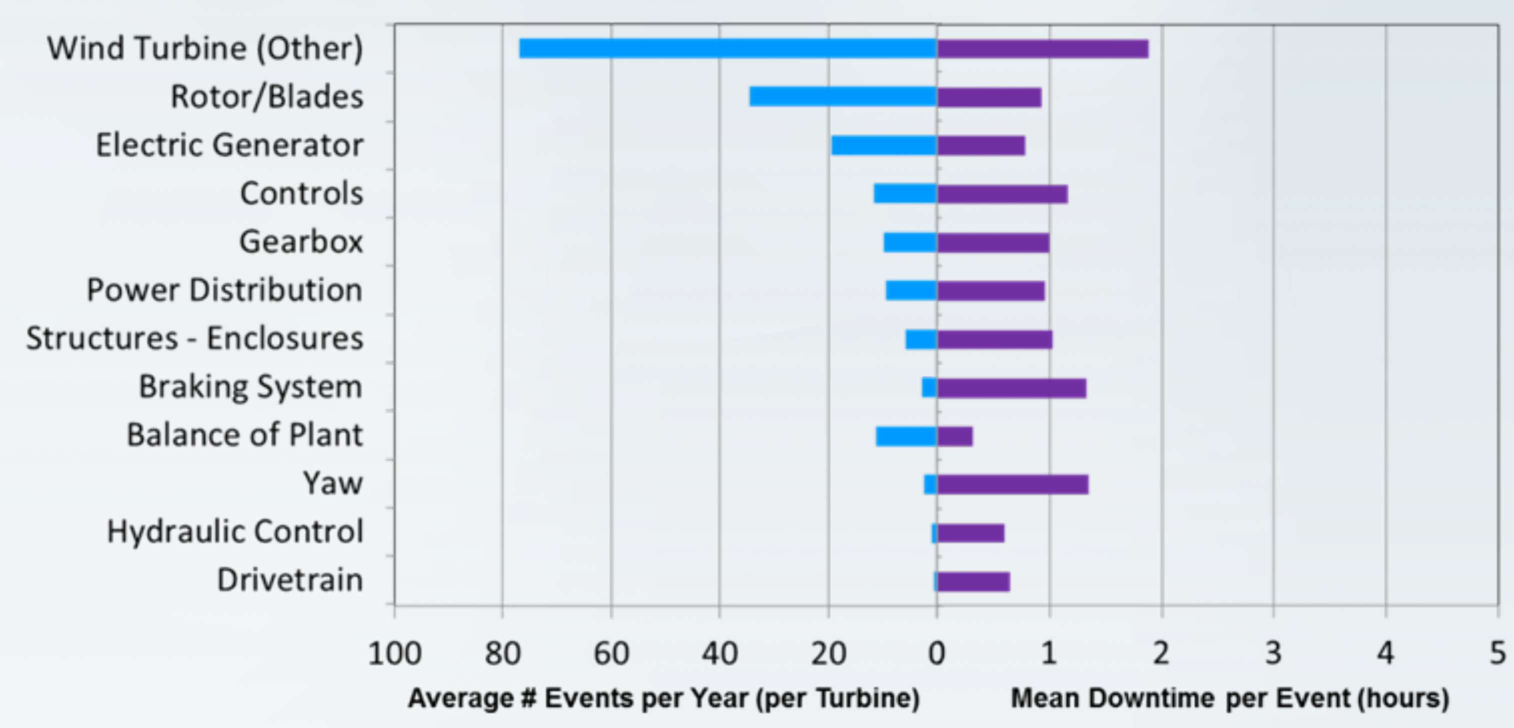
- Research plant-level performance and develop associated software

2013 Benchmark Results

Availability Time Accounting



Downtime Event Summary, By System



Conclusions

- Average Benchmark wind plant has 97.6% Availability at a turbine-level (Generating & Reserve time)
  - Results are stabilizing and generally align with other published industry metrics
- More owner/operators insight is critical to understand the complete reliability picture, including component-level issues

Proposed Future Work

- Expand national benchmark to better represent the U.S. fleet and gather more owner/operator insight
- Develop technology-exploration platform to create software tools for the industry

Expected Data partner Benefits

The investment costs for wind farm projects are high. The cost of O&M of wind turbines is partially a function of the reliability of the system components. CREW participation will benefit owner/operators through improved asset performance and reliability maximizing power performance yield, decreasing financial risk and uncertainty, and better understanding of reliability trends.

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Jon White jonwhit@sandia.gov

EVENT & SCADA DATA SOURCE:

SPS ORAPWind

The full Benchmark can be accessed at http://energy.sandia.gov/crewbenchmark

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Wind Blade Material Testing

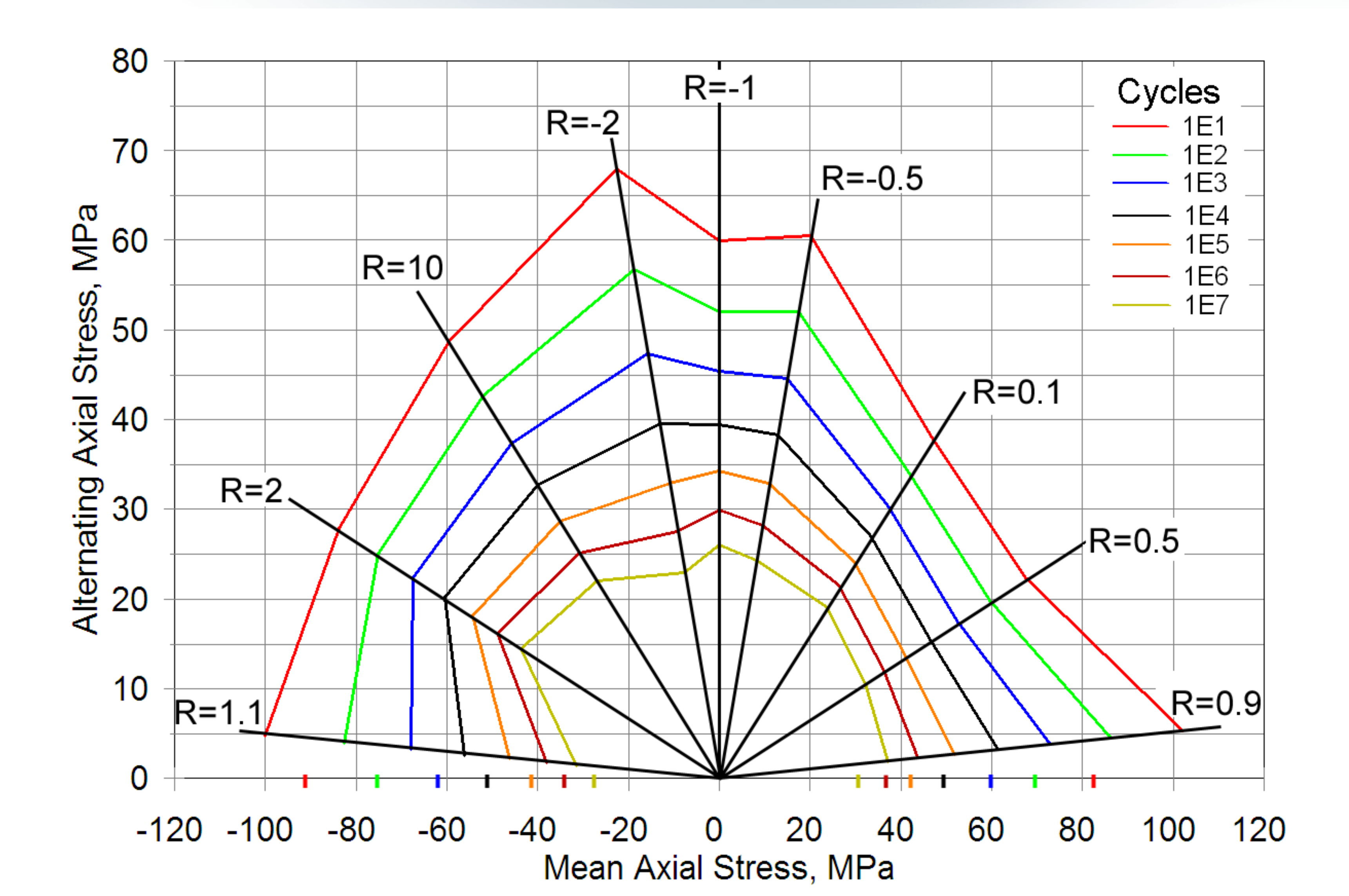


Figure 1. *Constant Life Diagram of a biaxial glass-epoxy laminate under alternating axial stress. Publicly available data such as this represent thousands of tests conducted over years making it infeasible for most material suppliers to conduct on their own.*

Scaling Up

Traditional blade testing consists of coupon-scale tests and full blade tests (Figure 3), but this approach is insufficient for designing the next generation of blades. Subscale structural testing (Figure 2) helps blade designers refine assumptions and improve blade reliability and cost.

Sandia Independent Testing

RESEARCH to improve materials performance and lifetime prediction in blades (Figure 1)

DIRECT SUPPORT OF US INDUSTRY: Characterization of current and potential blade materials from suppliers (resins, fabrics, adhesives, cores), and laminates and structural details from blade manufacturers

PUBLIC DATA: DOE/SNL/MSU Fatigue of Composite Materials Database is available free here: http://energy.sandia.gov/?page_id=19096

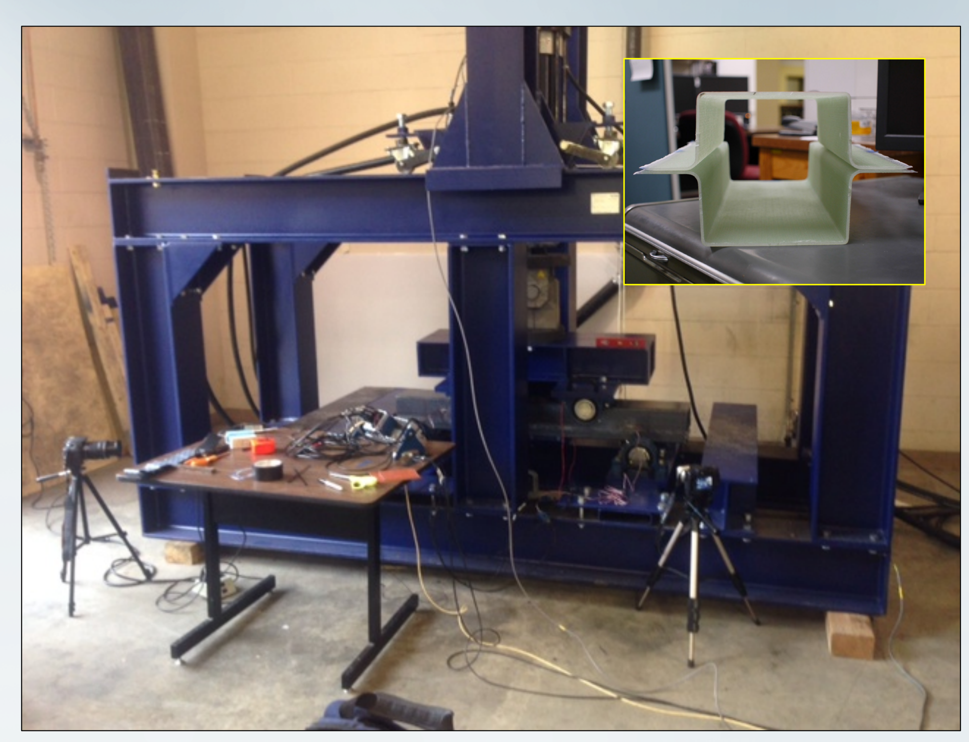
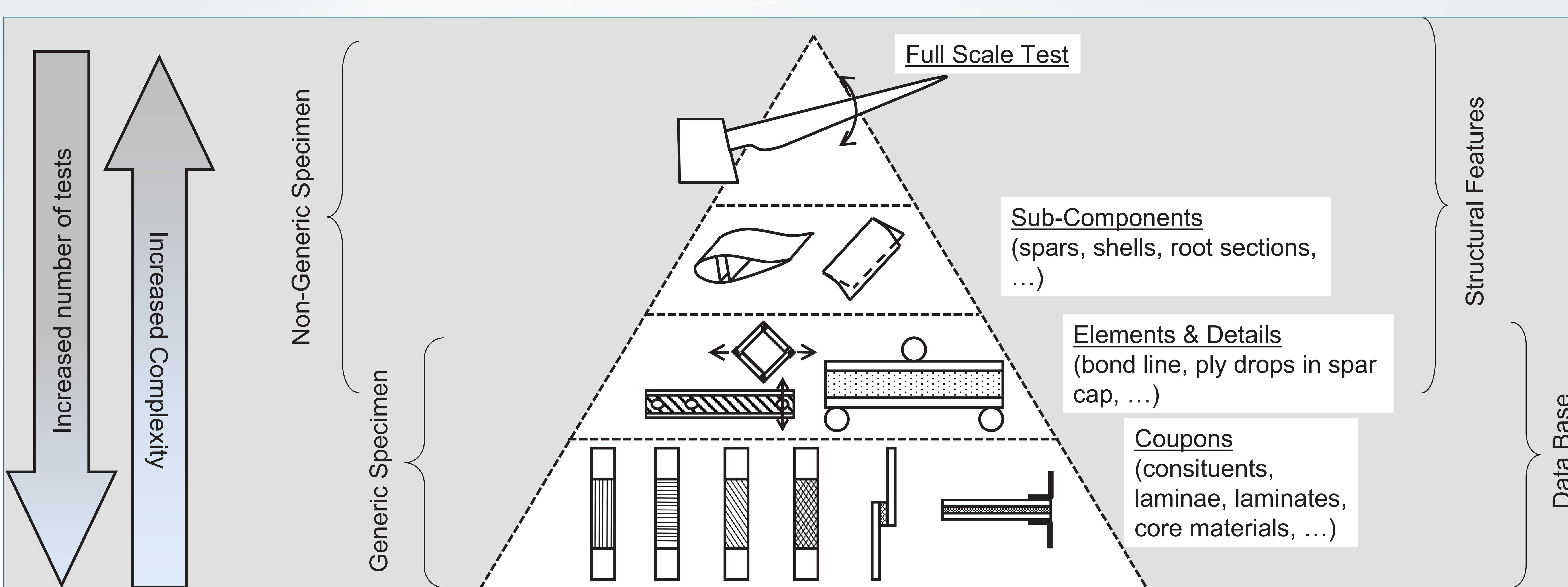


