Wind Research and Development

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

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Wind Research and Development

Mike Derby
Wind Technology
Program Manager

February 14, 2017

Enabling Wind Nationwide

Enabling U.S. Industry Growth and U.S. Competitiveness

- **GOAL**: Reduce the unsubsidized market levelized cost of energy (LCOE) for utility-scale land-based wind energy systems from a reference wind cost of $0.074/kWh in 2012 to $0.057/kWh by 2020 and $0.042/kWh by 2030.
- **GOAL**: Reduce the unsubsidized market LCOE for offshore fixed-bottom wind energy systems from a reference of $0.18/kWh in 2015 to $0.15/kWh by 2020 and $0.096/kWh by 2030.

Enhancing U.S. Energy Security and Independence

- **GOAL**: Accelerate widespread U.S. deployment of clean, affordable, reliable, and domestic wind power to promote national security, economic growth, and environmental quality.

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- **GOAL**: Expand the geographic development potential of wind power plants in the United States, particularly in offshore zones and the U.S. Southeast.

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- Wind plant optimization
- Resource assessment and characterization
- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- Advanced technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

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Who We Are: Wind Tech Team

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

Wind Energy Technologies Office (WETO)
Jose Zayas, Director
Jim Ahlgrimm, Deputy Director

- Wind Research and Development — **Mike Derby**
  - Manufacturing, Reliability, Testing and Facilities — **Megan McCluer**
  - Resource Characterization — **Joel Cline**
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  - Operations — **Shane Beichner**

The Wind Tech Team leverages unique DOE capabilities to:

- Convene diverse stakeholders in a national dialogue
- Disseminate impartial, state-of-the-art data
- Leverage expertise from the national laboratories
- Carry out visionary R&D beyond the scope of industry
- Engage and promote small, innovative stakeholders and companies
- Provide public, world-class testing facilities

How We Organize Our Work

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Technology Innovations

Crosscuts land-based, offshore, and distributed wind

- *Manufacturing*
- *Advanced components*
- *Testing facilities*
- *Reliability*

Wind Plant Optimization

Addressed in the Atmosphere to Electrons (A2e) initiative

- *Wind plant physics*
- *Resource characterization*
- *Technology development*
- *Risk and uncertainty analysis*

Distributed Wind (DWT) R&D

Specific to small and medium sized wind technologies

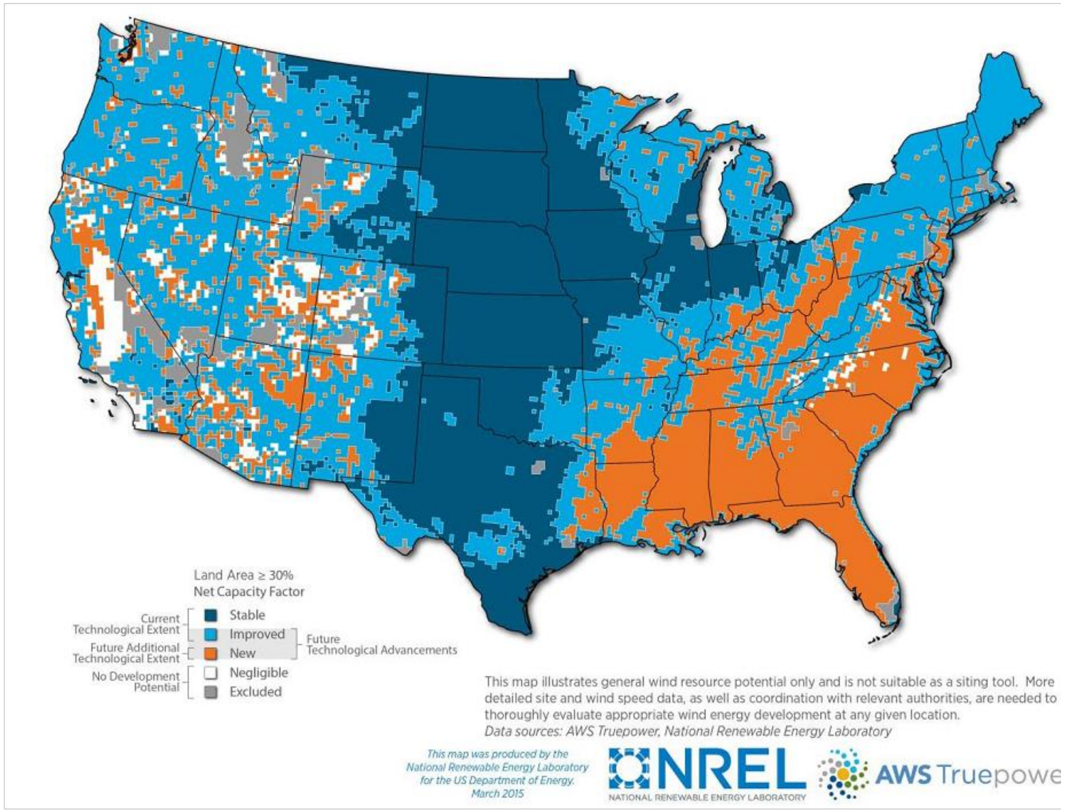
- *Market and cost analysis*
- *Resource and performance*
- *Turbine testing*
- *Component/system R&D*

Offshore Wind R&D

Specific to offshore wind technologies and systems

- *R&D and analysis*
- *Resource characterization*
- *Floating and fixed systems*
- *Demonstration projects*

Motivation: **Enable Wind Nationwide**



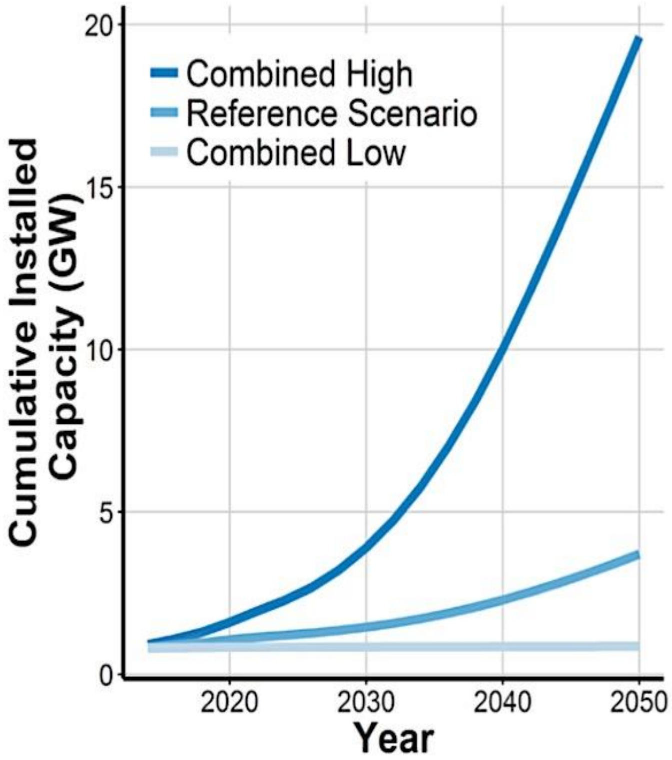
*Increasing hub heights from 96 to 140 meters would **unlock an additional 1,800 gigawatts (GW**) of wind power resource potential in the United States (Texas-sized!!).*

Motivation: **SMART Wind Power Plants**

SMART = System Management of Atmospheric Resources through Technology

- Target significant reductions in wind plant losses
  - *(20–30% observed in operational wind plants)*
- Significantly improve industry's predictive capability for wind plant flow
- Expand wind plant reliability to over a 30-year lifetime

Motivation: **Facilitate a significant role in the U.S. electricity sector for DWT**



The addressable resource potential for distributed wind turbines of less than 1 megawatt in size is estimated at 3 terawatts (TW) of capacity or 4,400 TW-hours of generation—**more electricity than the United States consumes in a year.**

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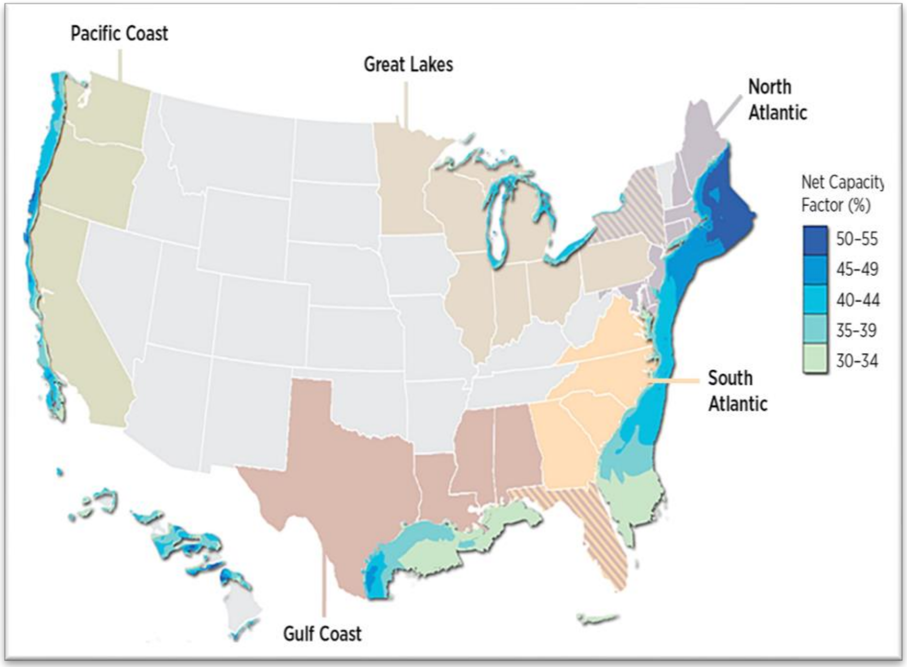
Motivation: **Enable cost effective offshore wind deployment**



The offshore wind resource is large

- 2,058 GW of offshore wind resource capacity technically accessible in U.S. waters using existing technology
- TWICE the current electricity generating capacity of the United States.

Cost reduction potential nationwide

- Reduce the unsubsidized market LCOE for offshore fixed-bottom wind energy systems from a reference of $0.18/kWh in 2015 to $0.15/kWh by 2020 and $0.096/kWh by 2030.

Budget Summary

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

Total Budget			
FY2014	FY2015	FY2016	**Total FY2014-FY2016**
$53M	$75M	$67M	**$195M**

Peer Reviewed Budget			
FY2014	FY2015	FY2016	**Total FY2014-FY2016**
$45M	$61M	$54M	**$160M**
85%	*81%*	*80%*	***82%***

Closing Thoughts

- We are a **strong team** of experienced, motivated subject-matter experts.
- We **leverage unique capabilities** to execute our program.
- Our projects are aligned to provide **maximum impact** to the industry.

Welcome and thank you to the Review Panel.

Technology Innovation

Megan McCluer
Senior Advisor, Manufacturing, Reliability, and Testing

February 14, 2017

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Motivation: Strengthen Domestic Manufacturing and Provide Economic Value

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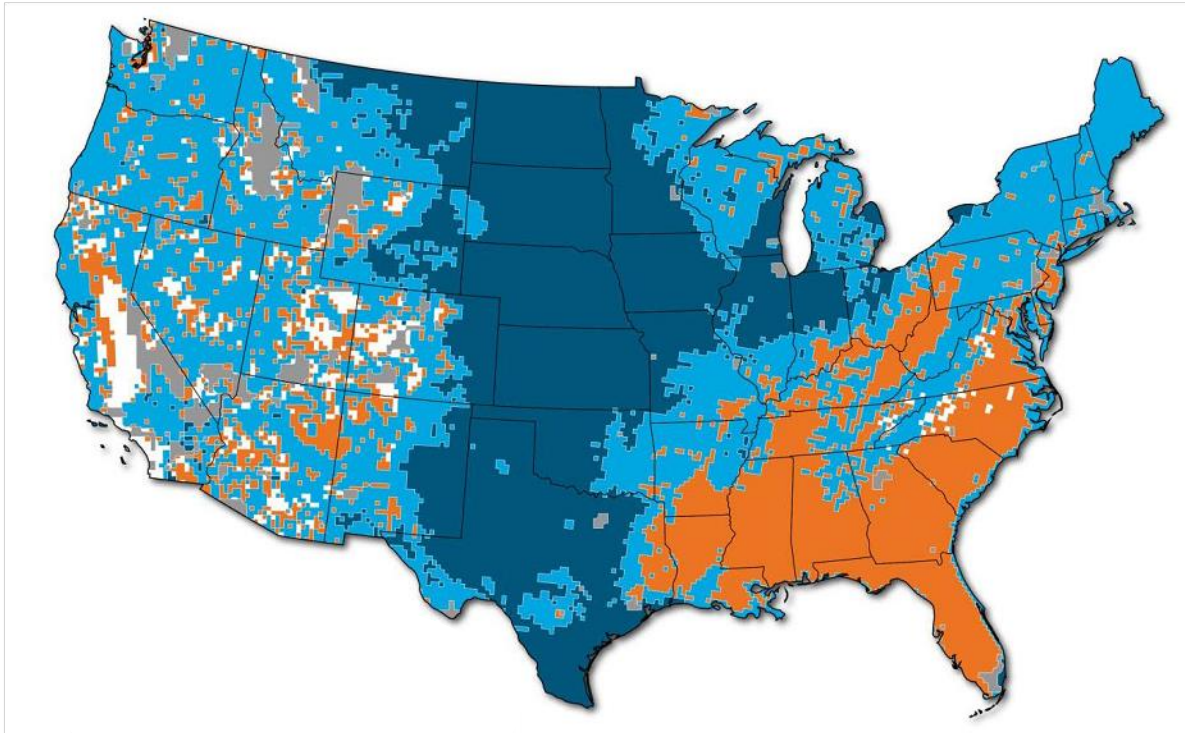
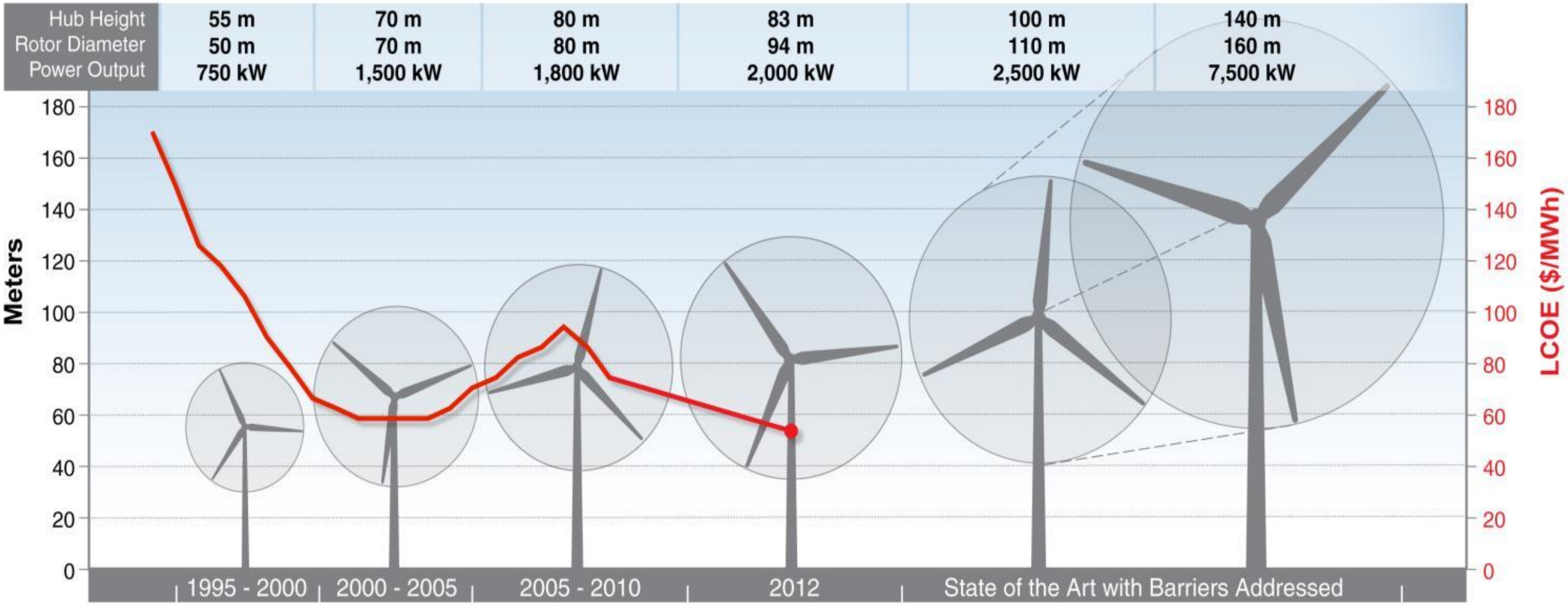


*Increasing hub heights from 96 to 140 meters would **unlock an additional 1,800 gigawatts (GW)** of wind power resource potential in the United States (Texas-sized!!).*

Enabling innovation to ensure domestic supply chain

- **Manufacturing**—logistics and new techniques
- **Advanced Components**—LCOE reduction & tall towers
- **Testing Facilities**—validation and discovery
- **Reliability**—mitigate wind project operations and maintenance (O&M) costs

Motivation: Larger Turbines



Bigger turbines (with longer blades and taller towers) will require continued investment in component R&D to allow larger components while keeping the cost of energy low.

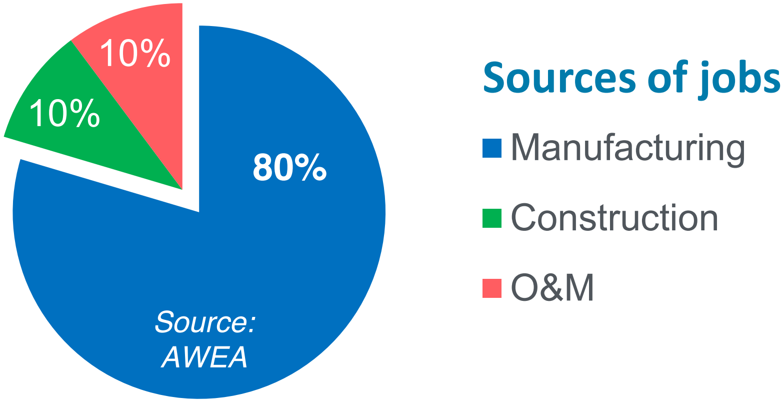
Domestic Manufacturing is Key to a Sustainable U.S. Wind Industry

Enable next-generation turbine scaling

- The next generation of turbines (particularly > 3 MW) and higher towers (> 100 m) face daunting logistical challenges in manufacturing, transport, and installation.

Manufacturing is where the jobs are

- 80% of wind industry jobs are related to manufacturing and supply chain activities.
- Wind generation now provides the third largest share of Electric Power Generation employment - 101,738 workers[1].



Domestic content is critical

- Understanding the drivers influencing industry procurement and investment decisions is crucial to effectively supporting growth.

Strategic Focus Areas

Challenges, Goals, & Approach

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Strategic Area	Challenges	Goals	Approach
Manufacturing	**Improvements require advancements in composite materials, automation, and manufacturing processes.**	Enable rapid prototyping, improve design flexibility, and develop innovative construction techniques to keep high-paying jobs in the U.S.	• **Additive manufacturing R&D programs** • **Investigate on- or near-site manufacturing**
Advanced Components	**New large rotor and tall tower designs must be able to scale up in size while remaining low cost.**	Innovative designs, robust design tools, and testing standards that enable low cost advanced components.	• **Drivetrain R&D** • **Blade R&D** • **Tower R&D** • **Wind plant system R&D**
Testing Facilities	**Modern, world-class test facilities are requited to validate component designs, conduct R&D, and establish standards**	Improve DOE capabilities and maintain existing world-class test facilities at the national labs.	• **Blade structural testing** • **Dynamometers facilities** • **Field testing for plant optimization**
Reliability	**It remains difficult to predict direct O&M costs or to avoid unplanned maintenance and replacement costs.**	Reduce performance uncertainty, prevent premature component failures, reduce project risk, and increase overall project financial performance.	• **Drivetrain Reliability Collaborative** • **Blade Reliability Collaborate** • **Standards development**

Projects Under Review

Manufacturing	
Additive Manufacturing in Wind Turbine Components and Tooling *(10:35am)*	Brian Post
On-Site Tapered Spiral Welding for Large Turbine Towers *(11:10am)*	Eric Smith
Hexcrete Tower for Harvesting Wind Energy at Taller Hub Heights *(11:35am)*	Sri Srinivasan
Advanced Components	
Advanced High Torque Density Magnetically Geared Generator *(9:35am, Wed)*	Jonathan Bird
Innovative Drivetrain Concepts *(4:10pm)*	Jon Keller
Next Generation Radar Technologies *(10:00am, Wed)*	John Shroeder
Testing facilities	
Testing Facilities and Capabilities at SNL *(1:35pm)*	Jon White
Testing Facilities and Capabilities at NWTC *(2:05pm)*	Dave Simms
Innovative Blade Test Methodology *(2:50pm)*	Scott Hughes
Reliability	
Rotor Reliability (Collaboratives, Monitoring, and O&M) *(3:30pm)*	Josh Paquette
Drivetrain Reliability (Collaboratives, Monitoring, and O&M) *(3:50pm)*	Jon Keller
Online Intelligent Prognostic Health Monitoring *(4:30pm)*	Wei Qiao
Wind Standards Development *(9:10am, Wed)*	Jeroen van Dam

Budget Summary

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

Total Budget			
FY2014	FY2015	FY2016	**Total FY2014-FY2016**
$16M	$10M	$9M	**$35M**

Peer Reviewed Budget			
FY2014	FY2015	FY2016	**Total FY2014-FY2016**
$15M	$10M	$9M	**$34M**
93%	*99%*	*99%*	***96%***

Key Projects Over Time

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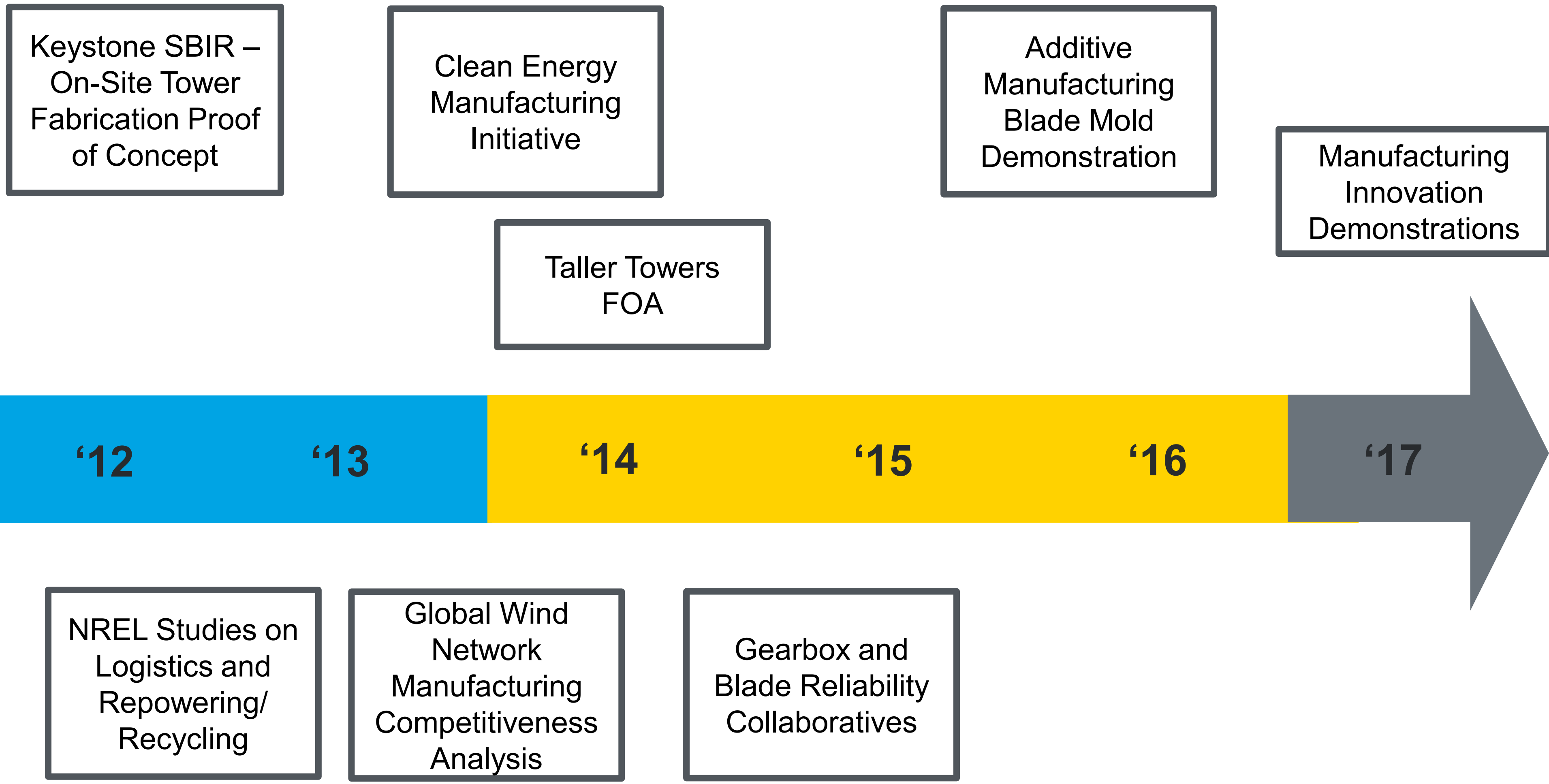

Activities & Accomplishments (FY14–16)

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Strategic Area	Accomplishments	Collaborators
Manufacturing	• Prototype for on-site tower manufacturing • Additive manufacturing demonstration project	• Keystone/ISU • Advanced Manufacturing Office • Oak Ridge Nat'l Lab
Advanced Components	• Completed magnetically geared generator project	• Portland State
Test facilities	• Facility upgrades at National Wind Technology Center (NWTC) • Development of new test techniques • Progressed on RD&T testing partnerships	• NREL/SNL • Domestic and international industry
Reliability	• Developed gearbox failure database • Design and testing of gearbox improvements • Nondestructive inspection evaluation and testing for wind turbine blades • Leading edge erosion analysis and tool development	• NREL/SNL • Domestic and international industry

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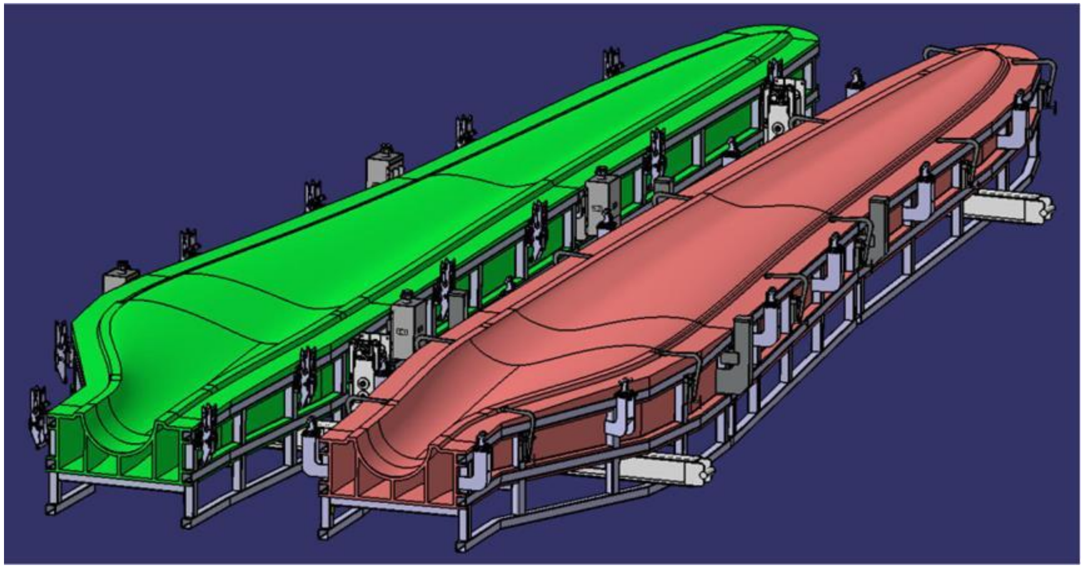

tpi

Oak Ridge National Laboratory

Additive Manufacturing in Wind Turbine Components and Tooling

Dr. Brian K. Post
Oak Ridge National Laboratory
postbk@ornl.gov, (865) 946 1582
February 2017

Project Overview

Additive Manufacturing (AM) in Wind Turbine Components and Tooling

Target: Demonstrate feasibility of using Big Area Additive Manufacturing (BAAM) to manufacture wind turbine mold. Quantify costs & explore potential for significant manufacturing cost reduction.

The Challenge: AM has traditionally been limited to small components. Wind molds are very large (often >30m in length). BAAM offers the potential to build large composite parts quickly and economically.

However, building an acceptable mold set requires thoughtful design, appropriate materials, and industrial partnership.

When successful, the molds will be used in the manufacture of 13 m research blades for the wind program

Partners: TPI Composites, Sandia National Laboratories, National Renewable Energy Laboratory (NREL)

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The Impact

The opportunity through Large Scale AM wind tooling is three-fold:

✓ Reduce development cycle (CAD to Part)

- Eliminate the manufacture of plugs
- Speed up design iteration

✓ Optimize the process

- Integrate functional subsystems (e.g. heaters)
- Realize complex designs (custom blades/ interchangeable sections)

✓ Reduced fabrication complexity and cost drivers

- Direct digital manufacturing
- Lower labor requirements

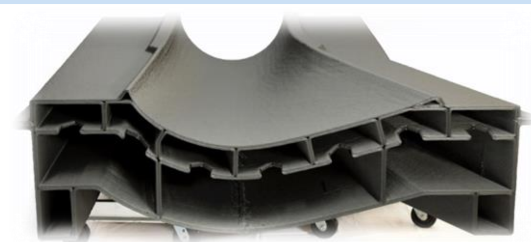
Technical Approach

Tasks

- **1: Understanding and documenting wind turbine blade mold requirements**
- **2: Risk Reduction: Design and construction of an AM mold section**
- **3: Design a complete blade mold to industry standards**
- **4: Constructing blade mold sections and assembly to complete final mold**
- **5: Constructing blades using the AM blade mold**
- **6: Final Report**

Traditional 50 m Mold	3D Printed 50 m Mold
Fabrication takes a total of **27 weeks** • 12 weeks: fabricate plug • Three (3) weeks: setup and inspect to confirm shape • Six (6) weeks: layup shell, attach frame, demold from plug • Six (6) weeks: Electrical connections, cure, QA, shipping prep	Based on 13 m mold results, a 50 m mold can be designed, printed and finished in only **20 weeks** • 12 weeks: print mold sections • Four (4) weeks: glass and finish mold sections • Four (4) weeks: attach frame, install heaters, QA, shipping prep
One pair of main plugs—reliable for 6–10 molds. One pair of molds typically reliable for 1,000 blades.	No plugs are needed. Direct CAD to mold
Wires are embedded into the fiberglass surface by hand during mold fabrication to heat the surface.	Air passages are incorporated into the design of the mold to accommodate heated air which is cycled throughout the mold.

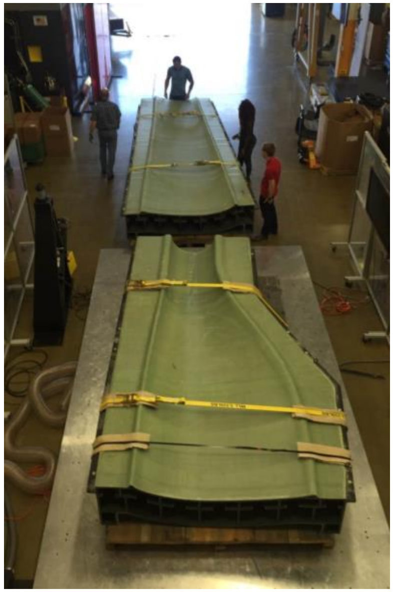
BAAM-CI at ORNL MDF



Wind turbine blade mold section manufactured on the BAAM-CI from 20% CF-ABS pellets

Technical Approach

Parameter	Target (this period)	Stretch (low volume)	Production
Substrate bond interface and coatings	Short beam shear test with no failure of interface at ambient	Short beam shear test with no failure of interface at 40ºC	Short beam shear test with no failure of interface at 70ºC
Mold temp (+/- 5ºC)	Ambient (need oven)	40ºC (resin flows)	70ºC (fast cure) with 100ºC peak
Mold distortion	Match HP to LP at ambient less than 1% of chord	Match HP to LP at 40ºC less than 1% of chord	Match HP to LP at 70ºC less than 1% of chord
Vacuum drop	30 mbar over 30 minutes	15 mbar over 60 minutes	15 mbar over 60 minutes
Assembly of mold pieces	Meet gap tolerance at room temp	Meet gap tolerance at 40ºC	Meet gap tolerance at 70ºC
Life	Four (4) blades	12 blades	1,000 (production)



Accomplishments to Date (FY 16)

- ✓ Blade Design Completed by Sandia
- ✓ Blade Mold Subsection Tests Completed by ORNL
  - – Heating, Deformation at Temperature, Surface Coatings, and Dimensional Accuracy Validated
- ✓ Complete Blade Mold Design Completed by TPI
  - – Including HP and LP skin Molds, Shear Web Molds, Bond Flanges, and Root Dams
- ✓ Complete Blade Mold Set (HP and LP Skins) Printed and Machined by ORNL
- ✓ Assembly of the HP and LP Molds Completed by TPI
- ✓ Printing of Auxiliary Molds and Flanges in Progress
- ❑ First Blade Completed at end of January 2017

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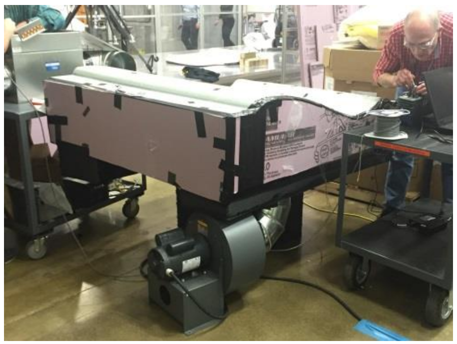
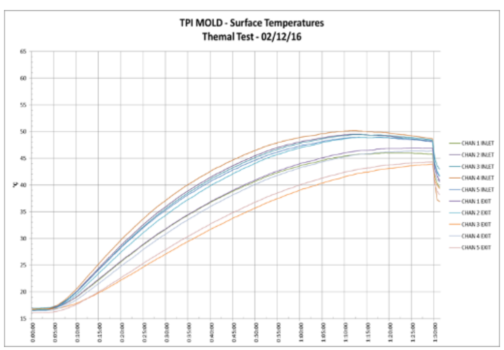
✓ Results from all tests meet design requirements



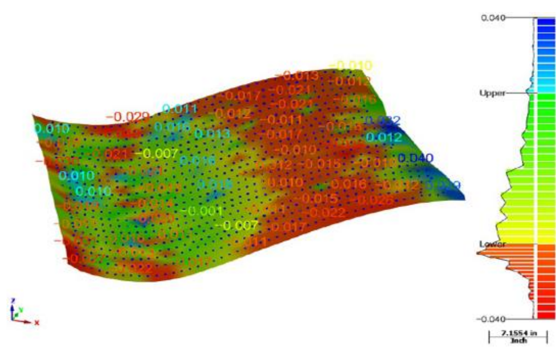
Experimental setup

Laser tracker in foreground

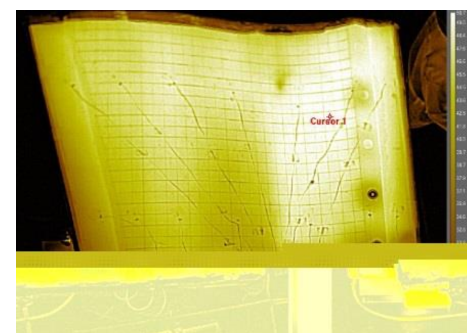
Thermal imaging on mold surface



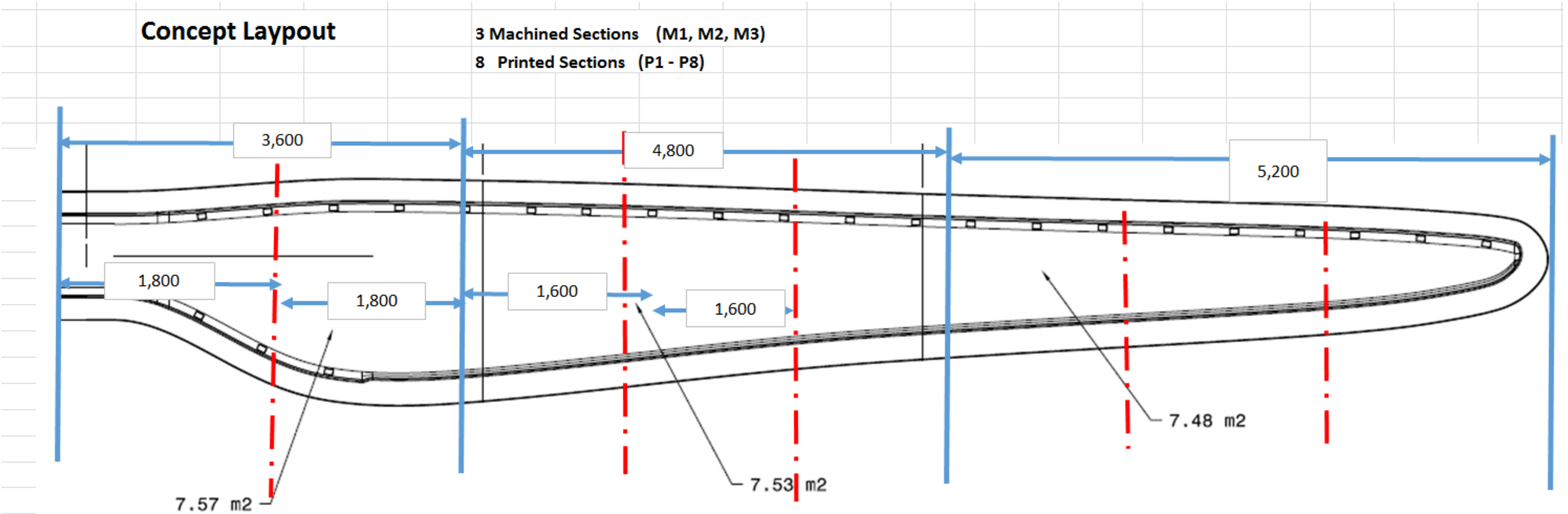
Surface temp

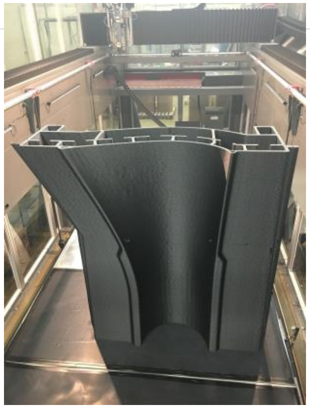


Profile data



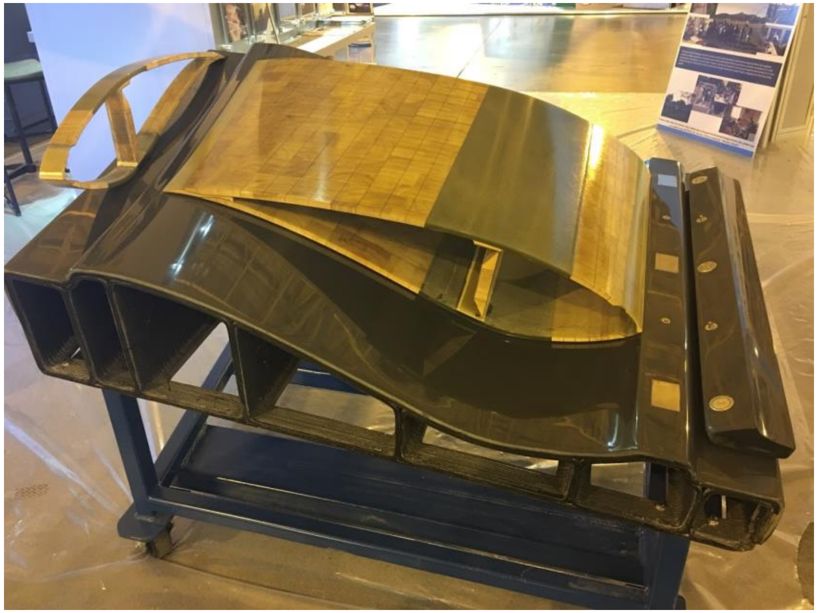
- **Mold printed in eight subsections** (1.6 - 1.8m long). ***Red dashed lines***
- **Subsections joined into three sections** (3.6 - 5.2m long) ***Blue lines***





Project Plan & Schedule

- ✓ ***Exhibition of a AM blade mold component*** at American Wind Energy Association (AWEA) Annual Forum, May 23–26, 2016 in New Orleans, LA



AWEA Blade Mold Section

- ***Completed construction of AM blade mold*** by end of Q1 2017
- ***Construction of first blade*** made with an AM mold by end of Q1 2017
- ***Flight of three blades,*** made with AM mold, on a turbine at the SWiFT facility by end of Q2 2017

Project Plan & Schedule

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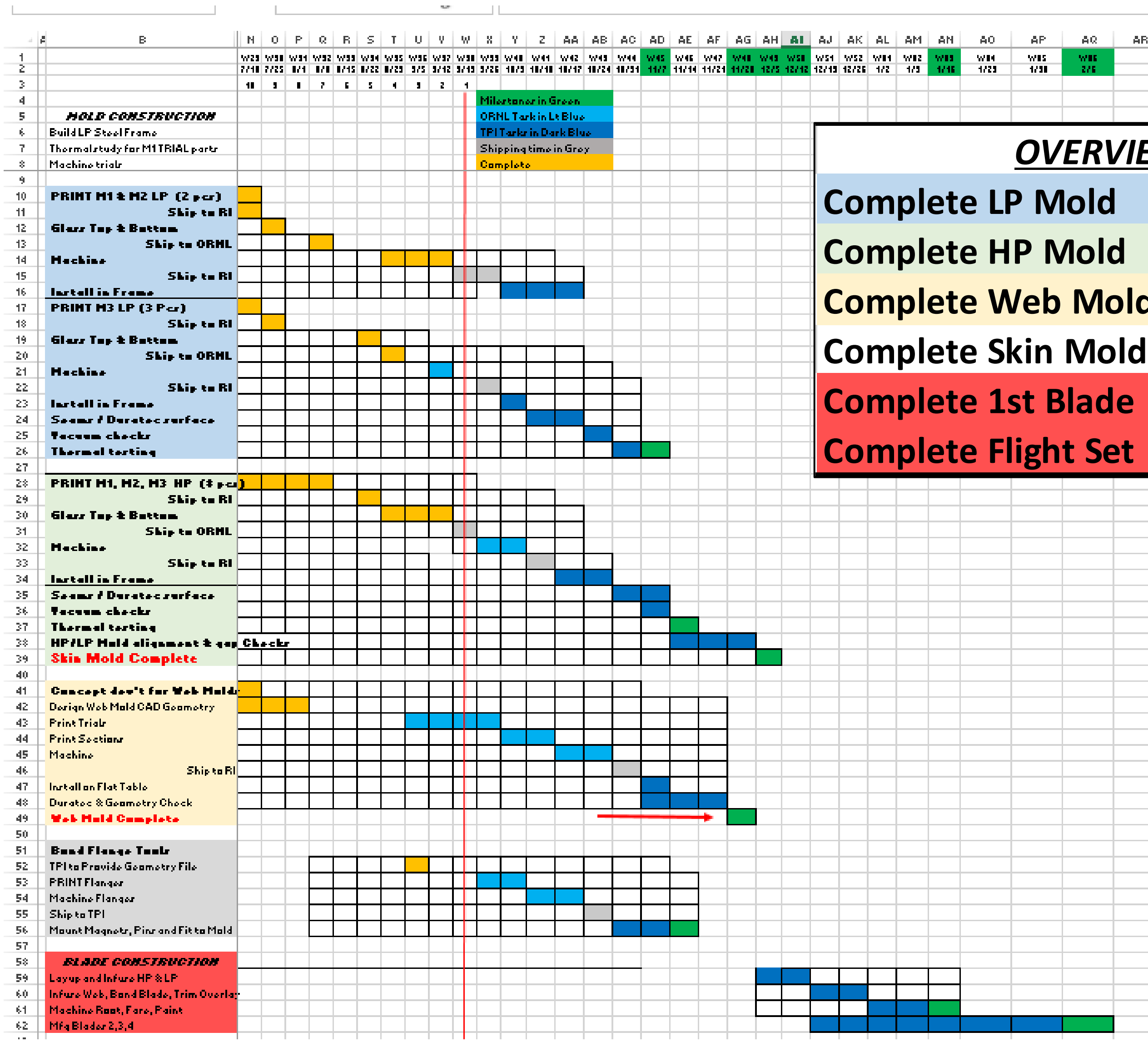


OVERVIEW				
Complete LP Mold			7-Nov	
Complete HP Mold			14-Nov	
Complete Web Mold Assembly			28-Nov	
Complete Skin Mold Assembly			5-Dec	
Complete 1st Blade			16-Jan	
Complete Flight Set			6-Feb	

Shear Web Molds Iteration 2 Completed Dec 9th

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
				$390K (Wind and AMO)	$240K (TPI)

- Inter-Office collaborative project with investment by both DOE Wind ($150K) and the Advanced Manufacturing Office (AMO) ($240K)
- Some delays to accommodate changes in blade design, machine availability, and transportation logistics (no expansion of budget)

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

Sandia National Laboratory
- Blade Design

TPI Composites
- Mold Design and Assembly / Blade Fabrication

Oak Ridge National Laboratory
- Design for AM / Printing of Blade Molds

National Renewable Energy Laboratory
- Cost Analysis and Blade Testing

Communications and Technology Transfer:

Conference Demos (AWEA Demo Mold):
- AWEA – New Orleans, LA (May 2016)
- Maker's Faire – Washington DC (June 2016)
- Blade Manufacturing Workshop – Albuquerque, NM (August 2016)
- Manufacturing Day – Washington, DC (October 2016)

Articles (20+ News Articles and Reports):
- Examples:
  - Transforming Wind Turbine Blade Mold Manufacturing With 3D Printing (EERE Publications: http://web.ornl.gov/sci/manufacturing/docs/Transforming-Wind-Turbine-Blade-Mold-Manufacturing-3D-Printing.pdf)
  - 3D Printed Molds Save DOE Time and Money on Wind Energy (3DPrint.com: https://3dprint.com/145252/3d-printed-wind-turbine-mold/)
  - Energy Department 3D Prints Wind Blade Molds to Reduce Costs (Composites Manufacturing Magazine: http://compositesmanufacturingmagazine.com/2016/08/energy-department-3d-prints-wind-blade-molds-reduce-costs/)
  - 3D printed wind turbine blades could provide cheaper, more effective wind energy (Wind Energy and Electric Vehicle Review: http://www.evwind.es/2016/03/22/3d-printed-wind-turbine-blades-could-provide-cheaper-more-effective-wind-energy/55713)

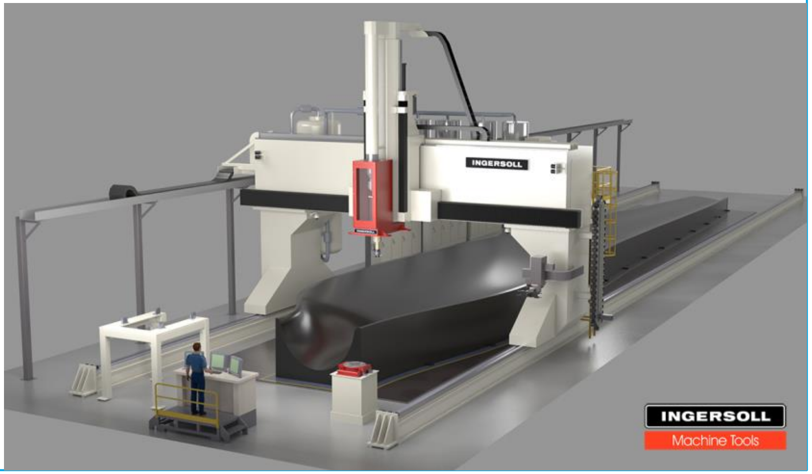
Next Steps and Future Research

FY17/Current Research:

- Production of wind blades for SWIFT facility
- Cost model development – comparison of AM vs. conventionally manufactured blade molds

Planned Future Research:

- Investigation of other opportunities in wind manufacturing for AM (Magnets, Heat Exchangers, Nacelle housings for example)
- Ingersoll WHAM
  - ORNL/Ingersoll 3D Printer
    - 1,000 lb/hr (10x BAAM)
    - 25'x35'x160' Envelope



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

Development of On-Site Tapered Spiral Welding for Large Turbine Towers

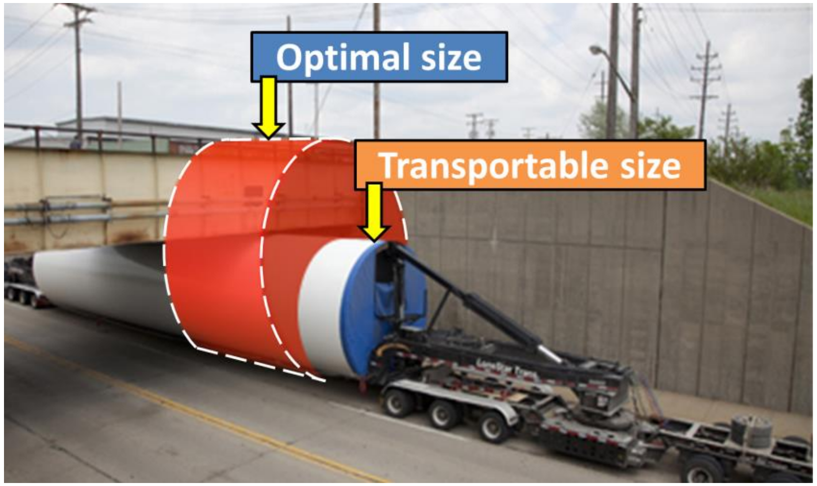
Eric Smith

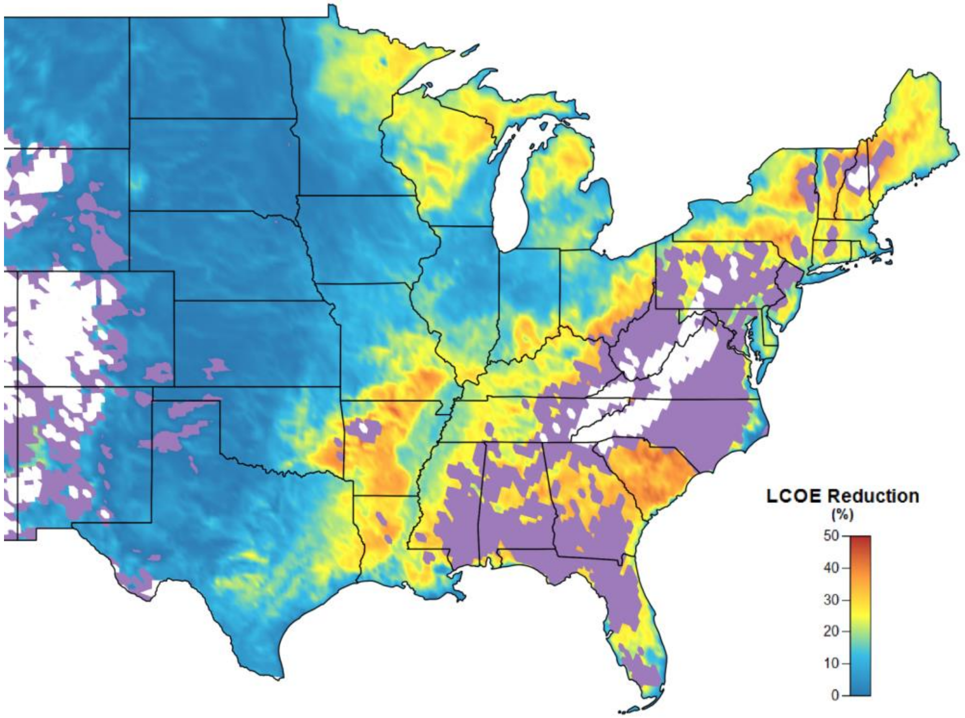
Keystone Tower Systems

Eric@KeystoneTowerSystems.com, 857 225 0552

February 2017

Development of On-Site Tapered Spiral Welding for Large Turbine Towers





KEYSTONE TOWER SYSTEMS · Vestas · DNV·GL · IBERDROLA · res AMERICAS powering change · PARSONS

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- Reliability improvements
- **Enabling access to better resources through tall wind**
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

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- Technical engagement initiatives
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- NextGen component innovations

The Impact

- Low cost tall towers that scale to 180m+ hub height
- Enable wind development at low wind speed sites
- Unlocking areas in Southeast, Great Lakes, and Northeast (increasing developable area in US 3x)
- Studied all aspect needed for in-field spiral towers

Technical Approach

This project addressed all aspect of on-site wind tower production:

- Tall tower design and certification
- On-site facility design and operation
- On-site facility deployment
- Tall tower erection
- All permitting, logistics, etc. related to tall towers and on-site production
- Full system economics.


DNV·GL

STATEMENT OF COMPLIANCE

A-Design Assessment

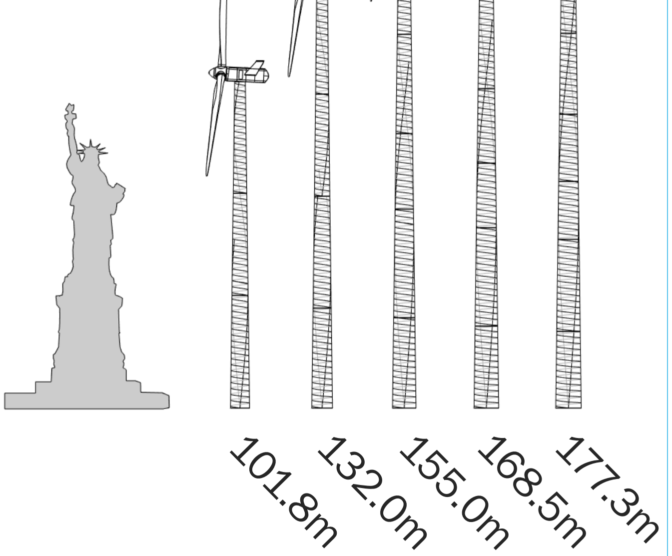
Spiral Welded Tower Design

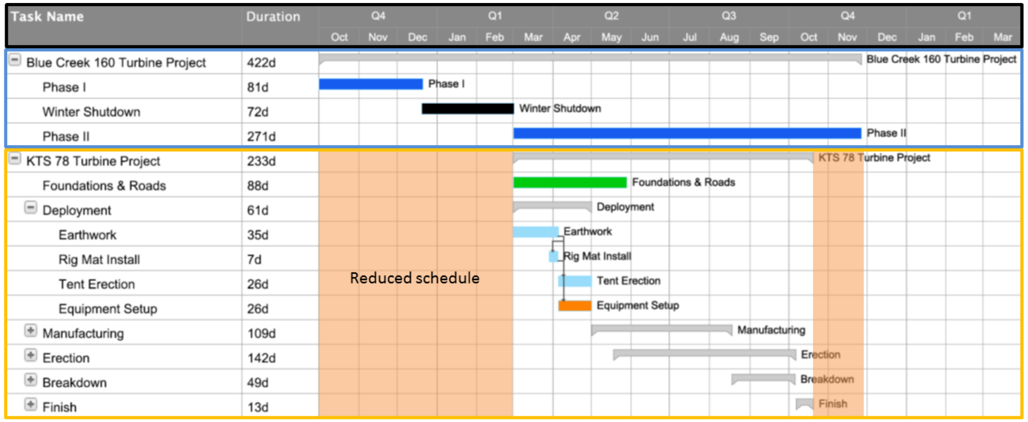
Keystone Tower Systems, Inc.

GL-IV-1:2010 Guideline for the Certification of Wind Turbines

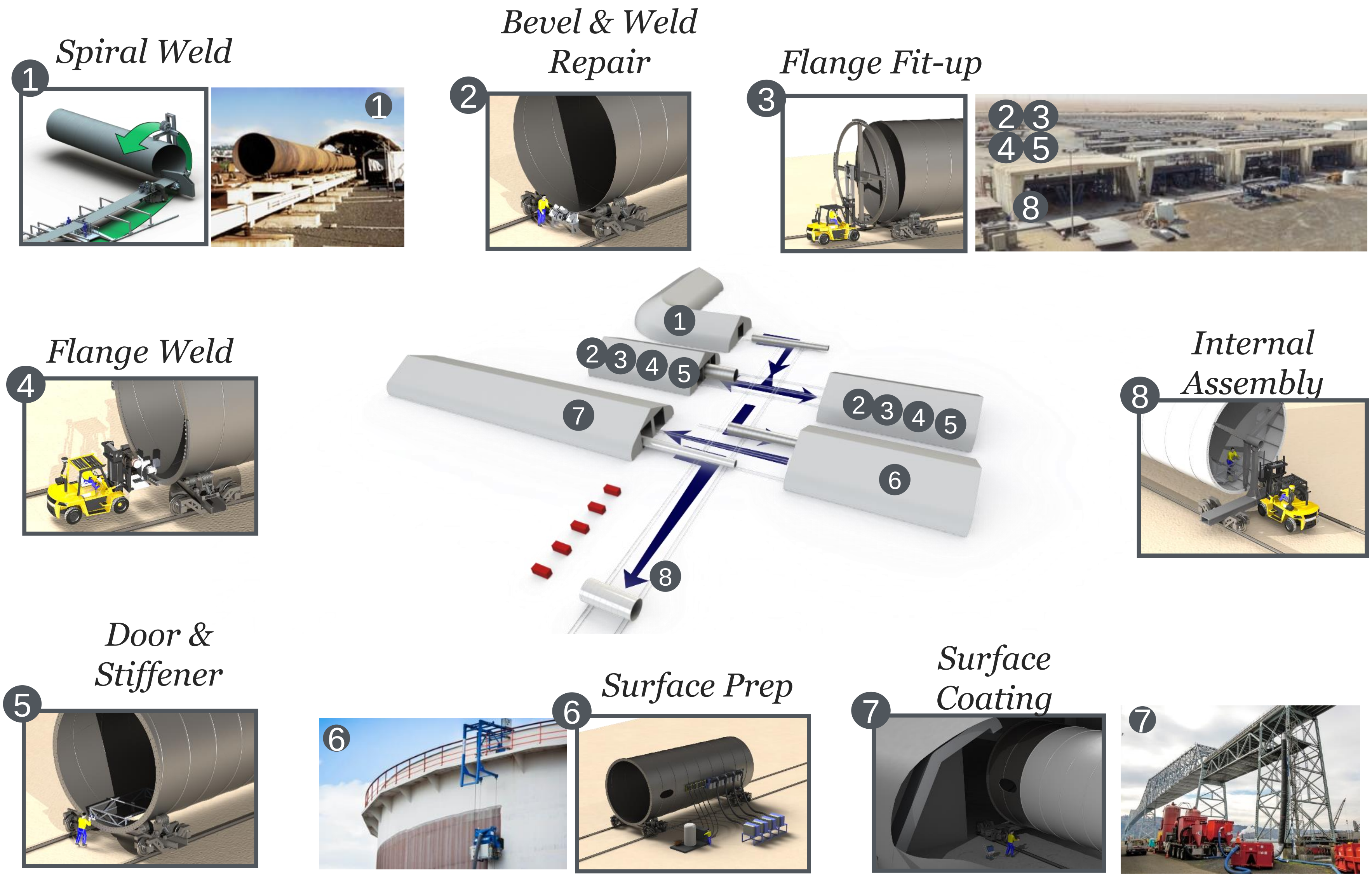
IEC 61400-22: 2010, Ed. 1: Wind turbines – Part 22. Conformity testing and certification

DNVGL-SE-0074 Type and component certification of wind turbines





Technical Approach



Accomplishments and Progress

Built prototype manufacturing line

Installed first spiral welded tower

Accomplishments and Progress

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

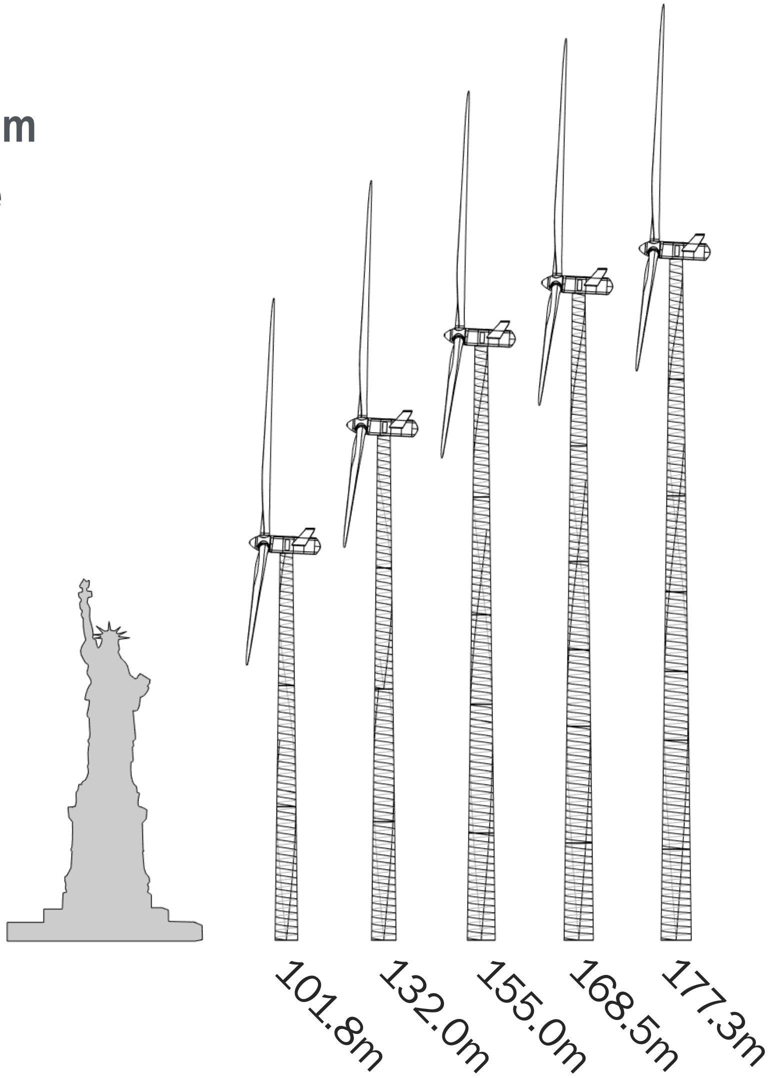
Tasks (tower design)

- Completed tower designs for hub heights up to 180m
- Achieved design-in for market leading 3MW turbine
- Received DNV-GL certification for designs

Resulting in

- Towers more than 2x taller than standard designs
- 200+ tons saved from each tower
- 40% tower cost reduction
- Over-dimension towers that can only be made domestically

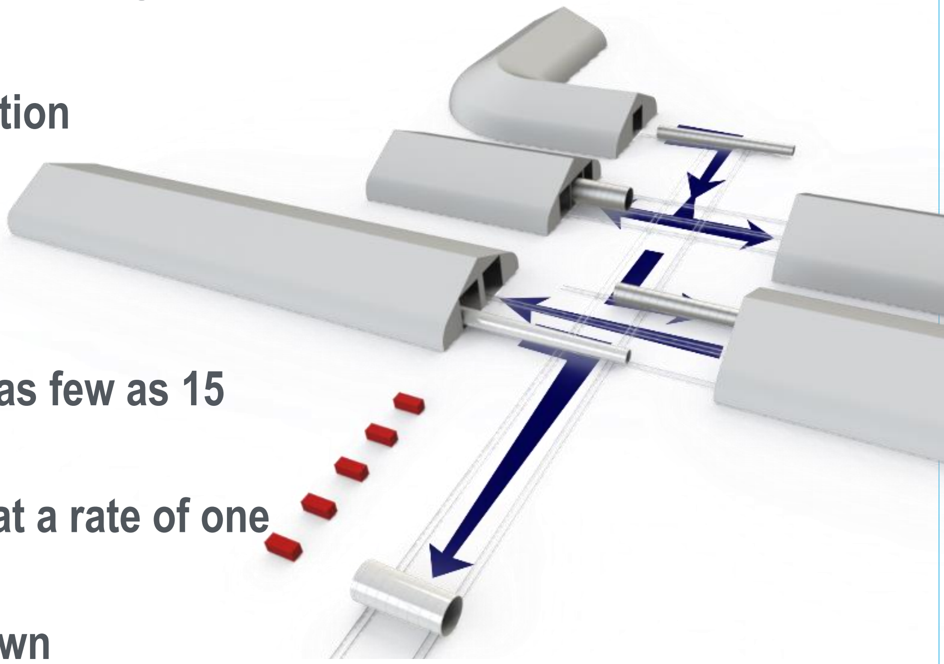
155m towers	Transportable steel	concrete hybrid	Spiral welded
Tower mass	640 tons	1640 tons	438 tons
# sections	10	52	5



Accomplishments and Progress

Tasks (factory design)

- Completed full factory design for all manufacturing steps
- Identified all equipment and operations
- Completed time and motion study of operation
- Developed in-field deployment plan



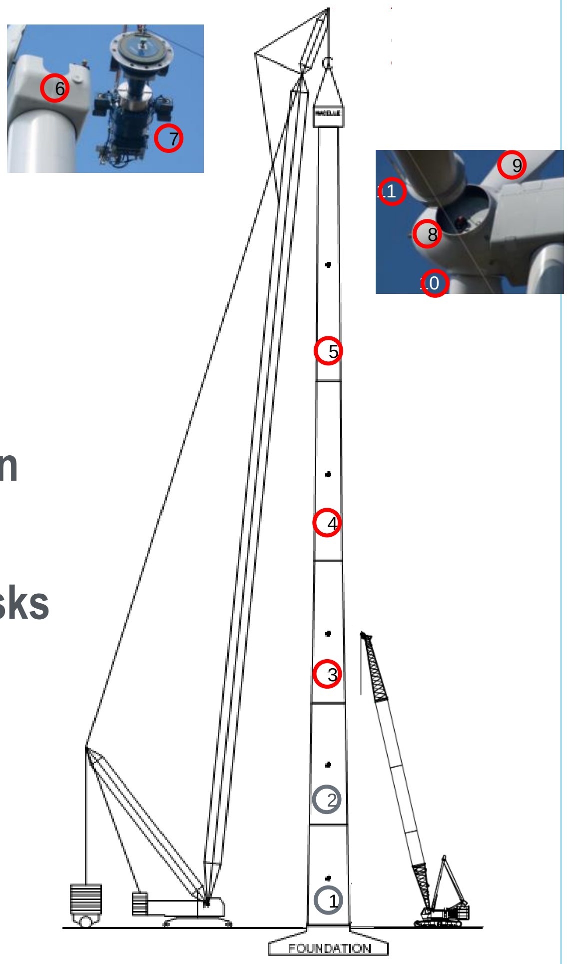
Resulting in

- In-field operation justified for projects with as few as 15 towers
- Towers can be manufactured and installed at a rate of one every two days
- Manufacturing can be completed using known technologies proven in adjacent industries (e.g. bridge building, mobile drilling operations)

Accomplishments and Progress

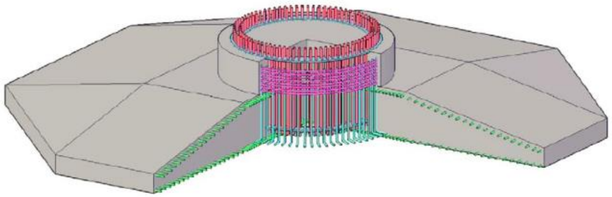
Tasks (development and construction)

- Redesigned a commercial wind project around spiral towers
- Studied all aspects of wind development that changes:
  - foundations, logistics, erection, permitting, O&M…
- Developed construction plans and timeline

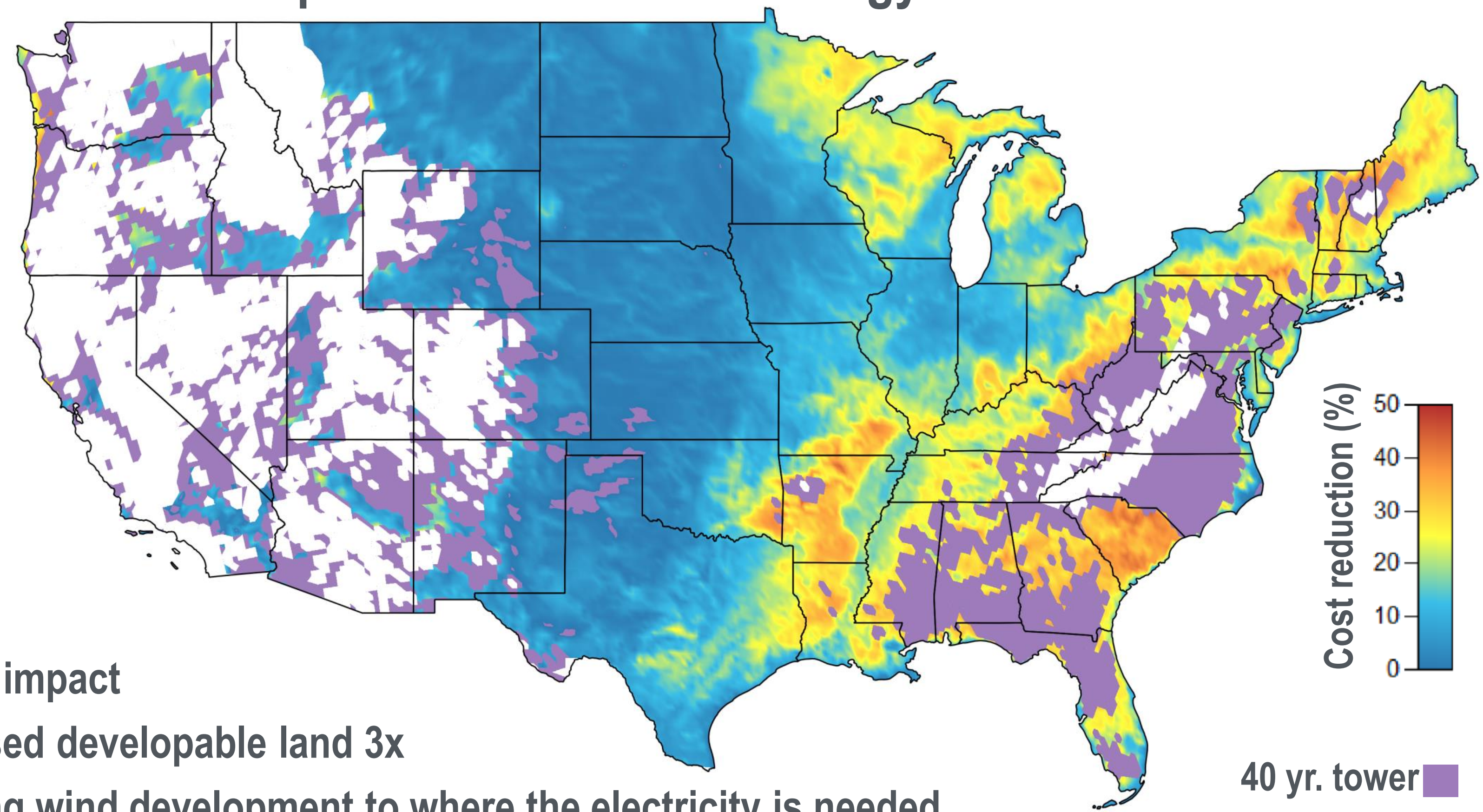


Resulting in

- 51% reduction in number of turbines for same energy generation
- 34% reduction in construction time
- Market ready solutions for all development and construction tasks



Impact on cost of wind energy



Economic impact

- Increased developable land 3x
- Bringing wind development to where the electricity is needed
- Up to 40% LCOE reduction relative to 80m towers
- Unsubsidized wind cheaper than new build natural gas in many areas

Project Plan & Schedule

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

- Initial project dates: 10/1/2014 – 3/30/2016

- The schedule was extended to allow sufficient time after the go/no-go decision point for review by DOE, and decision on whether to proceed with next project period

- The project had one Go/No-Go decision point
  - 3Q from start of project
  - Preliminary calculations of Levelized Cost of Energy (LCOE) with on-site spiral welded towers, for a typical low wind speed site
  - This calculation determined whether on-site tower manufacturing showed enough economic promise to continue with the project plan

Project Budget

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

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
43,406	12,747	647.738	190,215	308,681	97.759

- Actual expenses exceeded the budget by a small amount. The extra cost was included in Keystone's cost share. The project plan was not modified.
- The project is completed, and the entire budget has been expended.
- Cost-share funding came from Keystone equity funding and Parsons Construction, a project partner.

Partners, Subcontractors, and Collaborators:

Keystone's partners included the entire value chain, from tower design to on-site manufacturing.

Tower design requirements	Design certification	Project requirements	Foundation design / planning	In-field deployment and manufacturing
Vestas	DNV·GL	IBERDROLA	res AMERICAS powering change	PARSONS

Communications and Technology Transfer:

Invited talks at key conferences:

AWEA WINDPOWER 2015 Conference & Exhibition Orlando, FL May 18-21

SOUTHEASTERN WIND COALITION

IQPC International Quality & Productivity Center

Design in with leading

- Spiral mill manufacturers
- Turbine manufacturers
- Wind developers

Next Steps and Future Research

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

Planned Future Research:

Keystone is working with:

- manufacturing partners
- leading turbine manufacturers
- Southeastern utilities

to plan a 160m+ hub height demonstration project in the southeastern United States.

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

Hexcrete Tower for Harvesting Wind Energy at Taller Hub Heights

Sri Sritharan

Iowa State University

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February 2017

Project Overview

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

Hexcrete Tower for Harvesting Wind Energy at Taller Hub Heights:

- A cost-effective tower solution to reach taller hub heights
- Facilitate wind energy production in all 50 U.S. states
- Reduce levelized cost of energy (LCOE) and increase local manufacturing

The Challenges:

- Transportation dictates the hub height, supply chain and logistics
- Heavy reliance on foreign steel market
- Wind energy production is low where the electricity demand is high

Partners:

- Siemens Corporation, Corporate Research & Technology – Design optimization
- BergerABAM, Inc. – Engineering drawings and commercialization / implementation plan consulting
- Coreslab Structures (OMAHA), Inc. – Manufacturing of experimental test pieces and cost estimation

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- Reliability improvements
- **Enabling access to better resources through tall wind**
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
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Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- **Commercialization of innovations and technology transfer**
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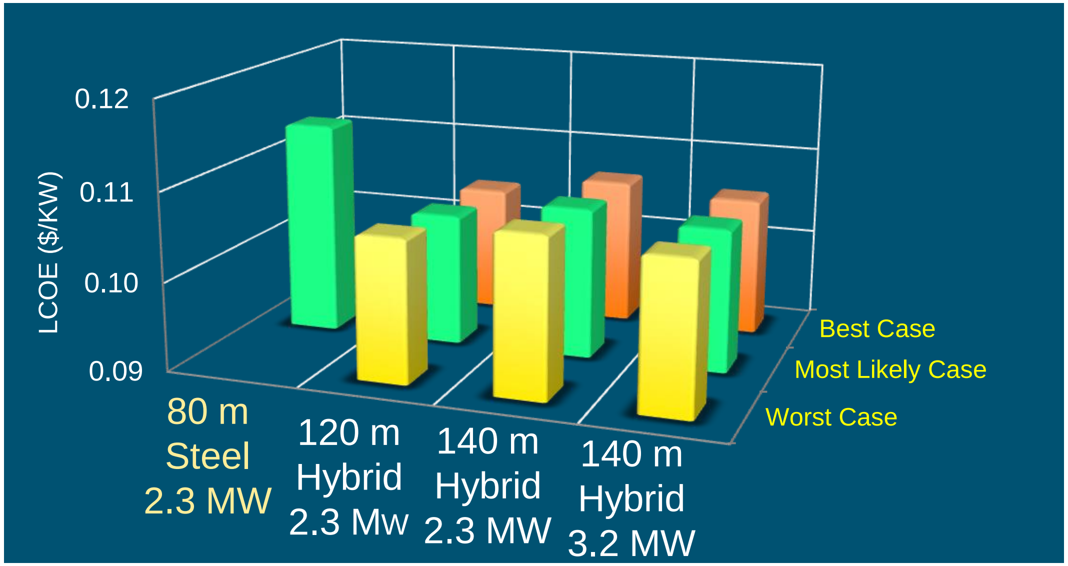
The Impact

- Wind energy production in all 50 states and 67% increase in U.S. land area for wind energy production.
- Reduction in wind energy cost (expected impact of Hybrid Hexcrete tower is below).



Enabling Wind Nationwide

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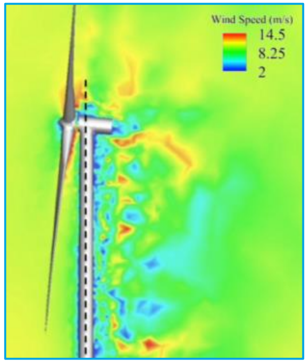
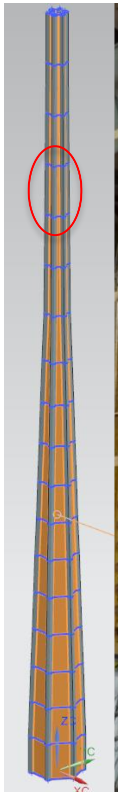
The Impact

- Both wind and concrete industry members have been engaged in the project, and their input have been accounted for in the design of tall Hexcrete towers.
- Industry members believe that the Hexcrete technology is ready for prototype demonstrations, which will help commercialize the new technology rapidly.
- Commercialization of Hexcrete technology will promote local manufacturing while providing energy security and energy independence for the nation.

Technical Approach

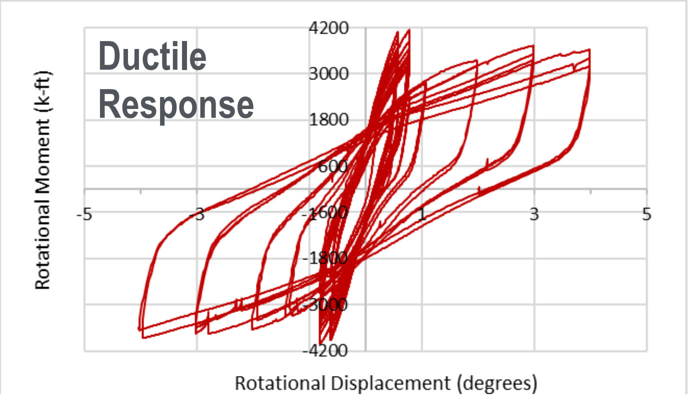
- Designed 120- and 140-m tall Hexcrete towers for loads from original equipment manufacturer in compliance with design codes
- Verified designs using fluid-structure interaction studies and optimized tower dimensions
- Conducted full-scale system and fatigue testing of Hexcrete components
- With input from industry partners, developed tower erection plan
- Produced engineering drawings and videos showing the tower assembly
- Evaluated LCOEs
- Formulated a commercialization plan





Technical Approach – Unique Aspects

- Addressed constructability of tower components and U.S.-based manufacturing in design
- Fully coupled fluid-structure interaction analyses of towers
- Structural testing to loads well beyond the specified extreme loads to ensure safety of turbine and rotor
- Significant engagement of wind energy and concrete industry partners in various facets of project
- Identifying potential industry partners to work on prototype towers with different configurations.



Accomplishments and Progress

- Demonstration of the feasibility of using Hexcrete technology for tall towers up to hub heights of 140 m
- Evaluating the expected cost of energy involving tall Hexcrete towers with realistic estimates for component fabrication, tower assembly, construction schedule and annual energy production
- When compared to conventional 80 m steel towers, tall Hexcrete towers are shown to reduce the LCOE by about 10% in wind rich regions (e.g., Texas and Iowa).
- Hexcrete towers can reduce the cost of electricity from wind by more than 20%.
- Made several invited technical presentations to conferences organized by wind energy and concrete industries as well as research institutions.

Project Plan & Schedule

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

- Project Dates
  - Initiation Date: October 1, 2014
  - Completion Date: August 30, 2016
  - Final Report submittal planned for November 30, 2016
- Explanation for slipped milestones and slips in schedule:
  - Structural testing was delayed due to challenges in manufacturing of reaction blocks for Hexcrete test (non-Hexcrete components not present in actual towers. but necessary for laboratory testing)
- Go/No-Go decisions:
  - FY14: none, project not active
  - FY15: Sept. 20, 2015 – completed 120 m tall optimized tower design and structural load testing on a full-scale segment of the tower
  - FY16: none

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$0	$0	$634.172k	$129.574k	$324.054k	$114.455k

- Project plan modification/budget variance: Instead of hiring a single consultant to produce the 140 m tower engineering drawings, we produced the drawings in house and used the funds to support two industry workshops: Construction Cost and SWOT.
- As of Nov 30, 2016: 100% expended. Project closed. [FY17 expenses: DOE = $41,774, Cost Share = $5,970]
- The Iowa Energy Center supported Task 6 (included in the reported cost share).

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

Lafarge North America, Iowa Energy Center, BergerABAM, Coreslab Structures of Omaha, Siemens, NREL, Barr Engineering, Bigge Crane and Rigging, Mortenson Construction, MidState Precast, Old Castle Precast, Pattern Energy, Patterson, Structural Technologies, Sumiden Wire Products, Wells Concrete

Communications and Technology Transfer

- Cost Estimation Workshop – March 30, 2015 **Outcome:** Addition of hybrid tower designs and tower erection plan
- Hexcrete SWOT Workshop – March 24, 2016 **Outcome:** Increased efficiency of Hexcrete technology and erection plan and further developed industry partnership
- Commercialization Workshop – June 23, 2016 **Outcome:** Formation of Joint Industry Partnership (JIP) and preliminary commercialization plan

Next Steps and Future Research

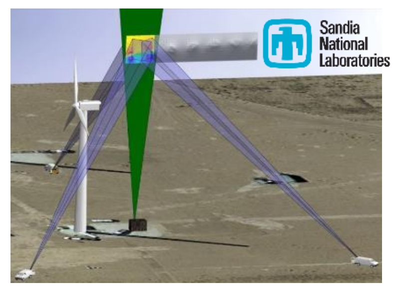
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Planned Future Research:

- None within the scope of current project
- Pending investments for full-scale demonstration of the Hexcerte technology, and its ability to promote domestic manufacturing and contribute to US economy due to its dependency on a domestic supply chain as opposed to relying on imported steel
- Discussion with potential JIP members to help build the Hexcrete prototype towers is ongoing.

Supporting industry's rapid development

Leveraging laboratory and international capabilities



Testing Facilities and Capabilities at SNL

SWiFT: an open technology innovation platform

Jon White

Sandia National Laboratories

jonwhit@sandia.gov (505) 284 5400

February 14, 2017

Project Overview

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

SWiFT Facility: only open-source wind farm in the world comprised of three research-grade wind turbines to study turbine-turbine interaction and advanced rotor blades, enabling high-reward research and technology development,

SWiFT meets the challenge: Large commercial turbine/wind farm R&D has frequently been restricted and conservative because of high-cost, high-risk, proprietary constraints and high uncertainty in the results.

Core Partners: DOE Wind Program, Sandia National Laboratories, Texas Tech University, Vestas Wind Systems, Group NIRE

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

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- **Reliability improvements**
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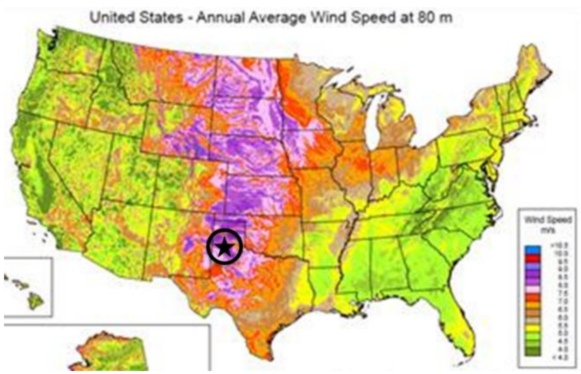
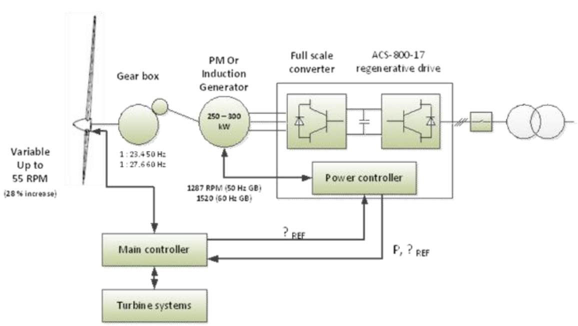
The Impact

- Support early-stage high-reward industry technology development to increase energy security and independence
- Develop the next generation of wind simulation capability by producing data with world-leading accuracy
- Lead the adoption of wind plant controllers by original equipment manufacturers (OEMs) and owner/operators through demonstration projects
- Expedite commercialization of new sensor technologies and methods
- Increase capacity factor of wind plants through development of advanced rotor blades
- Support job creation, infrastructure enhancement and rural economic development from its location at Texas Tech University, Lubbock, TX.

Technical Approach



Open-Source Controller

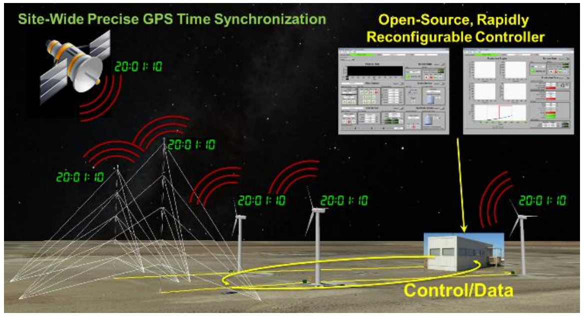


- SWiFT is located in the heart of the U.S. wind fleet to study turbine-turbine interaction and advanced rotors. The Texas site for the facility allows for high consistent predictable winds in flat terrain, that minimizes measurement time and uncertainty for scientific validation.
- Making all engineering documentation for the wind farm, turbines, components and controls publicly available with no proprietary restrictions has enabled cross-cutting collaborative research between laboratories, industry, and academia.
- High-capacity modern variable-speed machines secure large future test envelopes and cost-effective research, including new intelligent rotors systems with farm-level impact.

Technical Approach

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

- The modifiable and redistributable control system integrates the entire wind farm and instrumentation, enabling validation-quality future wind farm research.
- A site-wide, GPS-triggered, synchronized control and data-acquisition network allows time-based data analysis of all signals (instead of statistical representations), creating opportunities for future novel approaches to wind farm analytics and scientific data validation.
- Best-in-class, functional-scaling methodology enables technology transfer to any future utility scale, with high confidence due to exceptionally high data quality that leverages advanced site-wide synchronized controller and a broader Sandia capability in uncertainty quantification.



Accomplishments and Progress

Readiness Assessment

Vestas Multi-Rotor

- SWiFT was the first EERE facility to complete a rigorous Moderate Hazard Readiness Assessment. This validated the professional readiness of facility staff, processes, and equipment to perform high-reward projects.
- Developed rigorous control software development capability with integrated hardware in the loop.
- Vestas, the largest OEM in the world, used SWiFT control software, hardware-in-the-loop, and staff capabilities to enable a game-changing, high-risk research project.
- GE Renewables—Onshore Wind installed instrumentation and performed an uncertainty analysis of a critical quantity of interest on a prototype turbine that helped make informed product decisions on the next generation of wind turbine platforms.
- SWiFT partnered with the National Renewable Energy Laboratory (NREL) to demonstrate the first wake-steering wind plant controller.
- OEMs and Owner/Operators are using results of the wake-steering experiments to commercialize next generation products.

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$952k	$300k	$937k	$350k	$1,822.224k	$1,550k

- Attracting diverse and leveraged investments at SWiFT:

Research Integration & Collaboration

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

Communications and Technology Transfer:
All data from DOE funded activities at SWiFT is publicly available at the A2e Data Archive and Portal.

All engineering specifications and models are publicly available and downloadable.

FY17/Current Research: Test wind turbine and wind plant controllers with NREL, as well as other industrial partners. Testing a variety of advanced turbine instrumentation and LIDARs for unprecedented high accuracy wind plant data.

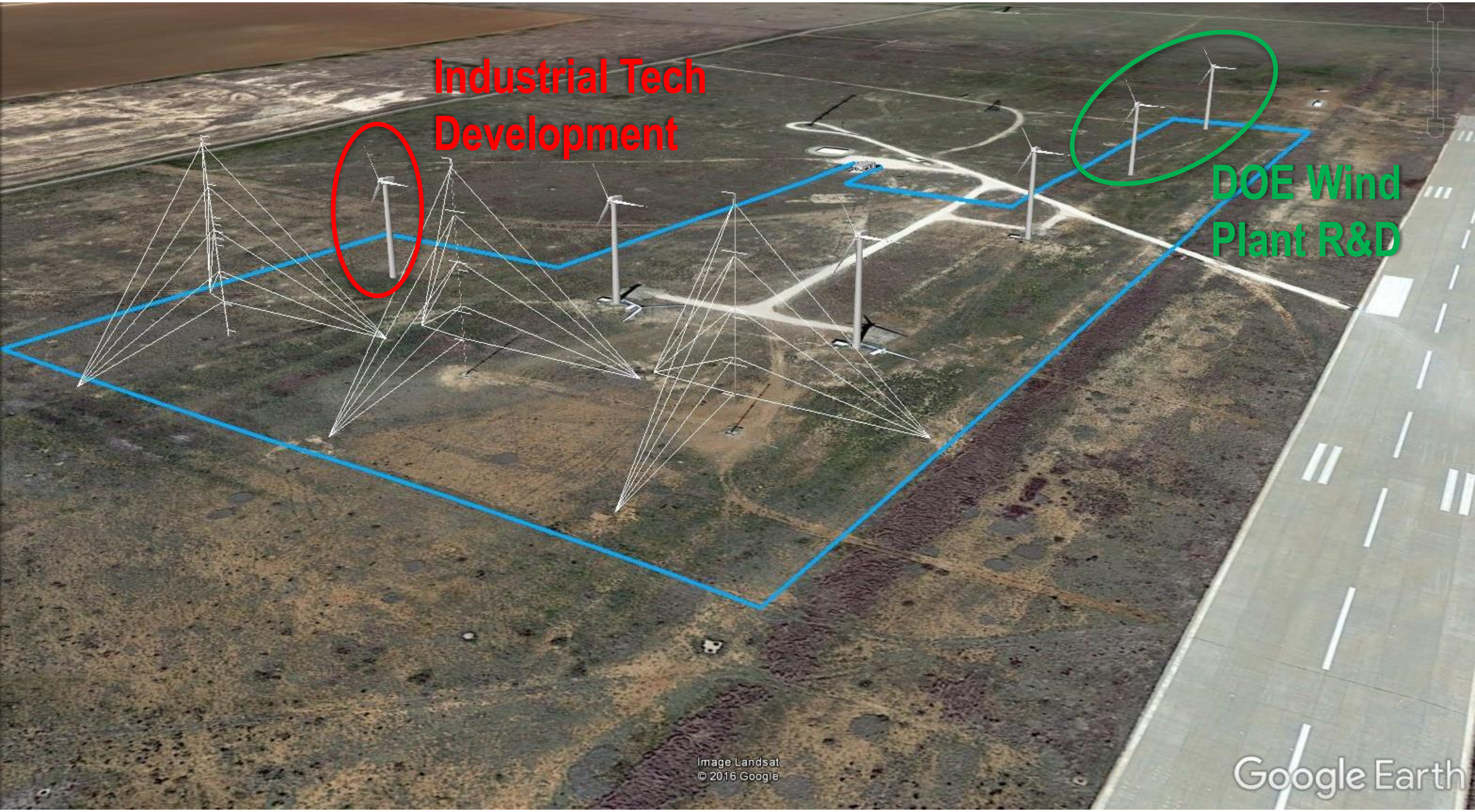
Next Steps and Future Research

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

Planned Future Research:

- Design and flight validation of technology required to enable extreme low specific power rotors
- Advanced rotor experiments and controllers for wind plants
- Flight test of the open source Sandia-designed National Rotor Testbed
- Sensor testing
- Demonstration of low uncertainty field testing
- Workforce development with owner/operator partner

Expanding Capabilities



Summary

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

Planned Future Research:

- *SWiFT is:* the only open-source wind farm in the world comprised of three research-grade wind turbines to study turbine-turbine interaction and advanced rotor blades through open collaboration.
- *The SWiFT value: is* to DOE and the wind industry by providing unparalleled cost-effective, accurate and rapid results for early-stage high-reward technology development and commercialization.
- *The SWiFT impact:* is to increase energy security and independence by facilitating the market adoption of cost-lowering innovations.

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


Photo by Dennis Schroeder, NREL 37992

Testing Facilities and Capabilities at National Wind Technology Center

Dave Simms

National Renewable Energy Laboratory (NREL)

David.simms@nrel.gov 303 384 6942

February 2017

Project Overview

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

Testing Facilities and Capabilities at National Wind Technology Center (NWTC):

- Operations & Maintenance (O&M) to keep NWTC testing infrastructure "mission ready"
- Development of new facilities & capabilities
- ~$4-5M annual funding (seven projects)

The Challenge:

- Provide specialized research facilities and capabilities, associated equipment, qualified operators and technical experts
- Tailored to best meet the needs of DOE researchers and industry partners

Partners:

- Formal agreements with ~75 partner organizations annually with staff involved in projects that utilized NWTC research facilities
- Main partners: Massachusetts Wind Technology Testing Center (structural), Clemson (dyno and grid), SNL SWiFT (field)

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- **World-class test and user facilities**
- Advanced technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

Research enabled by NWTC world-class facilities & capabilities touch all of these strategic priorities

Enabling Wind Nationwide

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- **World-class test and user facilities**
- Advanced technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

The Impact

- Custom-developed infrastructure tailored to demonstrate new renewable energy technology for energy independence, energy security, jobs, and rural economic development
- Allows safe and efficient proof-of-concept testing to extremes, experiments designed to anticipate test article failures
- Supported by skilled workers, technical experts
- High-caliber research-grade instrumentation and measurements enables model validation and ensures systems meet required standards
- Allows industry partners to focus on their technology innovations, not testing requirements (e.g. experiment design, safety procedures, data acquisition, etc.)
- Provides DOE insight on research priorities via interactions with industry partners.

Project Scope

Projects:

1. Field Testing O&M
2. Structural Testing O&M
3. Dynamometer Testing O&M
4. 5MW Dyno Integrated System Test (IST).
5. Grid Integration Testing O&M
6. Controllable Grid Interface (CGI) Expansion
7. Overarching Safety, O&M

Photo by Dennis Schroeder, NREL 38281

Photo by Dennis Schroeder, NREL 21902

Photo by Dennis Schroeder, NREL 31775

Photo by Dennis Schroeder, NREL 19010

Photo by Mark McDade, NREL

Note that NWTC facilities and capabilities are operated and maintained in a defined baseline configuration. Any enhancements beyond the baseline; e.g., additional requirements specific to supporting new research or customers, would be funded outside of these projects.

Technical Approach

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Photos clockwise from top by Dennis Schroeder, NREL 22073, 19010, 19012, 22132, 25889

DOE Wind infrastructure (included in this review)

Infrastructure owned and operated by others (e.g. Industry partners, other DOE Programs, NREL Site Ops…)

- Wind technology since 1977
- Pioneers in turbine & component testing methods, development of design & analysis codes
- Specialized research facilities & capabilities for use by DOE & industry
- Experiment design & execution to meet researcher needs (e.g. model validation, proof-of-concept testing)
- Testing to extremes, anticipate test article failures
- 305 acres
- Excellent DOE Wind & Water-Power Program stewardship
- Many partnerships
- Rigorous facility mgmt. per DOE requirements
- Exemplary safety record
- ISO 17025, A2LA accredited to many IEC Standards

Technical Approach

Total ~$15-20M annual expenditures

- DOE, NREL, and industry funding associated with operating, maintaining, developing, improving, and utilizing specialized NWTC research facilities
- Many projects underway concurrently:
  - Research testing projects (~30-60)
  - New capabilities, construction, renovation projects (~10-20)
  - Maintenance and upkeep of buildings and equipment.

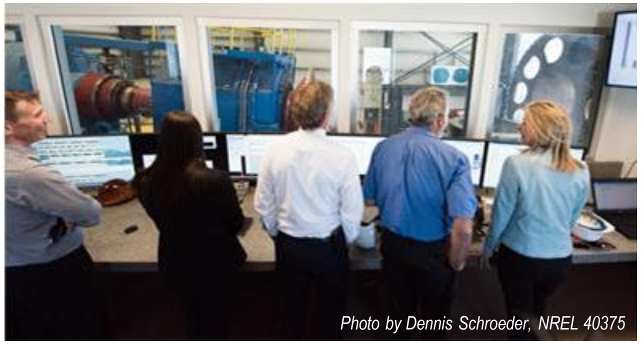
Photo by Dennis Schroeder, NREL 40375

Ensure compliance with all DOE requirements:

- Facility Management, extensive rigorous integrated project planning, enables efficient sharing and optimization of resources (facilities, equipment, people)
- Safety per DOE Integrated Safety Management System (ISMS)
- Quality, Security, Environmental, Property… per applicable requirements
- Develop and retain qualified workers, operators, cognizant system engineers and technicians, documentation and recordkeeping
- Educate and support industry partners, especially smaller companies.


Photo Pat Corkery, NREL 16562


Photo by Lee Jay Fingersh, NREL 16270


Photo by Dennis Schroeder, NREL 19067

Accomplishments and Progress

1. Field Testing O&M

- Qualified O&M of:
  - Five (5) DOE-owned research wind turbines:
    - DOE 1.5 (1.5MW, Site 4.0), CART-2 (600kW, Site 4.3), CART-3 (600kW, Site 4.2), NW-100 (100kW, Site 1.2), Skystream (3kW, Site entrance).
  - Four (4) instrumented meteorological research towers:
    - 135m (2, Site 4.0 & 4.4) , 80m (Site M2, includes interactive display & archive), upwind of each CART machine (Sites 4.2 & 4.3).
  - Specialized field test research infrastructure and capabilities:
    - Turbine control systems, electrical distribution systems, telecommunications systems, Variable Frequency Drives, video monitoring, cooling systems, elevators, un-instrumented met towers, parts and specialized tool storage, etc.
    - Supporting up to 32 possible field test sites, 12 data sheds.
  - Associated field test research project needs:
    - Development of qualified operators and technical system experts
    - Data acquisition systems, instrumentation, calibrations
    - Data analysis and processing systems and tools
    - Safety documentation, review.