Figure 2 (left). *A new subscale test fixture at Montana State University will enable testing to build a database of structural elements (inset) in addition to the existing coupon tests.*

Figure 3 (below). *A building-block approach to blade testing and simulation based upon a framework developed for aerospace will provide more accurate test data to improve design software and increase reliability of new blade designs.*



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2014 Wind Turbine Blade Workshop
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Siting – Radar: Wind Turbine RCS Mitigation

BENJAMIN KARLSON, BRUCE LEBLANC, BRIAN NAUGHTON

Sandia National Laboratories, Wind and Water Power Technologies

1. Introduction

Wind turbines have grown in size and capacity with today's average turbine having a power capacity of around 2.15 MW, reaching to heights of over 495 feet from ground to blade tip, and operating with speeds at the tip of the blade up to 200 knots. When these machines are installed within the line-of-sight of a radar system, they can cause significant clutter and interference, detrimentally impacting radar performance.

The goals of this project are to characterize the impact of wind turbines on current air surveillance radars, assess new technologies for near-term mitigation, and gain a better understanding of the issues to enable development of long-term strategies and reduce the barrier for wind energy deployment.

2. Project Areas

This effort is divided into 3 project areas:
1. Radar Cross Section (RCS) Reduction of Wind Turbines;
2. The Interagency Field Test & Evaluation (IFT&E) Program; and
3. The Tool for Siting, Planning and Encroachment Analysis, for Renewables (TSPEAR)

2a. Wind Turbine Blade RCS Reduction

Objectives

The wind industry has successfully followed an evolutionary process moving toward minimum cost, minimum weight, and high-efficiency designs, but interference with radar systems remains a problem. Some objectives of this effort include:
- Understanding the radar-to-wind-turbine interaction and potential techniques suitable for application at the turbine;
- Developing wind-turbine-radar-cross-section modeling capability for the purpose of understanding the turbine's signature and evaluation RCS reduction approaches;
- Developing and evaluating radar-absorbing materials (RAM); and
- Demonstrating that effective RAM can be integrated into blade fabrication process

Significant Findings

The integrated-absorber designs indicate that 20 dB or greater return loss can be achieved by integrating simple RAM into the existing blade fabrication processes. However, 20 dB return loss does not necessarily correspond to 20 dB RCS reduction for a complete turbine.

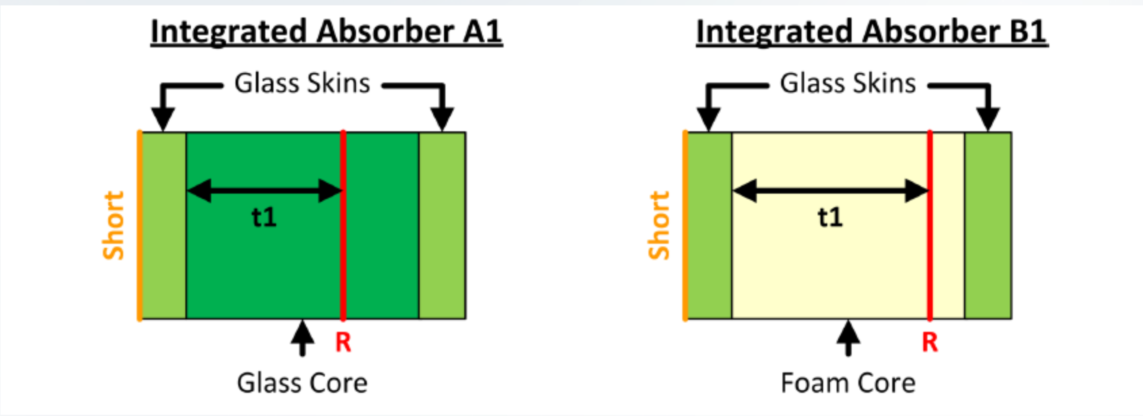


Figure 1- Integrated absorber design parameters include RAM position, RAM conductivity, and composite material properties

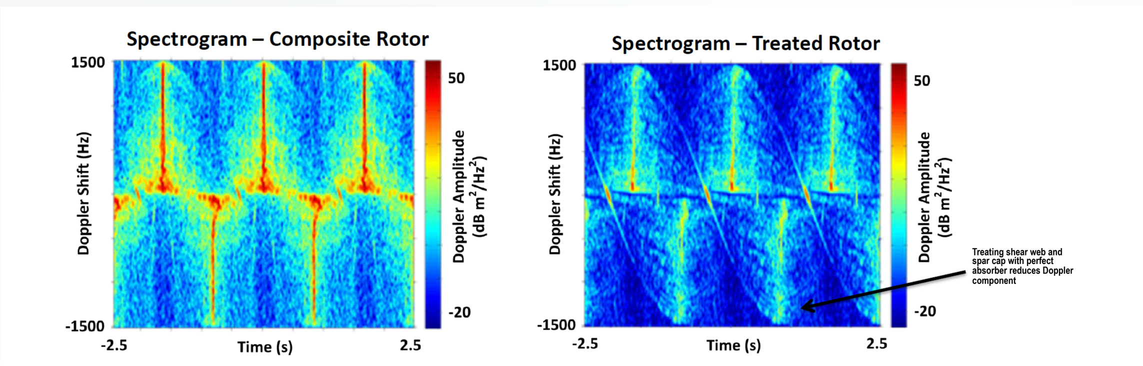
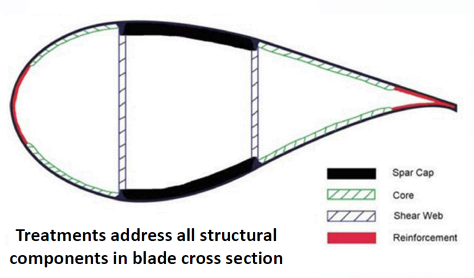


Figure 2- Sandia modeled RCS of 60 m blade. Models identify key areas requiring RAM treatment

RAM integrated in vacuum assisted resin transfer molding (VARTM) with no process modification. Treatments developed for both solid composite and sandwich constructions.



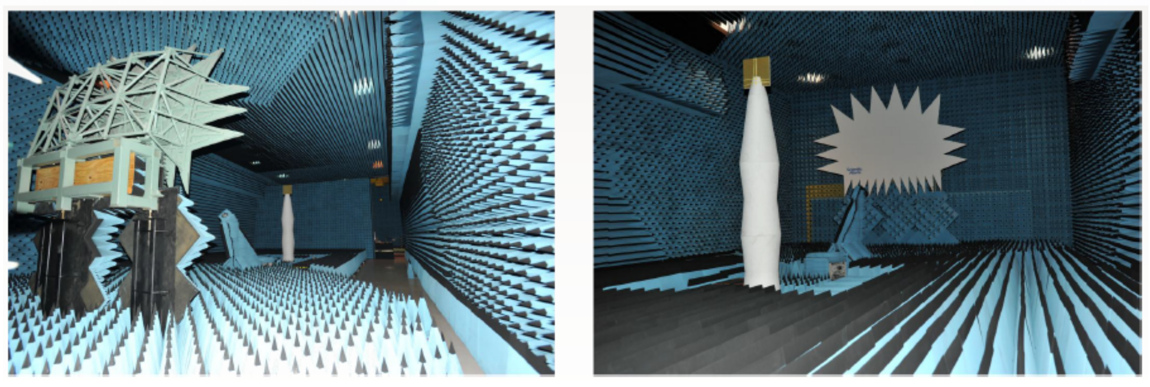


Figure 3- Integrated absorber design were measured at Sandia's facility for antenna and RCS measurement

2b. Interagency Field Test & Evaluation

Objectives

The Interagency Field Test and Evaluation (IFT&E) program was established to investigate and address the concerns of growing interference of wind turbines on the Nation's air surveillance radars. The program has three primary goals:
1. Characterize the impact of wind turbines on existing Program-of-Record (POR) air surveillance radars;
2. Assess near-term mitigation capabilities proposed by industry; and
3. Collect data and increase technical understanding of interference issues to advance development of long-term mitigation strategies.

Technical Approach

DOE and DOD recognized the wind turbine / radar interference problem and began to formally address it in 2010. Sandia and MIT Lincoln Laboratory partnered to conduct field test campaign over 2 years. A Request for Information (RFI) for proposed mitigation options was issued and responses collected.