Photo by Dennis Schroeder, NREL 26643

Photo by Dennis Schroeder, NREL 19023

Photo by Lee Jay Fingersh, NREL 18494

Photo by Lee Jay Fingersh, NREL 16387

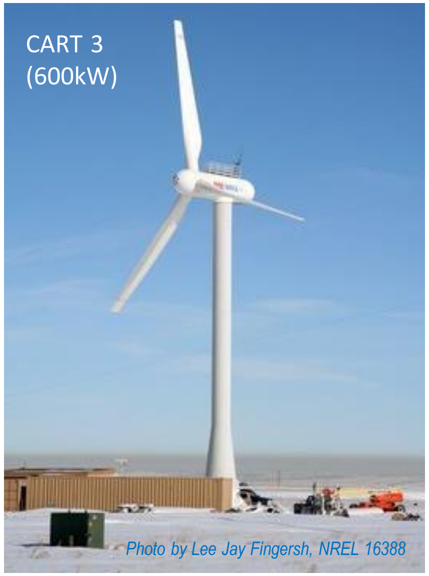

Photo by Lee Jay Fingersh, NREL 16388

Photo by Lee Jay Fingersh, NREL

Accomplishments and Progress

2. Structural Testing O&M

- Qualified O&M of:
  - Three (3) structural test facilities with test stands:
    - STL: up to 50m length test articles
    - 251: up to 21m
    - A60: up to 19m.
  - Specialized structural test facility research infrastructure and capabilities:
    - Indoor high-bay/ outdoor test areas
    - Test stands, winch systems, hydraulic systems, high-pressure hoses, actuators, resonant test systems, bridge cranes, control rooms, SCADA systems, parts and specialized tool storage, etc.
  - Associated structural test research project needs:
    - Development of qualified operators and technical system experts
    - Data acquisition systems, instrumentation, calibrations
    - Data analysis and processing systems and tools
    - Safety documentation, review.


Photo by Mike Jenks, NREL 17641


Photo by Mike Jenks, NREL 13889


Photo by Mark McDade, NREL 29072


Photo by Mike Jenks, NREL 14707


Photo Courtesy Sandia National Laboratories, NREL 17325

Accomplishments and Progress

3. Dynamometer Testing O&M
4. 5MW Dynamometer Integrated Systems Test

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- Qualified O&M of:
  - Three (3) dynamometer facilities
    - 225kW
    - 2.5MW
    - 5MW with non-torque loading (NTL) system.
  - Specialized dyno test facility research infrastructure and capabilities:
    - Indoor high-bay test areas, NTL system, generators, hydraulics systems, actuators, gearboxes, bridge cranes, variable-frequency motor drives, electrical infrastructure, control systems, video monitoring, cooling systems, SCADA systems, control rooms, parts and specialized tool storage, etc.
  - Associated dyno test research project needs:
    - Development of qualified operators and technical system experts
    - Data acquisition systems, instrumentation, calibrations
    - Data analysis and processing systems and tools
    - Safety documentation, review.
- 5MW Dynamometer IST
  - Thorough assessment of full range of behavior and capabilities of new 5MW dyno and associated NTL system
    - Via industry-supplied test articles
    - Documented results relevant to facilitating future experiment planning.


Photo by Dennis Schroeder NREL 32785


Photo by Mark McDade, NREL 40432


Photo by Mark McDade, NREL 27247

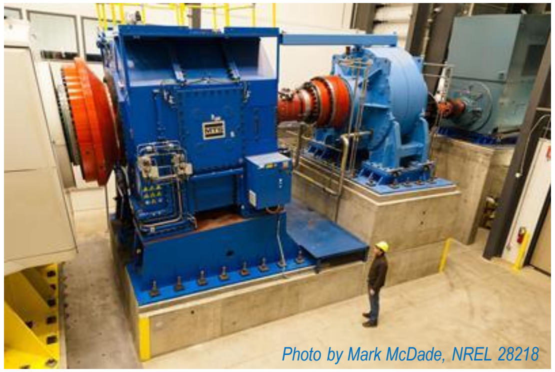
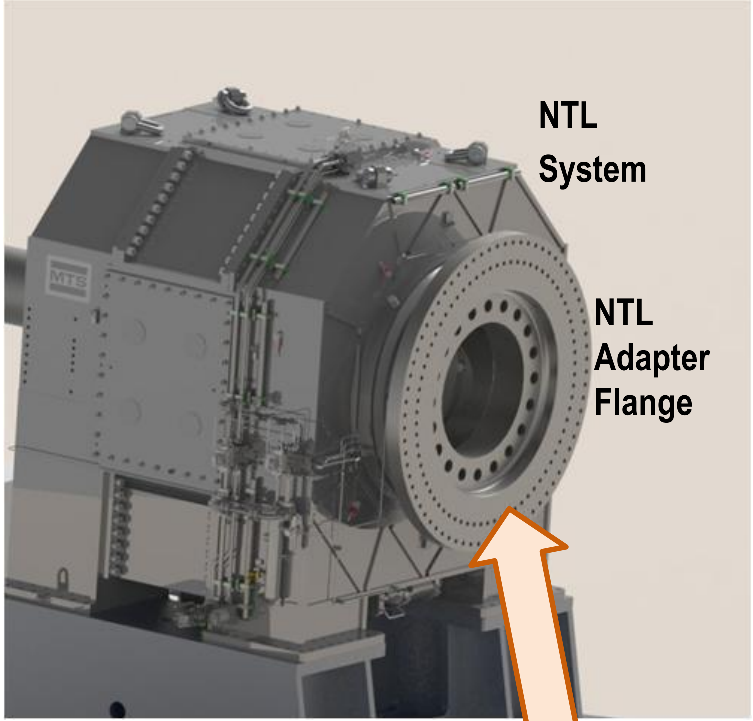


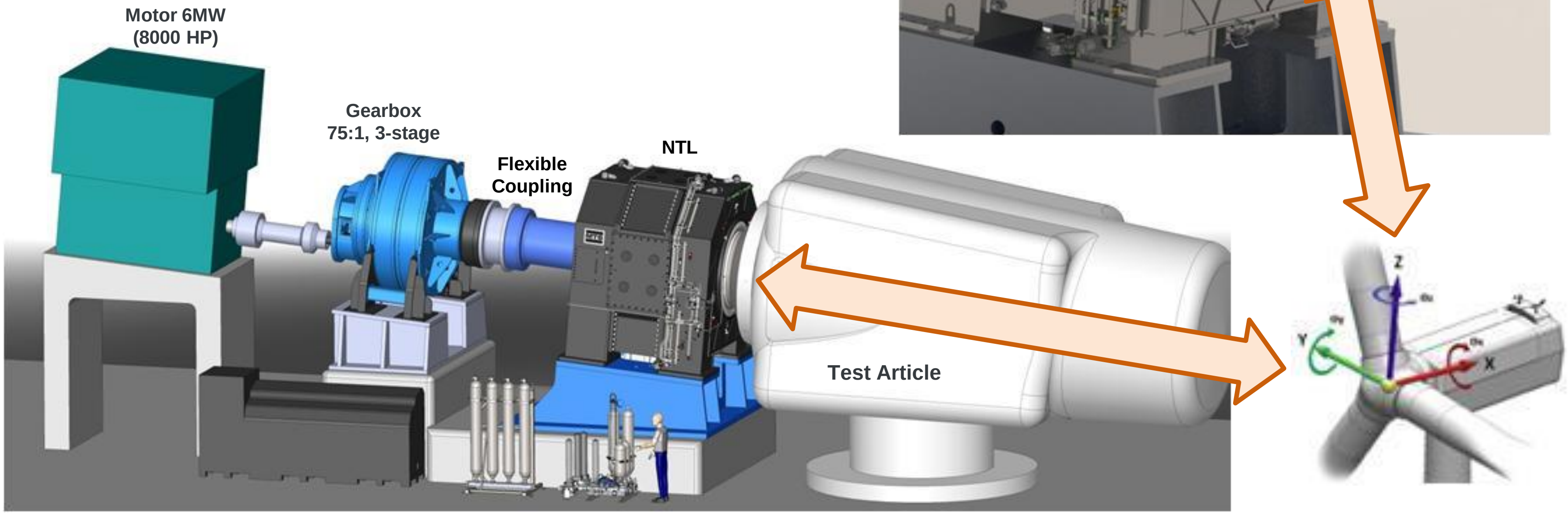
Photo by Mark McDade, NREL 28218


Photo by Mark McDade, NREL 27249

5MW Dyno Non-Torque Loading System

- Emulate impacts and dynamics of rotor loading throughout test article
- Produce forces in five degrees of freedom 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.
- Hydrostatic bearings for force actuation
- High priority for stakeholders.





Accomplishments and Progress

5. Grid Integration Testing O&M
6. Controllable Grid Interface Expansion

- Qualified O&M of:
  - 6.3-MW CGI and associated electrical interconnections to all plausible configurations of:
    - 2.5MW and 5MW dynos
    - Turbines (DOE 1.5, 2 600kW CARTs, GE/Alstom 3MW, Siemens 2.3MW, Gamesa 2MW)
    - New "grid-friendly" ancillary service control capabilities of DOE 1.5
    - Test pads (3@4MW ea., i.e. for power, storage systems).
  - Specialized grid integration test facility research infrastructure and capabilities:
    - Medium-voltage electrical Vista switches with associated safety processes and systems, transformers, cabling, controls
    - GPS-synchronized data acquisition systems (14 nodes, at all NWTC power generation/ load interconnections).
  - Associated grid integration test research project needs:
    - Development of qualified operators and technical system experts
    - Computers, instrumentation, calibrations
    - Data analysis and processing systems and tools
    - Safety documentation, review.
- CGI Expansion:
  - Interconnection of CGI to MW turbines, Controls Research Turbines (CARTs)
    - Designed and constructed 13.2kV electrical infrastructure (e.g. Vista switches, in-ground cabling)
    - Thoroughly characterized full range of behavior and capabilities of CGI (via partner-supplied test articles)
    - Documented results to facilitate future experiment planning.


Photo by Dennis Schroeder, NREL 21905


Photo by Mark McDade, NREL 29069


Photo by Mark McDade, NREL

CGI & Dynamometer Research Testing

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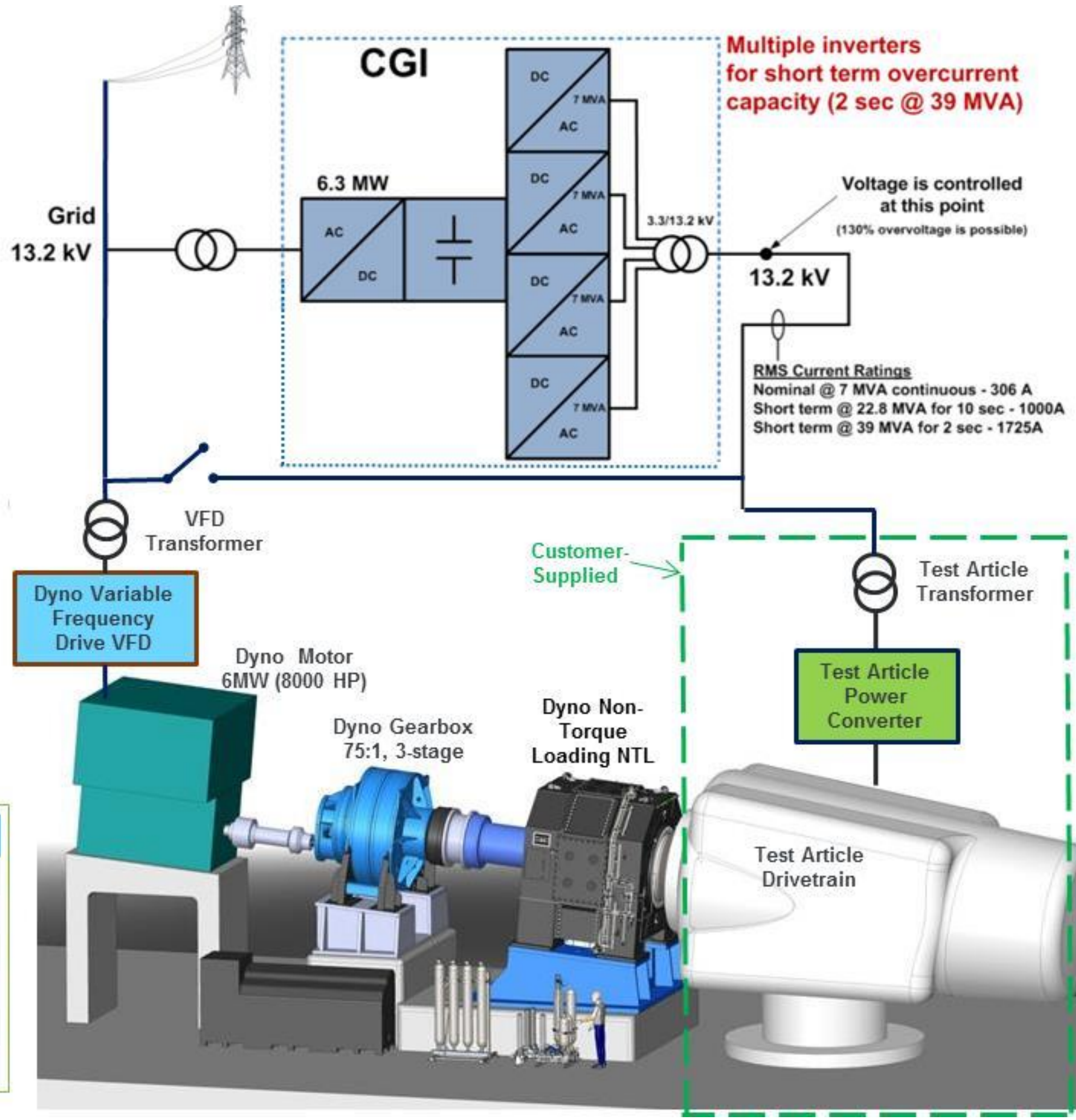
CGI initially interconnected to 2.5MW and 5MW dynos

- Command voltage profiles to emulate real power-line faults
- Characterize drivetrain structural impacts and dynamics caused by power-line faults

CGI provides wind turbine voltage fault ride-through testing

- IEC Power Quality standard for wind turbines (IEC 61400-21 ed.2)
- Low Voltage Ride Through (LVRT) testing is a certification requirement for all wind turbines
- Demonstrate self-recovery from short-term grid faults

Fault Type	Voltage drop (fraction of nominal L-to-L voltage)	Fault Duration (ms)
Three-phase, balanced	0.9	500
Three-phase, balanced	0.5	500
Three-phase, balanced	0.2	200
Two Line-to-Line (L-L), unbalanced	0.9	500
Two Line-to-Line, unbalanced	0.5	500
Two Line-to-Line, unbalanced	0.2	200



Expanded CGI Interconnections and Capabilities

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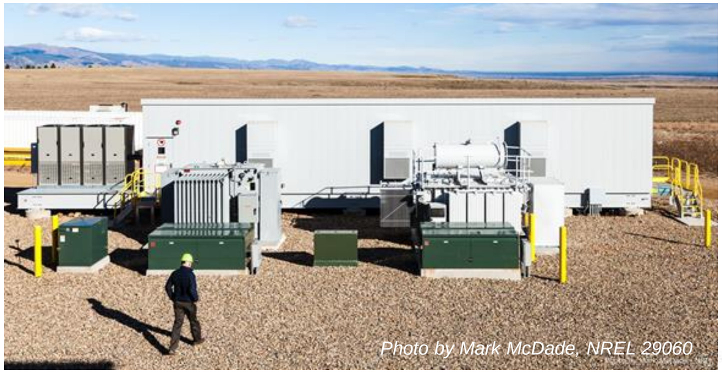
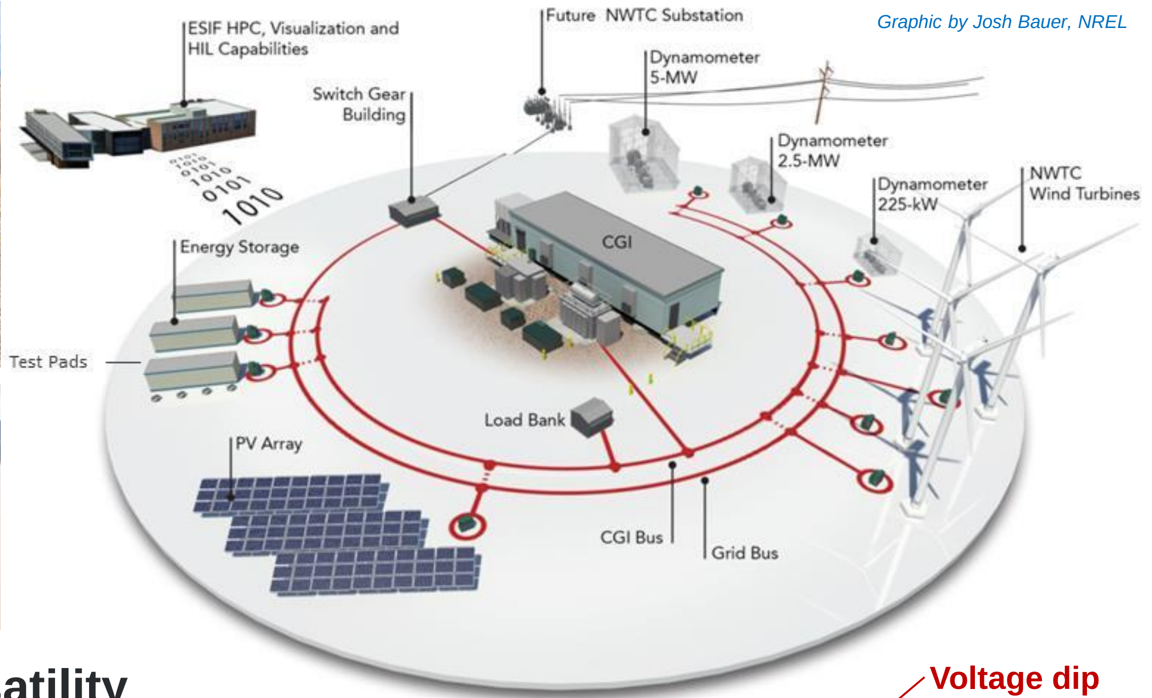


Photo by Mark McDade, NREL 29060

Photo by Mark McDade, NREL

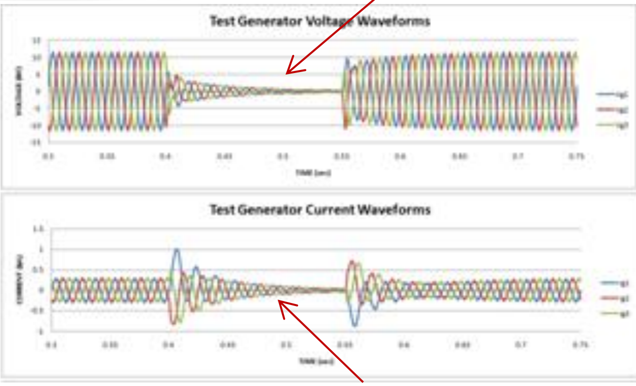


Graphic by Josh Bauer, NREL

Grid integration research versatility centered around the CGI:

- Expose test article(s) to precisely created and controlled grid power anomalies (e.g. grid faults, transients, frequency fluctuations) under safe conditions Isolated from utility
- MW-scale power converters, energy generation and storage systems, power control systems (within facilities or on test pads)
- Research validation of individual test articles or integrated systems; DOE or customer-supplied
- Single technology (energy storage, converters, wind, PV), or combinations of technologies
- Any device or interconnected devices that respond directly to electrical grid conditions
- Resulting data (some proprietary) enables NREL to characterize & document full range of facility capabilities, develop safe and effective operating procedures.

Voltage dip



Current response of Type 3 wind turbine generator

Accomplishments and Progress

7. Overarching Safety, O&M

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- Overarching safety management, accreditation, equipment maintenance, property management, quality assurance, and environmental compliance:
  - Qualified operation and scheduled preventative maintenance of non-facility-specific general use equipment (machine shop, tools, forklifts, boom trucks, ATV's, flat-bed truck, service vehicles, aerial lifts, etc.)
  - Research operations safety management (site-wide Safe Operating Procedure, compliance with DOE/ NREL lab-level procedures)
  - Specialized training, mentoring, proficiency development & tracking
  - QA (accreditation, audits, procedure revisions, software validation, etc.)
  - Property management, inventory, NWTC equipment database
  - Site-wide environmental assessments, National Environmental Policy Act, audits, etc.
  - Unscheduled inspections, maintenance and repairs resulting from pushing limits or extreme events
  - Work and Worker Authorization & Control, Hazard ID & Control, Configuration Management, DOE Integrated Safety Management System implementation, Integrated Project Management & Coordination
  - Documentation, access control, NWTC hazard awareness training, daily activity planning, project status/ activity displays, etc.




Photos by Dave Jager, NREL



Accomplishments and Progress

Highlights

- Completed thorough commissioning and characterization of full range of capabilities new 5MW dyno NTL system utilizing industry partner drivetrains
- Completed commissioning and detailed characterization of 6.3MW CGI via interconnection to:
  - Drivetrains in 2.5MW and 5MW dynamometers
  - MW-scale turbines and power conversion systems (on test pads)
  - New "grid-friendly" ancillary service control capabilities of DOE 1.5
- Completed training and transition of DOE-developed resonant blade test methods and equipment to Massachusetts Wind Technology Test Center
- New researcher-to-researcher collaboration with Clemson, joint hosting of International Grid Simulator Workshop
- Provided field testing expertise in support of A2e, SWiFT
- All milestones completed on time and within budget.

Photo by Dennis Schroeder, NREL 29781

Project Plan & Schedule

Jul 2016–Jan 2017: Field Testing Projects

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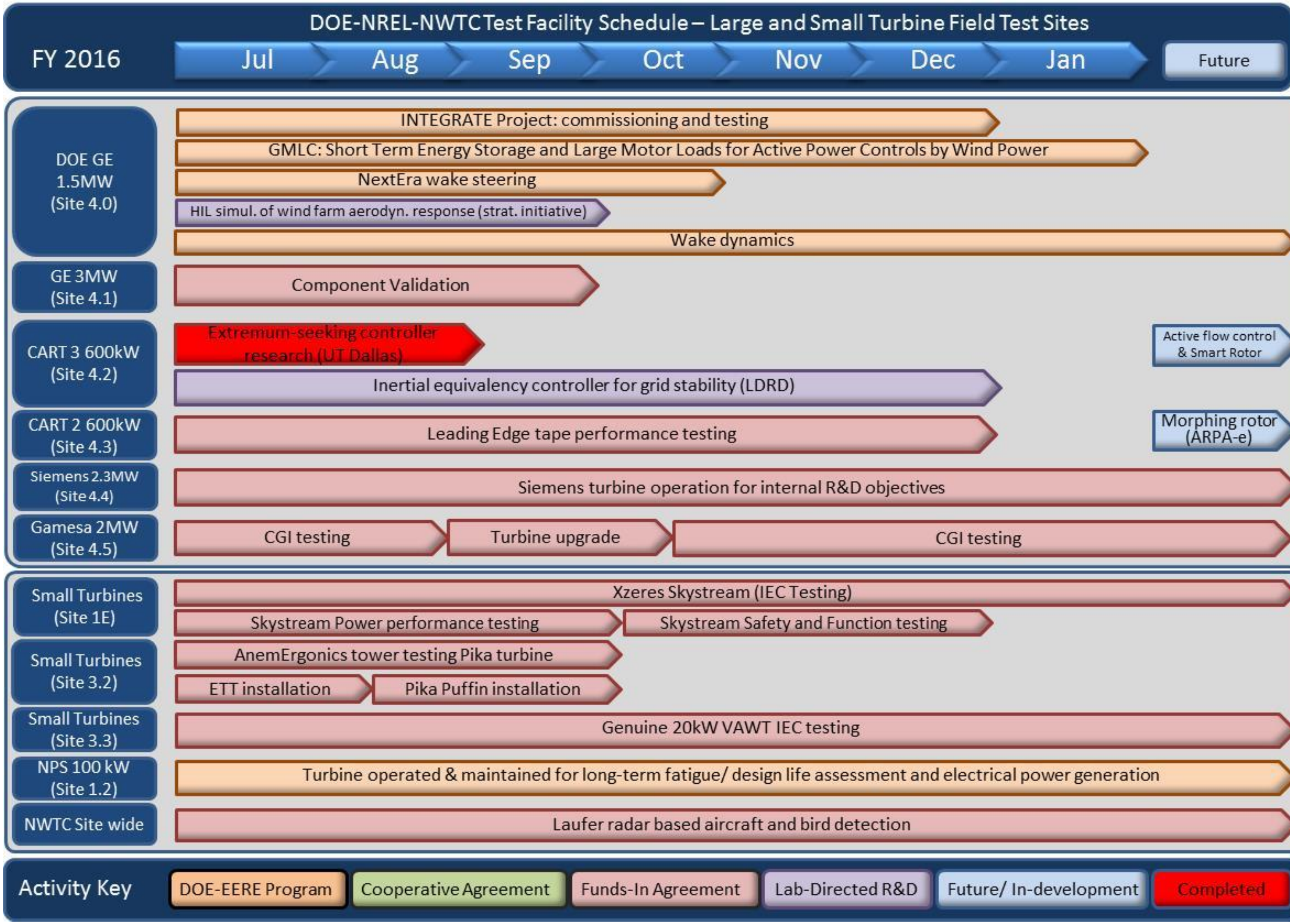

Project Plan & Schedule

Jul 2016-Jan 2017: Dyno, CGI, Structural Testing Projects

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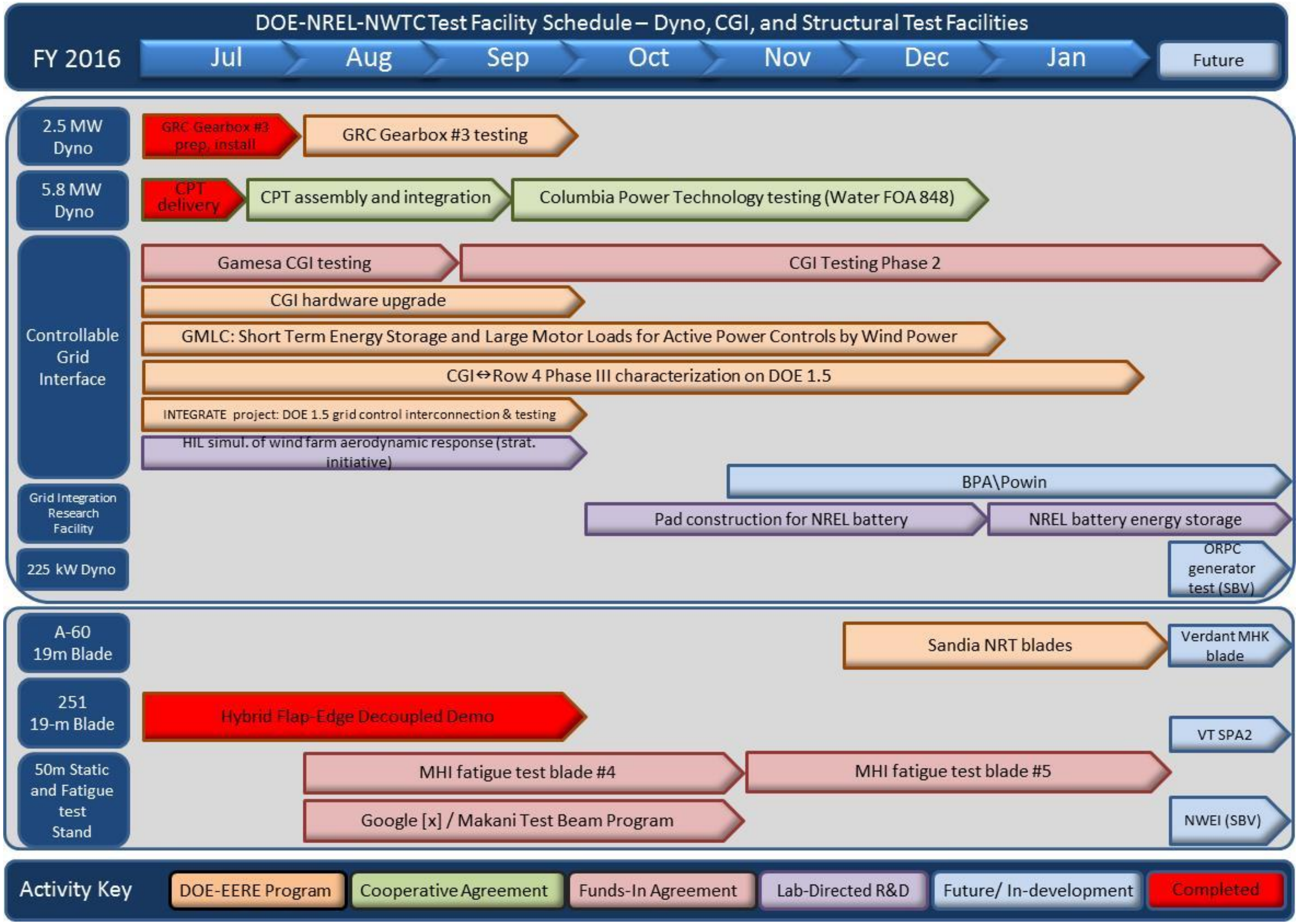

Project Budget

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Project	Budget History					
	FY2014		FY2015		FY2016	
	DOE	Cost-share*	DOE	Cost-share*	DOE	Cost-share*
1. Field Testing O&M	$1.01M		$1.10M		$999K	
2. Structural Testing O&M	$466K		$533K		$491K	
3. Dyno Testing O&M	$869K		$998K		$780K	
4. Dyno IST	$354K		$492K		$0	
5. Grid Testing O&M	$455K		$267K		$761K	
6. CGI Expansion	$1.19M		$236K		$0	
7. Safety, O&M	$882K		$865K		$1.07M	
Total	$5.23M	$11M	$4.49M	$14M	$4.10M	$12M

* Estimated other DOE, NREL, and industry funding associated with utilizing, developing, and improving specialized NWTC research facilities. Does not include "office-only" research activities (e.g. modeling, cost studies) or offsite support by research operations staff…

Research Integration & Collaboration

Partner Organizations Utilizing** NWTC Facilities & Capabilities, FY15

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Industry-funded WFO & Funds-in CRADAs

1. Alstom*
2. Anemergonics (SBIR)
3. Clarkson University
4. Gamesa*
5. Genuine Wind
6. Laufer Wind
7. Massachusetts WTTC
8. Michigan Aerospace (CART)
9. Mitsubishi Wind Americas
10. Pentalum Tech.
11. UT Dallas
12. Verdant Power
13. Xzeres (Southwest Windpower)

Cooperative Research Agreements

14. ABB Ltd.
15. Avent NRG
16. CENER, Spain (CART)
17. Clemson University
18. Columbia Power Technologies
19. DONG Energy
20. DTU, Denmark (CART)
21. ECN Netherlands (CART)
22. Garrad-Hassan (CART)
23. GE Wind*
24. RES Americas
25. Second Wind
26. Siemens Energy*
27. TU, Netherlands (CART)
28. Xcel Energy

*Also GRC partner

Other AOP Collaborations (NDA, MOU, Govt.)

29. SNL
30. PNNL
31. NASA
32. NOAA
33. AES Wind Generation (GRC)
34. Ansol (GRC)
35. AGMA (GRC)
36. Argonne (GRC)
37. Bosch-Rexroth (GRC)
38. Brad Foote Gearing (GRC)
39. Duke Energy Renewables (GRC)
40. EDF Renewable Services (GRC)
41. EDP Renewables (GRC)
42. Gearbox Express (GRC)
43. GEARTDECH (GRC)
44. Iberdola (GRC)
45. Infigen (GRC)
46. Invenergy (GRC)
47. KU Leven (GRC)
48. LMS International (GRC)
49. Moventas (GRC)
50. NextEra (GRC)
51. Norwegian Technology Institute (GRC)
52. Pacificorp (GRC)
53. Powertrain Engineering (GRC)

Other AOP Collaborations Cont. (NDA, MOU, Govt.)

54. Schaeffler (GRC)
55. SIMPACK (GRC)
56. SKF (GRC)
57. Terra-Gen Power LLC (GRC)
58. The Gear Works (GRC)
59. The Ohio State University (GRC)
60. The Timken Company (GRC)
61. AXYS Technologies Inc.
62. Colorado School of Mines (CART)
63. Cree
64. DNV-GL
65. Glosten
66. Leosphere
67. National Instruments
68. Romax Technology
69. Texas Tech University
70. Univ of Colorado (CART)
71. Univ of Maryland
72. Univ of Stuttgart (CART)
73. UMass
74. Vattenfall
75. Zephyr Wind (CART)

** Partner organizations with staff involved in projects that utilized specialized NWTC research facilities (e.g. dynos, field test sites & turbines, CGI, structural). Does not include "office-only" research partnerships, e.g. modeling, cost studies…

Next Steps and Future Research

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- Continue to maximize utilization of facilities supporting DOE and industry partner research
- Exploit field testing expertise to support upcoming A2e, SWiFT field experiment campaigns, offshore
- Expand grid integration research capabilities:
  - Increase NWTC electrical interconnection from 10MW to 19.9MW (NREL-funded) at transmission-level (115kV)
  - Incorporate 1MW-hr/ ~1MW battery storage (NREL-funded).

Photo by Dennis Schroeder, NREL 34121

Photo by Dennis Schroeder, NREL 35741

Summary

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

- Relevance to DOE/ Wind Industry
  - Specialized research facilities and capabilities tailored to specific needs of DOE researchers and industry partners
  - Enables demonstration of new technology for energy independence, energy security, jobs, and rural economic development. Enables research that touch all DOE strategic priorities.
- Methods/ Approach
  - Development, operations and maintenance of specialized research facilities and capabilities, and associated equipment. Development and retention of qualified operators and technical experts.
  - Safe and efficient proof-of-concept testing to extremes, experiments designed to anticipate test article failures
  - Research experiment design and execution. High-caliber research-grade instrumentation & measurements enables model validation and ensures systems meet required standards.
  - Enables industry partners to focus on their technology innovations, not testing requirements (e.g. experiment design, safety procedures, data acquisition, etc.)
  - Provides DOE insight on research priorities via interactions with the industry.
- Technical Accomplishments and Progress
  - Safe qualified operations supporting many users and customers. Successful new facility development. Met all milestones on time and within budget.
- Project Management
  - Extensive rigorous project management is necessary to ensure safety, meet milestones, satisfy customers. Optimizes resource utilization.
- Research Integration, Collaboration, Tech Transfer
  - Many industry partners utilizing facilities
  - Successful transition of DOE-developed expertise to new test facility operators (WTTC, Clemson, SWiFT).
- Proposed Future Research
  - Expand field testing support, grid integration research capabilities to support DOE priorities.

Photo by Scott Hughes, NREL 32520

Photo by David Snowberg, NREL 28798

Innovative Blade Test Methods

Scott Hughes

National Renewable Energy Laboratory

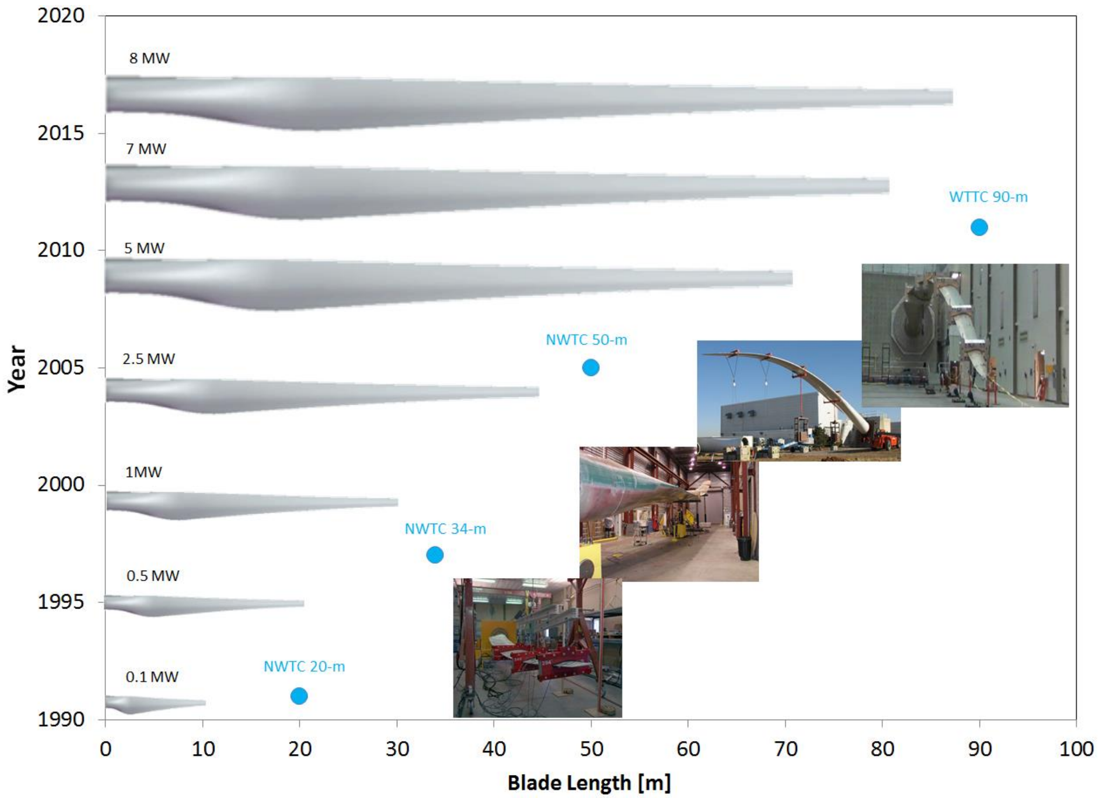
scott.hughes@nrel.gov, 303.384.7054

14 February 2017

Project Overview

Challenges:

- Blade reliability continues to be a significant source of O&M costs
- Current test practices are not representative of service loads
- Performance characterization from lab to field is lacking.
- Protracted time necessary to perform full-scale tests of large wind turbines blades
- Large gap in fidelity between coupon tests and full-scale testing
- Limitations in current test methods become increasingly critical as blades increase in size.



Project Goals:

- Develop test methods that provide faster and more cost effective approaches for wind turbine blade certification testing
- Develop unique domestic capabilities that enable rapid validation of novel blade materials and manufacturing methods .

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Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- **Reliability improvements**
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- **Commercialization of innovations and technology transfer**
- **World-class test and user facilities**
- Advanced technology demonstration projects
- Technical engagement initiatives
- **Standards and certification**
- Communicating the costs and benefits of wind energy

Enabling Wind Nationwide

Enabling U.S. Industry Growth and U.S. Competitiveness

- Wind plant optimization
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- **Reliability improvements**
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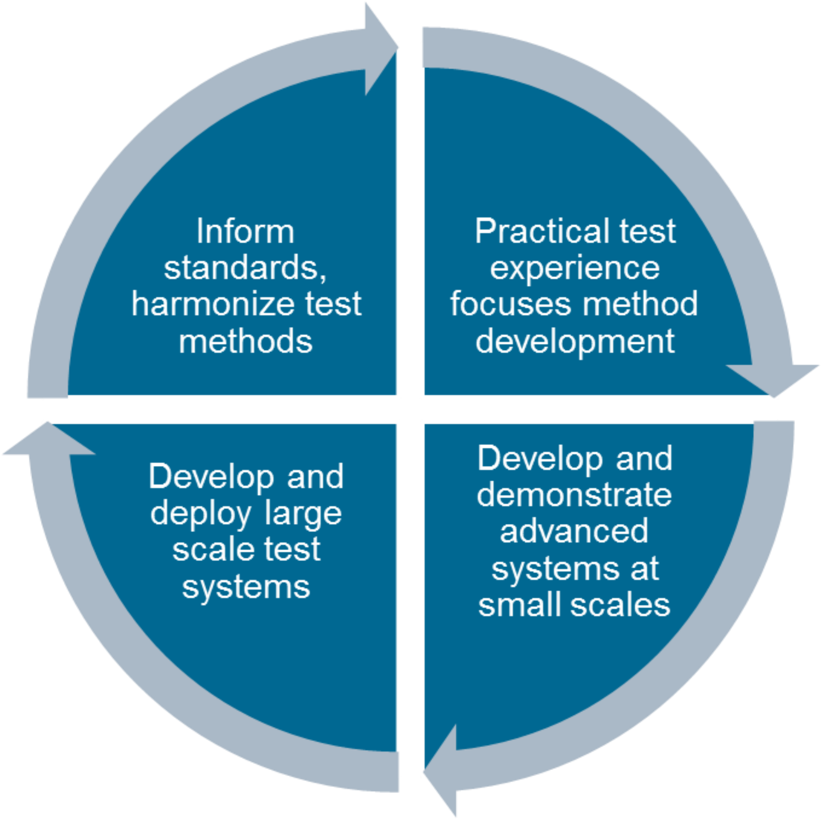
Impact of Project:

- Increase blade reliability
- Reduce technical and financial risks of large-scale deployment
- Reduce the time and cost of full-scale testing
- Amplify value of lab-to-field validation
- Inform development of international standards
- Improve uniformity of lab-to-lab results.

Technical Approach

- Improve best practices for advances in blade technology and scale
- Develop and support test system modeling tools
- Demonstrate and support development of blade sensing technologies
- Develop and demonstrate advanced test systems for implementation
- Inform development of standards based on practical test experience
- Collaborate with U.S. and international laboratories to inform test method development
- Collaborate with national and international laboratories to harmonize test methods.
- Transfer new test methods and tools to Wind Technology Testing Center (WTTC) and industry.



Accomplishments and Progress

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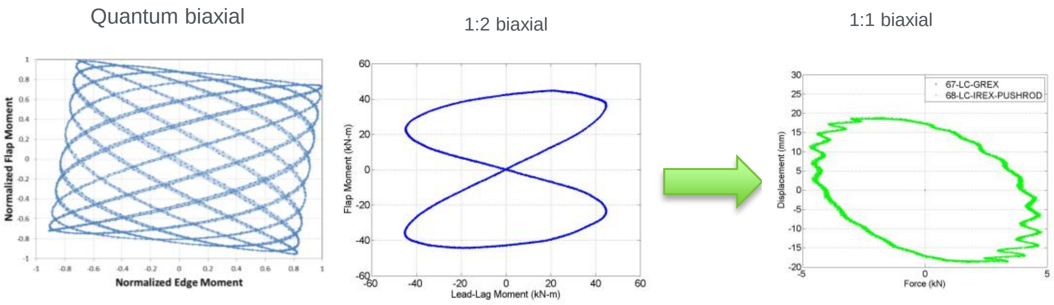
- Demonstration of a scalable 1:1 phase locked biaxial blade test method
- Demonstration of a scalable 1:2 lead-lag to flap biaxial test method
- Development of a flap / lead-lag decoupled biaxial test system
- Best practice guidelines for blade test uncertainty estimation
- Technical publications covering quantum biaxial and 1:2 test methods.

Photo by Scott Hughes, NREL



Project Plan & Schedule

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

Task	Completion Date
Prepare a conference paper for publication that details the development and testing of a large wind turbine blade using a biaxial blade fatigue test method	12/31/13
Host a kick off Web conference on rotor testing with international cooperative research participants of IEA Wind Task 35	2/19/14
Attain management approval on the readiness verification document for the 9 m scale hybrid biaxial test system at the NWTC	5/30/14
Complete summary test report of the 9 m scale hybrid biaxial test system at the NWTC	9/30/14
Gain subtask lead approval on NREL technical report documenting results of biaxial test method by 12/31/14	12/31/2014
Complete preliminary structural design of biaxial test system for testing a 50 m blade by 3/31/15	3/31/2015
Select industry partner for performing biaxial blade fatigue test of a 50 m blade by 6/30/15	6/30/2015
NREL will complete a test plan for conducting a biaxial fatigue test for a large (50 m) blade by 9/30/15	9/30/2015
Complete test plan for full scale biaxial demonstration test for flap and lead lag decoupled system	9/30/2016

Project Outcomes – Development and demonstration of three new biaxial fatigue test methods

Project Budget

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

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$636k		**$840k**		**$748k**	

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

- International Energy Agency Wind Task 35 – International testing laboratories, DTU, WMC, Fraunhofer, Offshore Renewable Energy Catapult
- Industry partner MHI for resonant and truncated-blade fatigue testing
- Leveraged funding opportunity announcement (FOA) with industry partner for torque characterization
- Sandia National Laboratories, MSU for segmental fatigue testing.

Communications and Technology Transfer:

- Higher-capacity GREX systems deployed at WTTC
- Test methods transferred to WTTC
- Quantum biaxial NREL technical report
- Sixty-meter blade biaxial test scenarios technical report
- Patents for quantum biaxial and base excitation test systems.

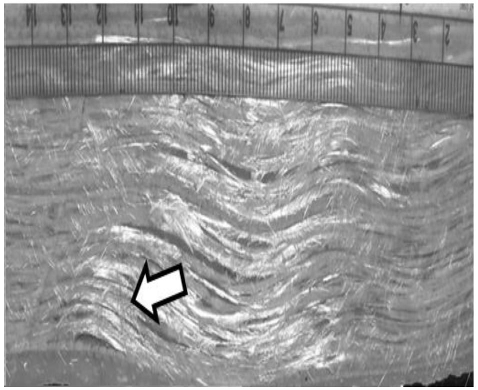
Next Steps and Future Research

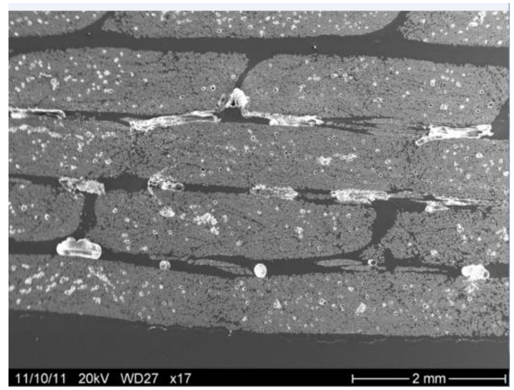
FY17/Current Research:

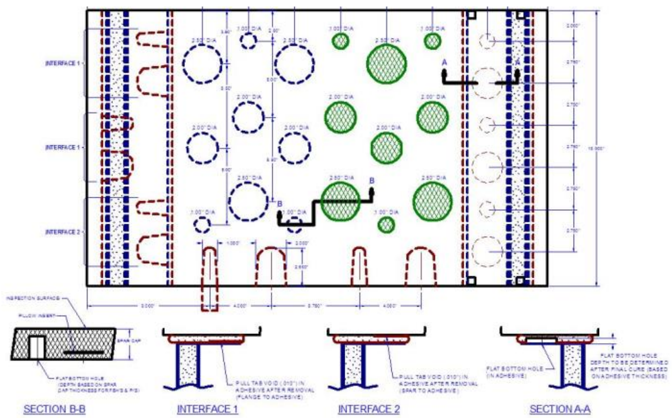
- Complete technical publications that enable the continued development and deployment of new biaxial test methods

Planned Future Research:

- If additional funding becomes available,
  - Joint industry partnership to validate single-axis-to-biaxial test methods
  - Decoupled flap / lead-lag test method demonstration
  - Full-scale decoupled biaxial resonant fatigue development
  - Full-scale component test method development
  - These capabilities would provide unique domestic and international capabilities that enable higher-fidelity and lower cost approaches for blade certification and validation of new materials and manufacturing methods.







Rotor Reliability (Collaboratives, Monitoring, and O&M)

Josh Paquette

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2/15/2017

Project Overview

Reliability and Composite Materials:

Major component failures constitute up to 10% of wind levelized cost of energy (LCOE) and have the potential to contribute further through life extension of plants

Efficient, effective use of materials is critical to continued growth in rotors and associated decreases in LCOE

The Challenge: To realize the LCOE reductions associated with larger rotors and improved reliability, wind blades need to move from a “safe-life” to a “durability and damage tolerant” design methodology and likely use advance materials. This necessitates better knowledge materials, quality controls, and the effects of defects and damage.

Partners: Montana State University (MSU), Texas A&M University, University of Texas at Austin, University of California at Davis, SPS, Iberdrola, Duke Energy, EDPR, EDF Renewable Energy

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- **Reliability improvements**
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- **World-class test and user facilities**
- Advanced technology demonstration projects
- Technical engagement initiatives
- **Standards and certification**
- Communicating the costs and benefits of wind energy

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- NextGen component innovations

The Impact

- Higher-quality blades leaving factories
- Improved assessment of the financial value of leading edge erosion repairs and other mitigations
- Ability to accurately model damage growth in blades
- Blade reliability is a subject area that will need continual improvement.
- Research is transitioning from factory NDI methods, damage growth, and leading edge erosion to repairs, field NDI, and lightning damage.
- Identify reliability and performance trends over time including component failure issues
- Improvement of operations and maintenance (O&M) practices through reliability quantification

Enabling Wind Nationwide

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

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- Standards and certification
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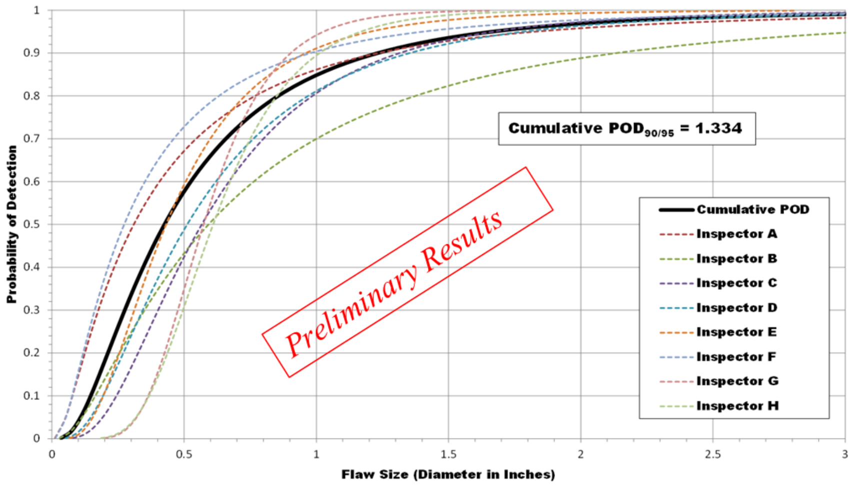
The Impact

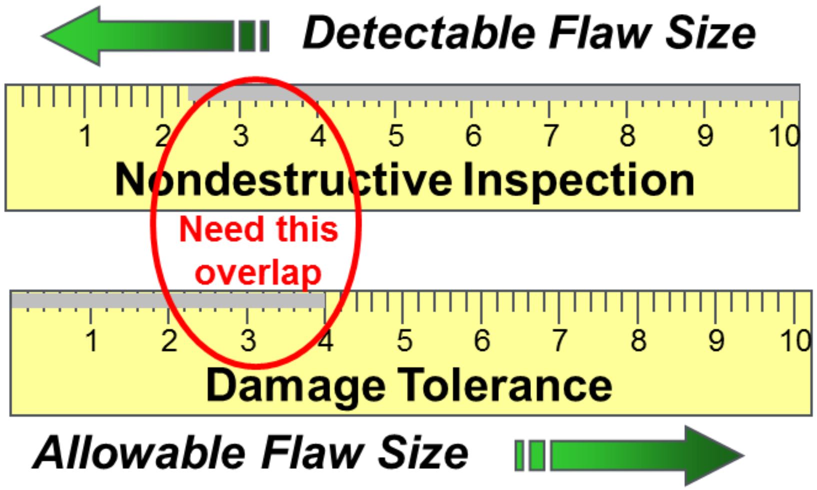
- Quantification of the strength and durability of new fibers, matrix materials, and material forms for blade designers
- Rigorous examination of composite materials test methods for use by private test labs
- The DOE/SNL/MSU Composite Materials Database is transitioning to an ongoing repository of the results of targeted research projects.

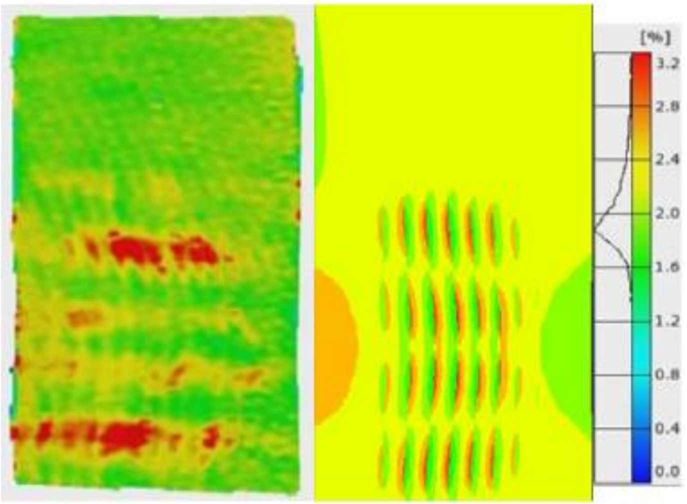
Blade Reliability

- Research has focused on providing broadly applicable tools and analysis to industry in
  - **Inspection Methods:** Quantifying efficacy of baseline and advanced Nondestructive Inspection (NDI) technology with real-world experiments
  - **Damage effects and progression:** Development of “knock-down” factors for several flaw types and sizes, along with validated finite element analysis (FEA) module for damage growth
  - **Performance losses from leading edge erosion:** Wind tunnel tests of simulated erosion profiles and accompanying transition model for computational fluid dynamics (CFD) analyses.

Durability and Damage Tolerance

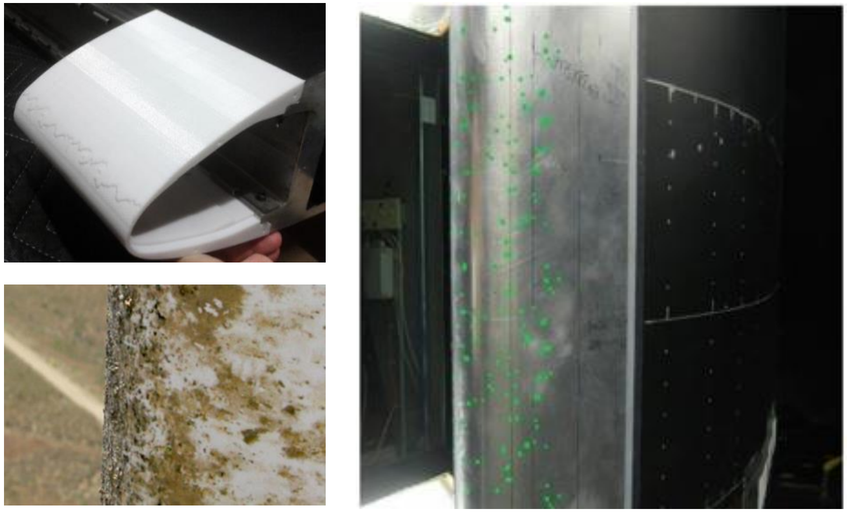






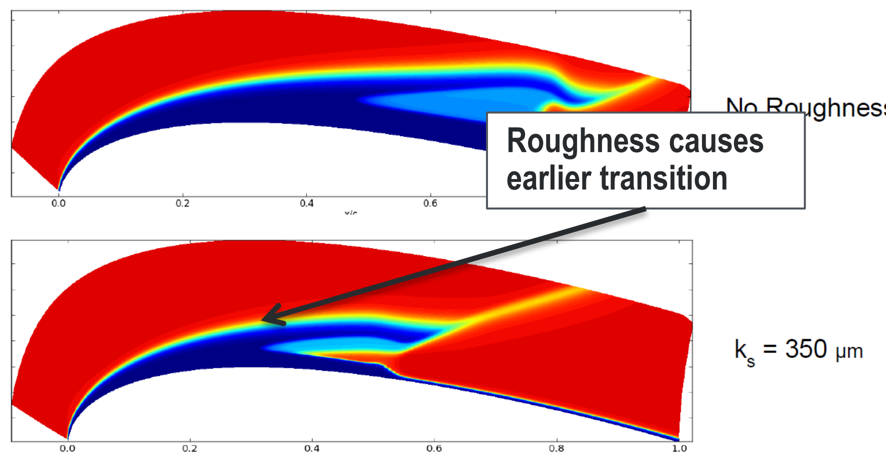
Experiment (DIC) Model (FEA-CZM)

Leading Edge Erosion



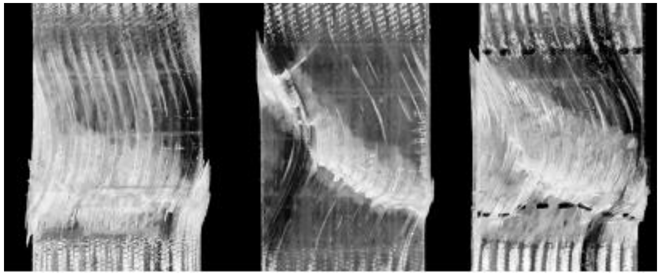
Wind Tunnel Testing of Simulated Eroded Airfoils

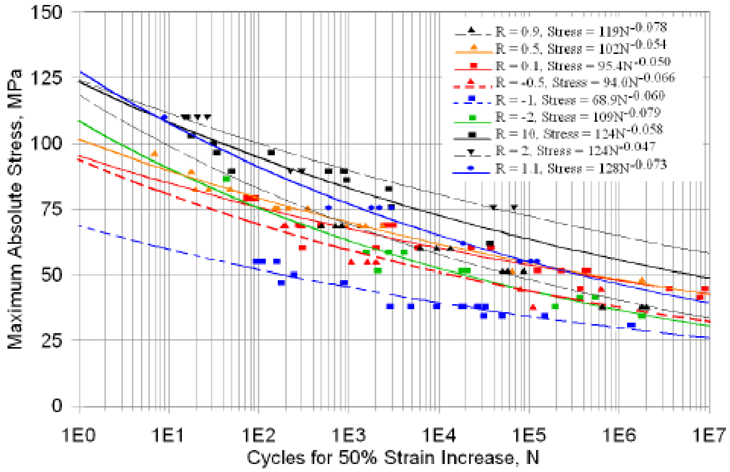
Roughness Model Development

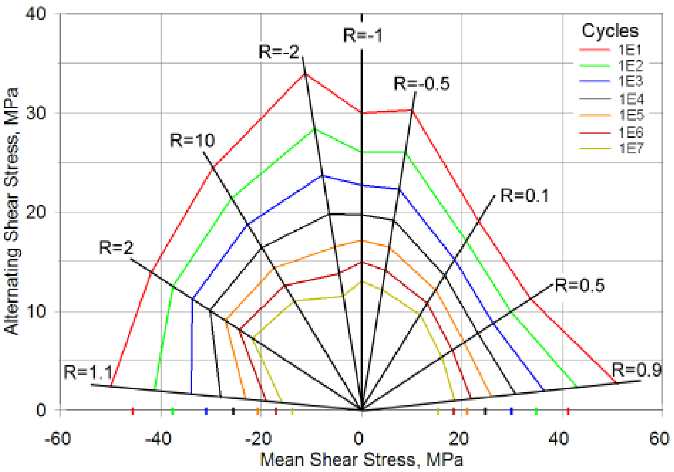


Blade Materials and Standards

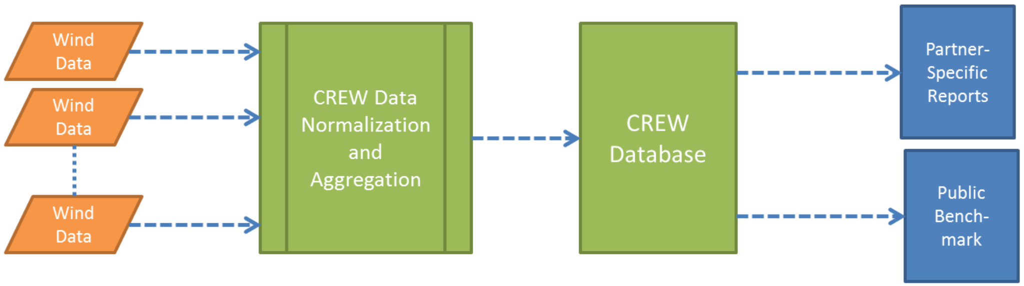
Materials Research: Test ideal and flawed specimens and substructures to determine strength and durability under different loading environments.







Continuous Reliability Enhancement for Wind (CREW)



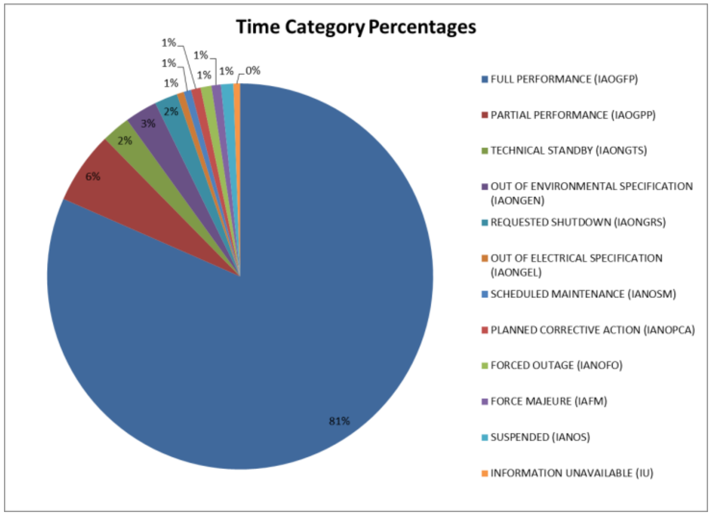
- Wind farm owners provide summarized performance and reliability data in monthly reports
- NDAs define terms for data sharing

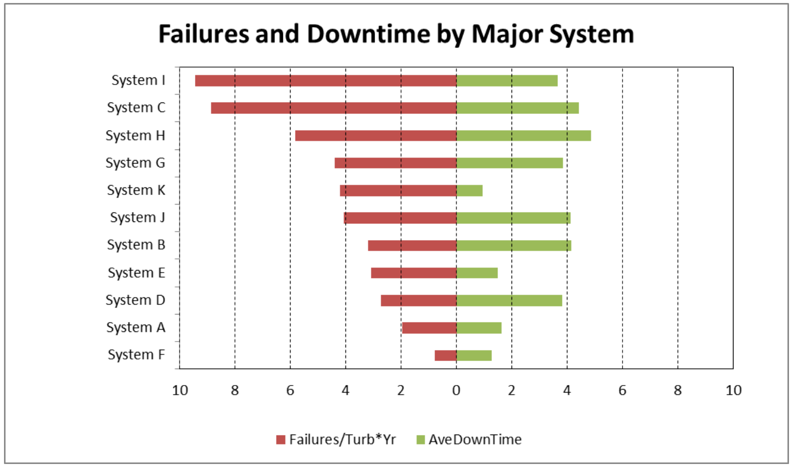
- Data will be scrubbed to remove and protect proprietary information

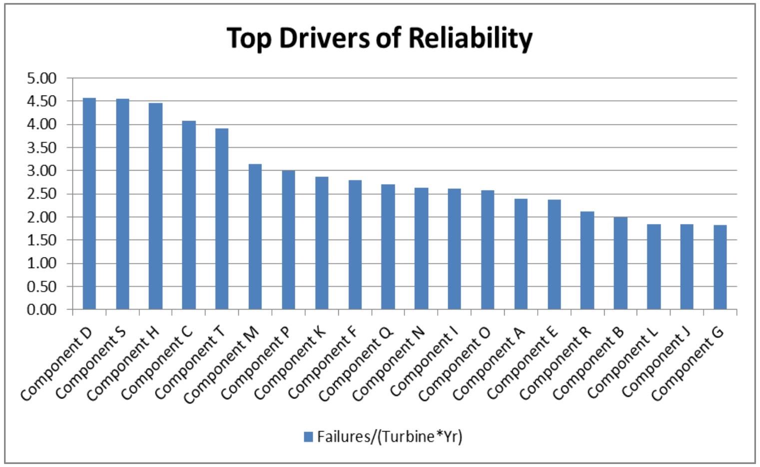
- Aggregated CREW database will be made available to researchers for analysis
- No proprietary information will be included

- Annual public benchmark will be performed to identify and quantify DOE technology improvement opportunities
- Data partners will receive a partner-specific report

Notional Results







Accomplishments and Progress

- Quantified Probability of Detection of baseline and advanced NDI
- Developed and experimentally validated FEA progressive damage modeling code for composite materials
- Designed and tested wind blade substructure specimens
- Developed and experimentally validated leading edge erosion aerodynamics model
- Completed multitude of wind tunnel tests of wind blade airfoils with erosion
- Designed data intake process and strawman for data auditing and executed two NDAs for data delivery
- Delivered Official Use Only (OUO) Partner Report

Project Plan & Schedule

- Project Schedule:
  - Blade Reliability: Initial Blade Reliability Collaborative project spanned FY14-FY15. New project focusing on Durability and Damage Tolerance began in FY16 and is scheduled to end in FY18.
  - Materials: The DOE/SNL/MSU composite materials database began in 1989 and ended in the original form in FY16.
  - CREW: Restart in Q4 FY14 to move from raw SCADA data to summarized SCADA data from owner/operators with sophisticated asset management department.
- CREW milestones delayed as a result of long lead times for NDA execution and realized risks from owner/operator participation.
- Go/No-Go Decision Points
  - FY15: Is the project justified in general and is it focused on the correct sub-topics?
  - FY16: Should the project proceed with lightning damage in carbon laminate research plan.?
  - FY16: Is CREW receiving reliability and performance data from multiple owner/operators that will enable statistical meaningful analyses?

Project Budget

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

	Budget History					
	FY2014		FY2015		FY2016	
Subject Area	DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
Blade Reliability	$470k		$700k		$535k	
Composite Materials	$400k		$275k		$0	
CREW	$1,000k		$200k		$200k	

- $240k of funds for Blade Reliability have been carried over into FY17
- All funds for Composite Materials are exhausted
- FY14 CREW high dollar amount due to contract for SCADA data with SPS. Carry over funds for FY15 shifted from CREW.

Partners, Subcontractors, and Collaborators: Montana State University, Texas A&M University, University of Texas Austin, University of California Davis, SPS, NextraTec, Iberdrola, Duke Energy, EDPR, EDF-RE

Communications and Technology Transfer:

Publication of over 10 Sandia Reports and conference papers

- 2014 and 2016 Sandia Blade Workshop
- 2014, 2015, and 2016 AIAA SciTech Conference
- 2015 and 2016 Wind Blade Manufacture Conference
- 2016 Torque from Wind Conference

Blade Reliability Collaborative Workshops: Demonstrated need for research into leading edge erosion and lightning damage

Results of over 12,000 material tests available through DOE/SNL/MSU Composite Materials Database

Next Steps and Future Research

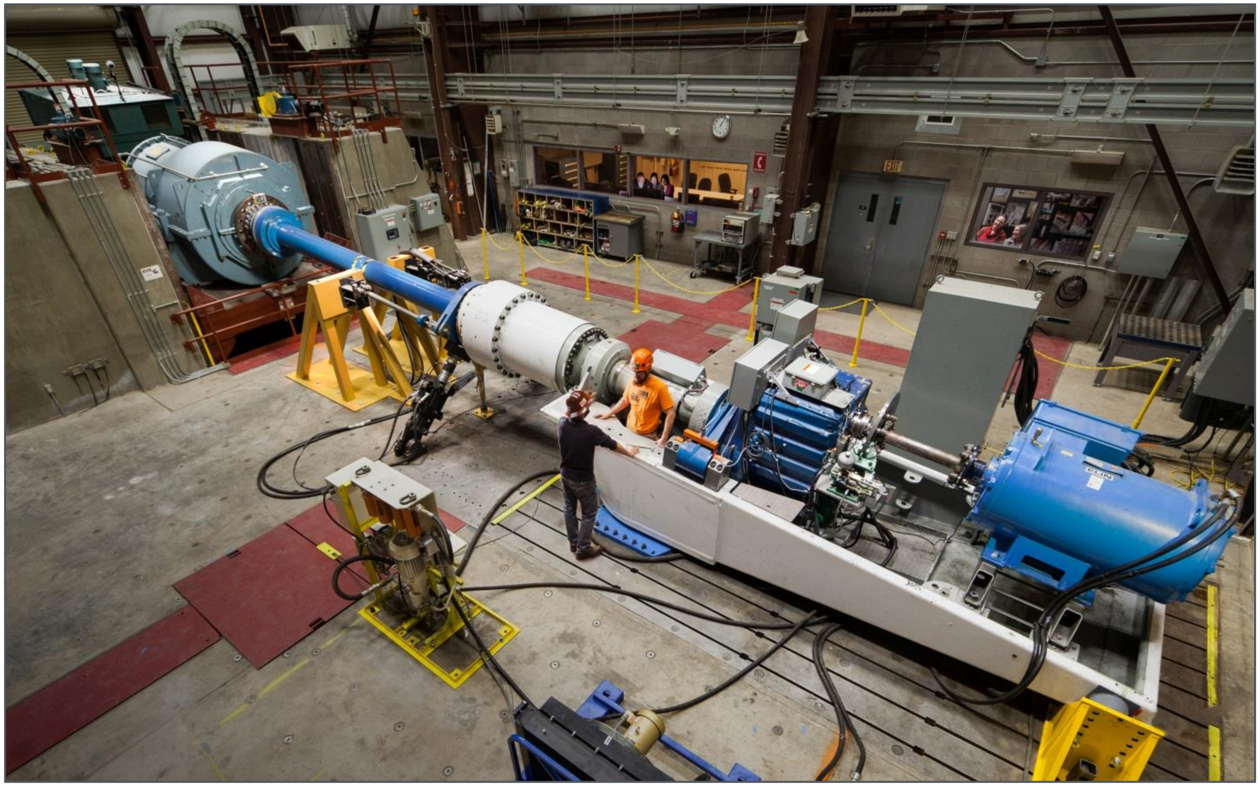
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY17/Current Research:

- Effects of Lightning Damage in Carbon Composites
- Creation of a Blade Lifetime Value Model
- Wind Blade Carbon Fiber Study
- Analysis of Wind Blade Repair Methods
- Field Deployment of Advanced NDI

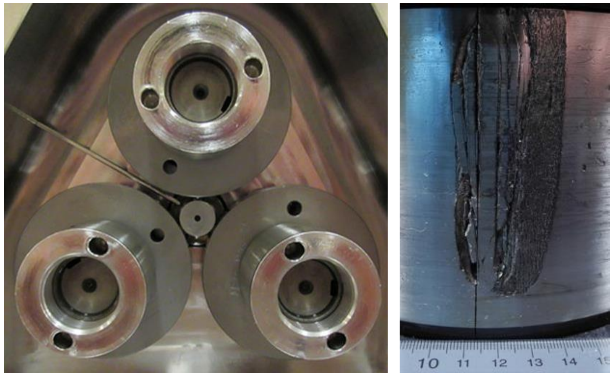
Planned Future Research:

- Probabilistic modeling of damage growth in blades including effects of inspection, repairs, and monitoring
- Leading edge erosion mechanisms and mitigations



GRC 750-kW Drivetrain in NWTC 2.5 MW Dynamometer

Improved 750-kW Gearbox



Bearing Axial Cracking Tests

Drivetrain Reliability (Collaboratives, Monitoring, and O&M)

Jonathan Keller

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February 2016

Project Overview

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

Wind Turbine Drivetrain Reliability: Conduct testing and analysis to improve drivetrain reliability, availability, and reduce wind plant operations and maintenance (O&M) costs.

The Challenge: Drivetrain failure modes are not accounted for in design standards, typically not attributable to quality control, complex in nature and generally independent of specific component suppliers. Drivetrain failures and remaining useful life (RUL) are difficult to detect and predict in operation.

Partners: NREL – full-scale testing and analysis
Argonne National Laboratory (ANL) – bench-top testing and analysis

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- **Reliability improvements**
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
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- Advanced technology demonstration projects
- **Technical engagement initiatives**
- Standards and certification
- Communicating the costs and benefits of wind energy

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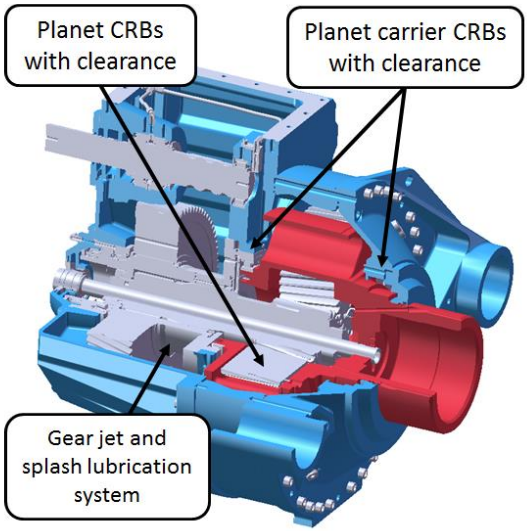
The Impact

- Increase main bearing and gearbox Mean Time Between Failures MTBF
- U.S. wind plant O&M is a $2B to $3B annual market; costs are increasing 5–10% per year
- Mitigation solution for bearing axial cracking
- Mitigation solution for main bearing wear
- O&M practices for drivetrain
- Remaining useful life for bearing axial cracking
- Industry awareness of reliability, failure modes, condition monitoring technologies and analysis methods

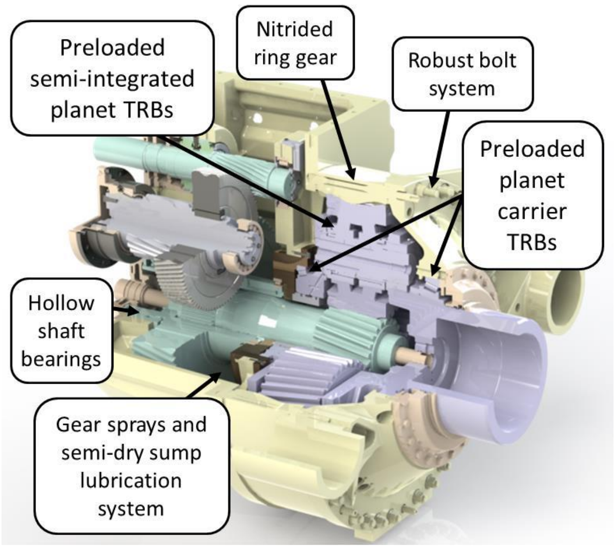
Technical Approach

Characterize predominant and unaccounted failure mode mechanisms and develop mitigation strategies. Develop remaining useful life tools for monitoring and prediction.

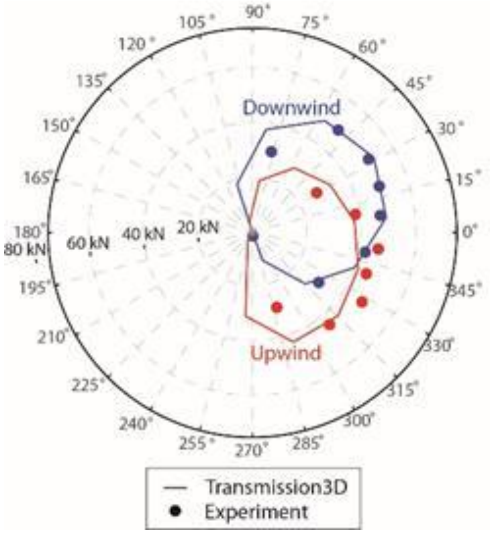
Gearbox planetary bearing faults: correct planetary design deficiencies and validate through dynamometer testing



Original 750-kW Gearbox



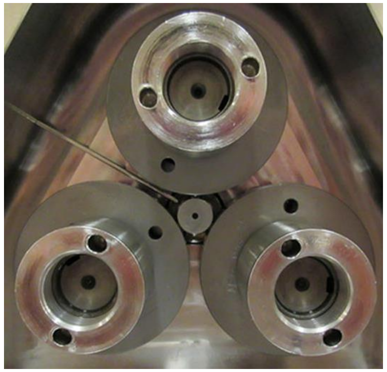
Improved 750-kW Gearbox



Improved Bearing Load Sharing

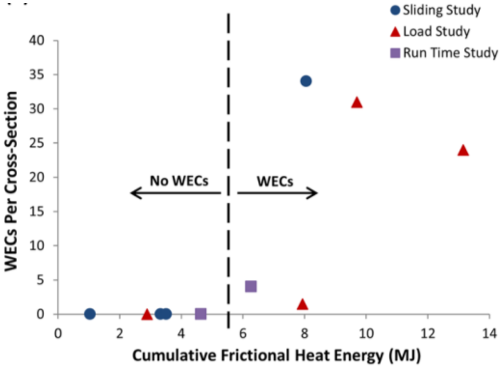
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Gearbox bearing axial cracks: Characterize root causes, develop lifing criteria, propose mitigation solutions



MPR tribological test rig

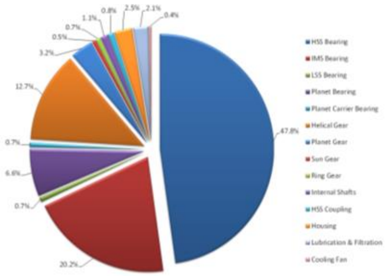
Roller with spall and white-etch crack



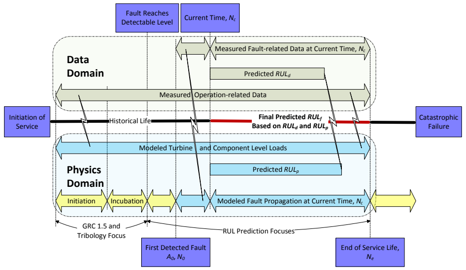
Frictional energy criteria

Condition monitoring (CM) and wind plant O&M: evaluate compact filters, collect and analyze reliability data, research RUL prediction

Compact filter testing



Updated gearbox damage distribution and data collection web portal



Hybrid modeling for component RUL prediction

Accomplishments and Progress

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

- Completed manufacture, instrumentation and testing of improved GRC 750-kW gearbox. Demonstrated improved load-sharing when subjected to rotor moments.
- Completed bench-top testing to characterize bearing axial cracking and proposed lifing mechanism. Completed dynamometer testing for bearing loads and developed instrumentation to measure bearing loads and sliding.
- Completed 1-year field test and analysis of compact filters and published “editor’s choice” journal article on oil and wear debris analysis. Completed bearing RUL research plan using physics-based and data-driven models.
- Conducted drivetrain reliability workshop and issued R&D needs report.
- Aaron Greco: 2016 Burt L. Newkirk tribology R&D award

Project Plan & Schedule

- Multi-year project with multiple tasks that begin and end
  - Planetary bearing faults: concludes mid FY17
  - Bearing axial cracking: FY15 to FY18
  - Main bearing faults: FY16 start, additional resources needed
  - O&M and CM: continues with sub-projects
  - Collaborative: continues
- Delay in improved 750-kW gearbox manufacture and testing due to prioritization of Next Generation Drivetrain manufacture and testing; and also subcontractor's schedule
- Go/No-Go:
  - FY15: gearbox failure database review
  - FY16: full-scale bearing axial cracking progress and plan

Project Budget

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

	Budget History					
	FY2014		FY2015		FY2016	
	DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
NREL	$2,327k*	$260k	$1,486k	$260k	$930k	$216k
ANL	$450k	$160k	$440k	–	$440k	$303k

* Includes carryover from FY13

- Project plans, budgets, and milestones reflect rebalancing in FY14
- 77% of funds expended to date
- Cost share represents Romax gearbox design contract, CRADA participation, plus estimated value of industry attendance at GRC meetings and Tribology Seminar

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators: NREL and ANL Cooperative Research and Development Agreement – SKF, Schaeffler, Afton Chemical.
Subcontractors – Romax Technology, McNiff Light Industry, Brad Foote Gearing, The Timken Company, Geartech, Univ. of Akron and DA Roberts. Many unfunded partnerships and NDAs exist through the collaborative.

Communications and Technology Transfer: Annual GRC meetings and/or Tribology Seminars draw 100+ attendees. DRC workshop R&D needs report. Eight peer-reviewed journal publications; plus numerous conference and technical papers and presentations. Dynamometer testing data available (DOI 10.7799/1254154) and annual gearbox damage distribution updates made public.

Next Steps and Future Research

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

FY17/Current Research: Extend bearing axial cracking benchtop test to wind turbine gear oils, include additive chemistry and contamination influences. Instrument and install gearbox in DOE1.5 turbine and measure bearing loads and sliding in operation. Predict bearing remaining useful life. Continue gearbox failure date collection.

Planned Future Research: Develop mitigation strategies for bearing axial cracks, including bearing coatings, and turbine controller changes. Investigate main bearing loads, motions and stray currents. Drivetrain component and turbine reliability analysis. Collect failure data for other critical drivetrain components.

Next Generation Drivetrain in NWTC 2.5 MW Dynamometer

Innovative Drivetrain Concepts (FOA)

Next Generation Drivetrain

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February 2017

Project Overview

Next Generation Drivetrain: Reduce Cost of Energy (COE) contributions from wind turbine drivetrains due to high capital costs and high weight, efficiency losses, reduced energy production, low-reliability and high-O&M costs.

The Challenge: Drivetrain cost, gearbox and power converter reliability, sizing issues with direct drive generators, cost and availability of permanent magnets, challenges with superconducting solutions. Dynamic loads from wind and grid events, starts, stops and idling.

Partners: Subcontractors – Wolfspeed (formerly CREE), DNV Kema Renewables (formerly BEW Engineering), and Romax Technology. Sub-tier – Powerex, Brad Foote Gearing, Miba and The Cinch. Cost-share – Vattenfall.

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Enabling U.S. Industry Growth and Enabling U.S. Competitiveness	Enhancing U.S. Energy Security and Independence	Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States
• Wind plant optimization • Resource assessment and characterization • **Reliability improvements** • Enabling access to better resources through tall wind • Distributed wind R&D • **NextGen component innovations**	• Facilitating coexistence between wind energy and wildlife • Offshore wind environments • Information synthesis and dissemination • Successful coexistence with radar systems • Wind energy workforce and education development • Advancing grid integration	• Commercialization of innovations and technology transfer • World-class test and user facilities • **Advanced technology demonstration projects** • Technical engagement initiatives • Standards and certification • Communicating the costs and benefits of wind energy

Enabling Wind Nationwide

Enabling U.S. Industry Growth and U.S. Competitiveness

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- Distributed wind R&D
- **NextGen component innovations**

The Impact

- Up to 25% increase in torque density
- Up to 21% decrease in drivetrain deployment cost
- Up to 5% increase in annual energy production
- Up to 13% decrease in Cost of Energy (COE)
- Measured performance, mitigated technical risks, and advanced Technology Readiness Levels of key drivetrain innovations, which increase drivetrain capacity, reliability, efficiency, and energy yield.
- Technologies advanced to TRL 6
  - Gearbox flex pins and journal bearings
  - Power converter control algorithms
  - Medium voltage, hybrid Si/SiC modules

Complete design, fabrication, and dynamometer testing of a 750 kW drivetrain with gearbox hardware and power converter software innovations.

- Demonstrate improved load sharing with flex pins
- Measure journal bearing durability in start-stop, dither and oil-restricted tests
- Measure dynamic torque response subject to grid faults

4-planets, flex pins and journal bearings

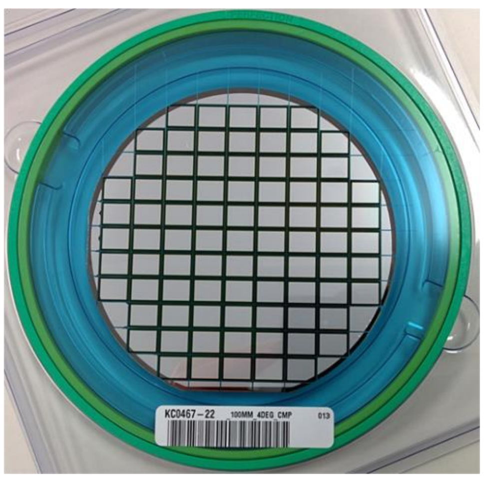
Journal bearing dither tests

Controllable Grid Interface tests

Technical Approach

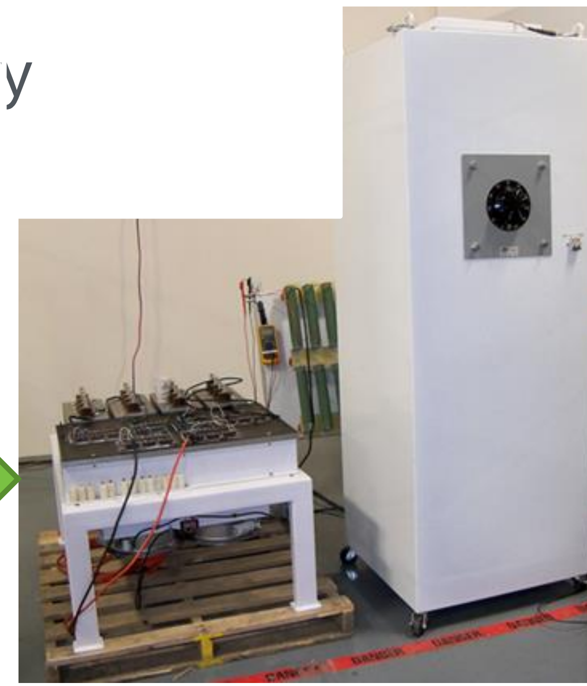
Complete design, fabrication and bench-testing of medium-voltage hybrid Silicon/Silicon Carbide (Si/SiC) modules.

- Install SiC barrier diodes in Si modules
- Validate switching loss reduction
- Project increase in inverter efficiency
- Expected reliability benefit



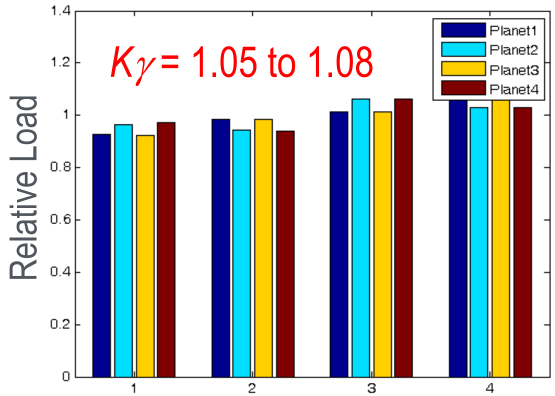
10 mm x 8 mm 4.5 kV/40A SiC barrier diodes. Photo by CREE

Medium-voltage hybrid module. Photo by Powerex

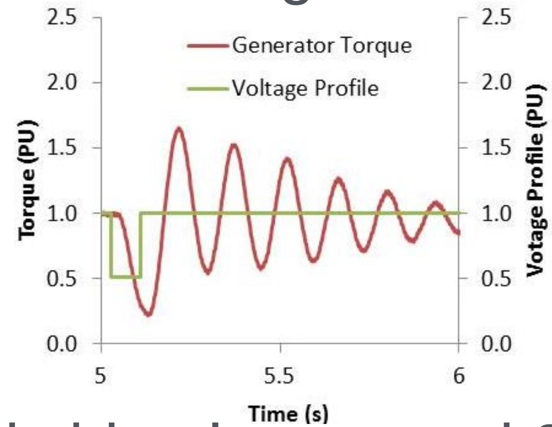


2.3 MW medium voltage module test stand. Photo by DNV KEMA

Demonstrated flex pin load sharing, journal bearing durability, and drivetrain dynamics in grid fault events.

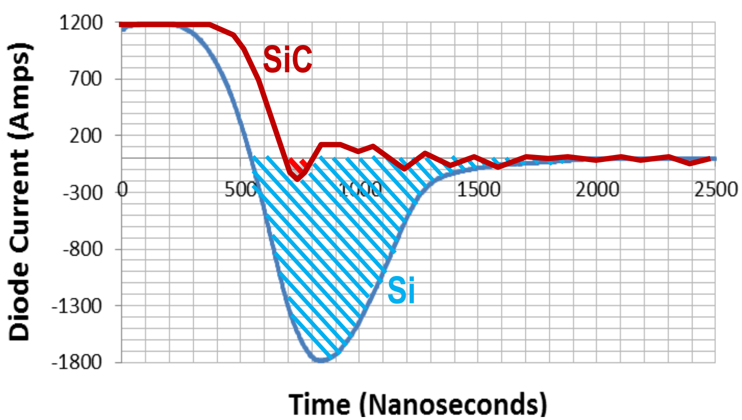


IEC 61400-4 assumes Kγ = 1.25 for 4-planet gearbox

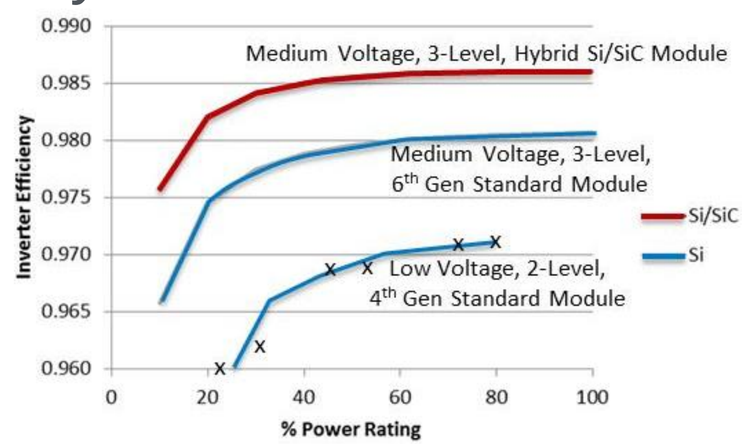


65% torque spike in 50% symmetric LVRT event

Demonstrated reduction in switching losses and 0.5% to 1.5% increase in inverter efficiency



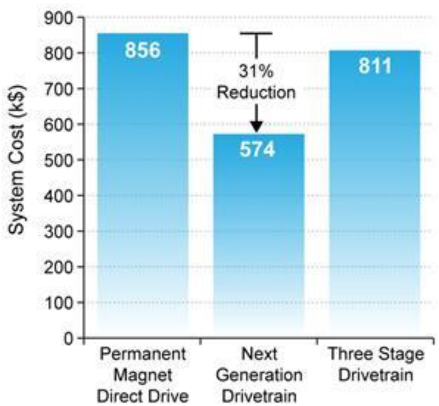
Reduction in IGBT turn-on and Diode reverse recovery losses increase efficiency



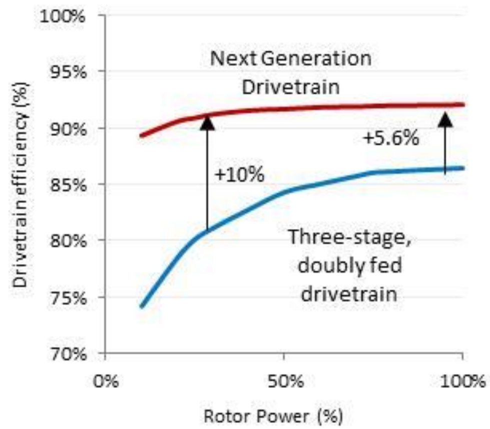
Project Plan & Schedule

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

- Phase I paper study—October 2011 to April 2012
  - Go/No-Go decision points—July 2012 and February 2013



Gearbox and Generator Cost at 5MW



Drivetrain Efficiency at 5 MW

	1.5 MW		5 MW	
	Baseline	NGD	Baseline	NGD
ICC ($/kW)	1,735	1,689	1,548	1,409
O&M ($/kW)	25.0	23.8	25.0	23.8
LRC ($/kW)	11.0	8.9	11.0	8.9
AEP (MWh/yr)	5,309	5,548	15,941	16,737
LCOE (¢/kWh)	4.85	4.47	4.92	4.27
	-8%		-13%	

Cost of Energy Metrics at 1.5 and 5 MW

- Phase II demonstration—July 2013 to July 2016
- Completion of hybrid Si/SiC module and gearbox fabrication were delayed approximately six months each; however, scope and budget were not affected.

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$1,582K	$331K	-	$147K	-	$271K

- All project funds expended (DOE and cost-share). Including project initiation work in mid FY13, Phase II totaled $1.8M DOE funding and $1.2M cost-share.
- Some additional, but untracked, cost share contributed by Miba and Powerex.

Partners, Subcontractors, and Collaborators:

Subcontractors – Wolfspeed (formerly CREE), DNV Kema Renewables (formerly BEW Engineering), and Romax

Sub-tier – Powerex, Brad Foote Gearing, Miba and Cinch

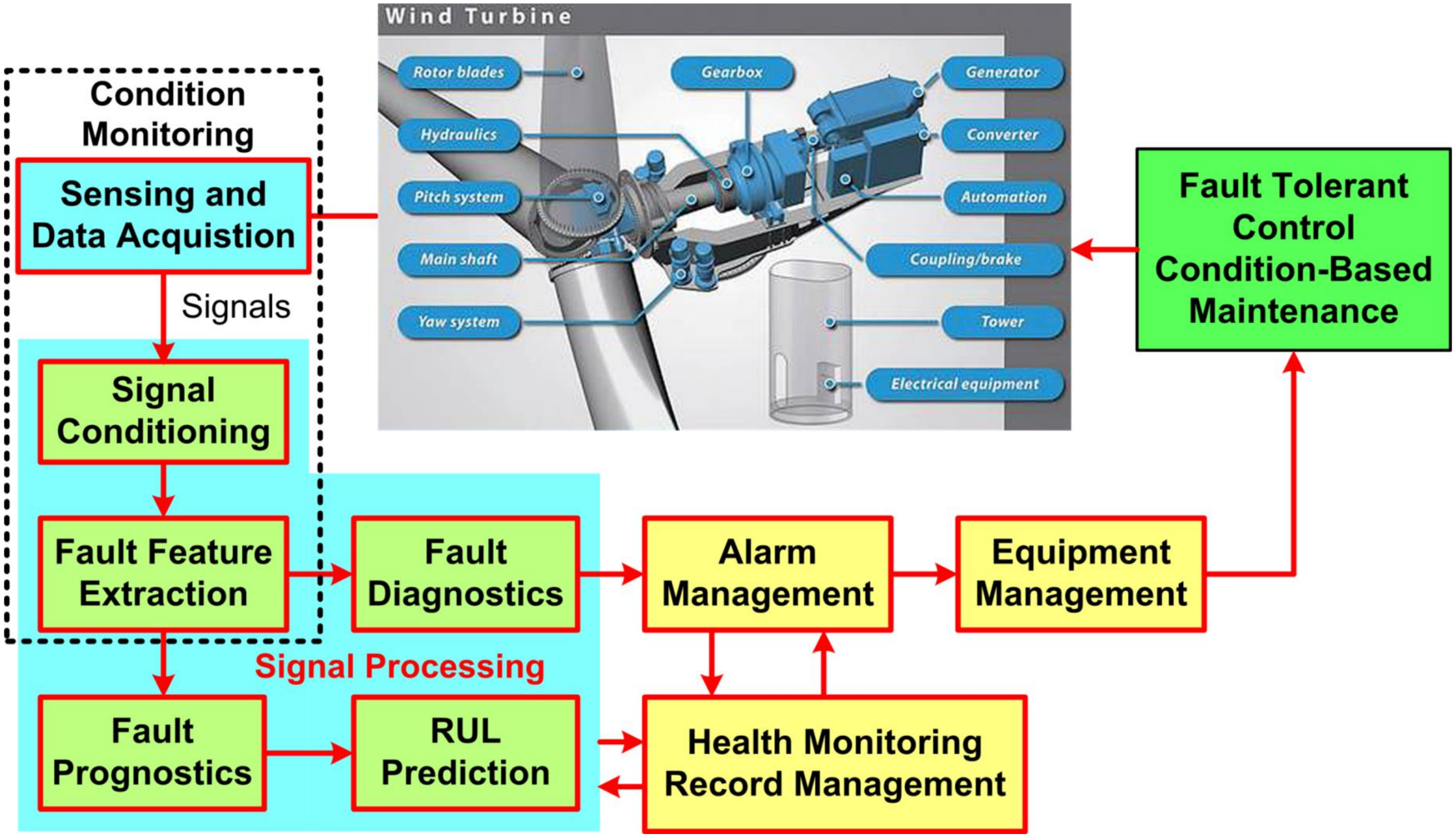
Cost-share – Vattenfall

Communications and Technology Transfer: American Wind Energy Association Windpower, Drivetrain Concepts for Wind Turbines, IEEE Applied Power Electronics, IEEE Energy Conversion Congress. EERE press release, Windpower Engineering industry article and promotional video.

Next Steps and Future Research

FY17/Current Research: All project goals completed. Project is closed.

Planned Future Research: Proposed follow-on work in generator development (Industry, ARPA-e IDEAS, DOE Small Business Voucher (SBV), and/or NREL Industry Growth Forum) and low-voltage power converter module field testing (DOE AOP). No funding secured at this time.



An Online Intelligent Prognostic Health Monitoring System for Wind Turbines

Wei Qiao

University of Nebraska Lincoln

wqiao3@unl.edu; (402) 472 9619

February 14 17, 2017

Project Overview

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

An Online Intelligent Prognostic Health Monitoring System (PHMS) for Wind Turbines: Low-cost, online, intelligent PHMSs were developed for wind turbine main drivetrains and pitch systems. The PHMSs can significantly reduce the failure rate and level, operation and maintenance (O&M) costs, and levelized costs of energy (LCOE), and extend the life of wind turbines.

The Challenge: Wind turbines are subject to high O&M costs (e.g., onshore: 10-15% of LCOE; offshore: 20-35% of LCOE). Existing condition monitoring systems and technologies: (1) require additional expensive sensors and data acquisition devices; (2) increase cost and hardware complexity; (3) cause additional reliability problem and O&M costs due to sensor failure; (4) focus on fault detection/diagnosis without fault prognosis capability; (5) have no or limited capability in fault diagnosis when wind turbines are operated in varying-speed conditions and the signals acquired contain heavy noises.

Partners: General Electric–Global Research Center (Subrecipient)

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- **Reliability improvements**
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- Advanced technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

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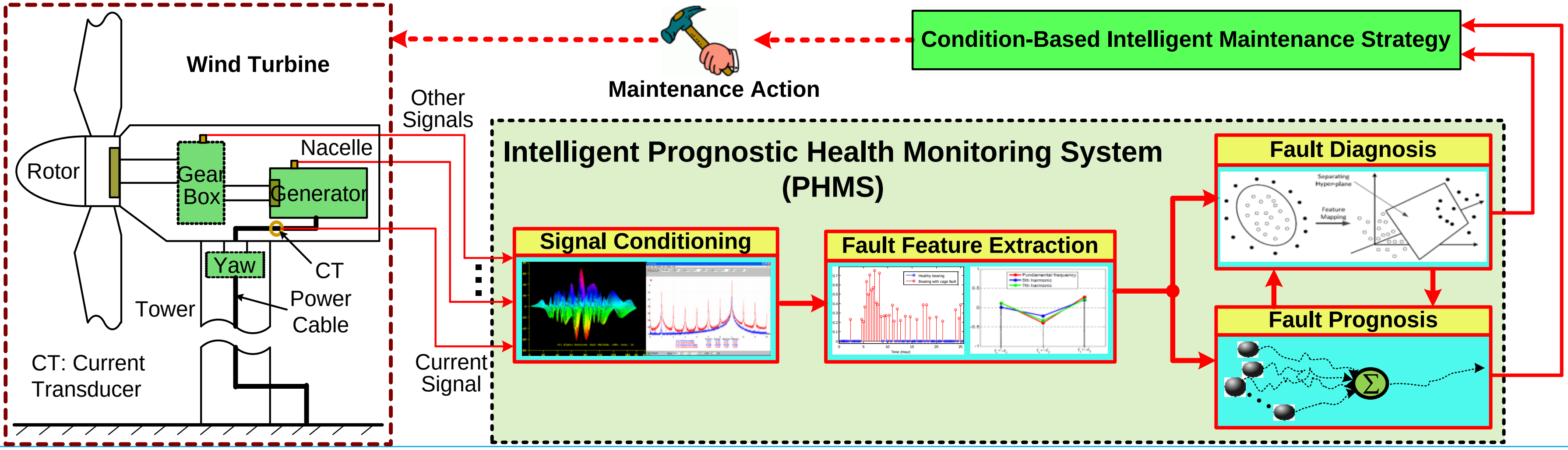
The Impact

- The PHMSs developed in this project are capable of online diagnosis and prognosis of all wind turbine failures having signatures in current and vibration signals and online predicting the remaining useful life (RUL) of the faulty wind turbine components.
- The PHMSs developed outperformed the state-of-the-art wind turbine condition monitoring technologies in terms of cost, hardware complexity, implementation, accuracy, capability, and system reliability.
- The PHMSs provide a low-cost, reliable solution for the wind industry to reduce the failure rate and level, O&M costs, and downtime, improve reliability, and extend the life of wind turbines.
- Multiple PHMS prototypes have been developed and validated for diagnosis and prognosis of various faults in wind turbines of different types and sizes, including MW wind turbines.