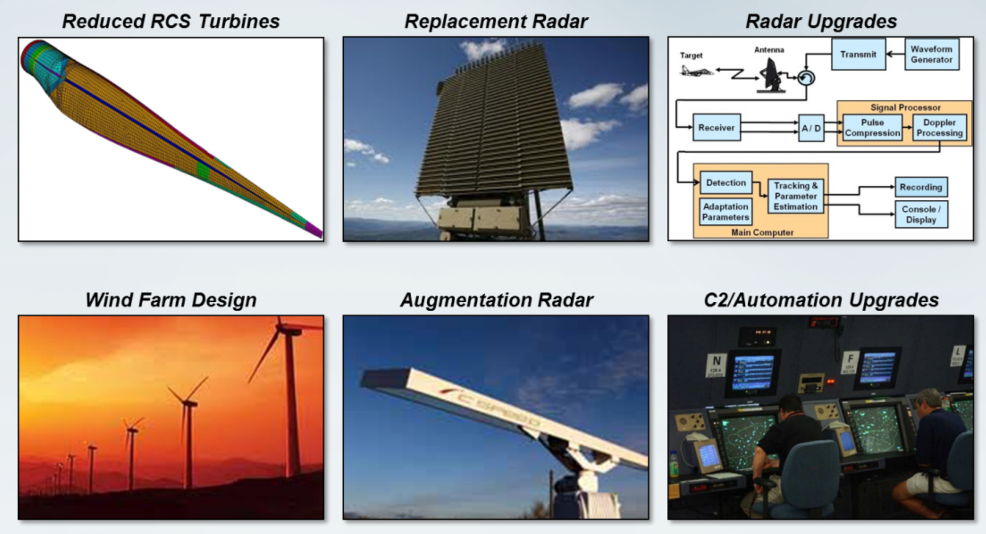


Figure 4- Proposed Wind turbine / radar interference mitigations

3 flight test campaigns were conducted at operational radar sites impacted by wind turbines.
- A CARSR in Tyler, MN – Apr 2012
- An ASR-11 in Abilene, TX – Oct 2013
- An ARSR-4 in King Mountain, TX – Apr 2013

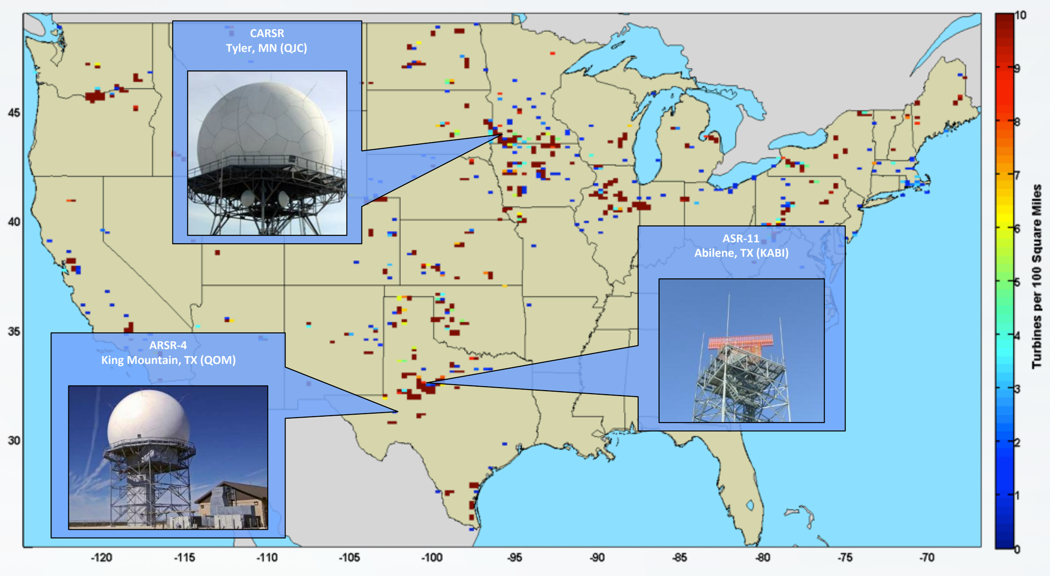


Figure 5- IFT&E Test Locations and tested Radar Systems

Significant Findings

Wind turbines cause problems for existing radars:
- Decrease sensitivity
- Increase false tracks
- Corrupt track quality

Several potential mitigation strategies exist
- Replace or augment radar
- New wind turbine design, or layout
- Improve signal and/or data processing

Several solutions show promise, no silver bullet
- High false alarm rates
- Integration questions
- Tracker performance

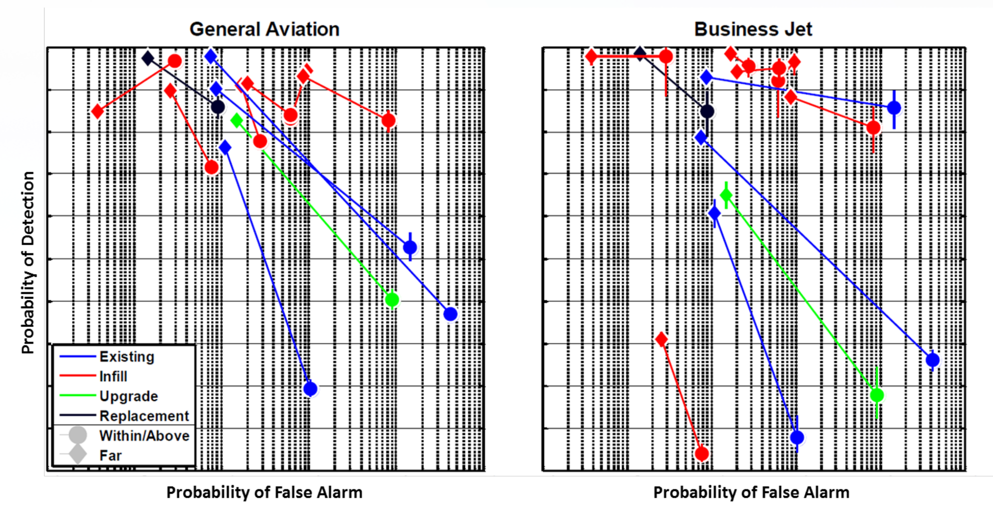


Figure 6- Probability of detection and false alarm summary of tested systems

2c. TSPEAR

Objectives

Tool for Siting, Planning and Encroachment Analysis for Renewables. This effort to develop accurate wind turbine / radar interference models will ultimately improve the understanding of the impact, and allow viable paths to increase the deployment of wind energy across the county. The TSPEAR toolkit aims to support energy developers and government agencies who desire to design, analyze, track progress, and maintain configuration control of complex energy projects. The initial effort is to support wind energy analysis with regard to radar systems.

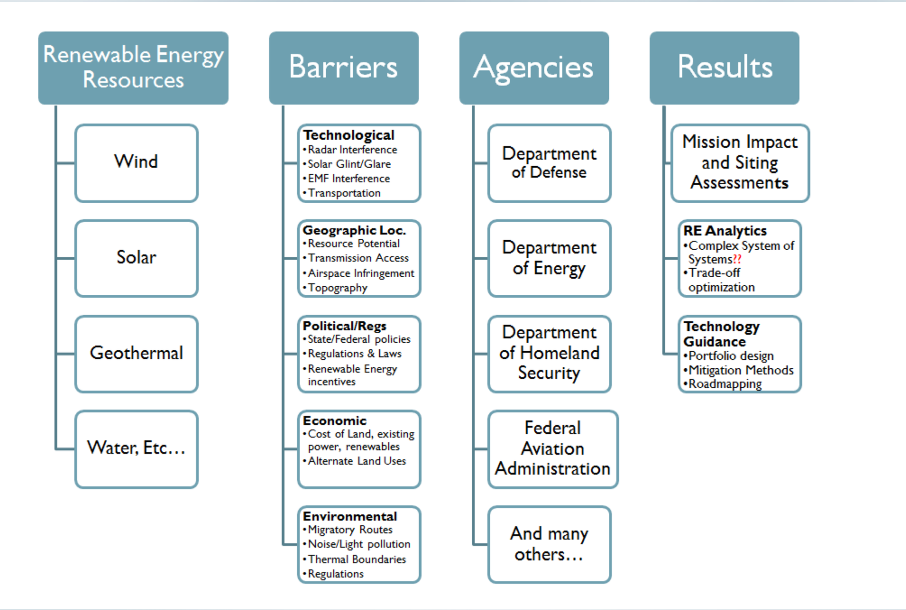


Figure 7- Envisioned scope of TSPEAR

Technical Approach

TSPEAR is designed to be a web-based siting, planning and assessment tool that supports renewable energy deployment. It is envisioned to be a state-of-the-art suite integrating new and existing tools and databases with quantitative underpinnings to support decision making. This effort is organized into a multi-phase approach to properly develop the TSPEAR framework:
- Phase I: Development of TSPEAR foundational framework; inclusion of radar assessment tab for CARSR;
- Phase II: Addition of radar models (ASR 9, ASR-11, and ARSR-4);
- Phase III: Addition of radar mitigation tools; connect to other databases (TBD)

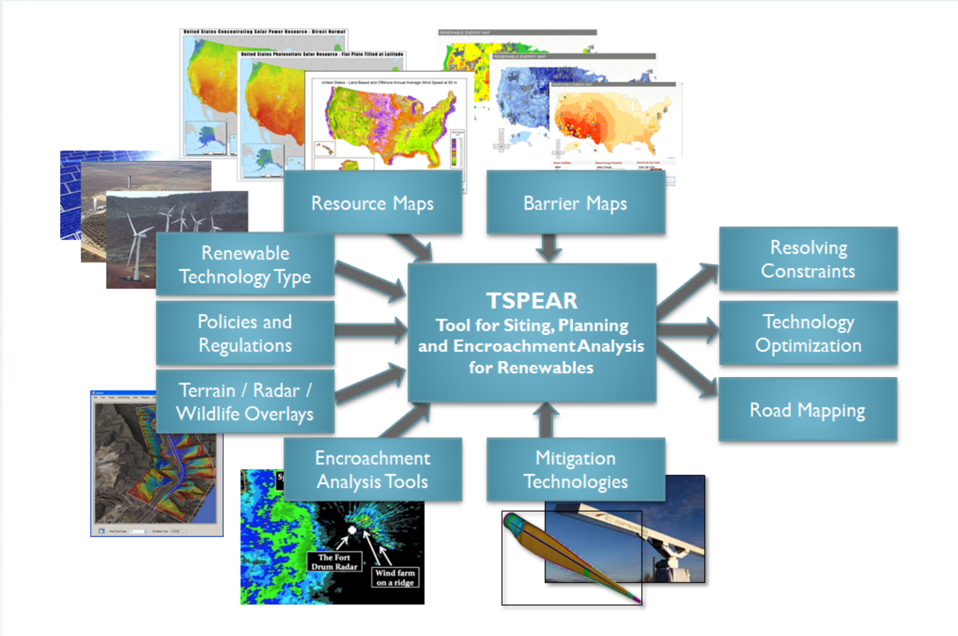


Figure 8 - TSPEAR web-based approach

4. Summary of Results and Findings

As part of DOE's approach to address siting barriers, Sandia has:
1. Investigated radar-absorbing materials (RAM) and blade fabrication processes that indicate a 20 dB reduction can be achieved;
2. Supported the IFT&E program to test and evaluate existing surveillance radars and proposed wind turbine-radar interference (WTRI) mitigation technologies which found promising results and has led to a Pilot Mitigation Project for future wind farms with radar interference issues; and
3. Developed a web-based framework (TSPEAR Phase I) with functional CARSR, ARSR-4, and ASR-9 models that can evaluate impacts of proposed wind farms.

5. Proposed Future Work

The WTRI effort will continue as more wind farms are proposed near radar systems. Sandia is investigating the options for an offshore WTRI field test. Sandia will continue to support the strategic WTRI plan and will assist in any potential Pilot Mitigation Projects. Additionally, Sandia will continue to improve upon the TSPEAR framework and incorporate other critical siting databases such as environmental, transmission, cultural, etc.

For more information, contact: Benjamin Karlson, bkarlso@sandia.gov

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Sandia National Laboratories

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

Reliability and Operations and Maintenance (O&M) Standards Development

Sandia National Laboratories, Wind Energy Technologies

Introduction

The National Standards Policy Advisory Committee defines a "Standard" as:

A prescribed set of rules, conditions, or requirements concerning definitions of terms; classification of components; specification of materials, performance, or operations; delineation of procedures; or measurement of quantity and quality in describing materials, products, systems, services, or practices.

The wind industry benefits from unbiased third parties engaging in the discussions about technical and performance criteria that inform Standards development. Sandia's unique expertise, especially in high-performance computing and reliability data and analysis, is needed to improve fact-based Standards which benefit market interactions.

Methods

Sandia has worked on a variety of Standards and Best Practices over the years. In FY2012-2014, the work included

- International Electrotechnical Commission (IEC) 61400-1 Design Requirements Standard
- IEC 61400-26 Availability Standard
- International Energy Agency (IEA) Task 33 Reliability Data Best Practices
- American Wind Energy Association (AWEA) Operations and Maintenance (O&M) Best Practices

Sandia's resources and expertise in high-performance computing , along with a strategic partnership with the University of Texas-Austin, creates a modeling competence used to evaluate the 61400-1 Design Requirements (Loads) Standard in an unbiased, fact-based environment. Sandia's long history in reliability analysis and expertise from the CREW reliability project uniquely positions Sandia to contribute to Standards and Best Practices in reliability, availability, O&M, and data collection and reporting.