Technical Approach

The drivetrain PHMS primarily uses current signals acquired from generator terminals or in the wind turbine control system to diagnose and prognose the faults and determine the health condition of wind turbines via:

- Signal conditioning: synchronous resampling and multiscale filtering-based frequency spectrum analysis methods for nonstationary, noisy signals
- Fault feature extraction: impulse detection (frequency domain) and statistical analysis (time domain)
- Fault diagnosis: support vector machine (SVM)-based intelligent pattern classification to detect the types and locations of wind turbine faults
- Fault prognosis and RUL prediction: statistical particle filtering-based method.



Technical Approach

The drivetrain PHMS can also be used to include vibration signals in wind turbines to provide additional prognostic health monitoring capability and improved diagnosis and prognosis accuracy and reliability.

- Signal conditioning: current-aided vibration order tracking method
- Fault feature extraction: impulse detection and statistical analysis
- Fault diagnosis: SVM-based current and vibration information fusion
- Fault prognosis and RUL prediction: statistical particle filtering

The pitch system PHMS: based on symmetrical component analysis of the current and torque signals of the DC motors driving the pitch system.

Developed three drivetrain test beds for experimental validation of PHMSs.

- A small direct-drive AIR Breeze wind turbine operating in a wind tunnel (UNL)
- An emulated wind turbine drivetrain consisting of a two-stage helical gearbox driving a doubly-fed induction generator (DFIG) (UNL)
- A wind turbine drivetrain test bed consisting of a planetary gearbox and a parallel gearbox driving a DFIG (GE)

Field test validation on multiple Skystream 3.7 direct-drive (no gearbox) wind turbines and multiple 1.6-MW DFIG-based wind turbines (with gearbox).

Accomplishments and Progress

The first work that developed a complete set of methods using current signals as well as combining current and vibration signals for diagnosis and prognosis of wind turbine mechanical faults and RUL prediction.

Laboratory test validation for the drivetrain PHMS on the three test beds.

- The PHMS successfully diagnosed all the faults generated artificially and accurately prognosed the fault development and predicted the RUL of the faulty components in the run-to-failure tests when the test beds were operated in varying-speed conditions and the signals acquired contained shaft speed unrelated components and heavy noises.
- These results could not be achieved by the baseline technologies developed in the previous research of UNL or GE's existing condition monitoring system.

Field test validation for the drivetrain and pitch system PHMSs.

- All of the faults occurred in the field wind turbines were successfully diagnosed by the PHMSs using current and/or vibration signals.
- The RUL of selected 1.6-MW wind turbines was predicted with sufficient days (e.g., 27 days) before the alarm system was triggered so that maintenance could be scheduled before actual failures occur.

Project Plan & Schedule

Project original initiation date: 12/15/2014; planned completion date: 06/14/2016.

The end date of Budget Period 1 (BP1) was extended to 2/29/2016 from 12/14/2015: (1) the start dates of Tasks 2, 3, 7, and 8 were delayed because it took two months to negotiate the subaward with GE; (2) to finalize the SOPO and budget for BP2.

Go/No-Go decision point for BP1: Task 5

SOPO Task Number	Title / Task Description	Task Completion Date		
		Original Planned	Revised Planned	Actual
1	Develop a current-based drivetrain PHMS	Jul-15		Jul-15
2	Improve the drivetrain PHMS by combining current and vibration signals	Jul-15	Aug-15	Aug-15
3	Develop an electrical-signature-based pitch system PHMS	Jul-15	Feb-16	Feb-16
4	Design and set up the lab experimental systems	Feb-15		Feb-15
5	Evaluate and improve the drivetrain PHMS by experimental studies	Dec-15		Dec-15
6	Prepare for field testing to validate drivetrain PHMS for small wind turbines	Dec-15	Feb-16	Feb-16
7	Design and integrate a PHMS prototype	Oct-15	Feb-16	Feb-16
8	Prepare for field testing to validate PHMS prototype for MW-scale wind turbines	Dec-15	Feb-16	Feb-16
9	Validate the drivetrain PHMS via field testing for small wind turbines	Sept-16		Sept-16
10	Validate the PHMS prototypes via filed testing for MW-scale wind turbines and additional laboratory testing	Sept-16		Sept-16

Project Budget

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

Budget History					
FY2014		BP1 (12/15/2014-2/29/2016)		BP2 (3/1/2016-9/30/2016)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$0	$0	$1,032.737k	$125.996k	$467.244k	$41.004k

- The project was completed. The planned cost-share contribution has been fully met. The project balance is close to zero, i.e., all the DOE funds have been spent.
- There was no variance of the total DOE share or total cost share from the planned budget.
- $38.323k of the original BP1 DOE budget ($1,071.06k) was carried forward into BP2 for the team to conduct more testing, validation, and improvement work in BP2.

Research Integration & Collaboration

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

Subcontractors: GE Global Research Center.

- All of the drivetrain PHMS methods developed by UNL have been successfully demonstrated for fault diagnosis and prognosis and RUL prediction of 1.6-MW GE wind turbines in varying speed and noise conditions. The current GE wind turbine condition monitoring system does not have these capabilities.
- The pitch system PHMS developed in this project is a new capability that does not exist in any of the current commercially available condition monitoring systems.
- GE is strongly interested in continuing the collaboration with UNL and, in the future, improving the PHMS and deploying the PHMS methods in the commercial wind turbine condition monitoring systems.

Communications and Technology Transfer:

- Six peer-reviewed journal papers and seven peer-reviewed conference proceedings papers have been published or accepted for publications. **Outcome:** over 2,200 downloads to date. Conference presentations to more than 400 people.
- Invited seminars were given to more than 500 people.
- Three patent applications were submitted.
- GE works on commercialization of the PHMS methods developed in this project.

Next Steps and Future Research

FY17/Current Research: Not applicable.

Planned Future Research:

- Extend to prognostic health monitoring for wind turbines via remote sensing and data acquisition: develop technologies to improve fault diagnostic and prognostic accuracy and reliability using big data collected from many wind turbines.
- Develop prognostic health monitoring technologies for electrical subsystems of wind turbines, such as power electronic converters, which have one of the highest failure rates among all wind turbine subsystems.

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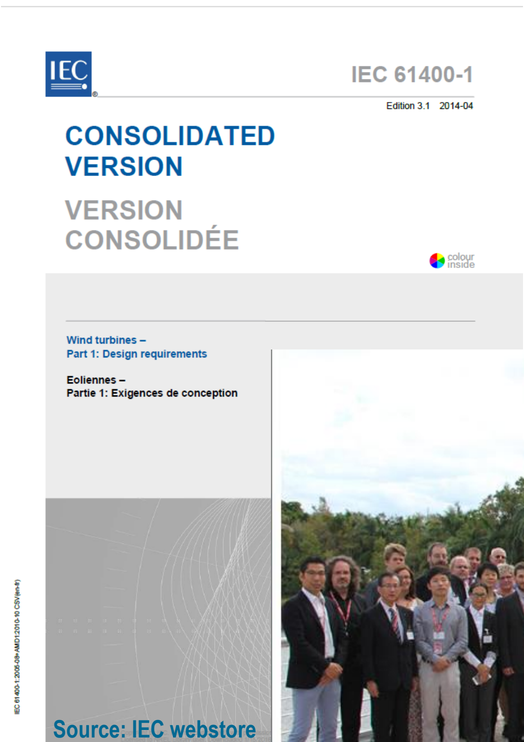
IEC

IEC 61400-1

Edition 3.1 2014-04

CONSOLIDATED VERSION

VERSION CONSOLIDÉE

Wind turbines –
Part 1: Design requirements

Eoliennes –
Partie 1: Exigences de conception

Source: IEC webstore


Credit: Angeline Gross

Credit: Karin Berger, Bachmann Electronic GmbH

Wind Standards Development

Jeroen van Dam

National Renewable Energy Laboratory

Jeroen.van.Dam@nrel.gov, 303 384 7009

February 15, 2017

Project Overview

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

Wind Standards Development:

- Clarity
- Consistency
- Predictability.

Lower Risk for investors

- Consensus
- Creates level playing field for U.S. industry to compete globally
- DOE labs have broad knowledge in modeling and testing, are impartial, and have central position in the U.S. industry.
- Allows for direct adoption of research-and-development (R&D) knowledge by industry
- Forum for collaboration with all relevant industry stakeholders.

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- Reliability improvements
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- Distributed wind R&D
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Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- Advanced technology demonstration projects
- Technical engagement initiatives
- **Standards and certification**
- Communicating the costs and benefits of wind energy

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The Impact

- Provides industry with clear, consistent design criteria that reflect industry consensus
- Creates standards that result in products that meet industry stakeholder expectations
- Creates standards that reflect our current understanding of the technology, and enables innovations to enter the market
- Global conformity assessment system with mutual recognition to remove trade barriers for U.S. industry.

Technical Approach

- Strive to have standardization at a level with maximum impact: international, supplemented by domestic if needed, minimizing conflicts.
- Participate and, when it makes sense, have a leading role in the development of international and domestic standards related to wind energy.
- The standards development work applies knowledge developed in other parts of the program. The DOE funding mainly covers preparation for, travel to, and attendance of meetings.
- Involvement is prioritized as follows:
  - Design standards: These have the largest possibility to impact technology through the cost of energy and reliability. Well suited to identify key R&D needs.
  - Standards that impact the program (e.g., A2e): These are related to turbine performance, measurement of atmospheric conditions, and wind power plant performance.
  - Standards where the program has major contributions to make (e.g., Gearbox Reliability Collaborative).
  - Areas where Labs have capability and there is a lack of other U.S. participation.

Technical Approach

Standard	Content
IEC 61400-101	General requirements for wind turbine plants
IEC 61400-1 (S)	Design requirements
IEC 61400-3-1	Design requirements for offshore wind turbines
IEC 61400-3-2	Design requirements for floating offshore wind turbines
IEC 61400-5 (S)	Wind turbine rotor blades
IEC 61400-11 (S)	Acoustic noise measurements
IEC 61400-12-1	Power performance measurements
IEC 61400-13 (C,S)	Measurement of mechanical loads
IEC 61400-15 (S)	Assessment of site-specific wind conditions for wind power stations

Standard	Content
IEC 61400-26	Availability for wind turbines and wind turbine plants
AWEA SWT-1 (C)	Small wind turbine safety and performance
AWEA RP (C)	Offshore wind
AGMA 6006	Design and Specification of Gearboxes for Wind Turbines
IEEE 1547	Standard for Interconnecting Distributed Resources with Electric Power Systems
NEC	National Electric Code
IECRE SG551 (C)	Test laboratory stakeholder group
IEA Task 33	Reliability Data: Standardizing data collection for wind turbine reliability and O&M analyses
(C), (S)	Marks where NREL provided convener and/or secretary

Technical Approach

- Play a central role in U.S. industry to engage and inform industry
- Support the development of a global conformity assessment system using the international standards.

Accomplishments and Progress

Set up annual U.S. Wind Energy Standards Summit:

- Educate industry on standards
- Coordinate U.S. position
- Engage industry
- Assess industry needs

Handed off to American Wind Energy Association (AWEA) to encourage leadership role in standards development. Summit returned to NREL in 2016.

United States maintained International Electrotechnical Commission (IEC) TC 88 chair.

Major contributors or leadership roles for several standards.

Gathered more than 30 accredited test laboratories to collaborate globally under the Wind Turbine Certification Advisory Committee (WT-CAC) to raise the quality of accredited testing.

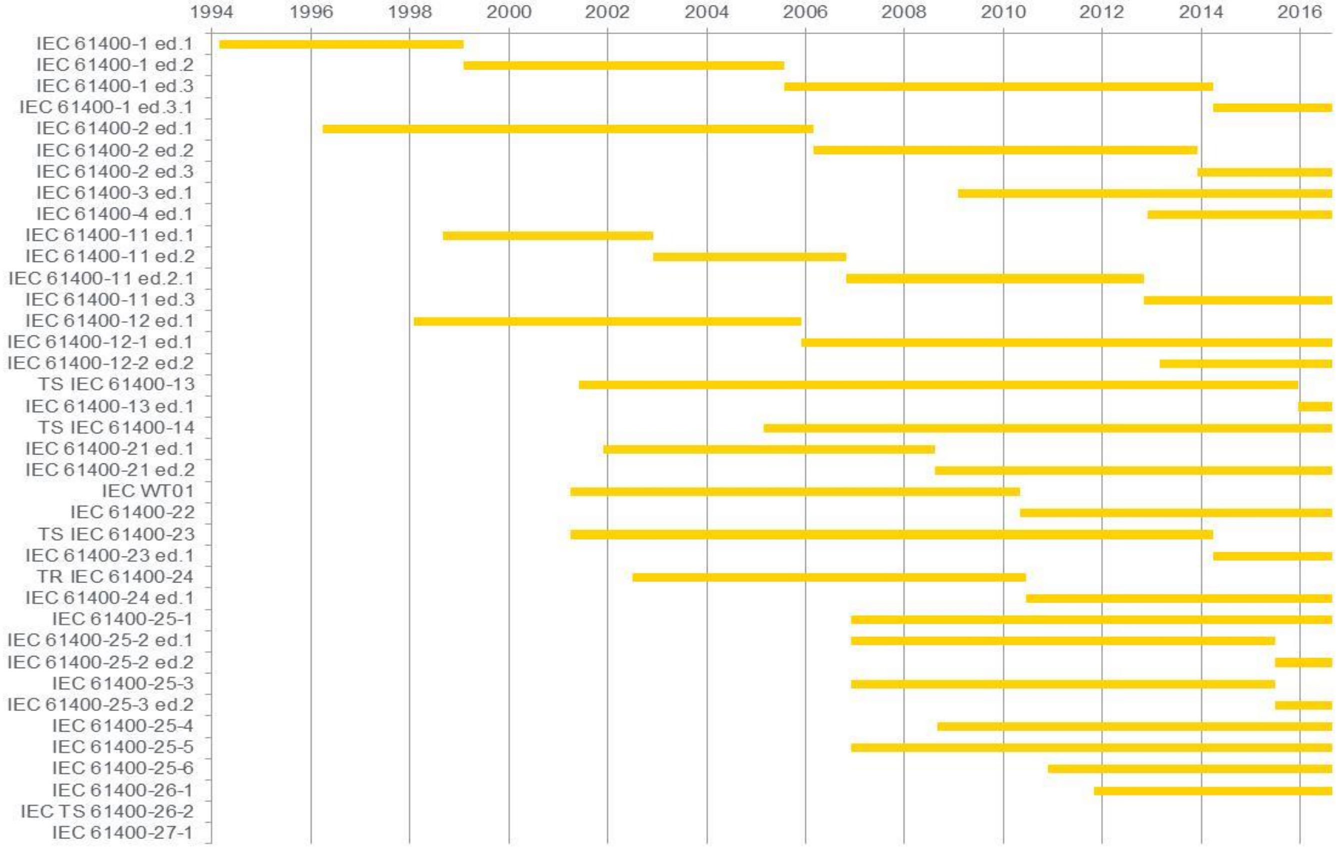
NREL employees received IEC 1906 awards:

- Paul Veers for role as secretary of IEC TC 88 MT 1
- Jeroen van Dam for WT-CAC/IECRE test laboratory stakeholder group.

Project Plan & Schedule

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

Published documents in IEC TC 88



- The project is an ongoing, multiyear activity; sub-activities start and finish on a typical 3- to 5-year cycle.
- Due to the collaborative and consensus-based work, there is no complete control of progress. The budget plan is laid out for the schedule as anticipated at the beginning of the year.

Project Budget

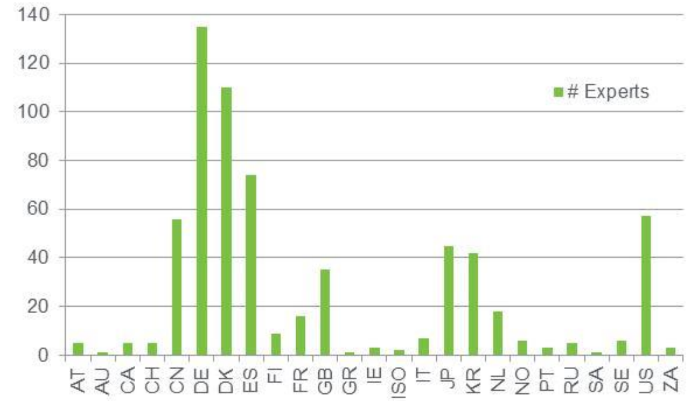
	Budget History					
	FY2014		FY2015		FY2016	
	DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
NREL	$356K		$495K		$450K	
SNL	$200K					
Total	$556K		$495K		$450K	

- Priorities are set at the beginning of each fiscal year.
- The budget typically only allows for funding the top priorities.
- The project scope is actively managed based on actual progress of sub-activities.

Research Integration & Collaboration

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

IEC TC 88 experts by country



Partners, Subcontractors, and Collaborators: Informal collaboration takes place with a broad group of international industry stakeholders (original equipment manufacturers, end users, certification bodies, consultants, universities, test laboratories, and research laboratories).

Communications and Technology Transfer: Annual U.S. Wind Energy Standards Summit to bring industry together to educate them on international and domestic standards. The first summit was attended by more than 70 participants. The 2016 summit was attended by more than 50 participants. The standards and the process to develop them are an effective means to communicate and transfer knowledge from the DOE Wind Program to industry.

Next Steps and Future Research

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

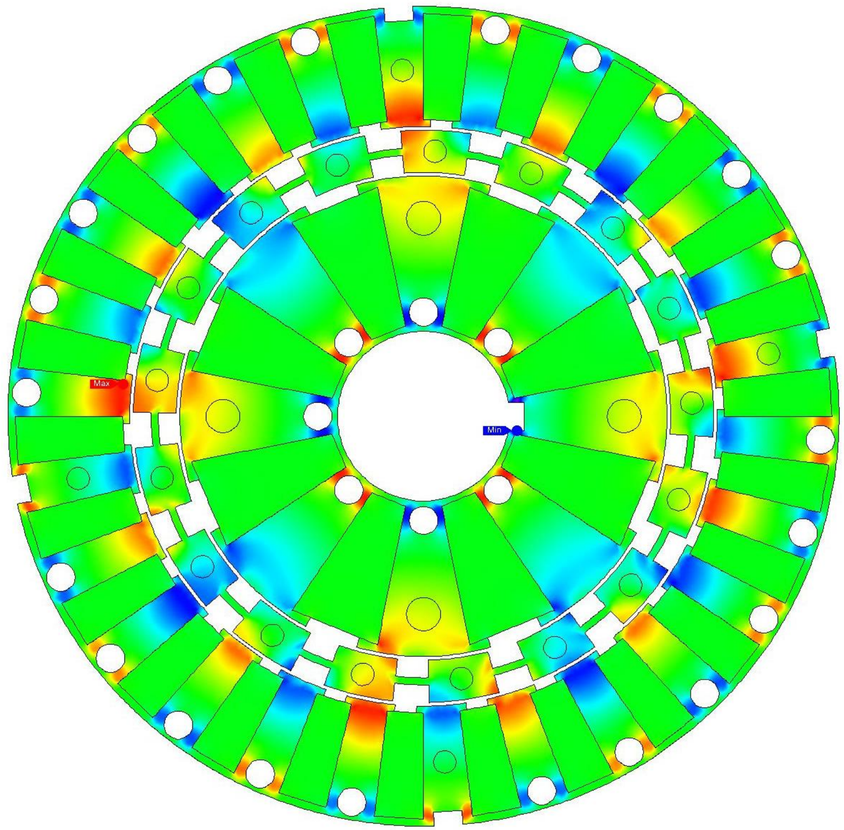
FY17/Current Research:

Complete ongoing revisions
Contribute to restructuring work of TC 88 under PT 101
Chair IEC TC 88 for remainder of six-year term
Assist IECRE to get established
Maintain central and facilitating role in United States for standards development.

Planned Future Research:

Standards require periodic maintenance to implement R&D knowledge and reflect the state of the art
IECRE has identified needs for standards for conformity assessment (e.g., pitch and yaw system design, safety and function testing)
Support restructuring effort to ensure the efficient use of limited resources in TC 88 with an increasing amount of documents.

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



Advanced High Torque Density Magnetically Geared Generator

Prof. Jonathan Bird

University of North Carolina at Charlotte (UNCC)

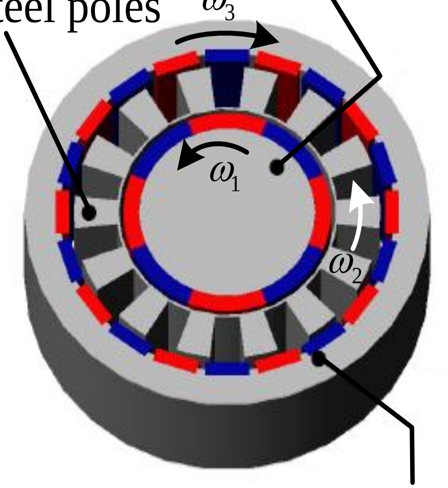
bird@pdx.edu, Phone: 503.725.9059

2/13/2017 2/17/2017

Magnetic Gear

A magnetic gear consists of :

- p_1 pole-pair permanent magnets on an inner ring rotating at ω_1,
- p_3 pole-pair permanent magnets on outer ring rotating at ω_3
- A middle ring with n_2 ferromagnetic steel poles that is rotating at ω_2.



If the relationship between the steel poles is chosen to be

$$p_1 = |p_3 - n_2| \quad (1)$$

Then the inner and outer rings that contain PMs interact with the middle steel poles (n_2) to create space harmonics.

$$\omega_1 = \frac{p_3}{p_3 - n_2}\omega_3 + \frac{n_2}{n_2 - p_3}\omega_2 \quad (2)$$

For the case when the outer rotor ring is stationary, $\omega_3=0$, the speed relationship is just

$$\omega_1 = \left(\frac{n_2}{n_2 - p_3}\right)\omega_2 = G\omega_2 \quad (3)$$

G is the gear ratio

Project Overview

Magnetic Gearing:
- Non-contact speed change
- No need for gear lubrication
- Inherent overload protection
- Can integrate a stator within magnetic gearbox

Objective:
- Design and fabricated a magnetically geared generator
- Be as small as a mechanically geared generator
- Be as reliable as direct-drive generator

Challenges:

Demonstrate that the torque density and magnet usage can be competitive with existing technology

Partners:
- Wesley Williams, Engineering Technology, UNCC
- Company Advisory board

Enabling Wind Nationwide

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Target and Performance Metric

	Magnetic Gear		Magnetically Geared Generator	
	Volume Density	Target Improvement	Volume Density	Target Improvement
Baseline	100Nm/L	-	50Nm/L	-
Target	300Nm/L	200%	300Nm/L	500%

Impact:

- Increasing reliability
- Reducing generator size
- Lower levelized cost of energy

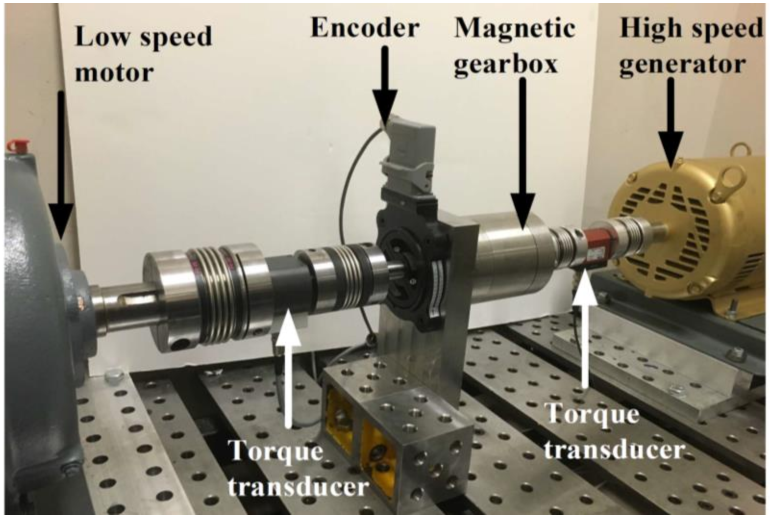
Project Endpoint:

- Demonstrate the potential for the magnetic gearing
- Position technology for further development to higher Technology Readiness Level.

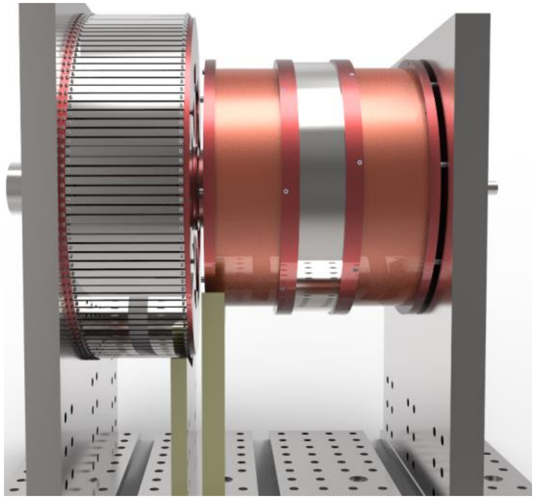
Technical approach:
- Numerical and analytic scaling analysis
- Build and test subscale designs first to mitigate risk

Key issues: - Complete experimental testing
- Magnet loss and thermal analysis

Unique Aspects: - Very high torque density
- Very high torque/kg magnet

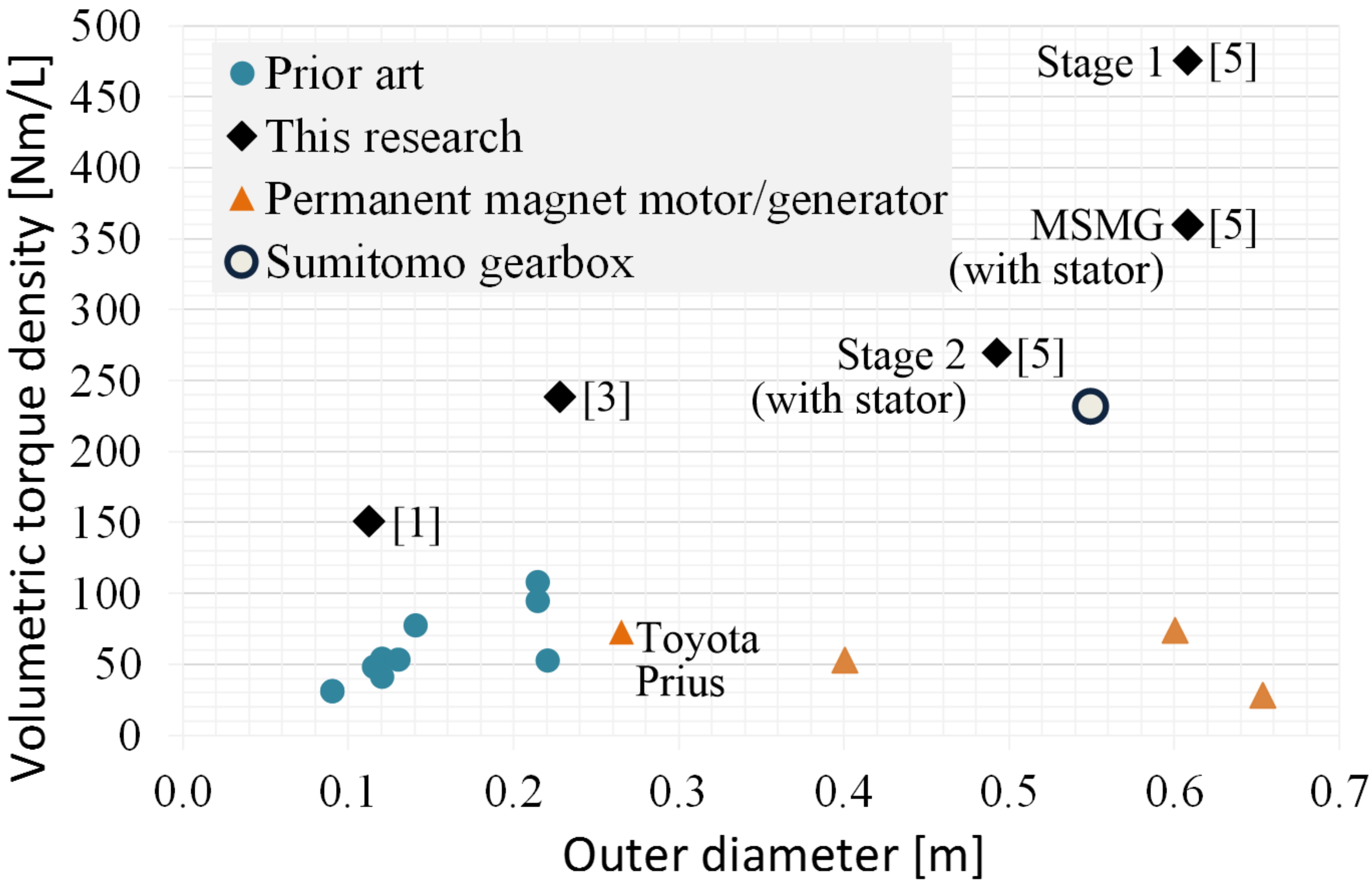


Reduce Risk by Sub-Scale Experimental Testing



59:1 Experimental Prototype

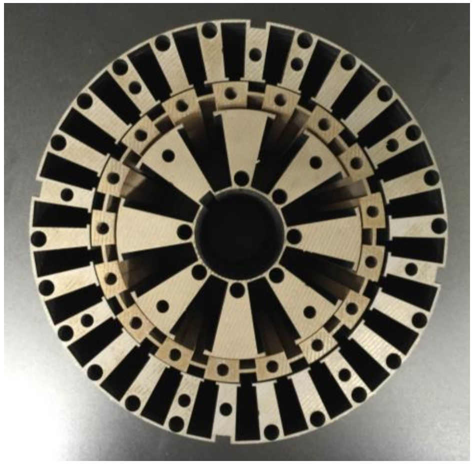
Technical Approach



Accomplishments and Progress

- A sub-scale laminated magnetic gearbox was designed and tested.
- An analysis of a nested vs. series connected magnetic gearboxes was completed.
- A series connected multi-stage magnetic gearbox design was completed.

  The stage 1 assembly of the multi-stage magnetic gearbox was completed.
- A low torque ripple integrated stator design was completed.



Sub-scale lamination structure

Project Plan & Schedule

Initiation date: 12/15/2015
Completion date: 6/15/2017

Schedule:
- Testing of stage-1 magnetic gearbox: 12/31/2016
- Testing of stage-2 magnetic gearbox generator: 2/31/16
- Complete scaling analysis of the magnetic gear gen.: 5/31/16
- Complete final report

Slipped milestone:
Delays were encountered due to changing design approach from nested to series connected magnetic gearbox

There was no *Go/No-Go decision point* for this project

Project Budget

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

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$0	$0	$114k	$80k	$137k	$14k

- **Portion of the project budget expended (as of 11/25):** 23%
- **Cost share:** North Carolina Coastal Studies Institute

Communications and Technology Transfer:

Patents –

Bird J., Li K., Williams W. *Laminated single and multistage magnetic gearboxes*, application in process, US patent office, 2016.

Publications –

[1] K. Uppalapati, J. Kadel, *et al.*, "A low assembly cost coaxial magnetic gearbox," to be presented at *South. Power Elec. Conf.*, Auckland, NZ, 2016, Dec 5-8.

[2] K. Li, S. Modaresahmadi, *et al.*, "Designing and testing a multistage series connected coaxial magnetic gearbox," Submitted to *IEEE Inter. Elect. Mach. Drives Conf.*, Miami, FL, May, 2016.

[3] K. Li, S. Modaresahmadi, *et al.*, "Designing a multistage nested coaxial magnetic gearbox," Submitted to *IEEE Inter. Elect. Mach. Drives Conf.*, Miami, FL, May, 2016.

[4] K. Li and J. Bird, "Ideal Radial Permanent Magnet Coupling Torque Density Analysis," Submitted to *IEEE Trans. Magn.,* 2016.

[5] K. Li and J. Bird, "Torque Density Comparison of Axial and Radial Halbach Couplings," presented at the *17th Biennial Conf. Electro. Field Comp*., Miami, FL, 2016, Nov 12-16.

Partners:

Members of Technical Advisory Board –

- General Electric Corporation
- Northern Power Corporation
- Pacific Energy Ventures
- Boulder Wind Power Corp.

A laboratory demonstration with the Technical Advisory Board in Charlotte, NC, is planned for May 25, 2017

Next Steps and Future Research

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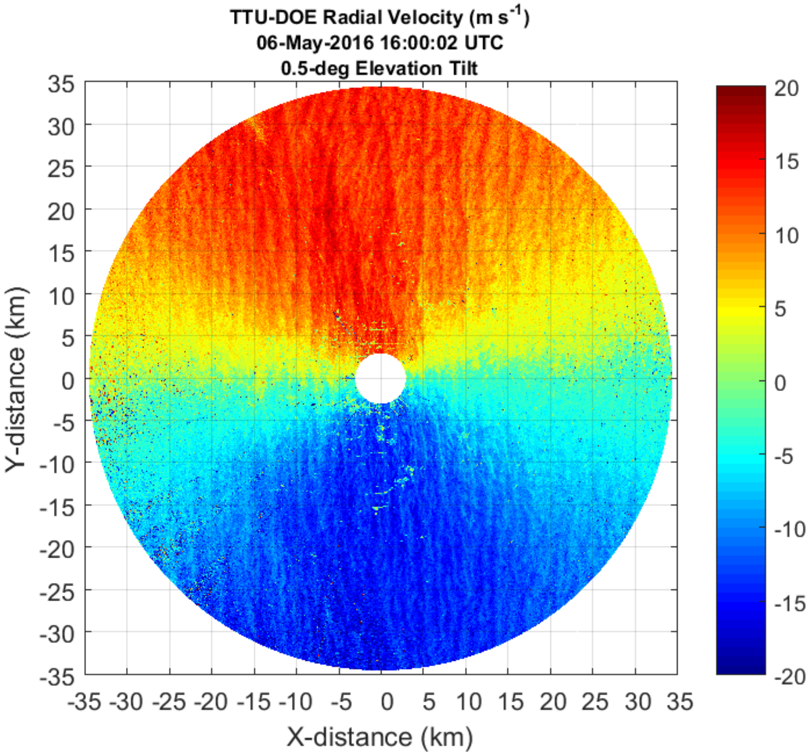
FY17/Current Research:

Upcoming Milestones
- Complete testing of magnetically geared generator
- Compare performance with equivalent sized generator
- Conceptionally scale up design

Upcoming Deliverables:
- Final report

Remaining Barriers:
- Loss analysis within magnets
- Thermal heating issues
- Unforeseen experimental testing issues

Planned Future Research:
- Scale-up technology
- Construct prototypes with partner



The Incubation of Next-Generation Radar Technologies to Lower the Cost of Wind Energy

Dr. John Schroeder

Texas Tech University

806 834 5678 / john.schroeder@ttu.edu

February 2017

Project Overview

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

The Incubation of Next-Generation Radar Technologies to Lower the Cost of Wind Energy:

Providing a technology to **measure wind plant complex flows** is fundamental to wind-plant-focused optimization efforts.

The Challenge:

Existing technology validated the approach of using radar derived wind fields, but deficiencies in **data availability and automation** hindered widespread application.

Partners:

SmartWind Technologies – commercialization

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- **Wind plant optimization**
- Resource assessment and characterization
- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- Advanced technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

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The Impact

- The target is to reliably measure complex flows across a large measurement domain (e.g. a wind plant) at sufficient temporal and spatial scales to resolve and track wind energy relevant flow features.
- The project provides a technology to simultaneously measure inflow/wake flow across a wind plant domain to validate LES simulations, wind turbine wake models, and turbine layouts; inform operational decision making and engineering design; and explore proactive controls to mitigate turbine-to-turbine interaction.
- A new radar prototype (Technology Readiness Level of 7) that can directly contribute to DOE's A2e initiative and serve as a template for commercialization.

Develop a new radar technology focused on measuring wind plant complex flows.

Highest priority =>

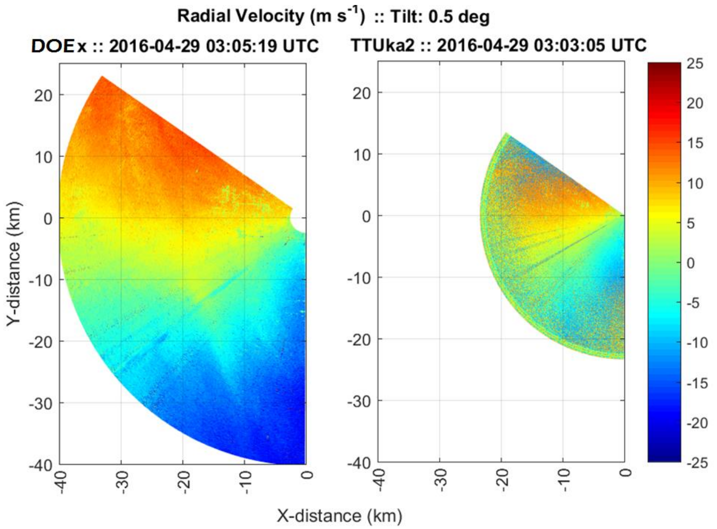
enhance data availability

Chosen wavelength impacts Rayleigh and Bragg scattering

Dual TWT transmitters deliver more power to the target

Lower PRF enhances range

RESULT: A radar with improved data availability in all atmospheric conditionsand expanded range.



Develop a new radar technology focused on measuring wind plant complex flows.

Secondary priority =>

semi-autonomous operation

Automatic restore to full operation in the event of a power failure

Basic QA/QC filtering focused on wind plant complex flows executed in real-time

NetCDF measurment format

RESULT: A stand-alone system with targeted post processing and a user friendly output format.

Accomplishments and Progress

Finalized Engineering Design Plan—January 2015 (on time)

Provided the detailed path forward through the procurement process

Completed Software Development —August 2015 (on time)

Provided the real time QA/QC processing and user friendly data formats

Completed Procurement, Integration, Deployment and Component Testing—April 2016 (on time)

Completion marked the installation of the radar onsite at Texas Tech University

Integrated System Testing and Validation—September 2016 (3-month delay)

Provided the basis for measuring the improvement relative to the previous technology

Final Report/Dissemination of Results—December 2016 (6-month delay)

Project Plan & Schedule

- Project Initiated: December 15, 2014
- Project Conclusion: December 15, 2016
- A slight delay was requested by the PIs to complete additional field testing.
- Go/No-Go decision points
  - DOE approved the engineering design report, January 2015
  - DOE approved the final integration, March 2016

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$0	$0	$107.496k	$104.756k	$1,241.079k	$72.481k

- The initial project budget was trimmed at the time of the award resulting in cuts to ancillary radar systems (e.g. no communications link, reduced post processing algorithm development, no system wide UPS).
- As of November 17, 2016, 97% of the budget has been expended; the project will conclude in December 2016.
- Texas Tech University provided the cost share funds for this project.

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators:

SmartWind Technologies is the commercialization partner for the project with a signed exclusive license agreement in place with Texas Tech University for relevant IP.

Communications and Technology Transfer:

Abstracts/Presentations – 2016 Sandia Blade Workshop, 2017 American Wind Energy Association (planned), 2017 TTU WISE Seminar

Commercial Sales – SmartWind Technologies provided installation of a dual-Doppler radar system in the UK to study an offshore wind farm.

Next Steps and Future Research

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FY17/Current Research: NA; the project has been completed. Any ongoing research is occurring outside the scope of the original project.

Planned Future Research: Future modifications/upgrades would be focused on providing more sophisticated post processing (QA/QC and objective analysis), and enhancements to the radar hardware (communications link, remote control, system wide UPS, etc.). The DOE-X radar may be moved to provide measurements across relevant wind plants.

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Wind Plant Optimization

Joel Cline
Resource Characterization
Team Lead

February 15, 2017

Enabling Wind Nationwide

Enabling U.S. Industry Growth and U.S. Competitiveness

- **GOAL**: Reduce the unsubsidized market levelized cost of energy (LCOE) for utility-scale land-based wind energy systems from a reference wind cost of $0.074/kWh in 2012 to $0.057/kWh by 2020 and $0.042/kWh by 2030.
- **GOAL**: Reduce the unsubsidized market LCOE for offshore fixed-bottom wind energy systems from a reference of $0.18/kWh in 2015 to $0.15/kWh by 2020 and $0.096/kWh by 2030.

Enhancing U.S. Energy Security and Independence

- **GOAL**: Accelerate widespread U.S. deployment of clean, affordable, reliable, and domestic wind power to promote national security, economic growth, and environmental quality.

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- **GOAL**: Expand the geographic development potential of wind power plants in the United States, particularly in offshore zones and the U.S. Southeast.

Enabling Wind Nationwide

Enabling U.S. Industry Growth and U.S. Competitiveness

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- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

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Wind Energy Technologies Office *Structure*

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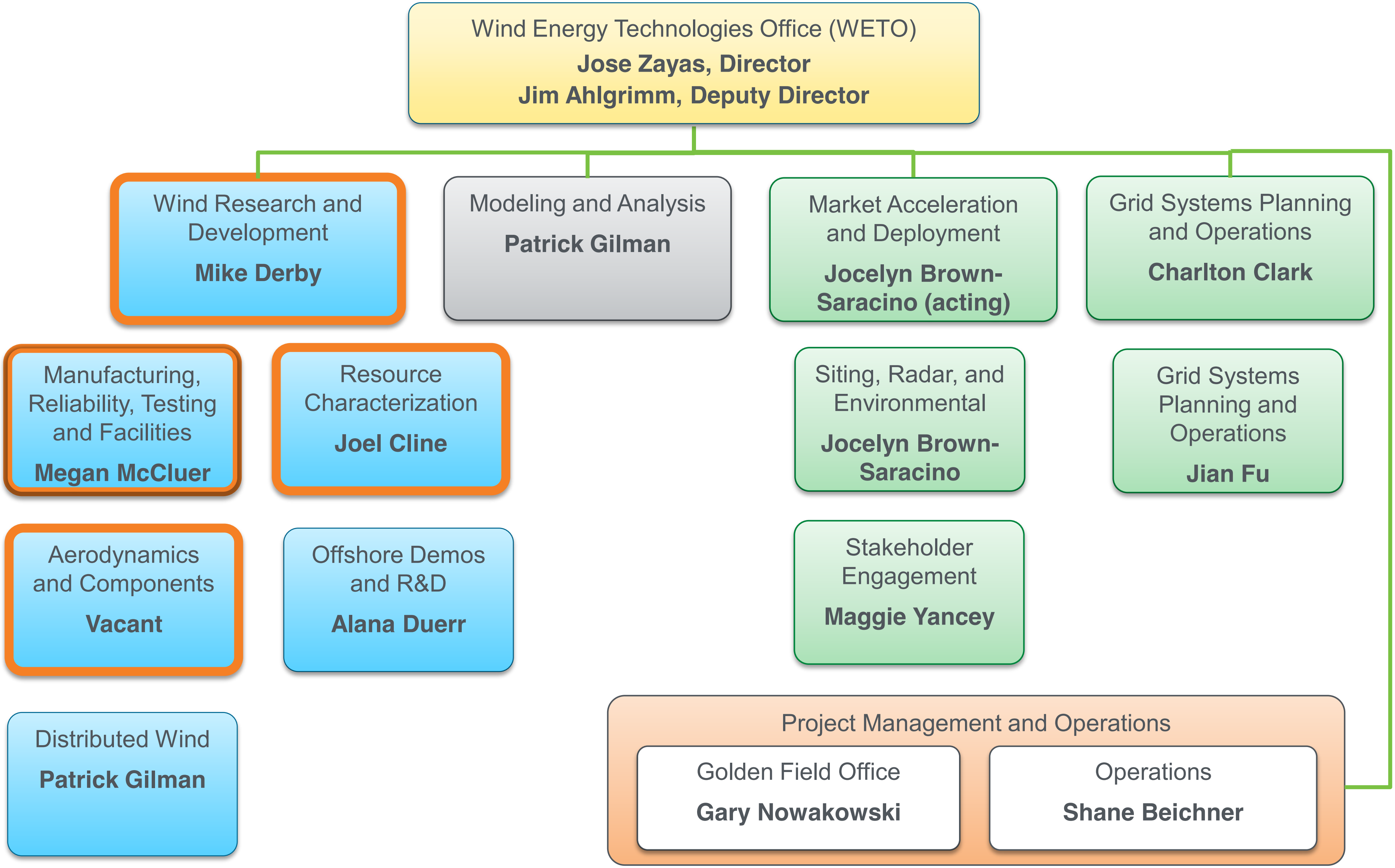

Motivation: Optimize Wind Plant Performance

Enable the design and deployment of cost effective, SMART Wind Power Plants

- *System Management of Atmospheric Resources through Technology*

- Enable next-generation wind plants that target significant reductions in wind plant losses (20–30% observed in operational wind plants)
- Significantly improve industry's predictive capability of wind plant flow
- Improve wind plant reliability over >30-year lifetime

Motivation: Improve Wind Plant Energy Estimates

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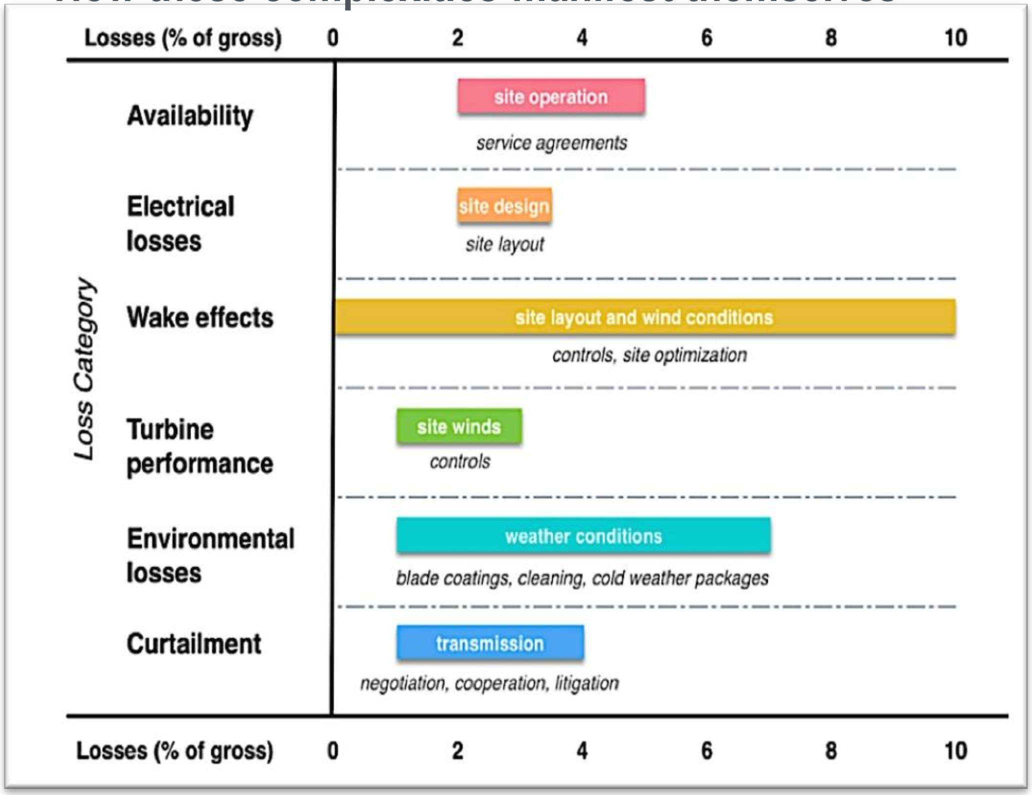
Wind power plant energy production is extremely complex given site-dependent drivers

Sources of complexity

- Atmospheric resource characteristics
- Site topography and terrain complexity
- Individual turbine performance within the plant
- Grid interconnection
- Turbine siting and array loss effects

How these complexities manifest themselves



Source: *Wind Plant Preconstruction Energy Estimates: Current Practice and Opportunities; Clifton et al. 2016*

Strategic Focus Areas

Challenges, Goals, & Approach

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Strategic Area	Challenges	Goals	Approach
Resource Characterization	**Short- and long-term economic risk and losses**	Improve wind energy markets and increase wind plant profitability	• **Improve foundational weather forecast models at wind plant scale**
	High resource uncertainty	Improve observations, uncertainty quantification, and site layout optimization.	• **Develop new offshore instrumentation** • **Reduce uncertainty**
	Incomplete physics reduced modeled predictability of wind plant inflow and optimization	Improve understanding of underlying physical phenomena (e.g. turbulence, sheer, stability, low level jets, etc.)	• **Improve complex terrain modeling at sub-grid scale** • **Develop IEA Guidelines**
Technology Development	**Wind plant losses are significant (e.g. wake losses)**	Develop new technology and analysis capability to help reduce wind plant losses	• **Look at wind plant as a system**
	Current real-time analysis capability is insufficient	Improve operational optimization capability	• **Improve wind plant controls and operational methods**
Wind Plant Physics	**Untapped national computational power to model entire wind plants**	Leverage high fidelity modeling at DOE national laboratories	• **Data Archive and Portal (DAP) to store data and model results – test cases**
	Formal V&V not typically utilized in rigorous way	Incorporate formal V&V process into model improvement efforts	• **Establish a formal Verification & Validation (V&V) process** • **Develop metrics for short-term and day-ahead forecasts**

Projects Under Review

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Resource Characterization	
PRUF: Performance Risk, Uncertainty, and Finance *(10:40am)*	Jason Fields
MMC: Model Development & Validation *(1:55pm)*	Sue Haupt
WFIP II: Wind Forecast Improvement Project Phase 2 *(2:15pm)*	Will Shaw
DAP: Data Archive and Portal *(3:20pm)*	Chitra Sivaraman
Technology Development	
Wind Plant Flow Control *(12:05pm)*	Alan Wright
ISDA: Integrated Systems Design and Analysis *(1:30pm)*	Katherine Dykes
Wind Plant Physics	
High-Fidelity Modeling *(11:05a)*	Mike Sprague
Wake Dynamics Measurement, Testing, and Validation *(11:40am)*	Brian Naughton

Budget Summary

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Total Budget			
FY2014	FY2015	FY2016	**Total FY2014-FY2016**
$10M	$12M	$9M	**$31M**

Peer Reviewed Budget			
FY2014	FY2015	FY2016	**Total FY2014-FY2016**
$9M	$12M	$9M	**$30M**
96%	*100%*	*99%*	***98%***

Key Projects Over Time

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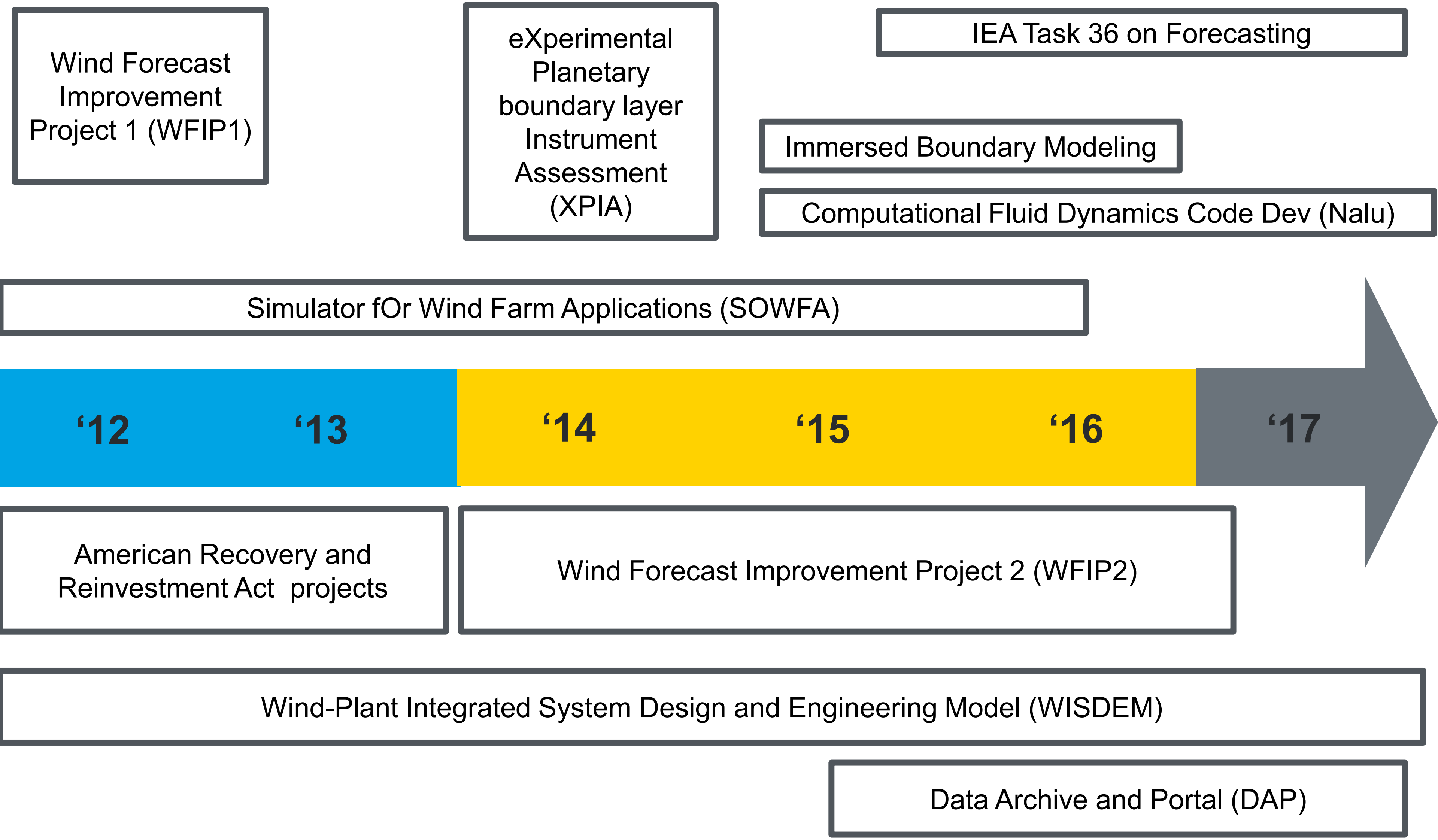

Activities & Accomplishments (FY14–16)

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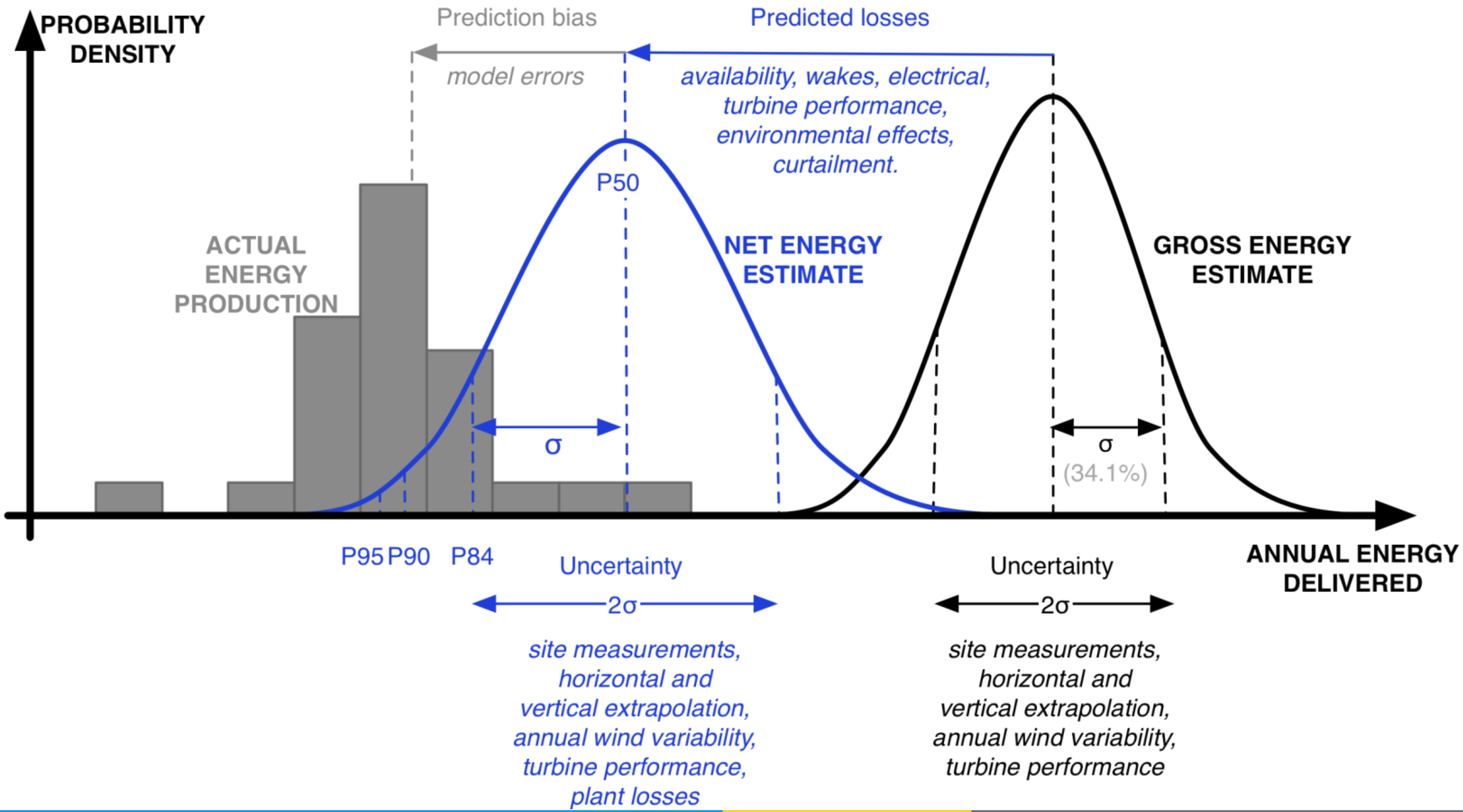
Strategic Area	Accomplishments	Collaborators
Resource Characterization	• Tested remote sensing devices against met towers • Investigated fundamental physics models at the sub-grid and wind plant scales • Initiated efforts to to correctly handle Complex Terrain at sub-grid or wind plant scale • Stored model and experimental results via the DAP project • Established guidelines for data storage and metadata • Implemented V&V process	• Vaisala • NREL /LLNL/ PNNL/ ANL / LANL/ SNL • NOAA (OAR, NWS) • IEA Tasks 36/32 – Forecasting/Lidar • Univ. of Colo., Notre Dame, Texas Tech, UCAR
Technology Development	• Incorporated lidars, wind profilers, radars, radiometers into research programs • Released system optimization software (WISDEM) • Released FLOw Redirection and Induction in Steady-state software (FLORIS)	• SBIR projects, National Data Buoy Center • NREL/SNL
Wind Plant Physics	• Improved high fidelity wind modeling capability in the SOWFA code and began transition to the Nalu code • Launched efforts to investigate wake steering • Identified specific physics to include in V&V process	• NREL/SNL

Notes: NREL/LLNL/PNNL/ANL/LANL/SNL= U.S. DOE national laboratories; UCAR=University Corporation for Atmospheric Research; NOAA=National Oceanic and Atmospheric Administration; OAR=Oceanic & Atmospheric Research; NWS=National Weather Service; SBIR=Small Business Innovation Research; IEA=International Energy Agency; SOWFA=Simulator fOr Wind Farm Applications



Performance Risk, Uncertainty & Finance (PRUF): Wind Plant Benchmarking

Atmosphere to Electrons

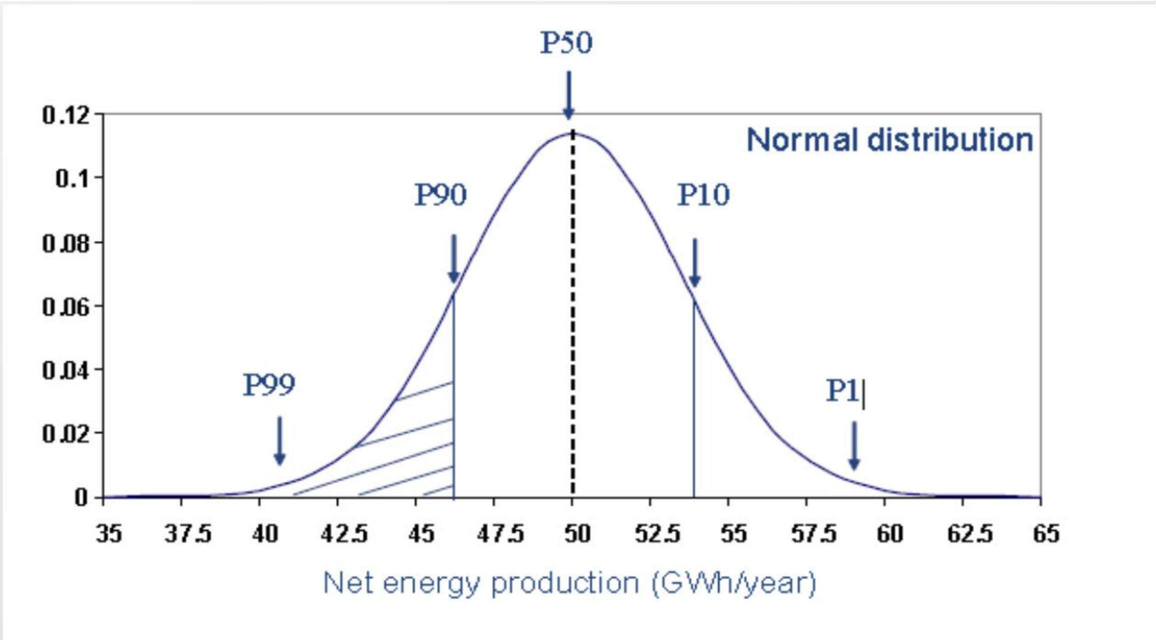
Jason Fields

National Renewable Energy Laboratory National Wind Technology Center

Jason.fields@nrel.gov 303 384 7150

Nov 25, 2016

PRUF-Benchmark: Improve industry prediction model accuracy by enabling large scale comparison of operational data to predictions



Bailey, 2013

The Opportunity: Improved, lower cost of capital – thru <u>reduced risk premiums</u> and improved project selection – <u>thru increased prediction accuracy</u> resulting in lower levelized cost of energy (LCOE)

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Enabling U.S. Industry Growth and U.S. Competitiveness

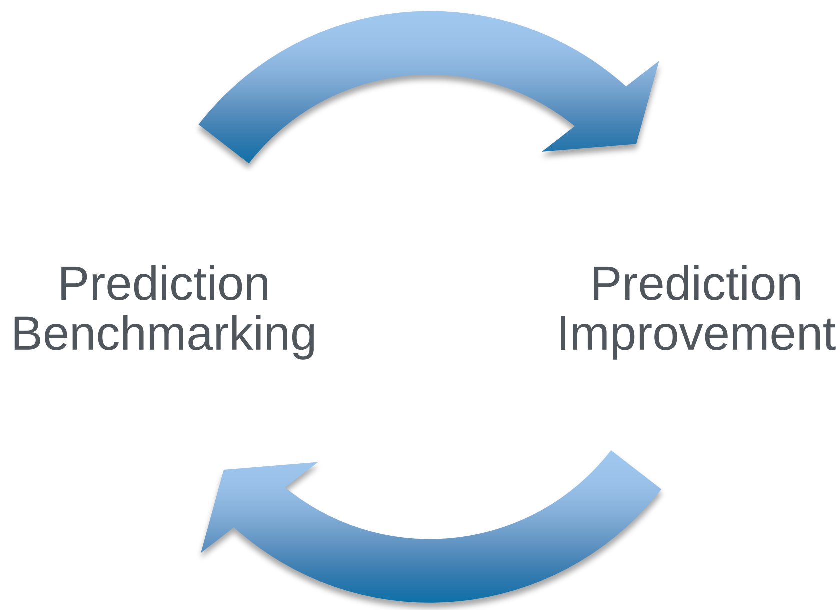
$$LCOE = \frac{CapEx \times FCR + OpEx}{AEP}$$

The Impact

- Market impacts
  - Better project selection & outcomes
  - Increase investor confidence
- Unleash model innovations
  - New methods can be validated quickly
- LCOE impacts
  - Influence LCOE very quickly
  - Up to 10% LCOE reduction thru reduced fixed charge rate (FCR) risk premiums

Unique Wind Energy Technologies Office project with focus on improving FCR by reducing risk premiums

Performance Benchmarking Cycle



What is being Benchmarked?

- Energy Yield Assessment
  - P50,P90, P95
  - Loss and uncertainty assumptions

What is being Improved?

- Energy Yield Assessment
  - Access to validation data
  - Reliability and accuracy of predictions

Continuous improvement opportunity by advancing models with expanding operational source data

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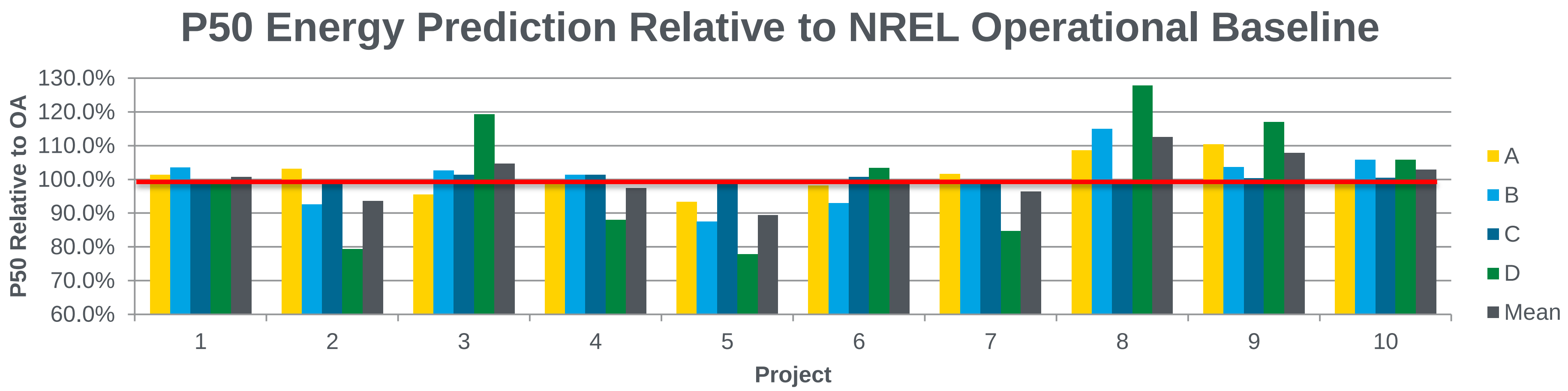
Performance Benchmarking Output



Continuous improvement opportunity by advancing models with expanding operational source data

Technical Approach-Project Structure

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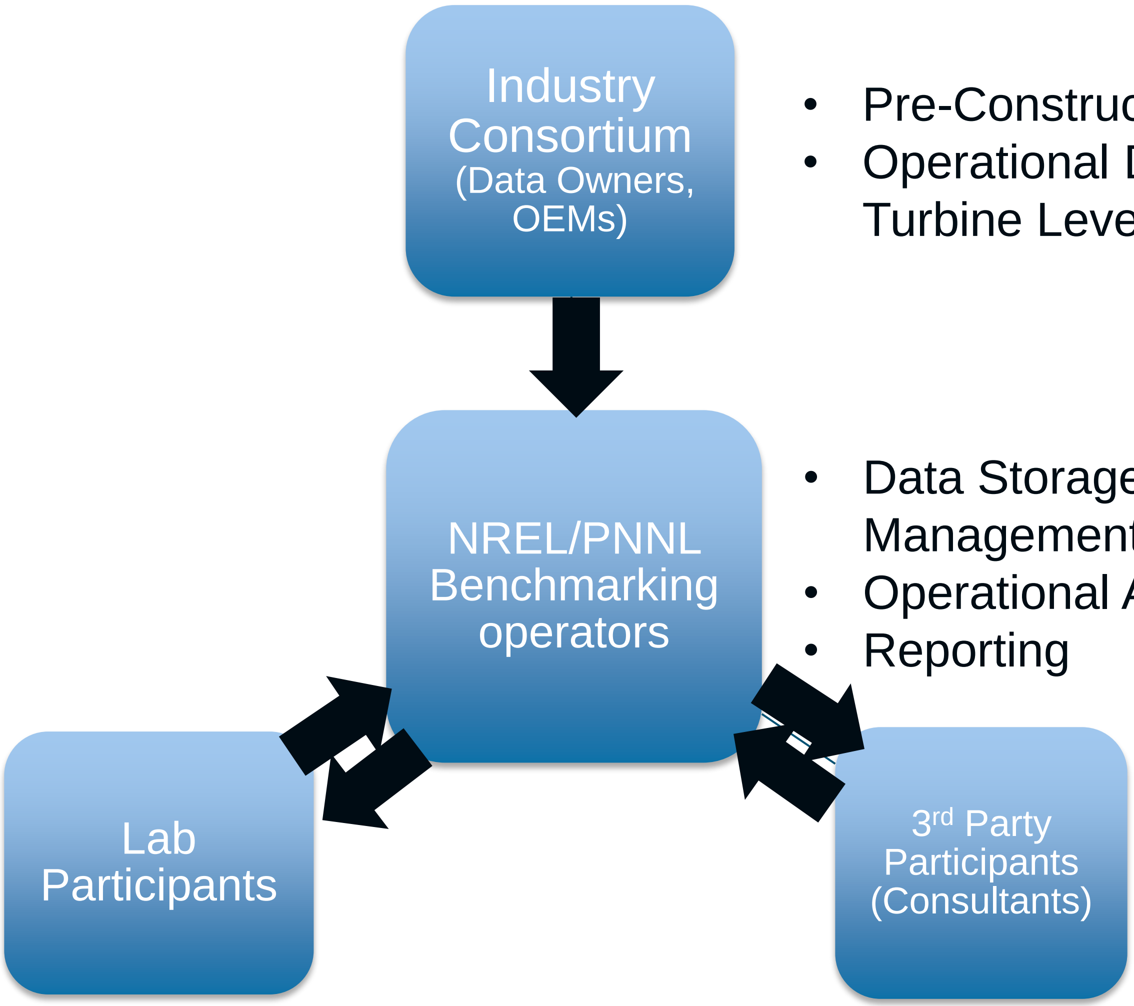

- Pre-Construction Data
- Operational Data: Turbine Level, 10-min

- Data Storage, Standardization, Access Management
- Operational Assessment
- Reporting

- Energy Estimates
- Refinement of methods using operational data

- Aim to develop physically perfect models which overcome all limitations of imperfect data

Research Integration & Collaboration

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Unprecedented Data Sharing & Collaboration

Industry Consortium:

edp renewables

res power for good

eDF renewable energy

Pattern

e·on Climate & Renewables

Consultancies*:

AWS Truepower

Chinook Wind

V-BAR

DNV·GL

natural power

Equipment Manufacturers*:

SIEMENS

Vestas

GE

ENERCON ENERGIE FÜR DIE WELT

Engaging these companies and many more.

*in discussions

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Unprecedented Data Sharing & Collaboration

Industry Consortium: 80+ Projects or 12,000+ MW

Wide range of projects: various technologies, geographies, vintages to answer critical and diverse questions

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
		$384k	*Industry contributing with large participation levels – multi FTEs	$270k	*Industry contributing with large participation levels – multi FTEs

- Benchmarking Project concept started in FY15
- FY15 and FY16 budgets only partially allocated to benchmarking
- Budget ramping up in FY17 to support expanded project scope

Moderate, initial start-up funds focused on project set-up and participation

Energy Yield Summary			
	Wind Farm Name Plate		MW
	Gross Output		GWhr/yr
#	Category	Loss %	Comments/Description/Inclusions/Exclusions
1	**Wake effect**		
1a	Internal wake effect		
1b	External wake effect		
1c	Future wake effect		
1d	Large Wind Farm / Deep Array		E.G. If zero indicate if this is included elsewhere
1e	Other (please describe)		
2	**Availability**		
2a	Turbine availability		E.G. This is time varying
2b	Balance of Plant availability		
2c	Grid availability		
2d	Other (please describe)		
4	**Turbine Performance**		
4a	Generic power curve adjustment		
4b	High wind speed hysteresis		
4c	Site specific power curve adjustment		
4d	Sub-optimal performance		
4e	Other (please describe)		
6	**Curtailments**		
6a	Wind sector management		
6b	Grid curtailment		
6c	Noise, visual and environmental curtailment		
6d	Other (please describe)		
	P50 Total Losses		
	P50 Net Yield		GWhr/yr
	Asymmetric production effect		
	Other (please describe)		
	Long Term Mean Total Losses		
	Long Term Net Yield		GWhr/yr

Stakeholder Negotiations

Concept Paper - vetted

Templates

- TPP submission
- Public report

NDAs

- Data owners and consultants

Data storage and dissemination

Data analysis

Critical milestone of NDA executions with wide range of owners/operators given agreed upon project plan scope

Project Plan & Schedule

Phase 1: Design of Experiment

Phase 1a: Pilot Project

Phase 2: WRA Benchmark – Energy Estimate Validation

Phase 3: WRA Improvement – Estimate improvement using operational data

Date	Event
Sep 2015 - March 2016	Scope development – coordinating with owner group
May 2016 to July 2016	Experiment design
July 2016	Partner presentation
August 2016	NDA execution
September 2016	**Project announcement at American Wind Energy Association WRA**

Next Steps and Future Research

FY17/Current Research:

- Complete Project Design of Experiment
  - Stakeholder input meetings
  - Pilot Project
  - Pre-construction/Operational Assessment metrics
- Operational Assessment
- Ramp up to full project launch in late FY17.

Follow on opportunities:

- Continue Benchmark/Validation cycle into out years
- Identify spinoff projects/deep dives
  - e.g. Wake model validation, controls
- Make data available to A2e/academia for further R&D.

Key Takeaways

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Project:

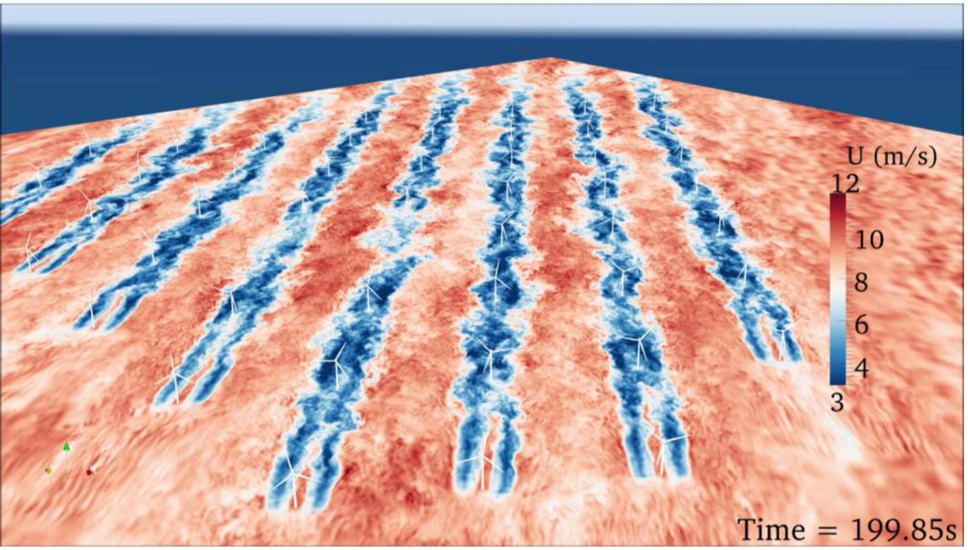
- Large data sharing and improvement project
- Legal hurdles solved, initial concept developed

Impacts:

- Major, near term market impacts
  - Immediate opportunity to reduce LCOE
  - Improve investor confidence
- Demonstrates ability for industry to execute Joint Industry Projects
- Quantum leap forward for the industry!

Remaining Challenges:

- Stakeholder needs integration
- Operational Assessment process



SOWFA simulation results for the Lillgrund wind farm (velocity magnitude); SOWFA was key to demonstrating the potential of high-fidelity modeling of wind farms. *Image from Matt Churchfield, NREL*

NREL's Peregrine supercomputer: Capable of 2.2 PetaFLOPS. *Photo by Dennis Schroeder, NREL 27774*

High-Fidelity Modeling

Atmosphere to electrons

Michael A. Sprague

National Renewable Energy Laboratory (NREL)

Michael.A.Sprague@nrel.gov , 303.275.4367

February 2017

Project Overview

A2e High-Fidelity Modeling (HFM) Goals:

- Create predictive modeling and simulation capabilities that will revolutionize the design and control of wind farms
  - Leverage DOE Office of Science supercomputing resources
- Advance fundamental understanding of flow physics governing whole wind plant performance
- Advance ability to predict the response of wind farms to a wide range of atmospheric conditions

The Challenge: Predictive simulation of complex flow and structural dynamics in wind plants will require a new class of models and leadership-class supercomputers

Partners: National Renewable Energy Laboratory
Sandia National Laboratories

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The Impact

- A better understanding of flow physics and the ability to predict complex flows will expose new pathways to reduced LCOE, create a foundation for new computationally efficient design tools, and reduce the uncertainty in wind plant performance
- Create scalable HPC simulation capabilities that can predict the complex fluid and structural dynamics in a wind farm, including wake formation, wake interaction, complex terrain, and realistic atmospheric conditions
- The main product will be a validated, open-source simulation environment capable of simulations spanning from those on a single workstation to those on the largest DOE supercomputers

Technical Approach

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- The HFM Project approach was framed through outreach to experts in wind energy and computational science
  - Modeling requirements were defined in the *High Fidelity Modeling: ModSim Environment Strategic Planning Meeting* (Denver).
  - Model and validation requirements were defined in the *Wind Plant Physics and Modeling Planning Meeting* (Washington, D.C.).
  - Each meeting had about 70 participants from national laboratories, industry, and academia.
  - Report on meetings is online: http://www.nrel.gov/docs/fy16osti/64697.pdf.

Technical Approach

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

- Create a modeling capability, with multiple levels of fidelity, that is backed by rigorous verification and experimental validation (V&V)
  - Will be the foundation for state-of-the-art **predictive** and **physics-based** simulations of whole wind plants
  - Will target simulations that aspire to "**ground truth**," and solutions will have known confidence intervals
  - Will be an **open-source community model** whose contributors and users will be from national laboratories, universities, and industry
  - Will be highly scalable and will run on DOE petascale and exascale supercomputers
- Validate the simulation capabilities with a **model-driven experimental and field-measurement campaign**
  - Phenomena Identification and Ranking Tables (PIRTs) were the means for defining the validation campaign
  - Collaboration with the A2e Wake Dynamics Project

Accomplishments and Progress

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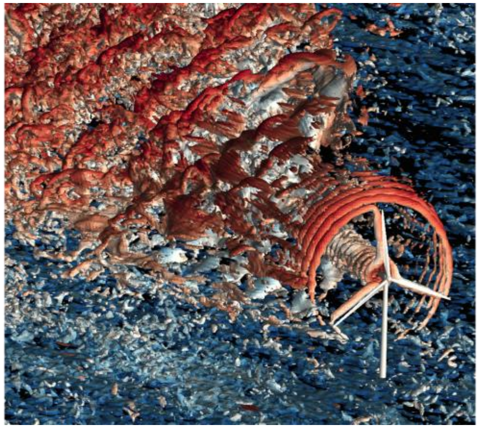
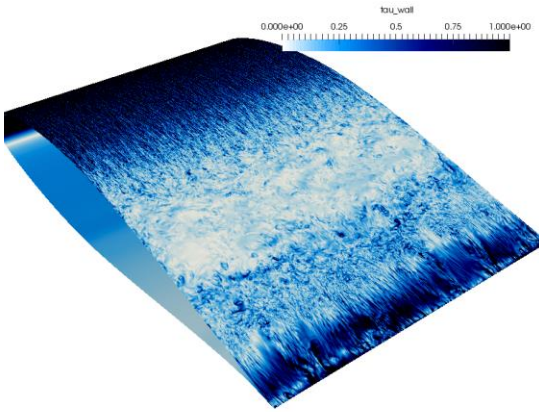
- Led Office of Science (SC) workshop on *Turbulent Flow Simulations at the Exascale*
  - https://www.orau.gov/turbulentflow2015/
- Selected open-source fluid and structure codes based on ModSim Meeting requirements
  - Computational fluid dynamics (CFD): Nalu, Sandia National Laboratories-supported, and petascale ready
  - Wind turbine control and structure dynamics: OpenFAST
- Equipped Nalu with capabilities established in the OpenFOAM-based Simulator fOr Wind Farm Applications (SOWFA) code
- Secured allocation for 10 million core hours at the National Energy Research Scientific Computing Center facility from DOE SC Advanced Scientific Computing Research
- FY16 establishment of HFM project was key to successful $10M Exascale Computing Project



SOWFA code demonstrated potential of HFM. *Image from Matt Churchfield, NREL*



Nalu wall-resolved LES study of a turbine blade section (Trinity Open Science project). *Image from Matt Barone, Sandia*

Project Plan and Schedule

- A2e planning meetings executed in FY15, as part of the "A2e High-Fidelity Modeling and Validation" project
- A2e HFM is a 3-year project, initiated in March 2016
  - ExaWind Exascale Computing Project is key to achieving HPC goals
- All milestones met successfully, and project is on track
- No FY16 Go/No-Go decisions

Project Budget

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

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost Share	DOE	Cost Share	DOE	Cost Share
		$357k		$668k	

- A2e planning meetings executed in FY2015
- A2e HFM Project started in March 2016
- 43% of current budget has been expended
- Secured Exascale Computing Program (ECP) funding starting in FY17: “ExaWind”
  - $10M over four years
  - 10-year challenge problem: Fully resolved wind plant simulation on next-generation exascale-class supercomputer

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators

- A2e HFM is a close collaboration between NREL and SNL.
- ExaWind Project includes Univ. of Texas at Austin and Oak Ridge National Laboratory
- Office of Science.

Communications and Technology Transfer

- Open-source Nalu simulation code
  - https://github.com/NaluCFD
- Open-source OpenFAST simulation code
  - https://github.com/OpenFAST
- Report on A2e planning meetings
  - http://www.nrel.gov/docs/fy16osti/64697.pdf
- Turbulent Flow Simulation at the Exascale Workshop
  - Website: https://www.orau.gov/turbulentflow2015/
  - Paper: http://arc.aiaa.org/doi/10.2514/6.2016-3321

Next Steps and Future Research

FY17/Current Research

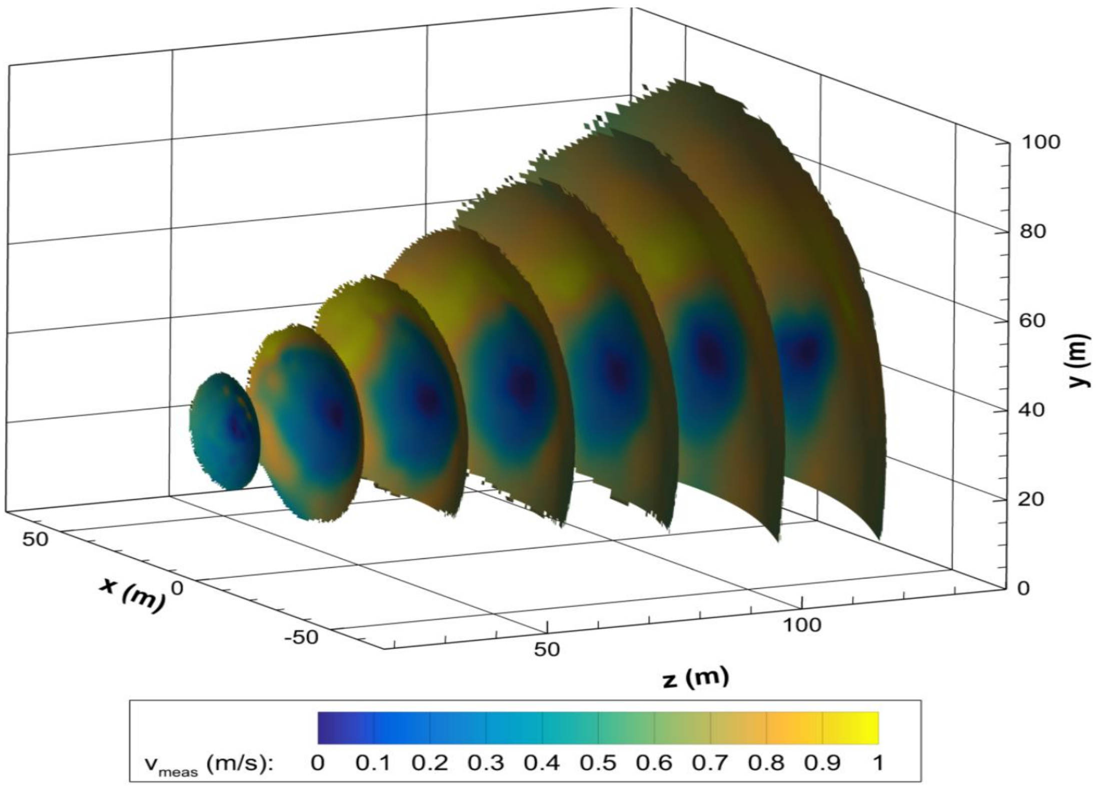
- Complete the transition from SOWFA to Nalu
- Validate Nalu actuator-line with the Windpark Egmond aan Zee (OWEZ); collaborate with A2e Wake Dynamics
- Create and disseminate documentation that compares the Nalu and SOWFA codes for actuator-line-based wind farm models.

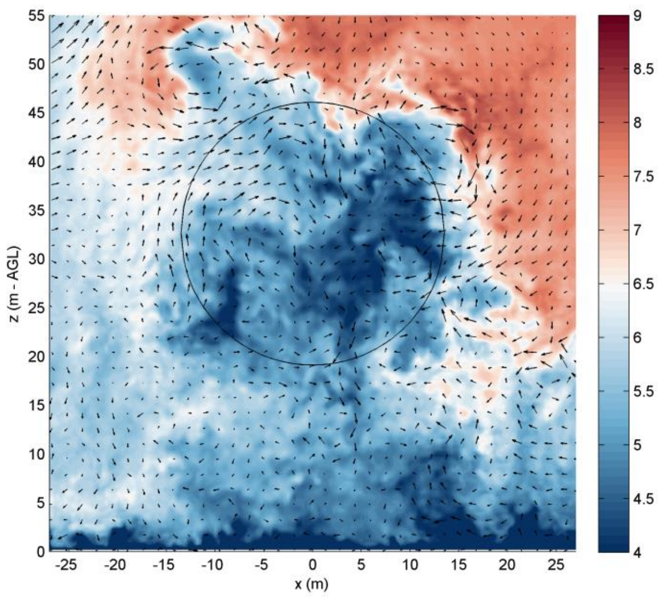
Planned Future Research

- Create blade-resolved predictive simulation capability
- Perform the highest-fidelity wind farm simulations to date
- Continue close collaboration with:
  - ExaWind project, for scalability, and next-generation computers
  - A2e Wake Dynamics, for validation.

Wind Energy Technologies Office Peer Review

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





Wake Dynamics Measurement, Testing, and Validation

Brian Naughton

Sandia National Laboratories

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February, 2017

Project Overview

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

A2e: Measurement, Testing, and Verification (Wake Dynamics): Enabling the design of optimized wind plants through validated computational tools.

The Challenge: Current wind plants underperform their design specification. The predictive capability of wind plant design tools will require a better physical understanding of performance under a variety of deployment conditions through experimental validation campaigns.

Partners: National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL): Lead experimental design, execution, and analysis. Texas Tech University and Technical University of Denmark (DTU): Provide unique measurement instrumentation and analysis.

Enabling Wind Nationwide

Enabling U.S. Industry Growth and U.S. Competitiveness

- **Wind plant optimization**
- Resource assessment and characterization
- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

The Impact

- Improved physical understanding of the roles played by major wind plant fluid dynamic phenomena
- Archived, public, validation-quality datasets suitable for the assessment of both high-fidelity modeling (HFM) and engineering models to represent complex wind plant aerodynamic behavior
- Benchmarks of current HFM and engineering models for wake dynamics and wake kinematics
- A formalized verification and validation (V&V) methodology to assess model accuracy, which will serve as a prototype to be applied across the A2e program on all scales
- Development of unique diagnostic methods to address data gaps of current experimental instrumentation.

Technical Approach

- The project is guided through a formalized Verification and Validation methodology as developed through broad industry participation and documented in foundational reports.
- This approach relies on an integrated and iterative simulation and experimental campaign to produce validated models to the wind industry.
- The computational code and experimental data are all made public via a web-based portal.
- Validation experiments are designed with the input of modelers to ensure the right Quantities of Interest (QoI) are measured with sufficient accuracy.
- The uncertainty in the simulations and experimental data are quantified and compared to provide a measure of predictive capability.
- Unique or new experimental instrumentation is developed or acquired to meet the requirements of the validation experiment.

Research Integration & Collaboration

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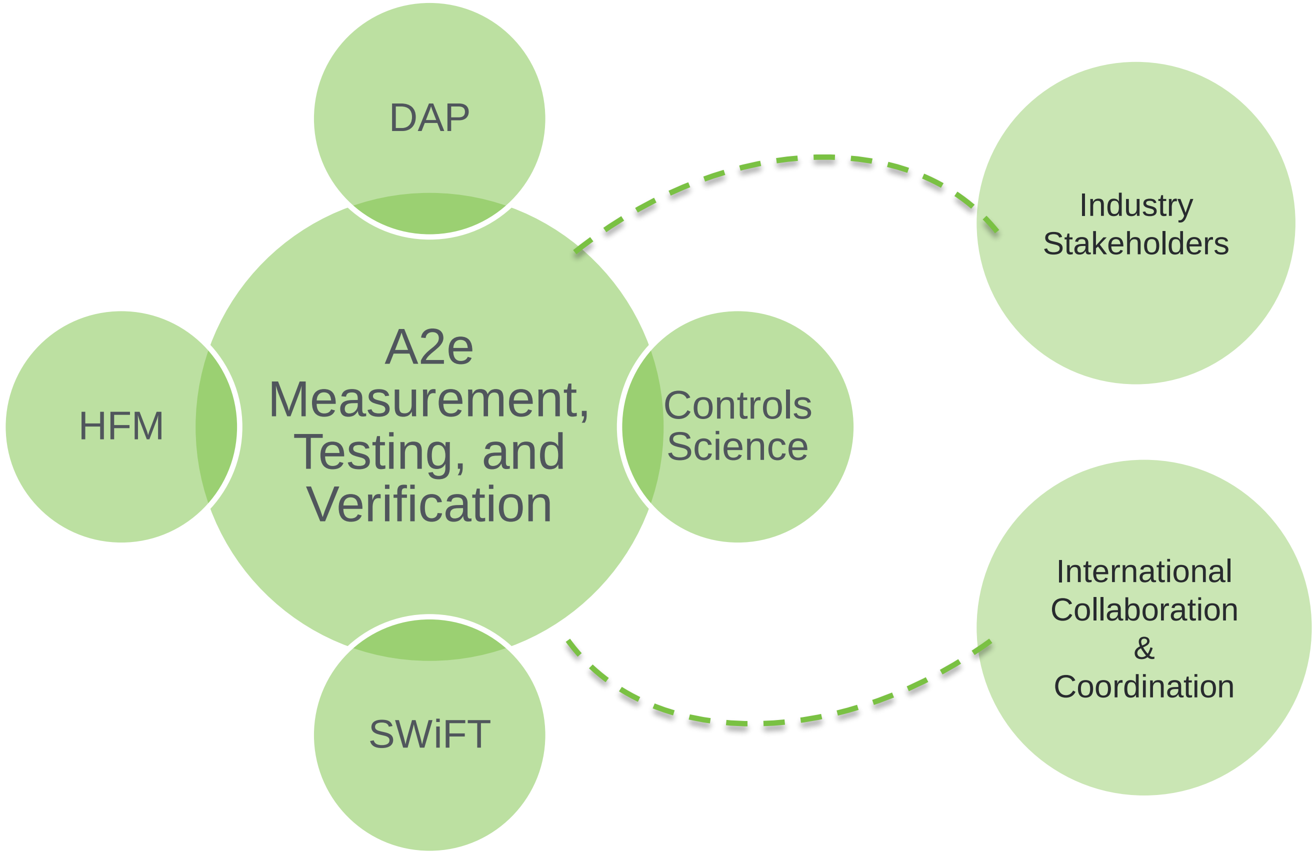
- Tight integration with other A2e areas and facilities through shared staff, funding, and “uber-PI” project managers
- Broad stakeholder input gathered to identify and prioritize research needs, establish common frameworks
- International collaboration & coordination to leverage existing experimental data, facilities, instrumentation, and knowledge.



Project Budget

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

	Budget History					
	FY2014		FY2015		FY2016	
	DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
SNL	$2,635k	$0	$3,225k	$0	$1,560k	$0
NREL	$1,091k	$0	$1,219.592k	$0	$885k	$0
Total	$3,726k	$0	$4,444.592k	$0	$2,445k	$0

Partners, Subcontractors, and Collaborators: SNL and NREL prime leads. Technical U. of Denmark, Texas Tech U., CU Boulder, U. of Milan, National Aeronautics and Space Administration, U.S. Air Force, U. of Wyoming, Wetzel Engineering, U. of Minnesota, DNV-GL.