497 Teraflops/sec
World Rank (2010): #10
(2013): #71

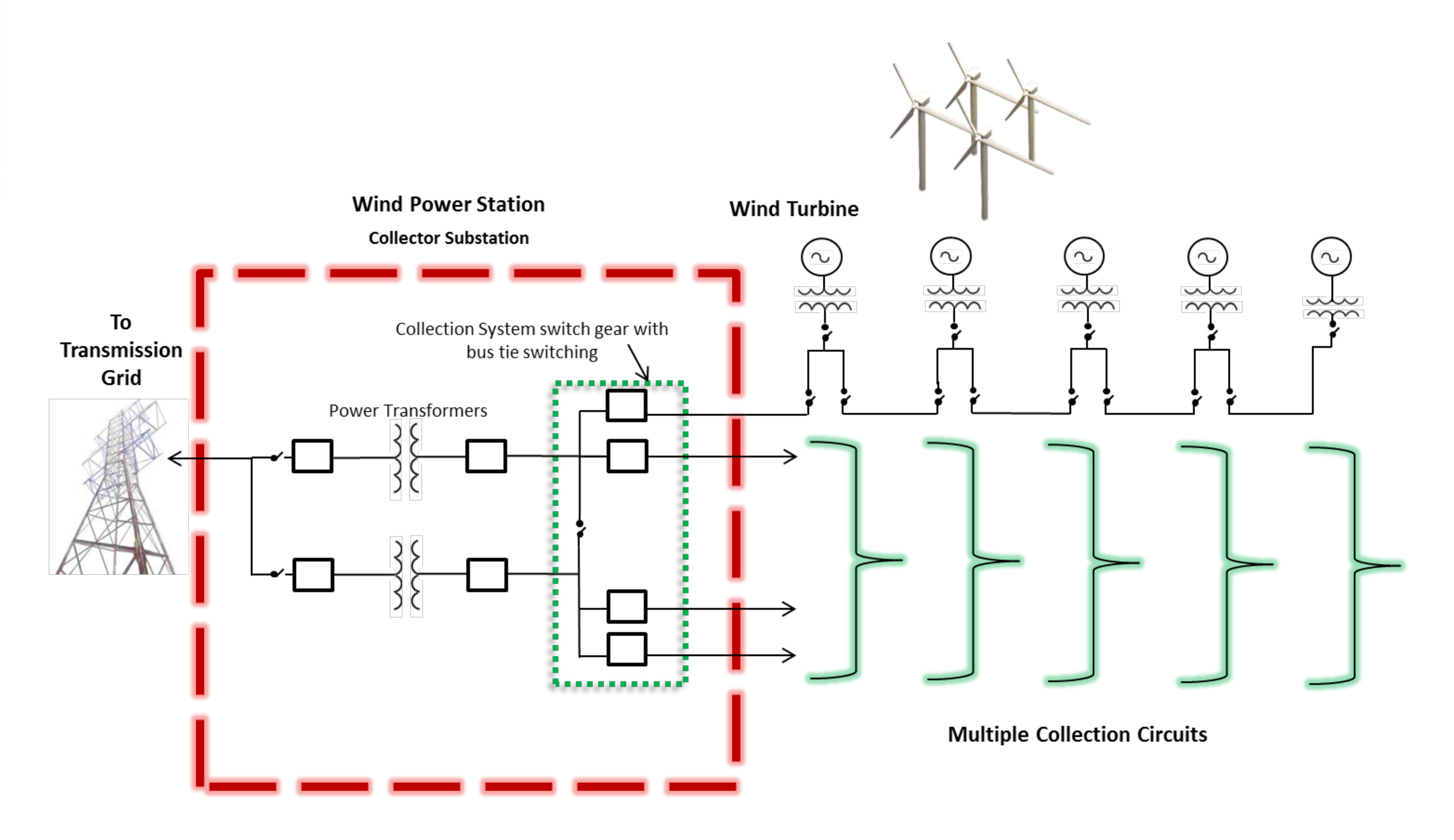
Results and Conclusions

IEC 61400-1 Design Requirements

The team created a 100-year loads database for a 5 mega-watt (MW) onshore turbine and a 64-year version for a shallow water offshore turbine. Their paper, "Decades of Wind Turbine Load Simulation," won "Best Paper" at the American Society of Mechanical Engineers Wind Energy Symposium. A simpler extreme load extrapolation procedure was developed that reduces ambiguity from extrapolating a short term distribution to an extreme 50-year value; this is currently under consideration for the next Standard revision.

IEC 61400-26 Availability

The Time-Based Availability Standard (61400-26-1) and the Production-Based Standard (-2) have both been published. The Plant-Wide Availability Standard (-3) is in development, with Sandia contributing reliability block diagram models of wind power stations with both turbine and Balance of Plant components.



IEA Task 33 Reliability Data Best Practices

This working group is drafting a publication for the Standardization of Data Collection for Wind Turbine Reliability and O&M Analysis. All known international initiatives in wind reliability are participating.

AWEA Operations & Maintenance Best Practices

The first edition was published, with significant Sandia contributions to the "Data Collection and Reporting" chapter.

Proposed Future Work

FY2015
The IEC and IEA work continues, with the IEC Design team expanding into a 13.2 MW floating turbine, the IEC Availability team tackling Plant-Wide availability, and the IEA Reliability team drafting a Best Practices contribution on reliability data collection.

OUT YEARS
As IEC standards evolve to address certification topics more completely, Sandia will ensure that its core competencies of load definitions, turbine–to–turbine effects, and blades/testing will contribute to select IEC standards through our research products.

For more information, contact: Ben Karlson bkarlso@sandia.gov

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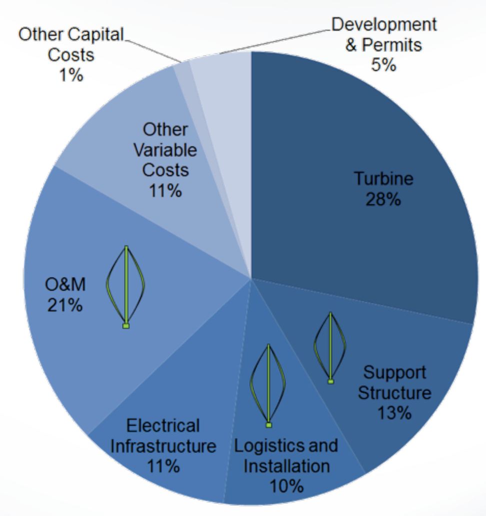
2014 Wind Turbine Blade Workshop
August 26th-28th

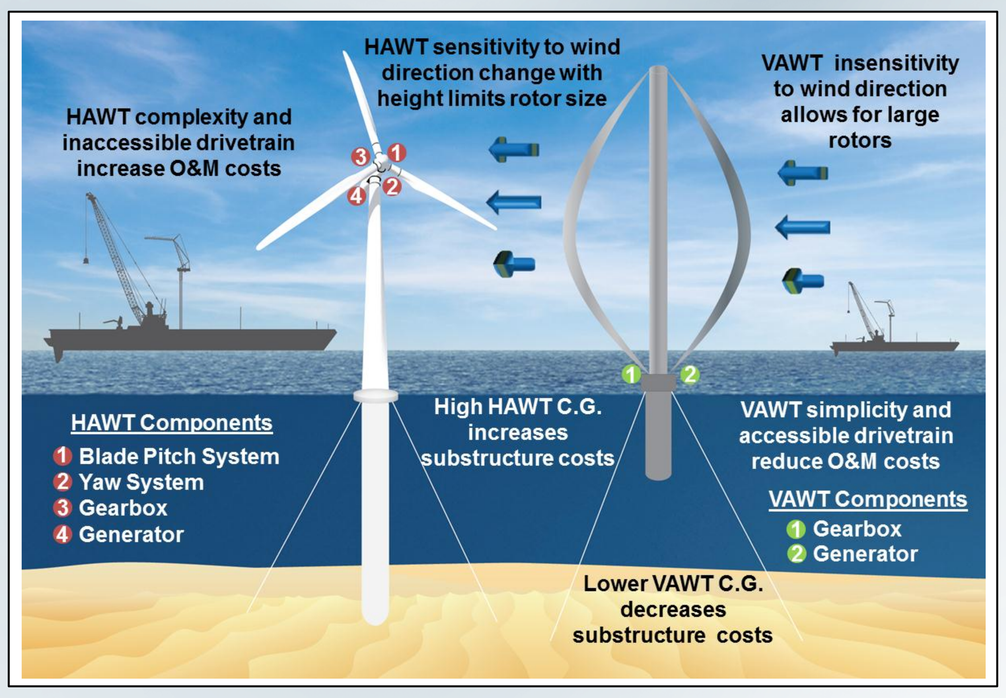
Offshore Wind: Innovative Deep-water Vertical Axis Wind Turbine (VAWT) Rotors

1. Introduction

The availability of offshore wind resources in coastal regions along with a high concentration of load centers in these areas makes offshore wind energy an attractive opportunity. Reductions in cost of energy are crucial for the viability of offshore wind, and are likely to come from decreases in installation and O&M costs while increasing energy production. Wind turbine rotor design has a significant impact on these areas.



VAWTs held significant interest in earlier days of wind energy technology, but in the early 1990s the configuration was largely abandoned and the horizontal-axis wind turbine (HAWT) was adopted as the primary turbine configuration. The VAWT, however, is poised to complement the need for lower COE in the offshore wind arena. Placement of the gearbox and generator at the base of the tower lowers installation, platform, and O&M costs by having these components readily accessible at water level. VAWTs possess a simple design and insensitivity to wind direction, allowing for economical scaling to large sizes, further decreasing COE.

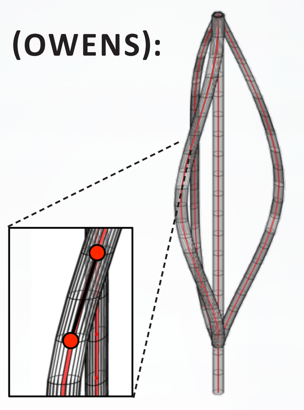


VAWT Design Tools

To remain a viable option for offshore wind energy, VAWTs will need to undergo significant development in coming years. Thus, a number of design tools are needed to aid in developing innovative offshore VAWT designs. The following VAWT design tools have been developed by Sandia National Laboratories (SNL) and project partners:

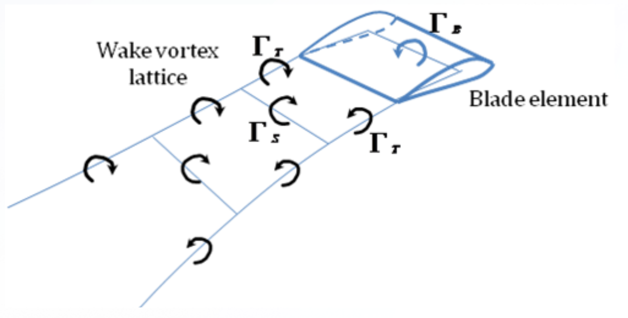
SNL OFFSHORE WIND ENERGY SIMULATION TOOLKIT (OWENS):

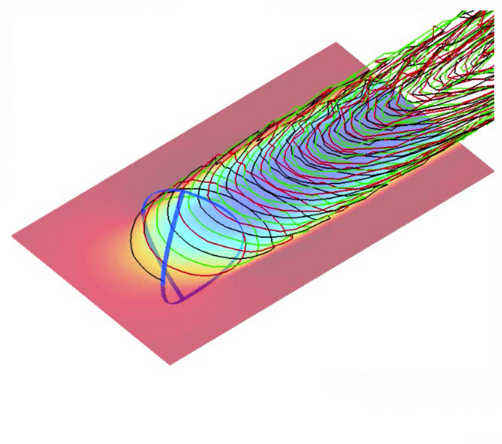
- Flexible, modular analysis framework
- Finite element structural dynamics formulation
  - 3D Timoshenko beam element
  - Rotational effects and geometric nonlinearities
  - Structural couplings (bend-twist, sweep-twist, etc.)
- VAWTGen mesh generator
  - Arbitrary VAWT geometries
- Coupling interfaces to external modules
- Employs network socket interface for low impact software development and maintenance



SNL CODE FOR AXIAL AND CROSS-FLOW TURBINE SIMULATION (CACTUS):

- Lifting line, free wake method
- Quick simulation setup
- Simulation time of seconds to minutes





WAVEC2WIRE HYDRODYNAMICS AND PLATFORM DYNAMICS CODE:

- Developed by SNL, University of Maine, and Wave Energy Center in Libson, Portugal
- Leveraged rigid body wave energy converter code for VAWT platform dynamics design tool needs
- Superposition of hydrodynamic, hydrostatic, viscous, mooring, and applied (topside) forces.