Project Plan & Schedule

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

	FY14 Q1	Q2	Q3	Q4	FY15 Q1	Q2	Q3	Q4	FY16 Q1	Q2	Q3	Q4
Verification & Validation	Industry stakeholder input meetings on physics and modeling needs				Verification and Validation Program Framework development				Prioritization of important phenomena and test objectives			
Instrumentation Development	SWIS 2m lab demonstration				SWIS 5m SWiFT field demonstration							
	Enhance accuracy of dual Doppler radar system				XPIA deployment of Doppler radars							
	NRT rotor design methodology development				NRT rotor functional requirements gathering				NRT rotor final design and manufacturing drawings			
Experiments			Experiment planning and simulation for Milano wind tunnel									
								Experiment Planning for SWiFT Wake Steering			Conduct Wake Steering Exp.	
											Full-scale experiment planning	

Accomplishments: V&V

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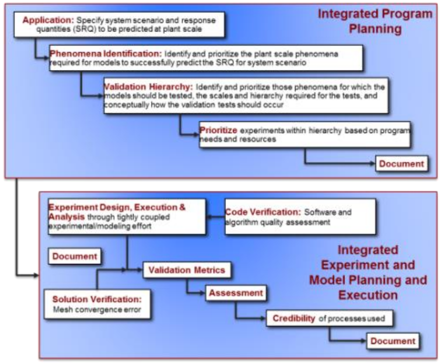
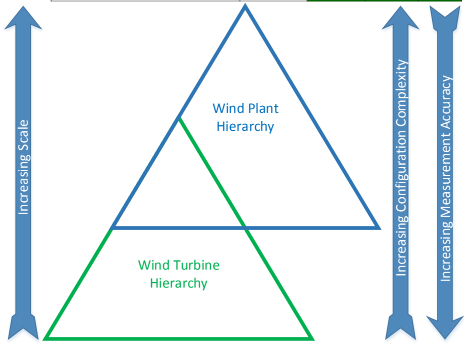
- A2e program adopted formal **Verification & Validation** approach to integrate modeling and experiments in Spring 2014
- Validation project planning and initial PIRT development began in Fall 2015
- Wind Plant Physics Planning Meeting: **Expanded PIRT**, input from 70+ experimentalists and modelers, Feb. 2015
- **PIRT** results incorporated into HFM and Wake Dynamics proposals, Spring/Summer 2015
- **Nalu Validation Roadmap** currently being developed based on the prioritized wind plant physics and the A2e V&V process:

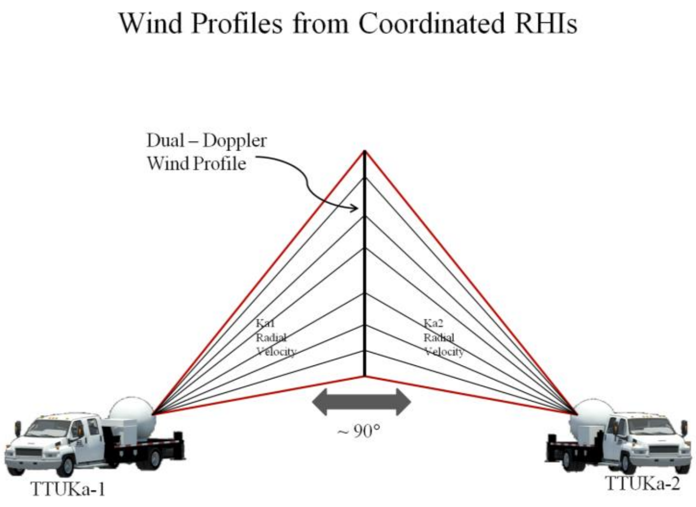
1. **V&V Framework** (September 2015)
2. **A2e High Fidelity Modeling: Strategic Planning Meetings** (November 2015)
3. **Test Objectives and Prioritization for Wind Plant Performance** (July 2016)
4. **V&V Integrated Program Planning for Wind Plant Performance** (Oct. 2016)

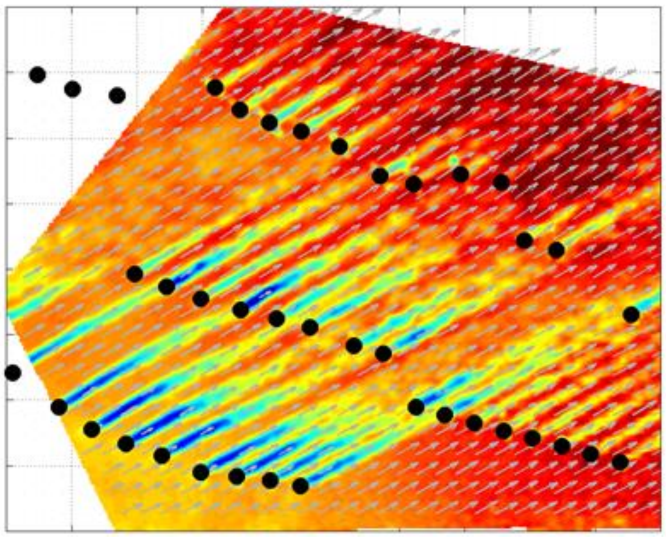


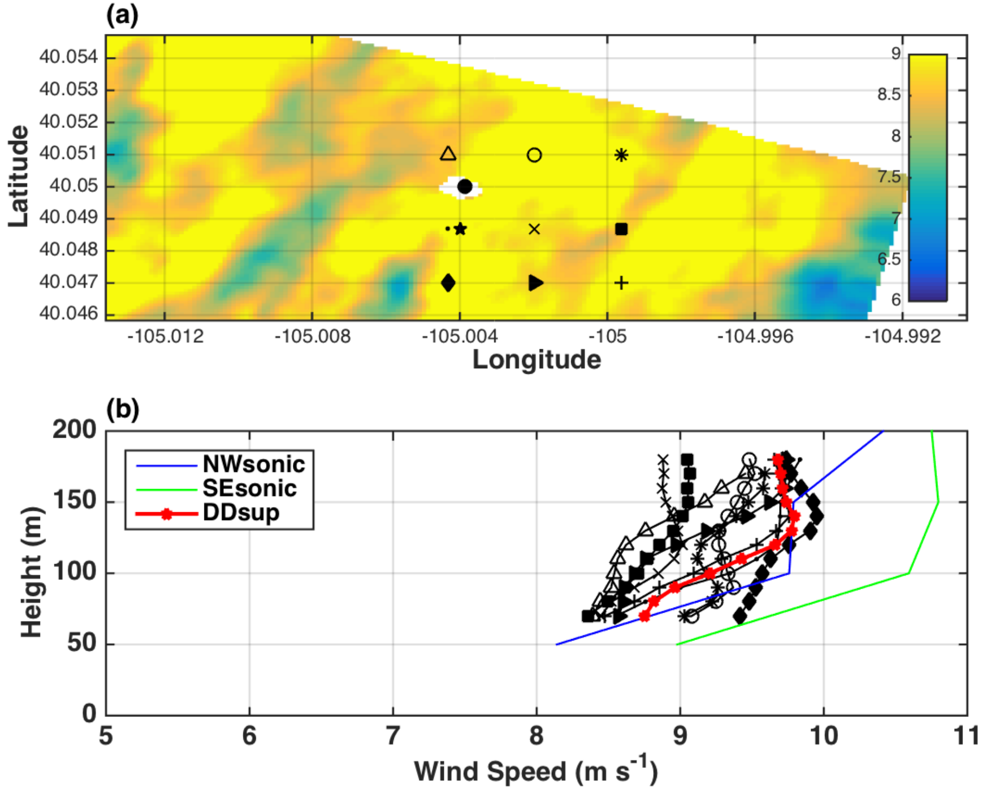
Phenomenon	Importance at Application Level	Model Adequacy		
		Physics	Code	Val
Turbine scale flow phenomena				
Blade Aero / Wake Generation				
Blade load distribution effects and rotor thrust	H	M	L	L
Tip and root vortex development, and evolution and merging	H	M	L	L
Vortex sheet and rollup (in addition to tip/root vortex)	M	M	M	L
Blade generated turbulence characteristics (energetic scales)	H	L	L	L
Root flow acceleration effect ('hub jet')	Unknown	M	L	L
Boundary layer state on turbine performance (roughness, soiling, bugs, erosion)	H	L	L	L
Boundary layer state (Re)	L	M	L	L
BL details near TE and LE	H	M	L	L
Rotational augmentation	H	L	L	L
Dynamic stall	H	L	L	L
Unsteady inflow effect (turb. intensity, spectra, coherence; veer, shear)	H	L	L	L
Blade flow control	M	L	L	L
Tower/rotor/nacelle wake interactions	H	M	L	L
Icing	L	L	L	L



Accomplishments: Instrumentation TTU Ka-band dual Doppler radar



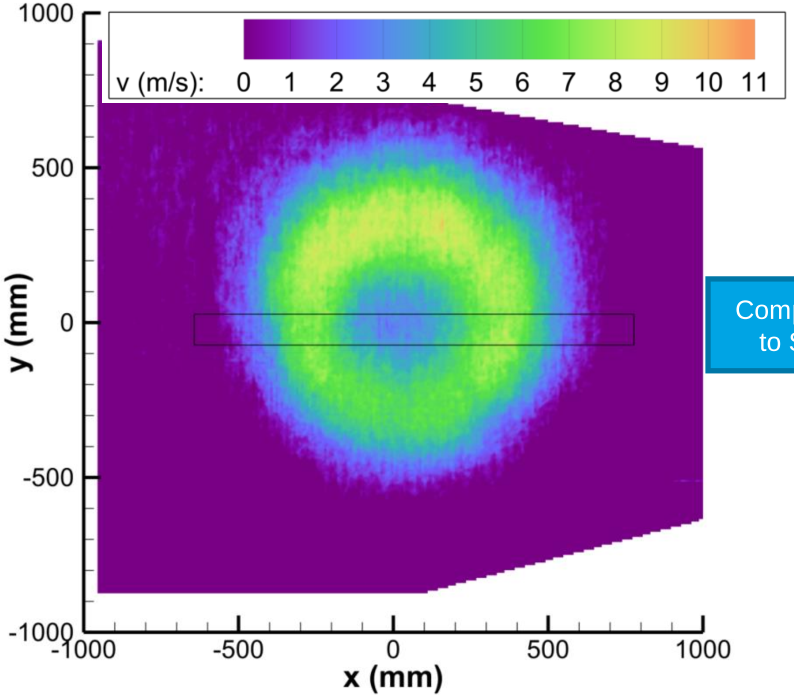




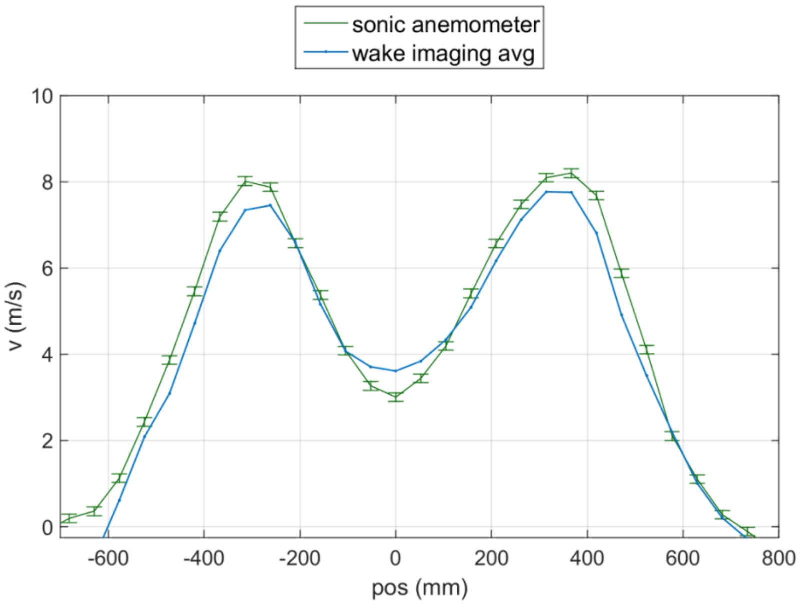
(top)XPIA, 2 April 2015: Spatial Variability of Instantaneous Wind Profiles at BAO tower

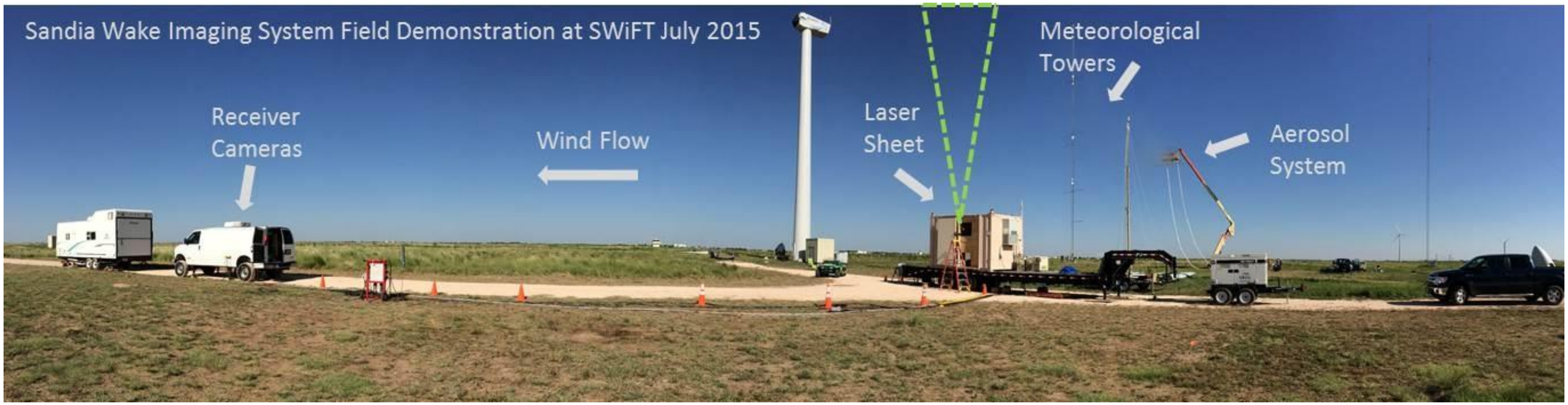
(left): Improved clear-air operation after software and hardware upgrades in 2014

Accomplishments: Instrumentation Sandia Wake Imaging System

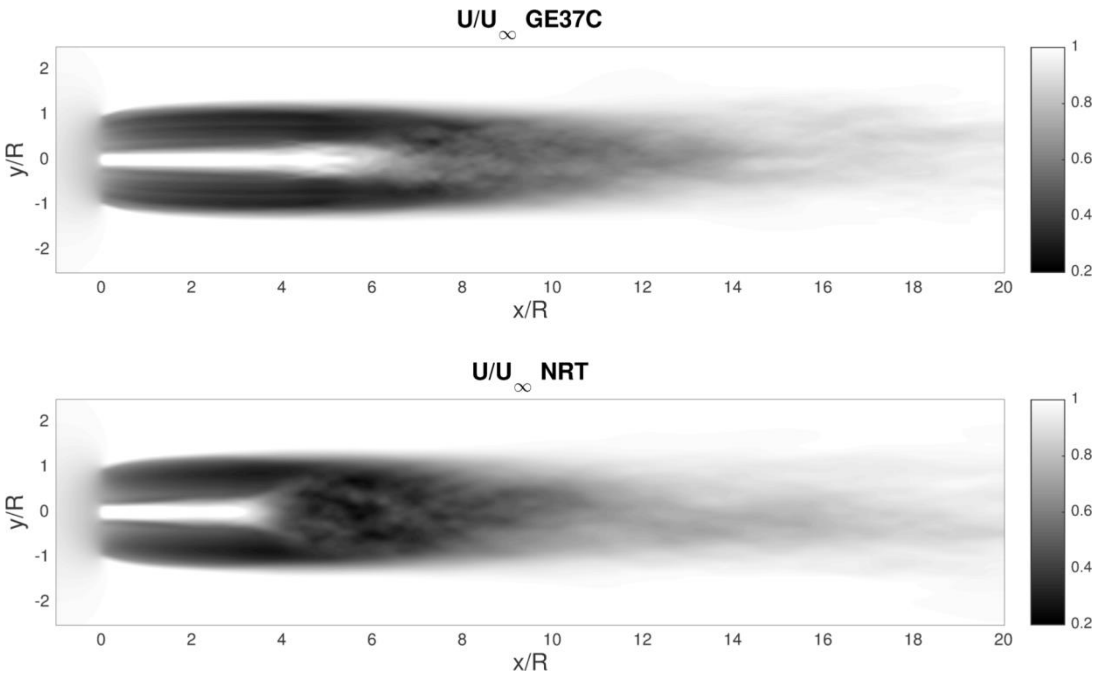


Comparison to Sonic



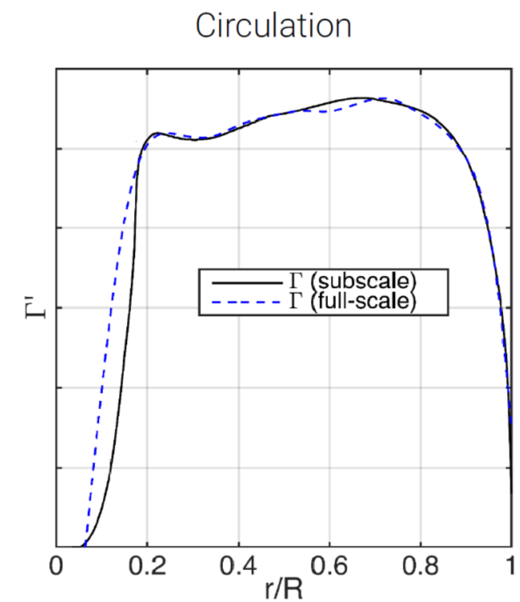


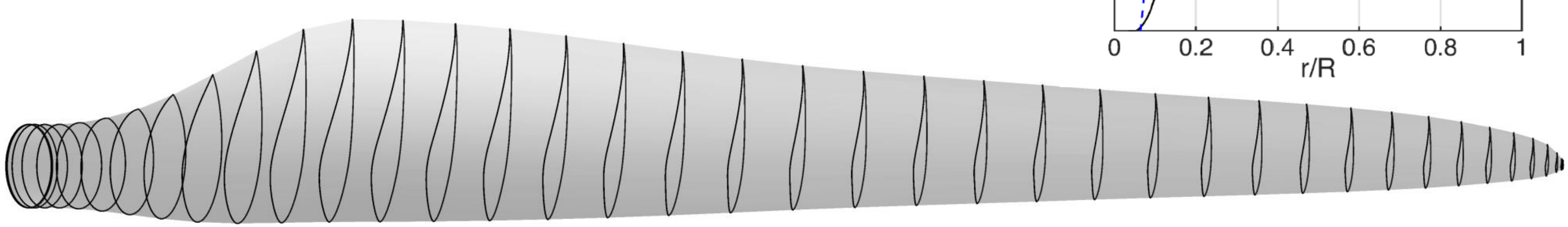
Accomplishments: Instrumentation National Rotor Testbed



Free wake vortex simulation of the two rotors in neutral inflow.

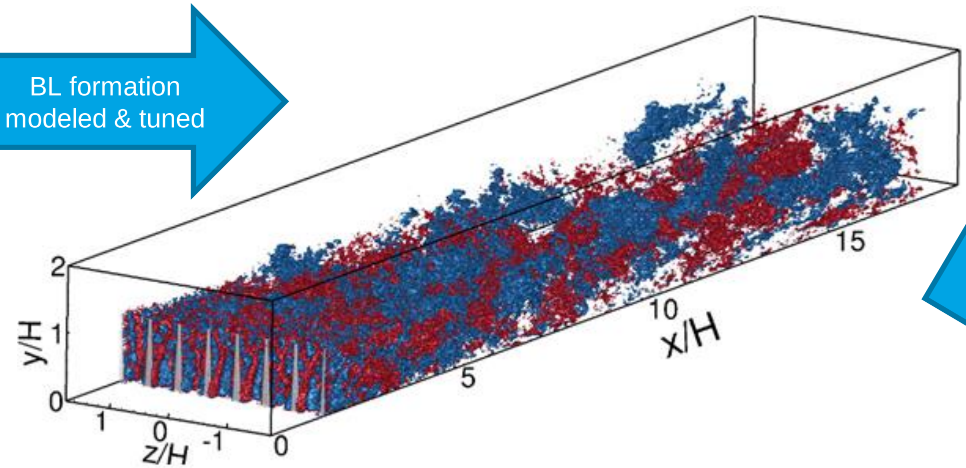
Developed a unique design method using a variety of computational tools to functionally scale the circulation distribution of a utility-scale blade to a 14m blade to be manufactured and installed at the SWiFT facility. This enhances wake research and validation capabilities.



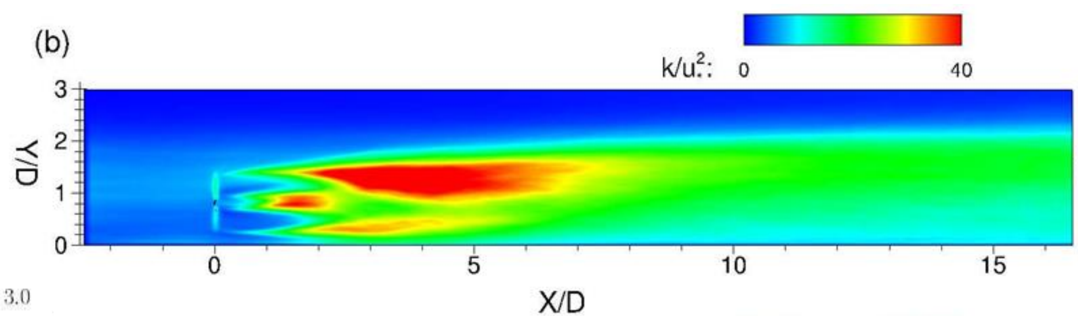


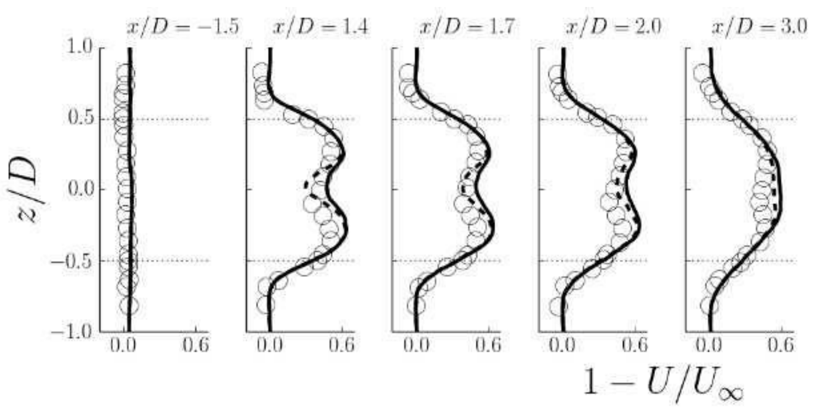
Accomplishments: Experiments
U. Milano Wind Tunnel

BL formation modeled & tuned



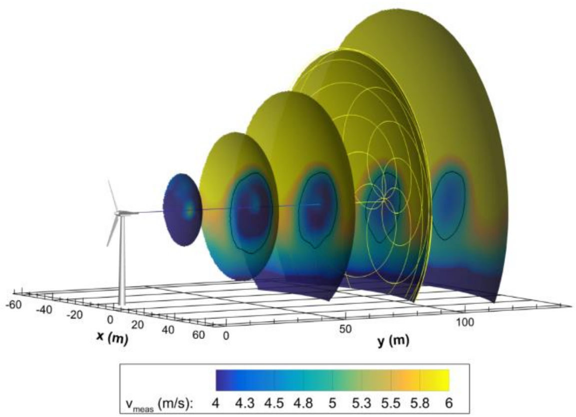
G1 rotor simulated with BL inflow



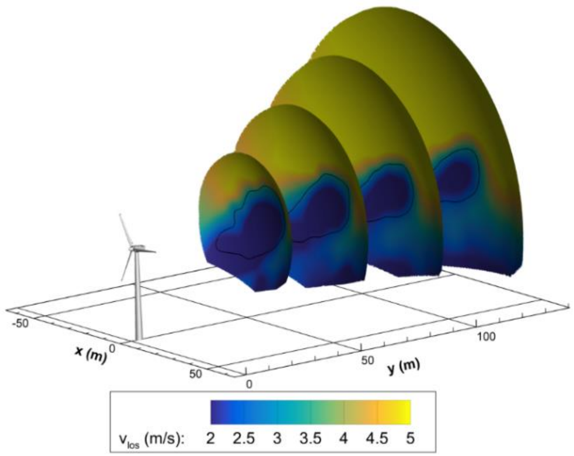


Experiment data compared to simulation

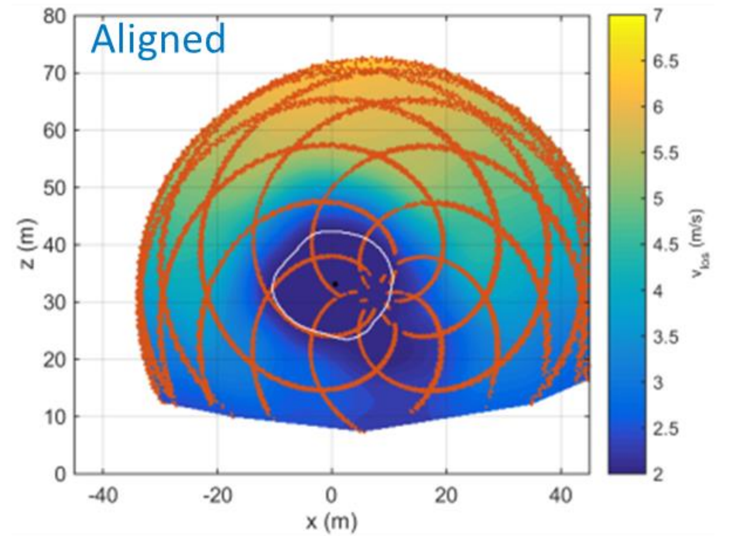
Accomplishments: Experiments Wake Steering at SWiFT

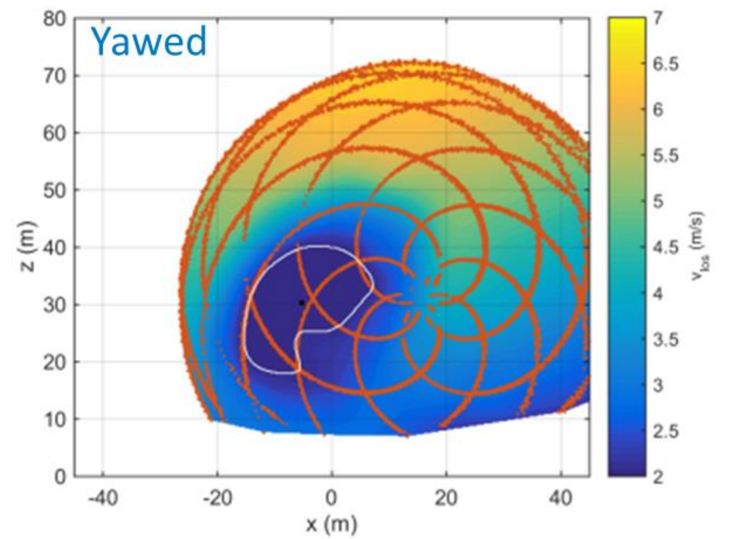


Experiment fully simulated with characteristic inflow, SWiFT turbine, and virtual lidar for planning purposes



Experiment data as expected from initial simulations





DTU SpinnerLidar installed in rear of SWiFT turbine to measure deflection of wake with yaw offsets. Control concept successfully demonstrated under stable inflow conditions.

Communications and Tech Transfer

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

The primary output of this project is a new foundation for developing the knowledge needed to support the continued innovation and growth of an increasingly sophisticated wind industry.

This foundation is constructed on a Verification and Validation methodology that provides quantified uncertainty in the modeling and testing data and ultimately the predictive capability to identify the most impactful new technologies to develop.

Key Deliverables:

- Stakeholder input and planning workshops
- NRT public blade design
- Improved Doppler radar wind plant measurement system
- V&V Framework report published September 2015
- A2e Data Archive & Portal: Public data sets available to researchers
- Numerous technical reports and presentations delivered through leading conferences and journals

Next Steps and Future Research

FY17/Current Research:

- Complete Wake Steering Experimental Campaign at SWiFT and NWTC and release data to A2e DAP
- Collect wake and loads data on GE1.5 at National Wind Technology Center
- Begin application of V&V through UQ of SWiFT wake data
- Manufacture and install NRT rotor for SWiFT experiments
- Develop instrument atlas as a reference for planning experiments
- Assess utility of existing available wind plant data sets
- Experiment design for full-scale wind plant wake experiment
- Convene SWiFT Science Panel to assess best use of facility

Planned Future Research: Implement V&V plan through experimental campaigns at full-scale, SWiFT, and compare results with HFM simulations to assess predictive capability. Develop unique instrumentation as needed to meet requirements of the validation experiment.

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Wind Plant Flow Control

Dr. Alan D. Wright

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February 2017

Project Overview

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

Improve plant performance through optimized wind plant control strategies. Build on the foundation of individual turbine controls research. Focus the knowledge of critical science issues gained through A2E to optimize such wind plant control strategies as:

- Wake steering controls
- Axial induction controls
- Load reduction controls
- Closed-loop coordinated plant control.

Partner with Sandia National Labs to:

- Demonstrate and validate innovative wind plant controllers
- Implement and field test new strategies at SWiFT

Critical challenges and issues addressed:

- Using the turbine to control flow through the plant to increase energy capture
- Reducing turbine loads when actuating plant flow
- Building robustness to changing atmospheric parameters into controls
- Accurately sensing plant flow for improved control
- Coordinating multiple turbines in the plant with closed-loop control.

Project Partner Roles

Partner	Role
Sandia National Labs	Wake steering controller and model field testing at SWiFT
GE	Wind plant controller development and collaboration
Gamesa	Wind plant controller development and collaboration
Envision	Wind plant controller development and collaboration
NextEra	Full wind plant controller field testing
TU-Delft	Wind plant controllers and model development
DNV-GL	Controller and control model comparisons
Avent/Leosphere	LIDAR evaluation for wind plant controls
ZephIR	LIDAR evaluation for wind plant controls
DTU Wind Energy (formerly RISO)	LIDAR measurements for wake steering controls at SWiFT
U. of Stuttgart (U of S)	LIDAR measurements of wakes during yaw-based wake steering; wind plant controls development
TU-Delft	Wind plant controllers and model development
U. of Colorado (CU)	LIDAR-based wind plant controls
Colorado School of Mines (CSM)	LIDAR-based wind plant controls
ECN	Controller model comparison
CENER	Wind plant controller development and validation

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- **Wind plant optimization**
- Resource assessment and characterization
- **Reliability improvements**
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- Advanced technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

Enabling Wind Nationwide

Enabling U.S. Industry Growth and U.S. Competitiveness

- **Wind plant optimization**
- Resource assessment and characterization
- **Reliability improvements**
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

The Impact

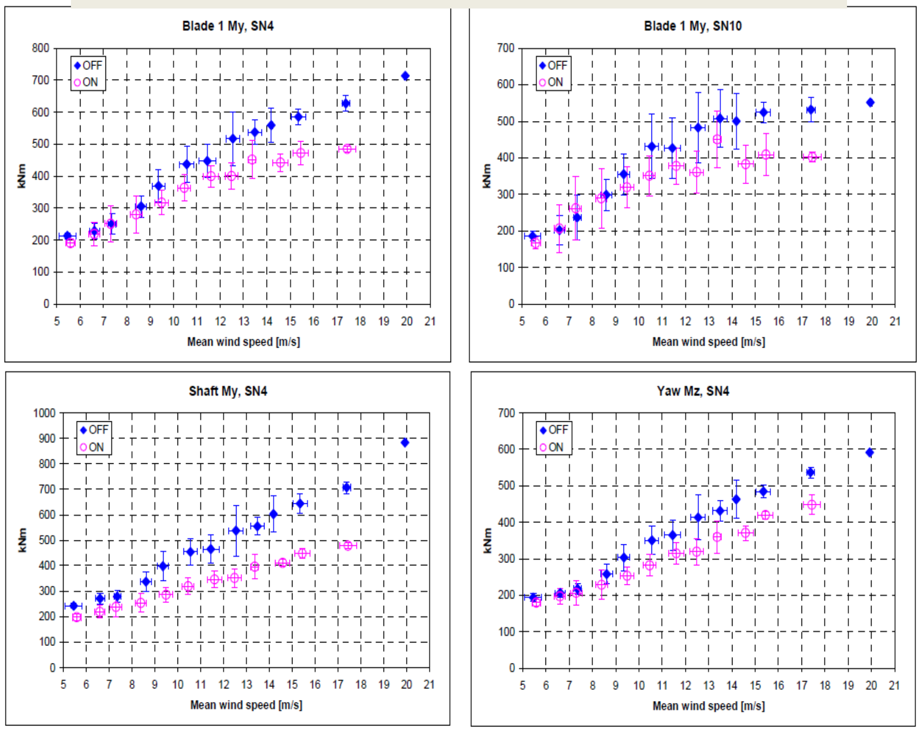
- Provides the industry with advanced control strategies for wind plants that decrease levelized cost of energy through increased energy capture, reduced loads, and increased reliability
- Applies improved understanding of wind plant flow physics gained through A2E to optimize plant flow control and sensing strategies
- Develops reduced order control-oriented models (FLORIS) widely used by the industry to optimize their control strategies
- Revolutionizes next generation of wind plants to accommodate wakes through advanced control
- Uses the individual control strategy building blocks to develop optimal closed-loop control strategies

Technical Approach

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

Leverage Foundational Work in Individual Turbine Controls

CART Independent Blade Pitch Control Showing Significant Load Reductions (pink)



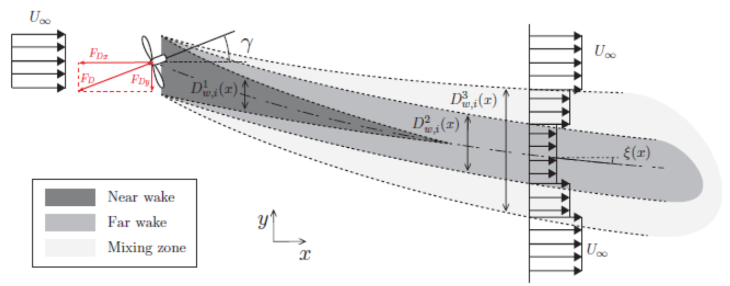
CART Lidar Feedforward Control

Goals: Increase power capture, decrease loads

Apply to Advanced Wind Plant Controls:

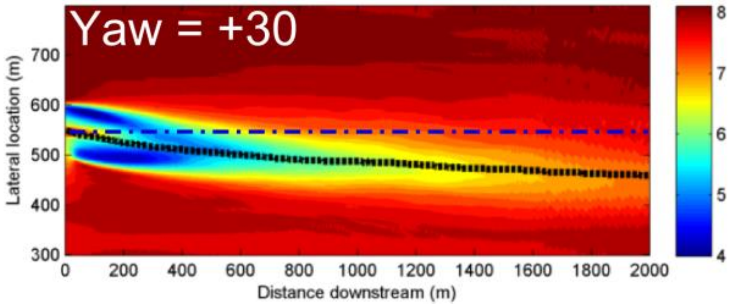
Control Model Development:

FLORIS



Control Strategies Development:

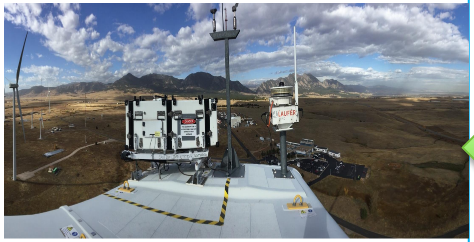
Yaw-based wake steering



Field Verification/Validation (wake measurements)

SWiFT test facility

DTU-Wind LIDAR mounted in SWiFT turbine nacelle



DOE 1.5-MW machine with Stuttgart LIDAR

Collaborations

GE, Siemens, Gamesa, Envision, Sandia, DTU-Wind, TU-Delft, U. of Stuttgart, CENER, ECN, DNV-GL, U. of Colorado, Colorado School of Mines, UT Dallas, CL-Windcon

Technical Approach

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

Issues Being Addressed:

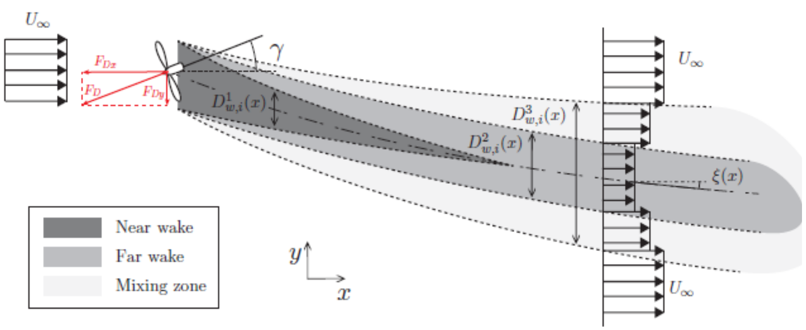
- Controller performance in real conditions
- Impact of wake steering on turbine loads
- Performance in changing atmospheric conditions: turbulence and stability
- Capture key aspects needed for control design.

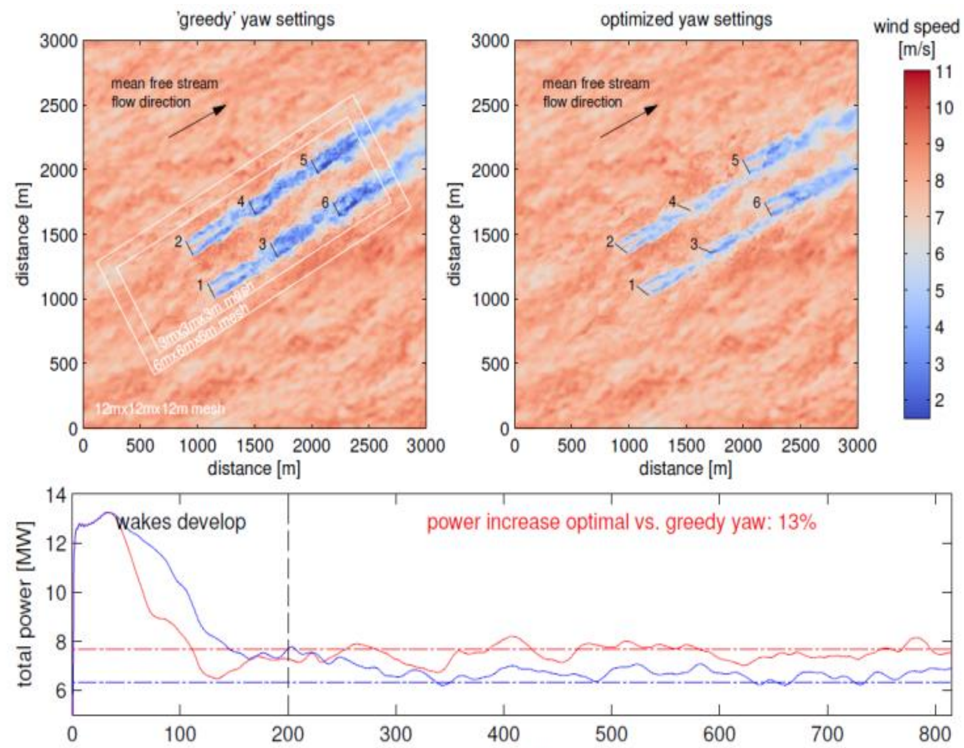
Unique Aspects:

- Incorporating new fundamental knowledge gained through A2E into controller models and advanced strategies
- Validating models and strategies through sub- and full-scale field testing
- Delivering updated results to industry and project partners worldwide.

Accomplishments and Progress—FLORIS

- FLORIS codes a control-oriented model wind farm
- Wake-steering controls designed about FLORIS perform well in HFM

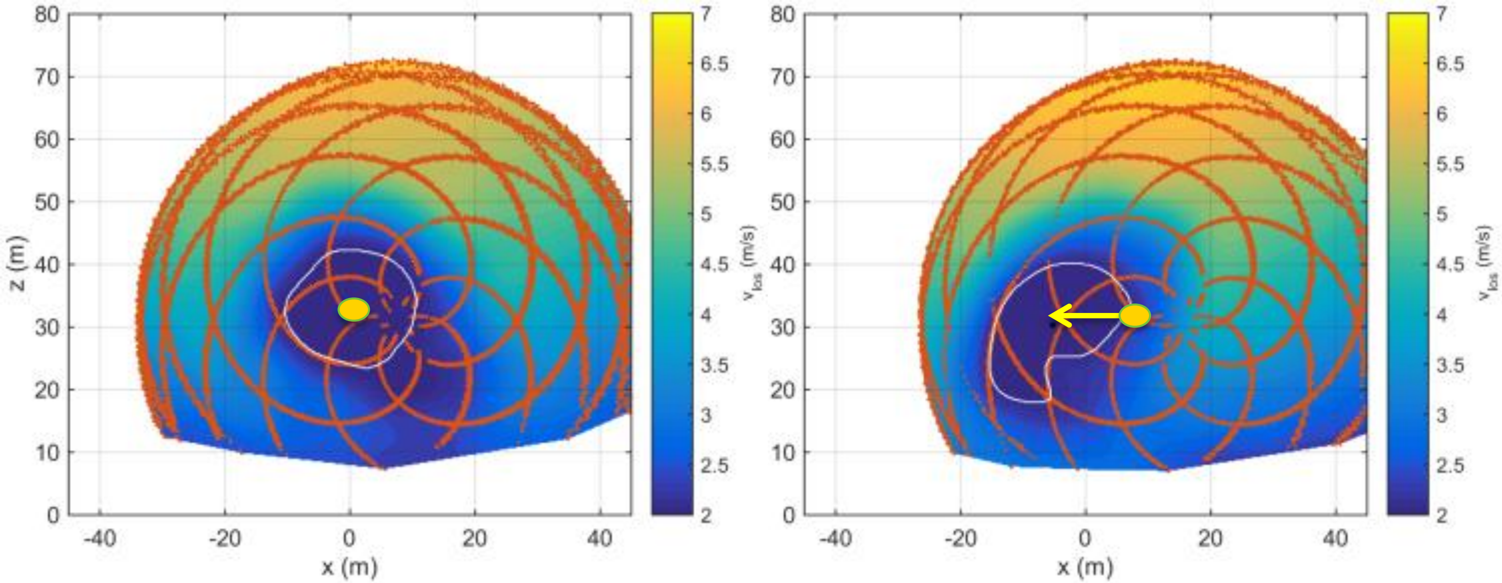




Accomplishments and Progress—Field Testing at SWiFT

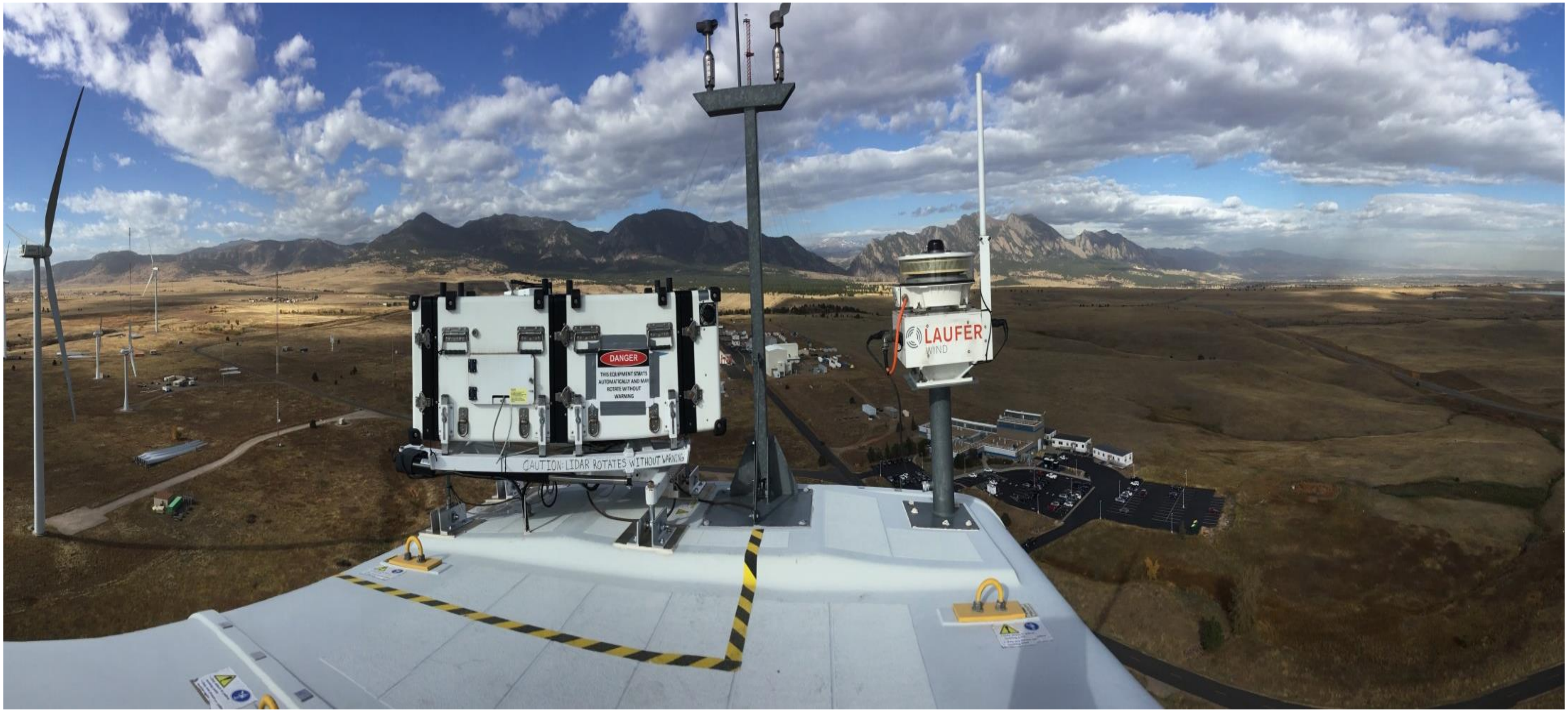
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Partnership with Sandia National Labs
- SWiFT campaign field test of wake steering currently in progress
- Early results demonstrate clear wake steering

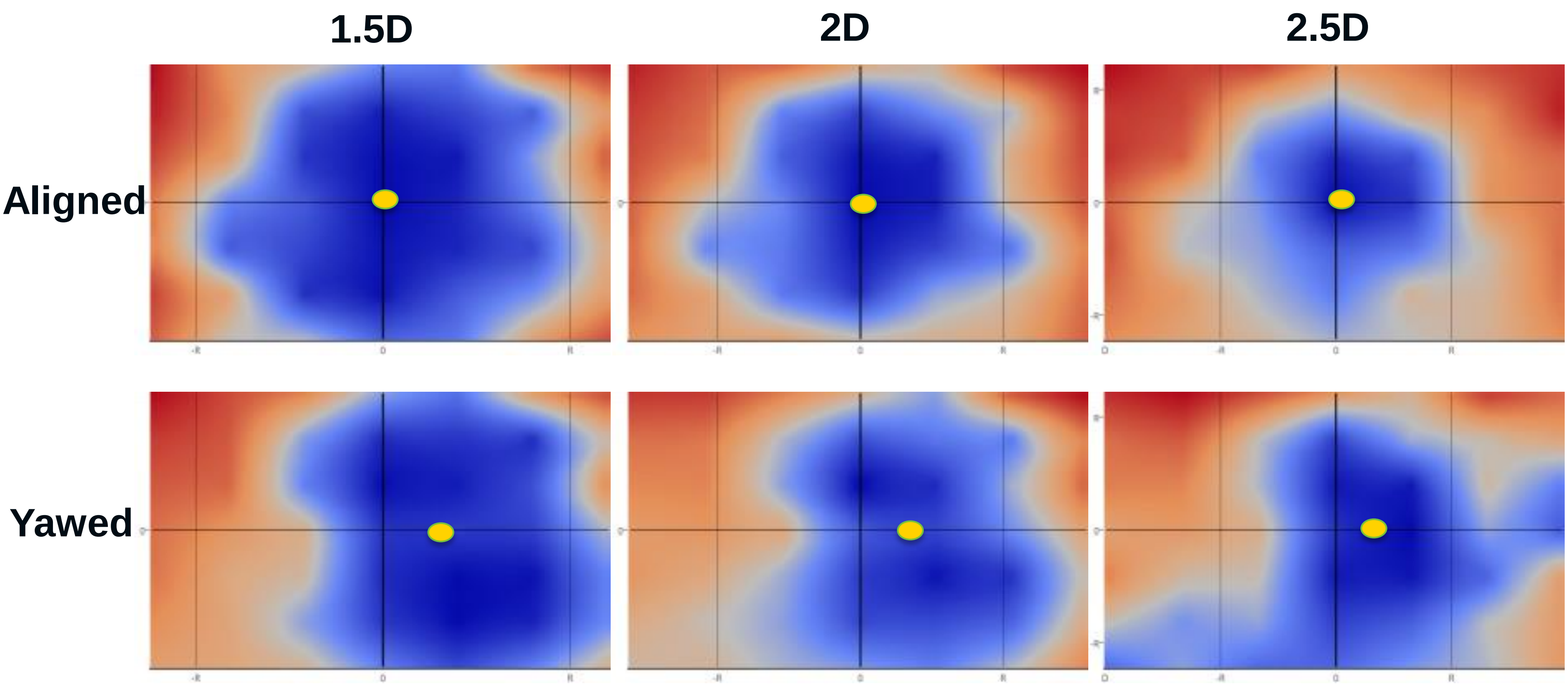


Accomplishments and Progress—Full-Scale Wake Steering

- Supporting test of wake steering (DOE 1.5 MW) at National Wind Technology Center
- Turbine and LIDAR yaw position controlled
- Collaboration with U. Stuttgart (LIDAR-sensing wake flow)

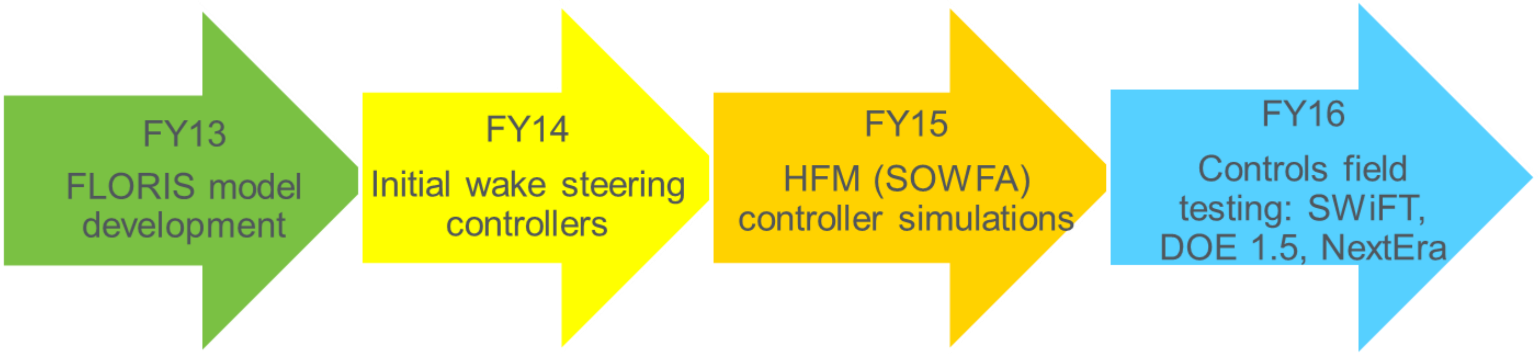


LIDAR data from both SWiFT campaign and full-scale campaign demonstrate clear wake steering in line with expectations.



Project Plan and Schedule

- Project Timeline:



- All milestones met on schedule
- Go/No-Go: Successful!
  - Conduct a point evaluation of FLORIS and assess its capability as a control design model (Sept. 30, 2016)
  - Recent field test results from SWiFT and the DOE 1.5-MW test have confirmed FLORIS wake deflection prediction capability under yawed flow (results are positive)

Project Budget

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

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost Share	DOE	Cost Share	DOE	Cost Share
$770k	$150k	$804k	$150k	$1,075k	$150k

- No variances to report
- No other funding sources, although some funds in Work for Others projects contribute to the project mission of the wind plant controls project.

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators

Partner: **Sandia National Labs—**wake steering field testing (SWiFT)
Subcontractors: Colorado School of Mines, University of Colorado

Collaborators: GE, Gamesa, Envision, DNV-GL, TU-Delft, U. of Stuttgart, DTU-Wind, CL-WindCon, NextEra

Visiting scholars: Dr. Pieter Gebraad, Dr. David Schlipf, Dr. Jan-Willem Van Wingerden, Dr. Jen Annoni, Dr. Peter Seiler, Dr. Mark Balas

Communications and Technology Transfer

Meetings and conferences: American Controls Conference (ACC), ASME Wind Symposium, The Science of Making Torque from Wind Conference

Invited conference sessions: Wind Energy Systems: Control and Optimization of Wind Farms (ACC 2015); Advanced Control of Wind Farms (I and II) (ACC 2016)

Special workshops: A2E Wind Plant Controls Planning workshop—2014 ACC Conference; IEA Task 32: "Optimizing LIDAR for Turbine Control" workshop, ACC 2016.

Publications

Fleming, P., Churchfield, M., Scholbrock, A., et. al. “Detailed Field Tests of Yaw-Based Wake Steering.” Presented at the 2016 The Science of Making Torque from Wind conference, Oct. 2016, Munich, Germany.

Fleming, P., Aho, J., Gebraad, P., Pao, L., and Yingchen, Z. “Computational Fluid Dynamics Simulation Study of Active Power Control in Wind Plants.” Presented at the 2016 American Control Conference, July 2016, Boston, MA.

Scholbrock, A., Fleming, P., Schlipf, D., Wright, A., Johnson, K., and Wang, N. “Lidar-Enhanced Wind Turbine Control: Past, Present, and Future.” Presented at the 2016 American Control Conference, July 2016, Boston, MA.