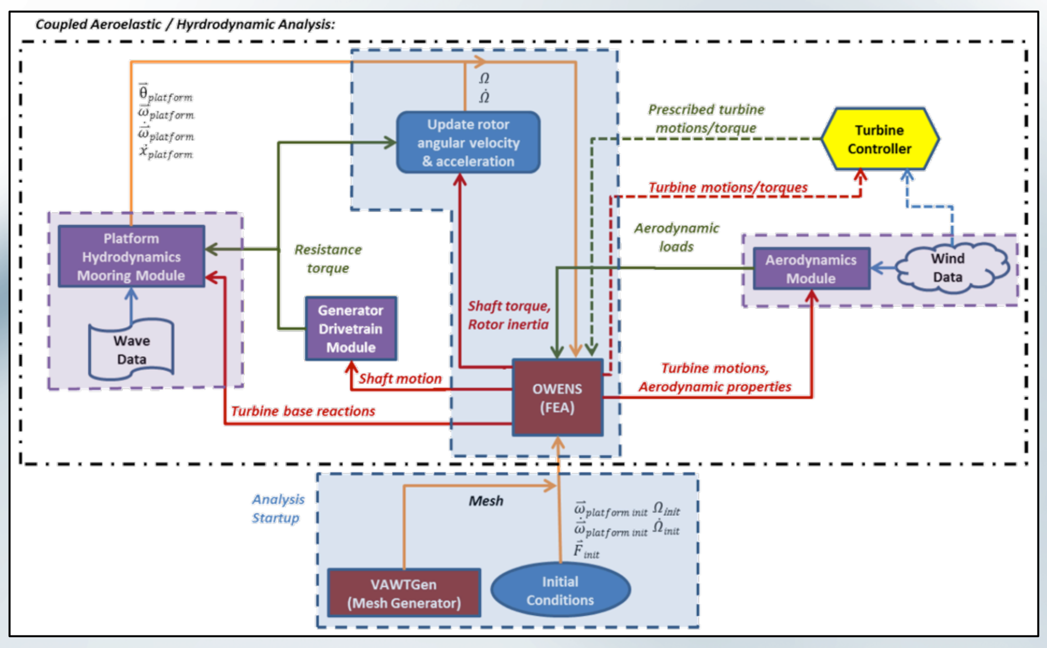
THE UNIVERSITY OF MAINE

WavEC Offshore Renewables

Analysis Framework

Flexible, modular analysis framework

- OWENS is the core driver code and structural dynamics module
- Network socket interface between modules simplifies software development
- Interfaces to aerodynamics, hydrodynamics/platform, generator/drive-train modules

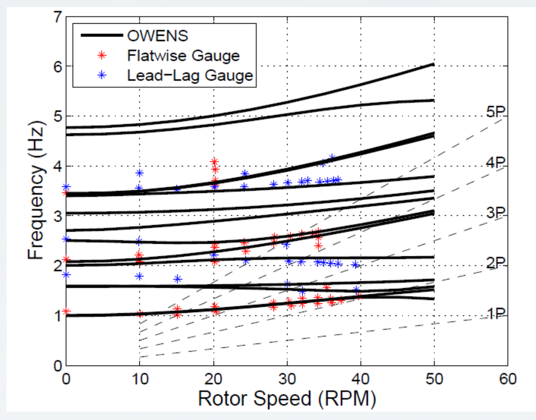


OWENS Verification & Validation

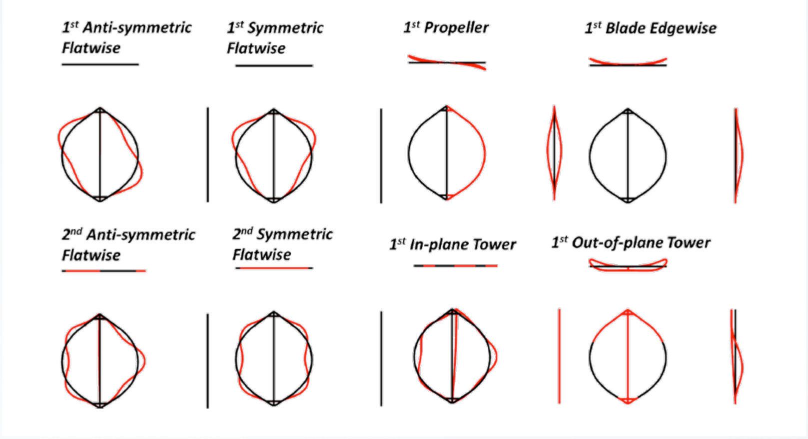
Verification was performed via analytical solution benchmarking ("whirling shaft" problem) and code comparisons to ANSYS FEM software. Validation drew upon modal test data for the Sandia 34-m VAWT test-bed from the legacy SNL VAWT program.

Sandia 34-m test-bed:

Sandia 34-m Campbell Diagram(Analytical & Experimental):



Sandia 34-m parked mode shapes predicted by OWENS:



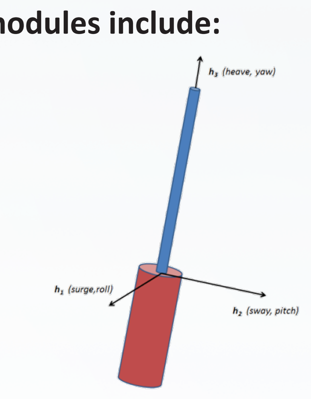
Code Coupling

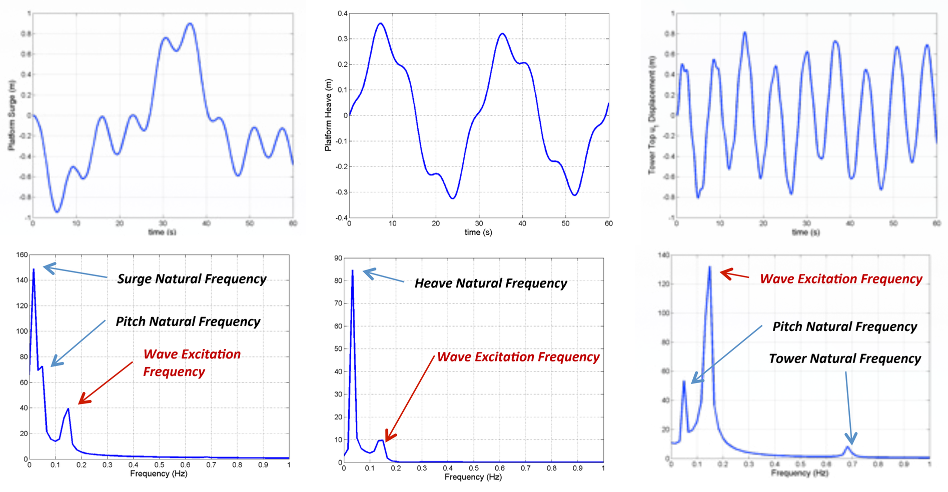
OWENS employs the above analysis framework, network sockets, and coupling algorithms to couple to external software modules. These modules include:

- WavEC2Wire hydrodynamics/platform dynamics code
- SNL CACTUS VAWT aerodynamics code
- TU-Delft hybrid VAWT aerodynamics code

Baseline platform coupling verification procedures:

- Flexible tower on rigid spar buoy platform
- Regular wave excitation with 7 second period (0.14 Hz)

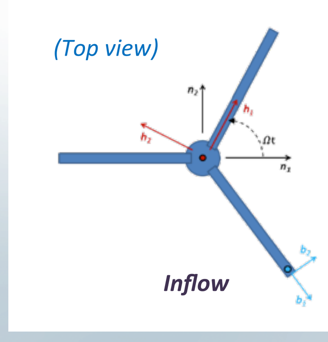




For more information, contact: D. Todd Griffith, dgriffi@sandia.gov

Tower Resonance In Vawt Designs

Tower resonance has historically been an issue for VAWT designs. Previous work employed experimentally observed rules of thumb to understand critical per-rev excitations for tower modes. An analytical expression for critical tower modes of an N-bladed VAWT was developed and verified using CACTUS aerodynamic simulations. Convenient "look-up" tables were developed for VAWT designers to understand critical per-rev frequencies that drive tower resonance.



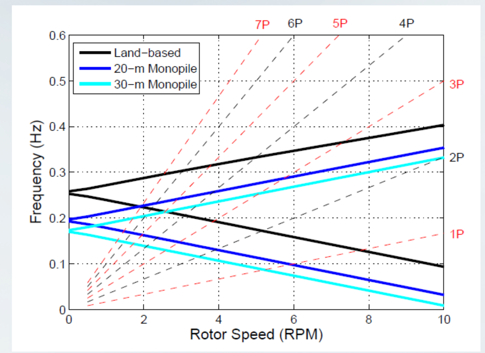
Critical Per-Rev Tower Excitation "Look-Up Table":

# of Blades	Per-Rev Sensitivity	Example Configuration
1	1,2,3,4	
2	1,3,5,7	SNL 17-m , SNL 34-m , DeepWind
3	2,4,5,7	VAWTPower VP60
4	3,5,7,9	
5	4,6,9,11	
6	5,7,11,13	Lux
7	6,8,13,15	
8	7,9,15,17	
9	8,10,17,19	
10	9,11,19,21	

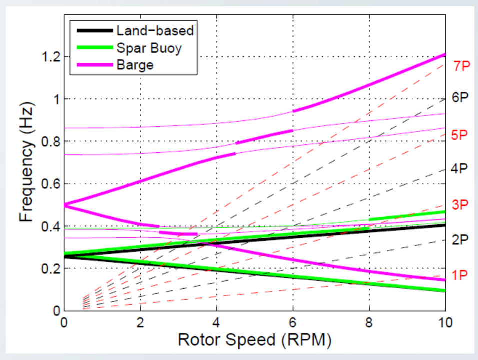
Rotor - Platform Design Impact Studies

OWENS was employed in VAWT structural dynamics design studies to examine impact of support structure (land-based, monopile, or floating) on the natural frequencies of the tower mode. Monopile support configurations exacerbate tower mode resonance concerns while innovative platform designs may alleviate resonance concerns via the floating support boundary condition.

Monopile Support Tower Modes Campbell Diagram:



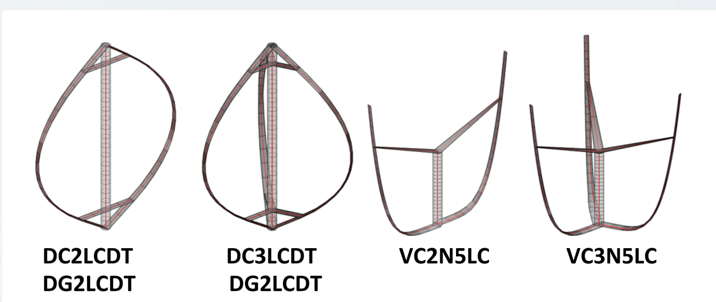
Floating Support Tower Modes Campbell Diagram:



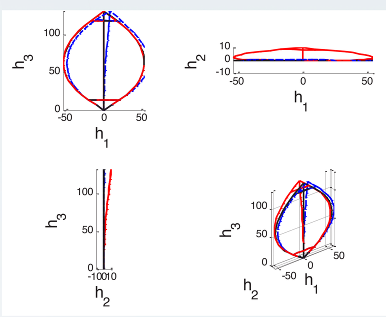
Aeroelastic Stability Investigations

The aeroelastic theory implemented into the SNL BLade Aeroelastic Stability Tool (BLAST) for HAWT blades was implemented alongside the finite element formulation in OWENS to allow for aeroelastic stability investigations of large, multi-MW VAWT designs.

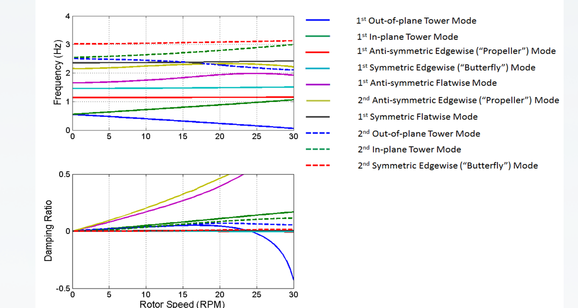
5MW VAWT Designs:



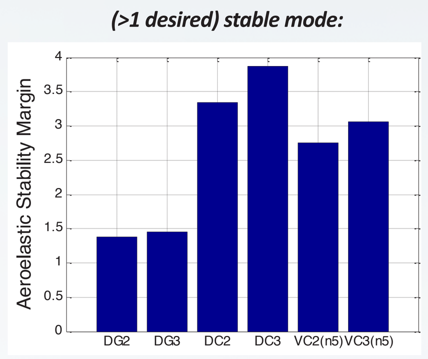
Mode shape for unstable mode:



DC2LCDT Turbine Frequency and Damping Trends:



Mode shape for an Aeroelastic Stability Margins: (>1 desired) stable mode:



Conclusions

VAWTs are a potentially transformative technology for lowering the cost of energy for offshore wind. A number of design tools have been developed by Sandia National Laboratories to facilitate the development of innovative offshore designs. The OWENS toolkit provides a modular analysis framework for multi-physics simulation and a robust finite element structural dynamics formulation capable of considering arbitrary VAWT designs.

A greater understanding of critical per-rev tower excitations as a function of blade number was gained through this work and coupled rotor-support structure studies showed an opportunity to alleviate VAWT tower resonance concerns through innovative platform designs. Aeroelastic stability investigations showed 5MW VAWT designs developed by SNL do not appear to have aeroelastic instabilities within design operating ranges. Initial investigations suggest glass composite designs may be more susceptible to aeroelastic instability than carbon composite (likely due to the increased stiffness to mass ratio of carbon composites).

Future work will continue to develop and validate the OWENS toolkit as external modules and validation data sets become available. The aeroelastic stability analysis capability implemented in OWENS will also be enhanced and validated in future work.

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Wake Imaging System

Visualizing the Invisible

Wind turbine wake formation and evolution is not sufficiently well understood, leading to uncertainty in wind plant performance including power production and loads. Novel flow measurement instrumentation is needed to provide field data to enable validation of improved research codes and design tools used to optimize wind plant performance. The primary objective of this project is to develop and demonstrate a measurement system capable of imaging the near-wake velocity profile of a turbine at the Sandia Scaled Wind Farm Test (SWiFT) facility (Figure 1).

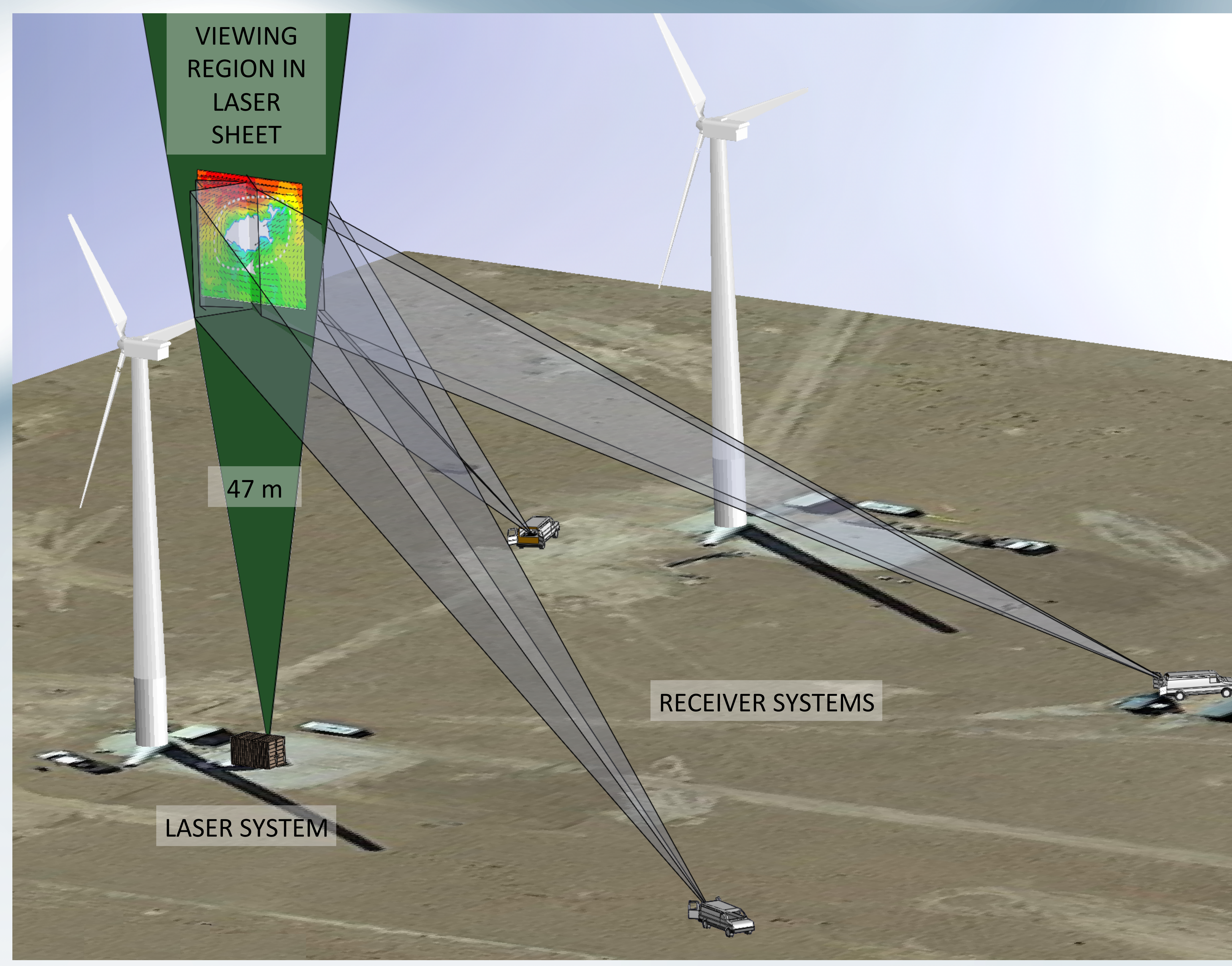

Figure 1: *Notional schematic of the Wake Imaging System deployed at the SWiFT facility. Each receiver system would measure a single component of the flow velocity as represented by the 10m x 10m viewing area in the wake of a 225 kW turbine.*

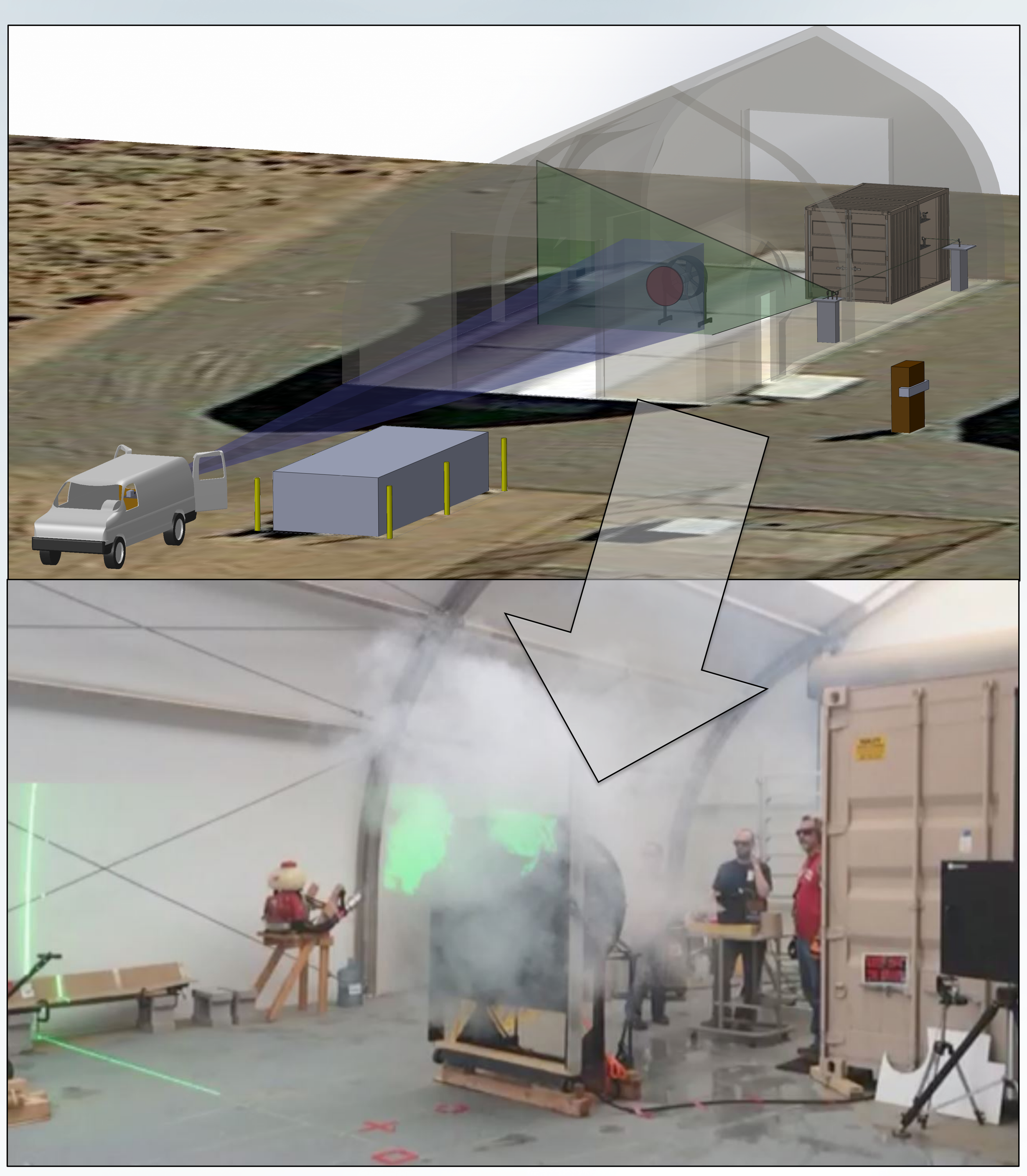

Figure 2: *Schematic of the intermediate-scale experiments in a outdoor test structure (top) and actual inside photograph of initial system tests showing the laser sheet scattering from the mineral oil aerosols (bottom).*

Planar Doppler Velocimetry

A technique called Planar Doppler Velocimetry (PDV) was chosen to measure flow structures at the time and length scales needed at the SWiFT facility. A laser sheet illuminates the flow field which contains aerosols (natural or seeded) which scatter the laser light, shifting the frequency up or down based upon their velocity and direction (i.e. Doppler effect). A two-camera system with a filter that converts frequency shifts to intensity differences is used to create a velocity image with the help of software algorithms and calibration data. Unlike particle image velocimetry, the individual particles do no need to be tracked, however the optical system is much more complex. Instantaneous velocity images are possible.

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2014 Wind Turbine Blade Workshop
August 26th-28th

Wind Turbine Generator Modeling

BENJAMIN KARLSON

Sandia National Laboratories, Wind and Water Power Technologies

1. Introduction

Positive-sequence power flow and dynamic models are required for demonstrating compliance with system reliability criteria and for planning system expansions. As more wind power plants interconnect with the electric power system, it becomes increasingly important that they are properly modeled in power system simulations. Generic, standard and publicly available models have not been readily available to the regional reliability organizations and grid operators who are responsible for maintaining the grid.

Development and validation of these planning models for wind power plants continues to be a high priority for the industry. NERC has clearly stated that developing and improving access to validated, non-proprietary planning models is a pre-requisite for large-scale integration of variable generation. With the availability of Wind Turbine Generator (WTG) models, planning of wind energy can be accomplished in a manner that allows for reliable power without an overbuilt system.

NERC POINT OF VIEW:
"Validated, generic, non-confidential, and public standard power flow and stability (positive-sequence) models for variable generation technologies are needed. Such models should be readily validated and publicly available to power utilities and all other industry stakeholders. Model parameters should be provided by variable generation manufacturers and a common model validation standard across all technologies should be adopted..."

Developing and improving validated, non-proprietary planning models is a prerequisite for large-scale integration of variable generation.

2. Technical Approach

The effort to develop and maintain standard public dynamic simulation models for the purpose of power system analysis has a wide industry reach. From the transmission planners who need the models for their mission to the wind manufacturers that own detailed proprietary models to the power system simulation software modelers who implement the models, this work requires significant collaboration among many players.

Sandia is the chair of the Renewable Energy Modeling Task Force (REMTF) within the Western Electricity Coordinating Council (WECC) that has been leading this effort.

Sandia is the lead U.S. delegate to the International Electrotechnical Committee (IEC) technical committee for electrical simulation models for wind power generation. Through these groups Sandia has been able to successfully collaborate with industry to develop the second generation of generic WTG models.

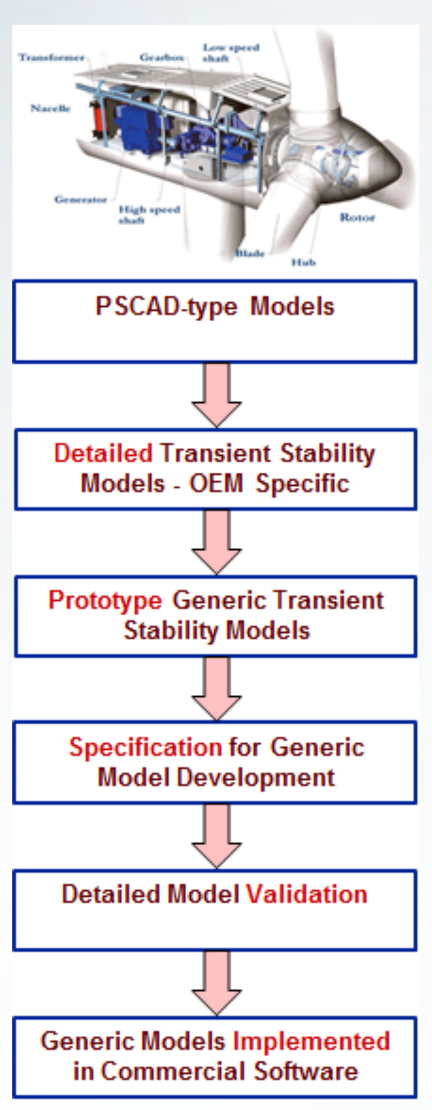

Figure 1 – Generic Model Development Process

In addition to those groups above, Sandia has partnered with NREL and the Electric Power Research Institute to develop model validation techniques. EPRI, through non-disclosure agreements was able to obtain data from turbine manufacturers.

Model validation is generally a four step process:

1. Define the model structure
2. Collect measured data
3. Simulate the same set of events as occurred during data collection and compare against measure data
4. If the data sets match adequately, then the model is valid for that event. If not, then refine model or model parameters and repeat

3. Results

Phase 2 Wind Turbine Generator (WTG) Models

Deficiencies were identified in the initial generation of the generic wind turbine generator models in 2010. This lead to both the WECC and IEC groups to focus on expanding the first generation models to attempt to cover a wider range of control strategies and has led to the creation of a second generation of models with a focus on the type 3 and type 4 WTGs.

An important new aspect of the second generation models is the decision by both groups to move towards a modular approach. That is, the models are made up of smaller modules that are truly generic and usable for any appropriate renewable generation system. This allows for additional versions to be developed for each module as changes are deemed necessary in the future. This also facilitates the differences between the two approaches (WECC and IEC) to be addressed simply through the development of different modules.

Module	Use			
REPC_A	Wind/PV plant controller	PV Plants	WT4 Plants	WT3 Plants
REE_A, REE_B	Wind /PV electrical controls	PV Plants	WT4 Plants	WT3 Plants
REGC_A	Generator/Converter model	PV Plants	WT4 Plants	WT3 Plants
WTGT_A	Drive Train		WT4 Plants	WT3 Plants
WTGAR_A	Aerodynamic Model			WT3 Plants
WTGPT_A	Pitch Control Model			WT3 Plants
WTGTQ_A	Torque Control Model			WT3 Plants
lhvrt	Voltage/current Protection Model			

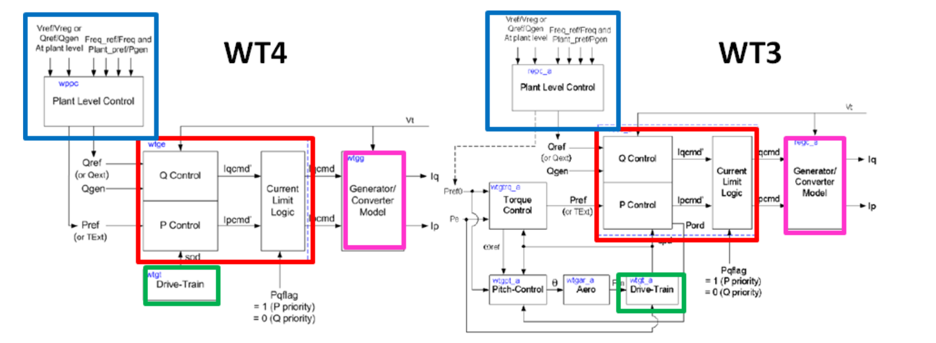

FIGURE 2 – Modular approach to the second generation of WTG models

Other wind models

- WT1 Plants: REGC_A + WTGT_A + WTGPT_A
- WT2 Plants: REGC_A + WTGT_A + WTGPT_A + REE_A

The second generation of models were approved by the WECC in January 2013. Leading up to these approvals much work was done within the group to actually test and attempt to validate the model structures against field measured responses of various vendors' equipment for single wind turbine generators. One example is shown in Figure 3 with the use of the EPRI Wind Turbine Generator Model Validation Tool.

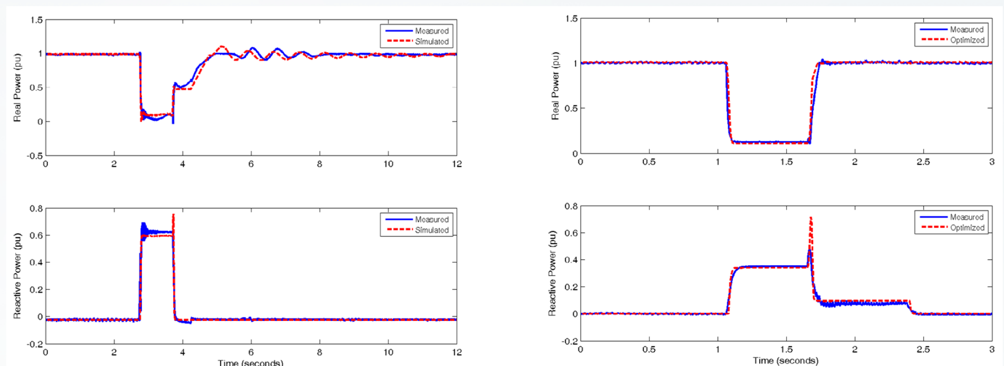

Figure 3 *– Comparison of simulation and measured response. Left: A type 3 WTG response to a voltage dip at the high side of the step-up transformer. Right: A type 4 WTG response to a voltage dip at the high side of the step-up transformer. P.Pourbeik, A. Ellis, J. Sanchez-Gasca, Y. Kazachkov, E. Muljadi, J. Senthil and D. Davies Generic Stability Models for Type 3 & 4 Wind Turbine Generators for WECC, Working Group Joint Report – WECC Renewable Energy Modeling Task Force & IEEE Working Group on Dynamic Performance of Wind Generation*

While the focus of the model improvements was on the type 3 and type WTG, improvements were made to the type 1 and type 2 WTGs. The first generation of generic models were developed based on limited knowledge of specific manufacture's wind turbines controls. User experience indicates that the existing pseudo governor model for type 1 and 2 wind turbines did not represent very well the effect of pitch control in some manufacture's turbine behaviors and as a result work was done to modify the pseudo governor structure.

Model implementation

The second generation of WTG models have been implemented and released in GE's PSLF, Siemens PTI PSSE, and PowerWorld.

Short-circuit Modeling

Due to the longer history of use and experience with synchronous machines in the electric power grid, the short-circuit behavior of power plants using these types of machines is well understood compared to a wind power plant. It is the goal of this guideline to educate utility engineers on short-circuit modeling of wind power plants in order to increase the level of understanding of wind power plant behavior.

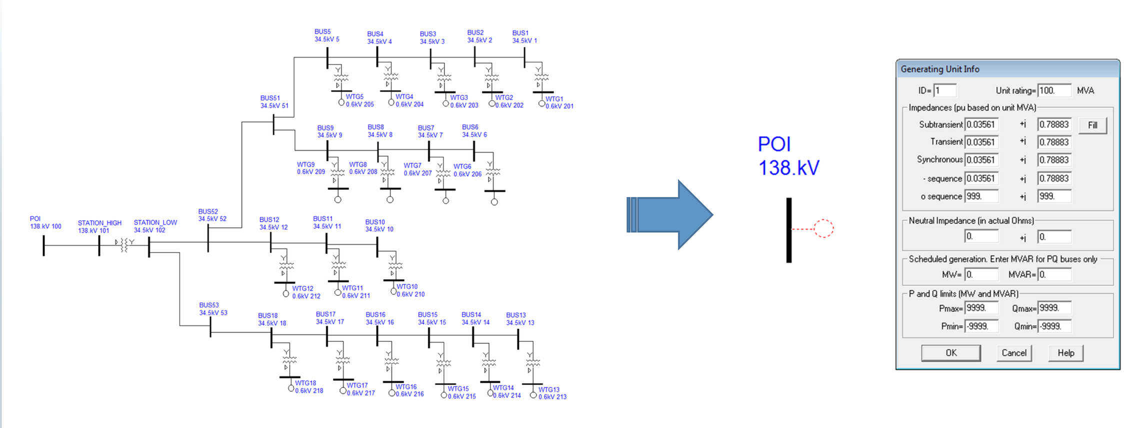

Figure X – Simplifying the WPP for Short-Circuit Studies

Conventional generators are typically modeled on an individual basis, however, wind farms employ many machines that make modeling individual generators not practical.

The methods presented in this work aim to assist in determining the maximum short-circuit contribution from a wind power plant for system impact studies (verifying current is within interrupting ability of protection devices), relay coordination, and arc flash hazard studies.

4. Conclusions

In the end, the ultimate goal of these efforts is to have suitable models for wind power plants that adequately represent the dynamic behavior of the entire plant at the point of common coupling.

5. Summary of Results and Findings

- In FY13 and FY14, Sandia successfully led industry efforts to improve on the first generation of WTG models
- ***Coordination and participation in industry effort is paramount***
- The models have a modular approach allowing for easier implementation and maintenance
- Validation efforts are underway and current techniques demonstrate that the models behave reasonably well for power system simulations
- A method for determining the maximum short-circuit contribution from a wind power plant was presented

6. Current Work

Continuing efforts include:

- Renewable energy plant controller improvements. The module lacks capability to:
  - Supervise multiple WTG units in a wind power plant
  - Coordinate with wind power plant shunt compensation devices
- Dynamic model validation at the wind plant level; this will require installation of monitoring equipment at the interconnection points
  - To support initial model development
    Pursuant to NERC MOD 10/12 and WECC Modeling Procedure
  - Increase confidence in facility connection study process
    Pursuant to FERC LGIP, NERC FAC-002
  - Comply with network planning procedures
    Periodic plant model verification per NERC MOD 26/27
- Future revisions of the models are inevitable as new features are added and grid codes are adopted.

WECC/REMTF guides on wind models
http://www.wecc.biz/library/WECC Documents/Documents for Generators/Generator Testing Program/

For more information, contact:
Benjamin Karlson, Benjamin.Karlson@sandia.gov

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The National Rotor Testbed

March 2014 Wind Power Peer Review

B.RESOR, D.MANIACI, J.BERG, B.LEBLANC, B.NAUGHTON

Sandia National Laboratories, Wind and Water Power Technologies

1. Purpose and Objectives

In order to capitalize the SWiFT investment, a modern designed blade must be benchmarked.

At the same time, the A2e Initiative is in need of unique rotor hardware at multiple size scales to support a long term (5-7 year) model validation campaign.

2. Impact

This project will lead to improved understanding of the relationships between *rotor design* and *wind plant performance* in terms of dynamic power and loads related to

- array effects,
- wake recovery and
- turbine-turbine interaction.

The ultimate impact is on increased wind plant AEP and wind plant reliability.

3. Assumptions

A2e programs and wind plant performance is key to future industry success:

- Increase wind plant AEP through better understanding of array effects, wake recovery and turbine-turbine interaction
- Increase reliability through better understanding of dynamic loads related to array effects, wake recovery and turbine-turbine interaction

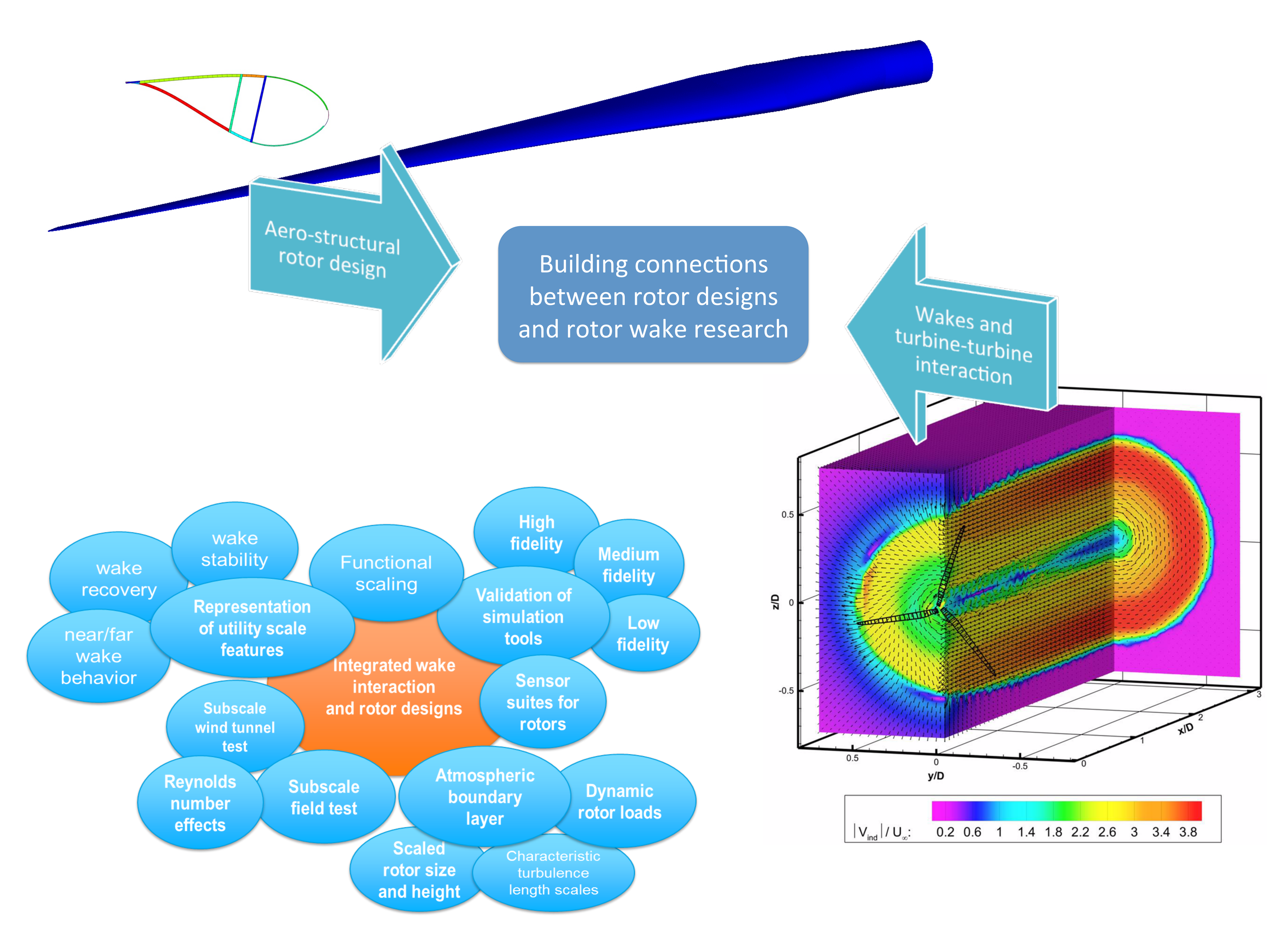
A variety of functionally scaled tests will allow for complex structures and their physics to be isolated and to maximize efficiency of test budgets

4. Challenges

Challenges associated with this problem include:

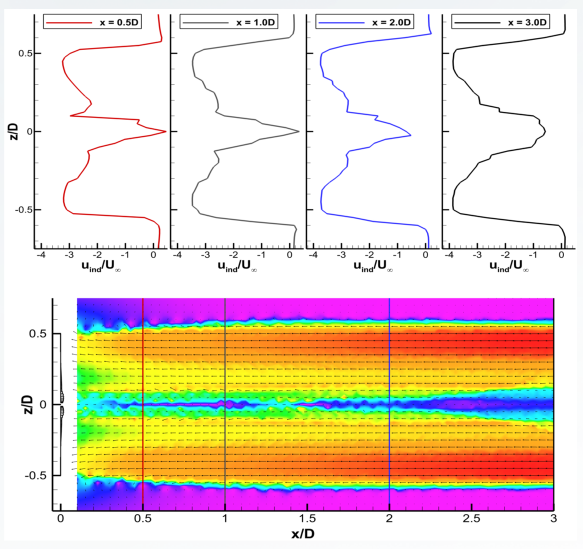
- Open-ended research questions related to turbine wake behavior
- Reynolds number effects related to scaled testing,
- Relationships of wake behavior to rotor design.

The new open source baseline for rotor innovation and turbine-turbine interaction research



5. Approach

Wake Character from Vortex Method



Medium fidelity wake models are able to relate rotor and wake character in a quick-turnaround design environment

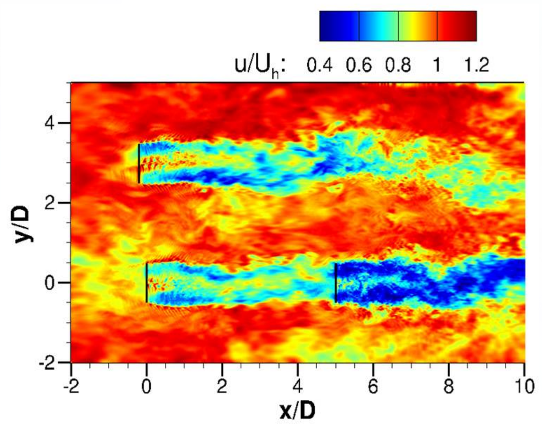
Medium fidelity vortex wake methods are used to guide rotor design decisions in situations where

- Blade element momentum may be incomplete or
- Relationship between wake behavior and rotor design is needed

Wake character Large Eddy Simulation

High fidelity wake models provide realistic previews of upcoming field tests and provides insights to needs of validation

High fidelity LES methods will be used to guide rotor design



KEY QUESTIONS:

- Are the wakes of a MW-scale turbine rotor and the SWIFT rotor similar ?
- If different, how to translate scaled knowledge to full scale ?
- How do changes in blade loading distribution resulting from NRT scaled design studies affect the development of the SWIFT wake?

Functional Scaling Drivers for Rotor Design

Prioritized design drivers for a scaled rotor:

- Design within allowable rotor loads for the SWiFT turbines
- Recreate the shape of the circulation distribution along the rotor span

Match absolutes:

- Tip speed ratio of the full scale rotor
- Tip velocity of the full scale rotor
- Campbell diagram in the lowest frequency range

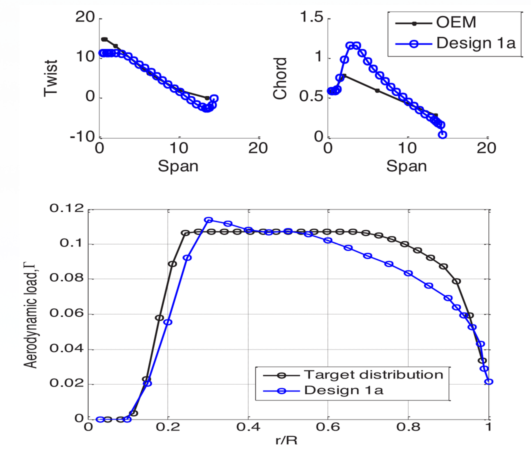
Match aerodynamics features:

- Delta between $C_{l,max}$ and design C_l values along the span of the blade
- Steady – ensure that inboard blade does not operate in a stalled or high drag condition
- Dynamic – ensure that inflow gusts translate to equivalent dynamic loads

Rotor Designs

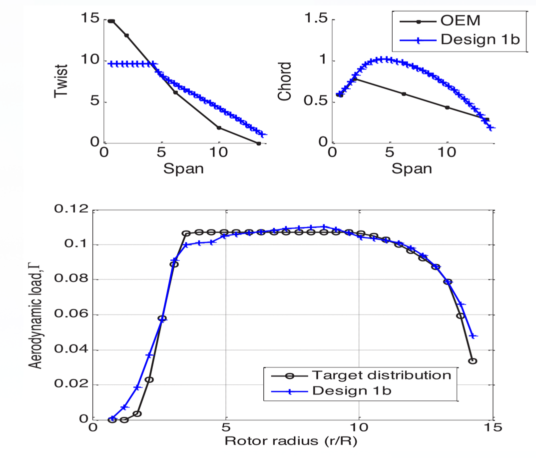
29 m rotor --- 78 m/s max tip velocity --- DU-airfoils

Design 1A



- Rotor loads fall within desired limits
- Designed with process for maximum AEP
- TSR is approximately matched
- No control over circulation distribution

Design 1B



- Aerodynamic load (circulation) distribution is matched
- Specified TSR is matched
- Rotor loads exceed desired limits

6. Partners, Subcontractors, and Collaborators

- The DOE Atmosphere-to-Electrons Initiative
- Sandia SWiFT Facility
- Wetzel Engineering, Inc. – Advisors and design prep for manufacture
- Airfoils, Inc. – Analysis and selection of airfoils for rotor testbeds
- University of Minnesota – LES simulations to address turbine scaling and sensitivity of wake character to rotor design
- External Advisors
  - General Electric
  - Vestas
  - NREL
  - Siemens
  - UC-Davis
  - NextraTEC

7. Proposed Future Work

These rotors provide the industry with a relevant, open source baseline rotor testbed for public and proprietary research. The initial design represents only the beginning of an exciting future in exploration of wind energy technology innovations.

- Aeroacoustics of blades (quiet blades)
- Aeroelasticity of blades (flexible blades)
- Testing of sensing and measurement technology for blades and wakes
- Blade aerodynamics: tip design, root design, airfoil design and modifications
- Active, passive and hybrid load control
- Wind farm control
- SHM/damage testbed for validation of monitoring capabilities
- Blade subcomponent ground and flight testing
- Baseline and low-radar interference blade
- Material and manufacturing technologies demonstration blade
- High capacity factor rotor

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