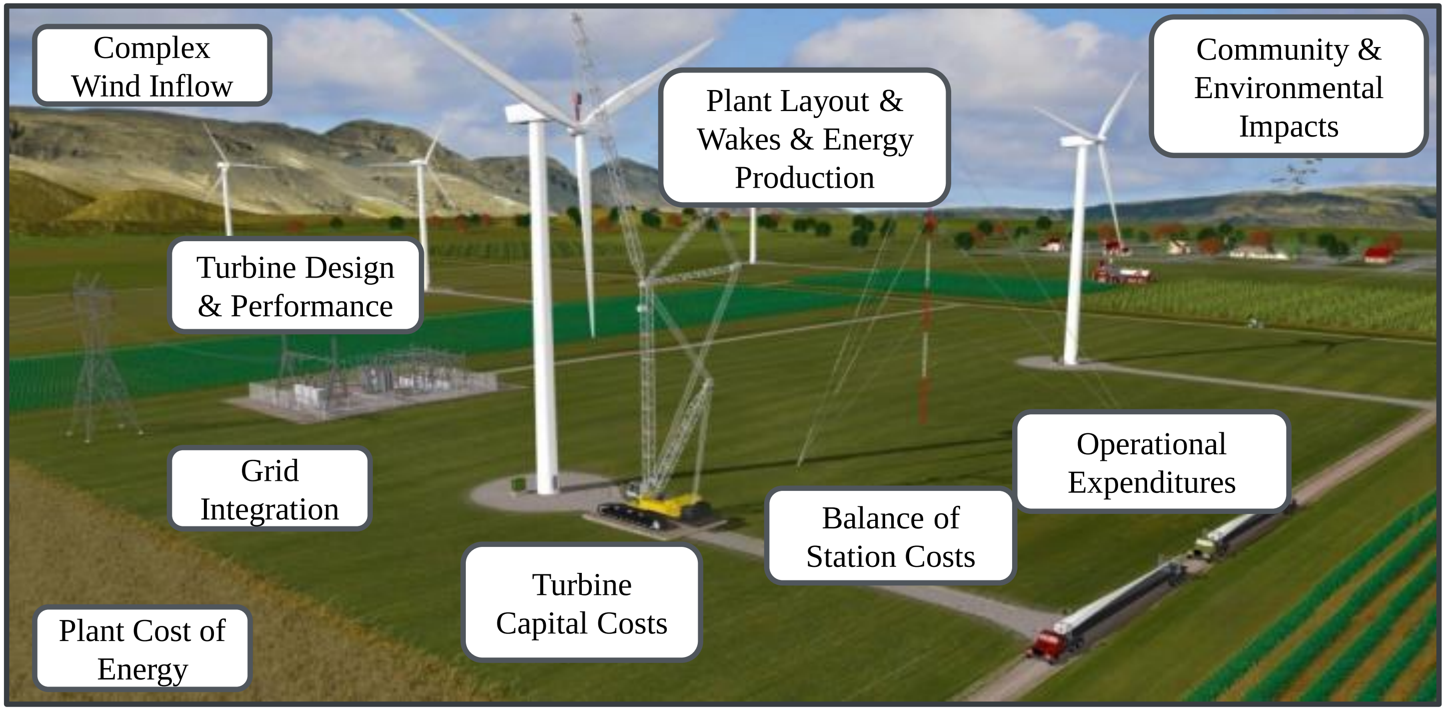
Haizmann, F., Schlipf, D., Raach, S., Scholbrock, A., et. al. “Optimization of a Feed-Forward Controller Using a CW-Lidar System on the CART3.” Presented at the 2015 American Control Conference, July 2015, Chicago, IL.

Fleming, P., Gebraad, P., Lee, S., van Wingerden, J., et. al. “Evaluating Techniques for Redirecting Turbine Wakes Using SOWFA.” *Renewable Energy* (2014) 1-8.

Fleming, P., Scholbrock, A., Jehu, A., Davoust, S., Osler, E., Wright, A., and Clifton, A. “Field-Test Results Using Nacelle-Mounted Lidar for Improving Wind Turbine Power Capture by Reducing Yaw Misalignment.” *The Science of Making Toque from Wind 2014*.

Fleming, P., Gebraad, P., Lee S., van Wingerden, J., et al. “Simulation Comparison of Wake Mitigation Control Strategies for a Two-Turbine Case.” *Wind Energy* (2014).

Fleming, P., Gebraad, P., Churchfield, M., van Wingerden, J., et. al. “Using Particle Filters to Track Wind Turbine Wakes for Improved Wind Plant Control.” Presented at the 2014 American Control Conference, June 2014, Portland, OR.



A full wind plant involves stakeholders and large technical complexity
Graphic: Al Hicks, NREL

Integrated System Design and Analysis (ISDA)

Atmosphere to Electrons

Katherine Dykes
National Renewable Energy Laboratory
Katherine.dykes@nrel.gov 720 243 0614

Project Overview

The Challenge: Insights from wind energy scientific advancements are not readily adaptable to industry practice. A level of translation is needed to demonstrate levelized cost of energy (LCOE) value of new insights, validate design-level modeling capability, and influence next-generation design standards and processes

The ISDA Goal: Reduce the cost of energy by (1) using the results of experiments and high-fidelity modeling to improve design capabilities and standards, and (2) creating optimization capabilities that demonstrate system impact of innovation

Partners: Siemens Wind Power (validation efforts), DTU Wind Energy (system optimization), International Energy Agency (IEA) Wind Task 37 (15+ partners, system optimization).

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- **Wind plant optimization**
- Resource assessment and characterization
- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- Advanced technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

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The Impact

- The project will enable LCOE reductions through demonstrations of wind plant system optimization and improvements to industry design capabilities.
- The ISDA project is the vehicle to use the knowledge and capabilities generated from broader wind program projects to directly influence design capabilities, methods, and standards.
- The outcome for the project will be:
  1. Robust validation and uncertainty quantification methodologies for industry engineering and design tools, and
  2. Demonstration and establishment of best practices for wind plant optimization.

Technical Approach

Transition process from FY14 to FY16 and beyond

- Evolution from a turbine focus to a plant focus
  - Aero-elastic toolset FAST transitioned to modular, community-developed toolset with enhanced capability, to represent modern aero-elastically active turbine
  - Systems engineering first established turbine optimization capability and extended to plant optimization
- Direct industry engagement through collaboratives
  - Validation joint projects with industry
  - IEA Wind Task 37: Systems Engineering
  - OpenFAST

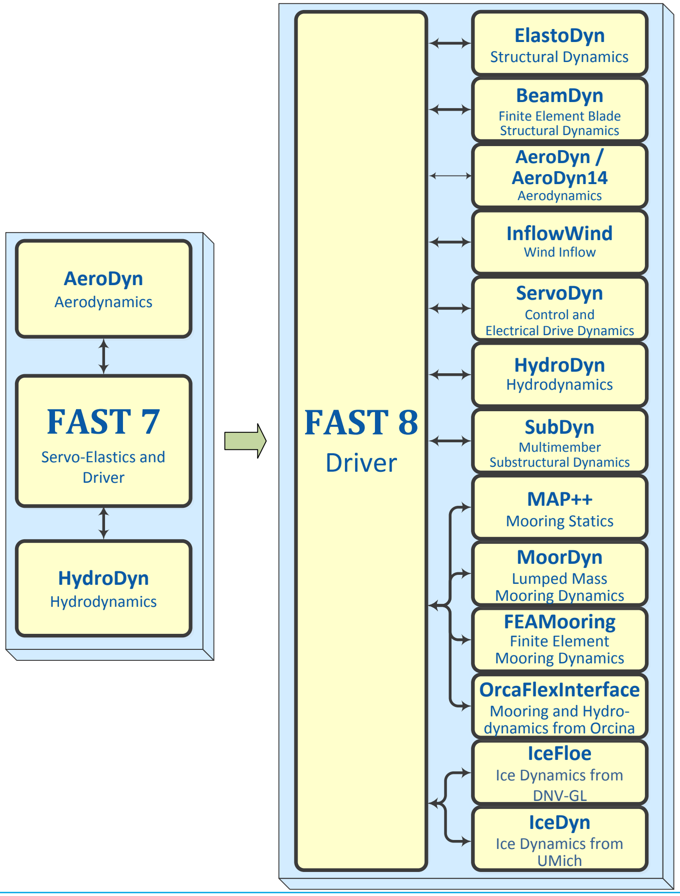
Technical Approach

Task 1: Multi-Physics-Model Development and Validation

Objective: Improve physics and perform validation of engineering models by incorporating new scientific knowledge, experimental insights, and computational methods.

Approach

1. Translate aero-elastic model suite to a modular framework with improved aerodynamic and structural physics.
2. Validate improved physics through experimental campaign.
3. Linearize the new modular aero-elastic model suite for support of controls and optimization applications.



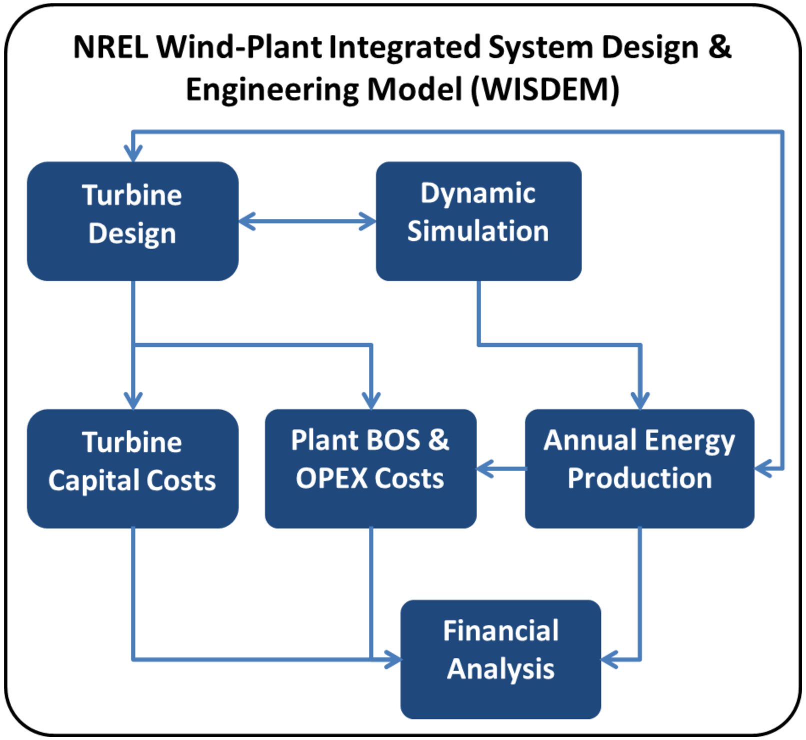
Technical Approach

Task 2: Systems Engineering and Optimization

Objective: Create new whole-system design and optimization processes and demonstrate potential reduction in LCOE.

Approach

1. Connect physics and cost models into an open-source software framework for multidisciplinary design, analysis, and optimization (MDAO)
2. Perform MDAO research analysis to demonstrate wind plant LCOE improvements
3. Collaborate with wind industry practitioners and researchers to establish MDAO best practices and transfer expertise to industry.



Accomplishments and Progress

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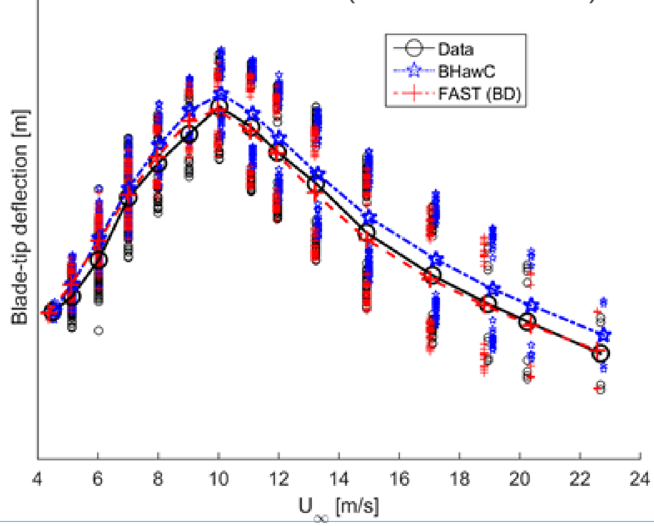
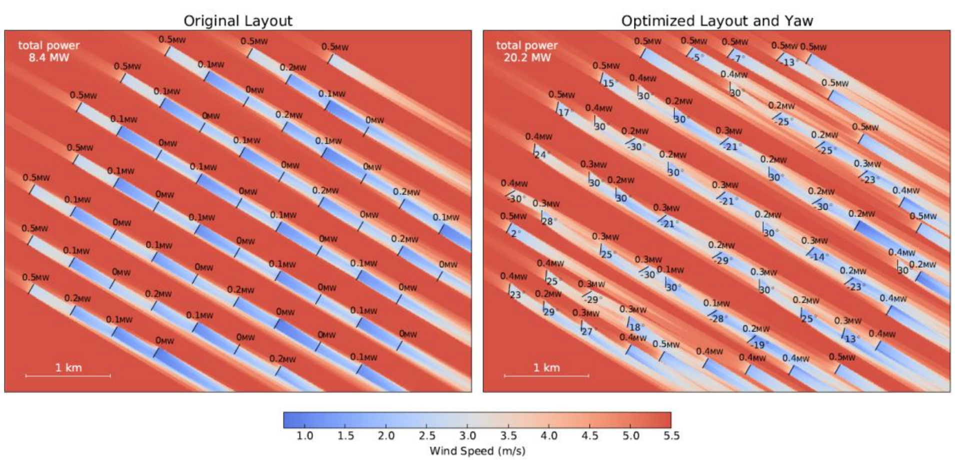
- Completed transition of wind turbine multi-physics code FAST7 to modular format FAST8
  - Completed validation of advanced aerodynamic and structural physics with industry partner Siemens Wind Power
- Completed studies demonstrating value of multidisciplinary analysis and optimization (MDAO) to wind turbine and plant design
  - Received DOE Technology Commercialization Fund award for field demonstration of technology around wake steering control

A Validation and Code-to-Code Verification of FAST for a MW-scale Wind Turbine with Aeroelastically Tailored Blades (Guntur et al. 2016)



Maximization of the Annual Energy Production of Wind Power Plants by Optimization of Layout and Yaw-Based Wake Control (Gebraad, P. et al. 2016)



Project Plan and Schedule

- Separate projects in FY14 and FY15 merged under ISDA umbrella in FY16
- All milestones successfully achieved
- No Go/No-Go decision points during FY14–FY16.

Project Budget

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

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-Share	DOE	Cost-Share	DOE	Cost-Share
$2,345k	$0	$1,570k	$0	$1,450k	$0

- No budget variances
- Carryover from FY16 is $490k; 91% of current project budget has been expended.
- No cost-share but significant in-kind contributions from Siemens Wind Power (data and analysis) and DTU Wind Energy (software development).

Research Integration and Collaboration

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

Partners, Subcontractors, and Collaborators

- This project is linked with A2e projects HFM, Wake Dynamics, Controls and PRUF (Performance Risk, Uncertainty, and Finance)
- Project Partners: Siemens Wind Power (CRADA), DTU Wind Energy, and IEA Wind Task 37
- Project Subcontracts: Brigham Young University and University of Colorado at Boulder.

Communications and Technology Transfer

Open-source software available at http://nwtc.nrel.gov

	Software Downloads	Workshops and Tutorials	Journal Articles	Conference Papers	Technical Reports
Multi-Physics Model Validation and UQ	10,000+ per year	2 and 2	6	9	2
Systems Engineering and Optimization	n/a: Github downloads are not tracked	3 and 2	10	14	4

Next Steps and Future Research

FY17/Current Research

- Host a workshop to identify mechanisms and strategies as to how A2e efforts can connect to industry design capability
- Implement initial efforts for uncertainty quantification of engineering models
- Demonstrate wind plant optimization that explicitly incorporates key uncertainties into the design process.

Planned Future Research

- Demonstrate (1) advancements in validation and uncertainty quantification of engineering models, and (2) improvements in wind plant LCOE through application of MDAO
- Lead IEA Wind international collaborations targeted at validating and improving industry (1) engineering models and UQ (new task), and (2) wind plant optimization (task 37).

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

The DOE A2e Mesoscale to Microscale Coupling Project

Atmosphere to Electrons

A2e Initiatives

U.S. Department of Energy

Sue Ellen Haupt, Joel Cline, Will Shaw, Larry Berg, Matt Churchfield, Jeff Mirocha, Branko Kosovic, Caroline Draxl, Raj Rai, Rao Kotamarthi, Many Others

Project Overview

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

Mesoscale to Microscale Coupling (MMC) Project:

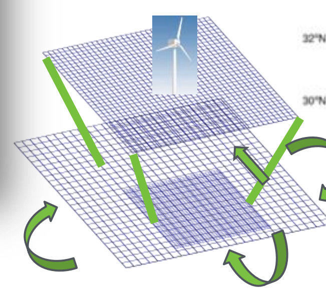
Develop, Verify, and Validate physical models and modeling techniques that bridge the most important atmospheric scales that determine wind plant performance and reliability and aid wind plant optimization. Enabling simulation of critical microscale flow characteristics affecting turbine and wind plant uncertainties and performance will allow substantive improvements in wind plant design, operation, performance projections, and plant-level controls.

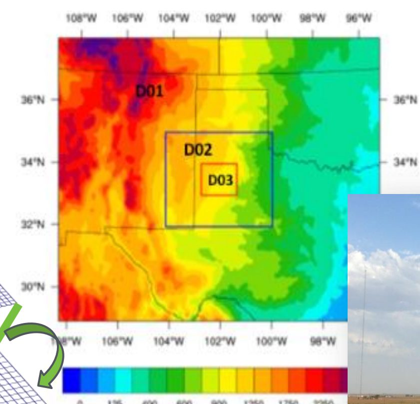
The Challenge:

Without appropriate larger scale forcing, microscale models cannot correctly capture flow details, making wind plant optimization less effective.

Partners:

Pacific Northwest National Lab (PNNL)
National Renewable Energy Lab (NREL)
Lawrence Livermore National Lab (LLNL)
Argonne National Lab (ANL)
Los Alamos National Lab (LANL)
Sandia National Labs (SNL)
National Center for Atmospheric Research





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- **Target:** Identify modeling framework(s) to develop coupled mesoscale–microscale atmospheric models for wind plant optimization and evaluate and recommend coupling methodologies
- **Impact:** Development of plant-level control systems requires a realistic representation of turbulent wind flow into and within wind plants. Current microscale models cannot account for many conditions found in real-world turbine locations. Properly coupled models will dramatically improve this.
- **Endpoint:** Proper microscale representation of the turbulent atmosphere will allow development of plant-level control systems to optimize wind plant performance.

Technical Approach

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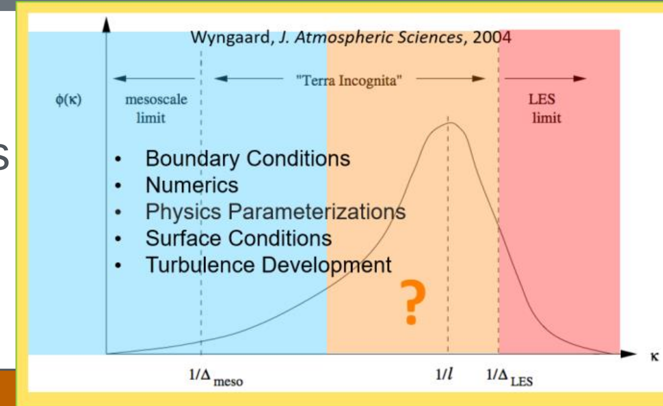
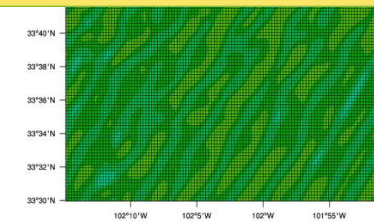
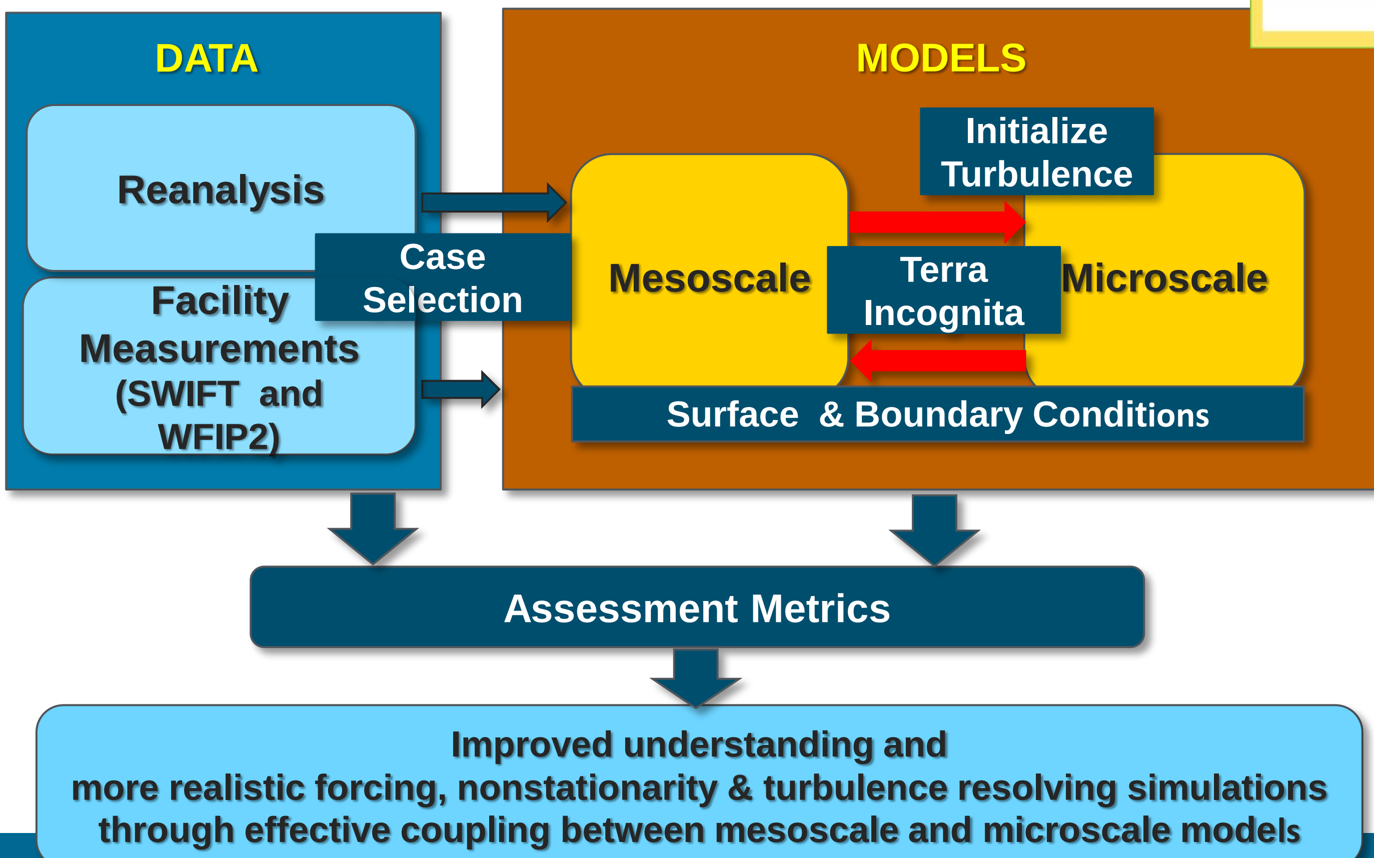
- Grounded in data: Verification & Validation, including Uncertainty Quantification
- Correct modeling of microscale turbulence that impacts turbines and plants
- Blending across “terra incognita” between scales is difficult, yet important to wind plant scales



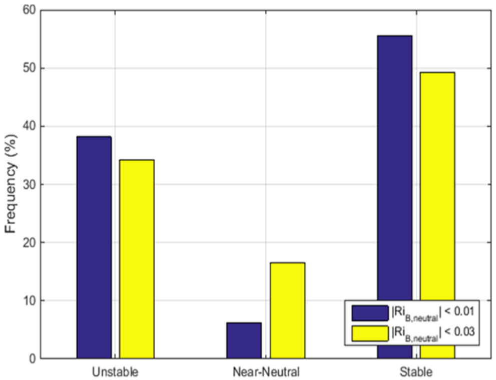


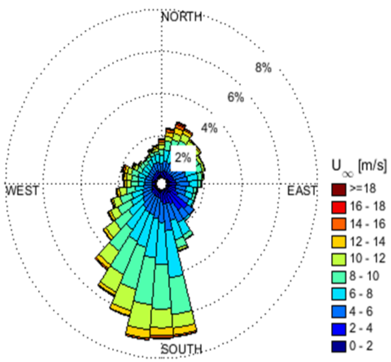


- Coupling across scales is difficult, yet critical
- Downselect models to meet industry needs
- Develop coupling techniques
- Turbulence generation
- Nonstationarity

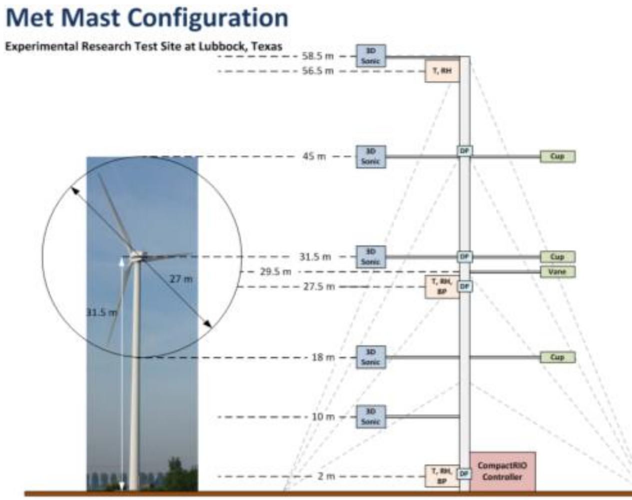
Accomplishments and Progress— Initial Benchmark

- Sandia/Texas Tech (TTU) Scaled Wind Farm Technology (SWiFT) site
  - Unstable Boundary Layer (BL)
  - Neutral BL
  - Stable BL
  - Non-stationary
- TTU 200 m met tower and surrounding observations





730 days over 2012–2014



Accomplishments and Progress—Summary from FY15 Canonical Cases

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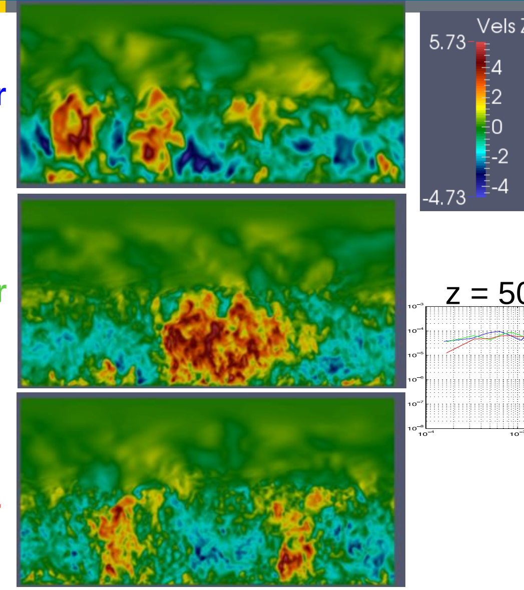
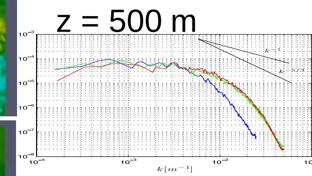
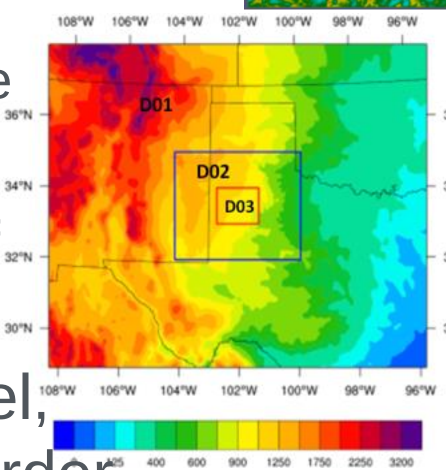
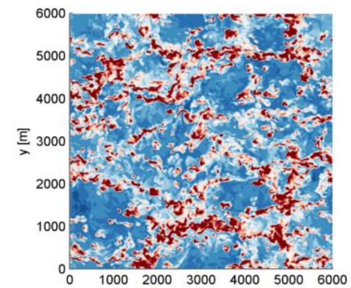
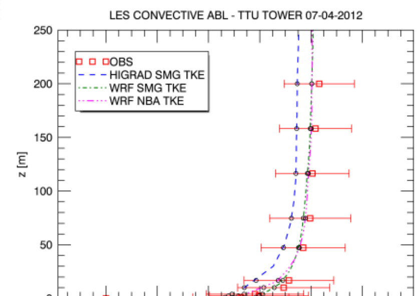
- Case Selection:
  - Stable BL is dominant at SWIFT site and very important for harvesting wind, but hard to model
  - Difficult to find good quality neutral case
  - Difficult to define a typical case
- Important issues for coupling:
  - Terra Incognita issues
  - Initializing turbulence in microscale
  - Surface conditions
- Large Eddy Simulation (LES) of neutral BL shows importance of carefully selecting subgrid model, grid cell size aspect ratio, and order of advection scheme











Accomplishments and Progress— Modeling the Low Level Jet

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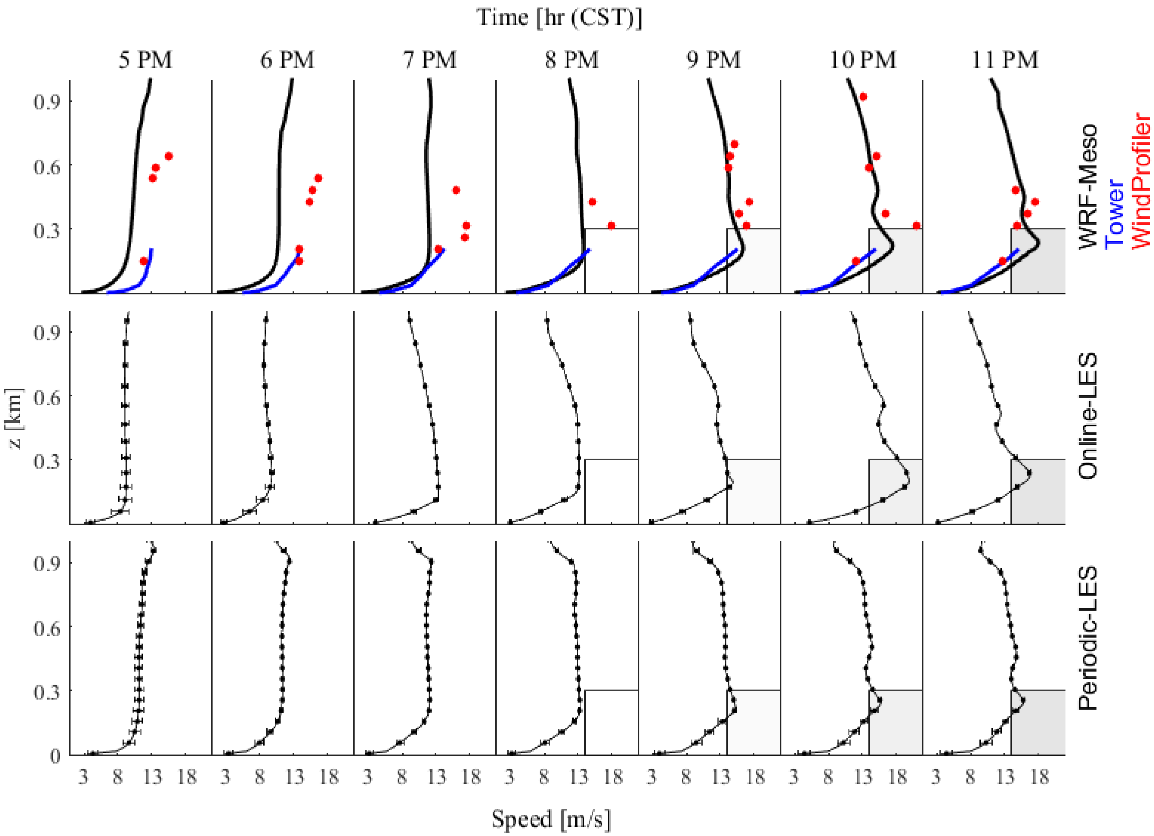
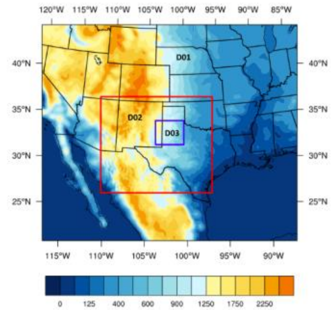
Inability to correctly capture low level jet (LLJ) without mesoscale nesting will compromise ability for industry to make use of high fidelity modeling capabilities.

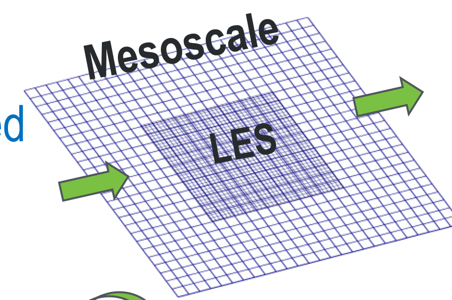
Mesoscale forcing provided by Weather Research and Forecasting (WRF) model. Large Eddy Simulation (LES) embedded.

Nov. 8, 2013 Diurnal Case



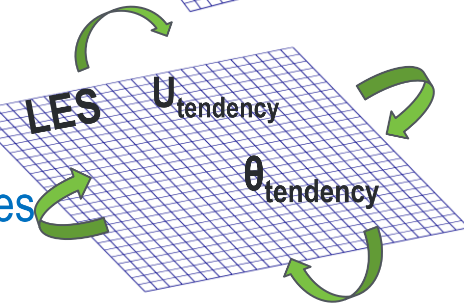


Mesoscale WRF captures LLJ



LES embedded in WRF captures LLJ

LES w/o mesoscale greatly underestimates LLJ



Need mesoscale to capture important features like LLJ

Accomplishments & Progress— Spatial/Temporal Inhomogeneity

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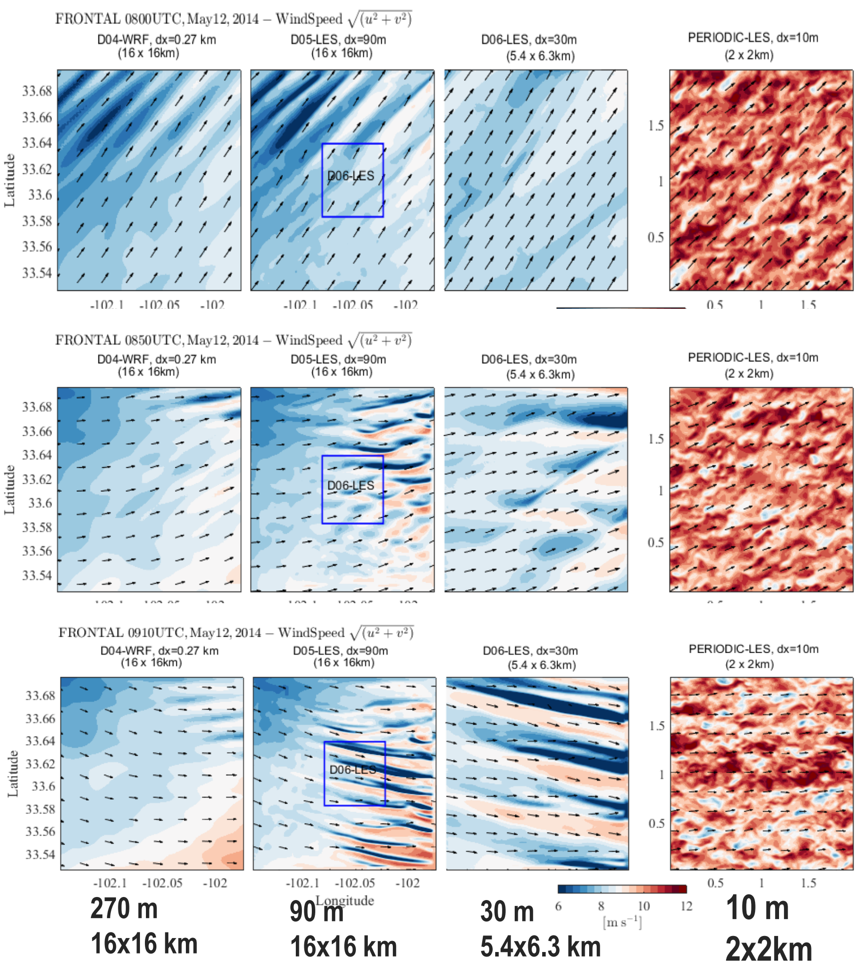
Frontal case: May 12, 2014 ONLINE nesting simulation. Domains D04-D06 (LES) forced by WRF D03. Blue box in D05 shows area of D06.

Periodic forcing from WRF tendencies and heat flux

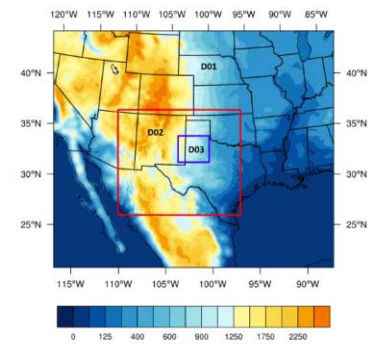


0800 UTC

0850 UTC

0910 UTC

- See change in flow through all scales during frontal passage
- Forced by mesoscale
- Microscale follows mesoscale via forcing
- Turbulence obvious at finest scale.



Project Plan & Schedule

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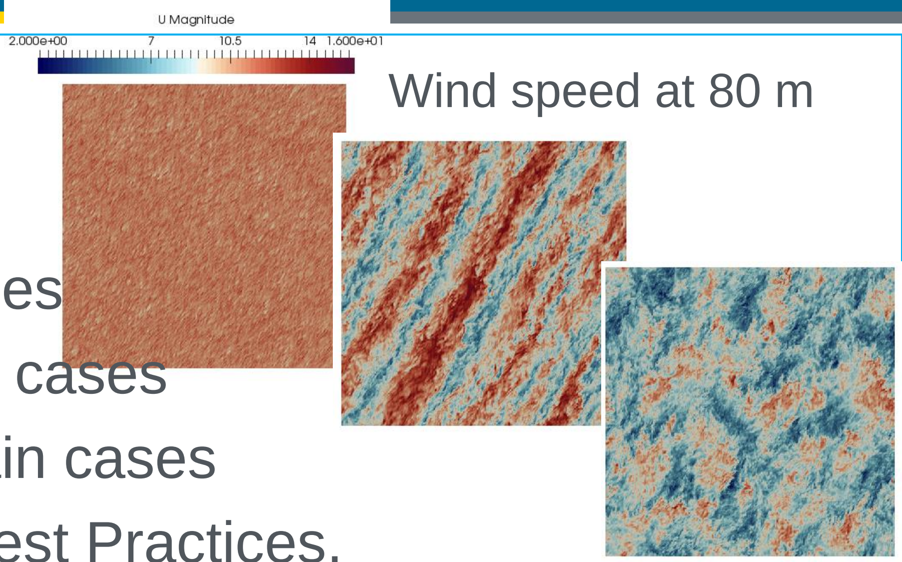
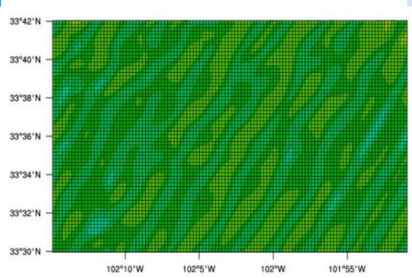
- Team funded March 2015
- End Date: September 30, 2017



Wind speed at 80 m

- Year 1 (FY15): Model canonical cases
- Year 2 (FY16): Model nonstationary cases
- Year 3 (FY17): Model complex terrain cases
- Outcome: Recommendations for Best Practices, Framework for coupling.



	FY2015	FY2016
Quarter One	N/A	Complete report on first year findings
Quarter Two	N/A	Select nonstationary cases for modeling at workshop at NCAR
Quarter Three	Select first-year cases at workshop at NCAR	Implemented and tested new coupling strategy (tendency forcing)
Quarter Four	Present findings at first year workshop with industry and other A2e teams at NCAR	Complete modeling for nonstationary cases and submit to NCAR for assessment

Project Budget

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

	Budget History			
	FY2015		FY2016	
	DOE	Cost-share	DOE	Cost-share
ANL	$200K	—	$200K	—
LANL	$200K	—	$200K	—
LLNL	$200K	—	$200K	—
NREL	$200K	—	$200K	—
PNNL[1]	$325K	—	$410K	—
SNL	$200K	—	$50K	—

[1]Includes $100K to NCAR for subcontract for PI leadership and formal Verification and Validation

- No significant variances from planned budget
- All planned funds have been expended except mandated 25% carryover to FY 2017 for DOE labs.

Partners, Subcontractors, and Collaborators:

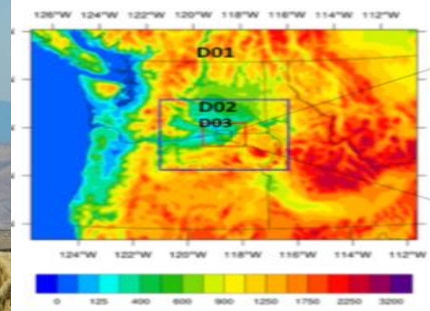
Collaborative Team: Pacific Northwest National Lab
National Renewable Energy Lab
Lawrence Livermore National Lab
Argonne National Lab
Los Alamos National Lab
Sandia National Lab
National Center for Atmospheric Research

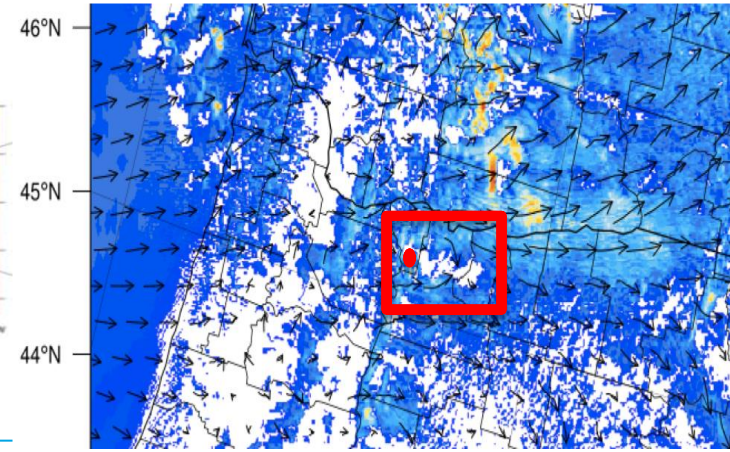
Communications and Technology Transfer:

- First year workshop – Sept. 2015 – included industry
- Seven Presentations at AMS Symposium on Boundary Layers and Turbulence, Salt Lake City, UT, July 2016
- Work with A2e team to transition to High Performance Computing facility
- Two major annual reports, data provided on Data Archive Portal

Next Steps and Future Research

FY17/Current Research: Expand methods to complex terrain





Planned Future Research: Transition to high performance computing environment

- Better mesoscale methods for the wind industry
- Coupling to force the features important to harvesting power
- Correct turbulence structures at the microscale
- Nonstationary
- Multiple land interfaces
- Test for uses such as controls

Modeling informs Wind Plant Optimization

Wind Forecast Improvement Project in Complex Terrain (WFIP 2)

WJ Shaw/JM Wilczak/J McCaa

PNNL/NOAA/Vaisala

will.shaw@pnnl.gov/

February 2017

Project Overview

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

Wind Forecast Improvement Project in Complex Terrain (WFIP 2):

This project aims to reduce costly wind forecast errors by improving simulation of atmospheric physics in complex terrain and transferring this knowledge to foundational forecast models and decision support tools.

The Challenge:

Forecast models for wind power must account for atmospheric processes ranging from 1000s of km (storm systems) to most energetic turbulent eddies (10s of m); models do not currently do this well in hilly terrain where wind turbines are often sited.

Partners and their Roles:

Vaisala Team (FOA awardee)—Field observations, analysis, and development of decision support tools;

National Oceanic and Atmospheric Administration (NOAA)—Field observations, analysis, and improvements to operational weather forecast models

DOE National Laboratories—Field observations, analysis, parameterization improvements, and uncertainty quantification

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- **Resource assessment and characterization**
- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- **Advancing grid integration**

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- Advanced technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

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- Wind energy workforce and education development
- **Advancing grid integration**

Target: Execute a field and modeling study to improve underlying physics of wind power forecasts

Impact: Better forecasts facilitate orderly integration of wind power and thus reduce its cost

Endpoint: Improved foundational weather forecasts and quantified uncertainty will lead to more efficient wind plant and utility operations

Research Integration & Collaboration—Full Partners List

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

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

Argonne NATIONAL LABORATORY

Lawrence Livermore National Laboratory

NREL National Renewable Energy Laboratory

Pacific Northwest NATIONAL LABORATORY

VAISALA

Hay Canyon Wind Farm – with Mount Hood in the background – is among those in the study area. Photo courtesy of Iberdrola Renewables

NOAA – National Oceanic and Atmospheric Administration, U.S. Department of Commerce

NOAA Earth System Research Laboratory – Serving Society through Science

ARL Air Resources Laboratory – Conducting research and development in the fields of air quality, atmospheric dispersion, and climate

National Weather Service

Data Partners:

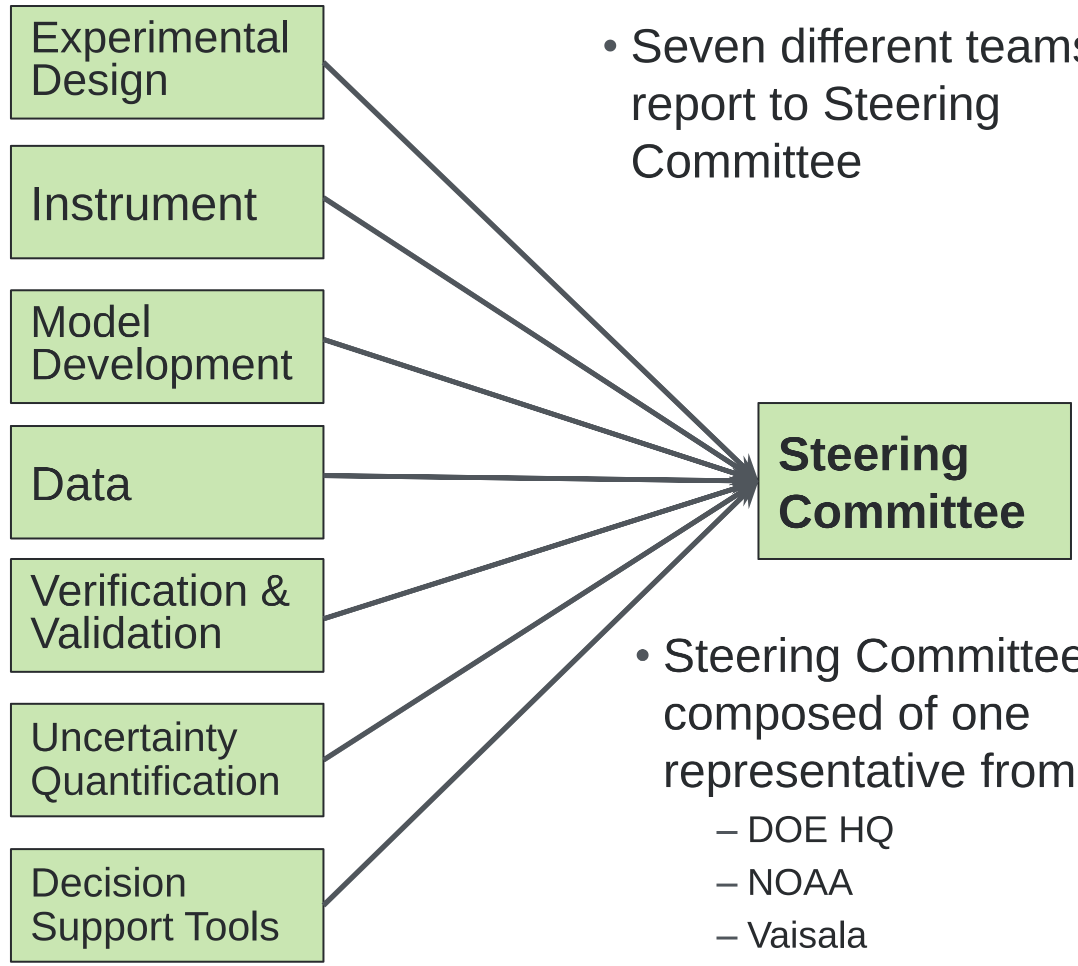
IBERDROLA RENEWABLES; SOUTHERN CALIFORNIA EDISON (An EDISON INTERNATIONAL Company); PGE; Eurus Energy; SIEMENS

Team Members:

University of Colorado Boulder; Texas Tech University College of Arts & Sciences; Bonneville Power Administration; Lockheed Martin; University of Notre Dame; NCAR National Center for Atmospheric Research; Sharply Focused

Research Integration & Collaboration—Teams and Structure

- Funding Opportunity Announcement released by DOE in 2014
- **Vaisala, Inc.** selected as awardee
- Awardee works with larger, integrated WFIP 2 team:
  - NOAA-Oceanic and Atmospheric Research
  - Four DOE Laboratories:
    - Argonne National Laboratory (ANL)
    - Lawrence Livermore National Laboratory (LLNL)
    - National Renewable Energy Laboratory (NREL)
    - Pacific Northwest National Laboratory (PNNL



- Seven different teams report to Steering Committee

- Steering Committee is composed of one representative from:
  - DOE HQ
  - NOAA
  - Vaisala
  - DOE Labs
  - DOE Contracting

Project Plan & Schedule

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

Project Duration: FY 2015–2018

FY 2014

- Preparatory year, with prior DOE and NOAA projects developing field study concept and capabilities as well as modeling and analysis tools
- Industry partner (Vaisala) engaged through FOA award

FY 2015

- First year of WFIP 2; kickoff at LLNL in October 2014; teams and Steering Committee established
- Integrated science plan developed
- Majority of field instrumentation installed
- Data archival (DAP) and data/model display (NOAA) established

FY 2016

- Oct. 1, 2015 declared start of 18-month field phase base on installed instrumentation
- Final instruments installed July 2016; delays due to land leasing issues

Project Budget

	Budget History					
	FY2014		FY2015		FY2016	
	DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
Vaisala	—	—	$625K	$125K	$625K	$125K
NOAA	$400K	$2,600K	$800K	$2,200K	$800K	$2,300K
DOE Labs	$574K	—	$800K	—	$1,000K	—

- No significant variances from planned budget
- All planned funds have been expended except mandated 25% carryover to FY 2017 for DOE labs

Technical Approach—Integrated Science Plan

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Integrated Science Plan

- Document jointly produced by Vaisala team, NOAA, and DOE labs
- Described key science issues and identified collaborating partners for each

Key Activities within the Science Plan

- Phenomena identification, categorization, and analysis from observations
- Improvement of model physics
- Improvement of numerical techniques
- Verification and validation of model improvements, including uncertainty quantification
- Development of decision support tools
- Delivery of all data, including proprietary data from collaborating wind plant operators, to the A2e Data Archive and Portal

WFIP 2 Study Area: Measurement Strategy

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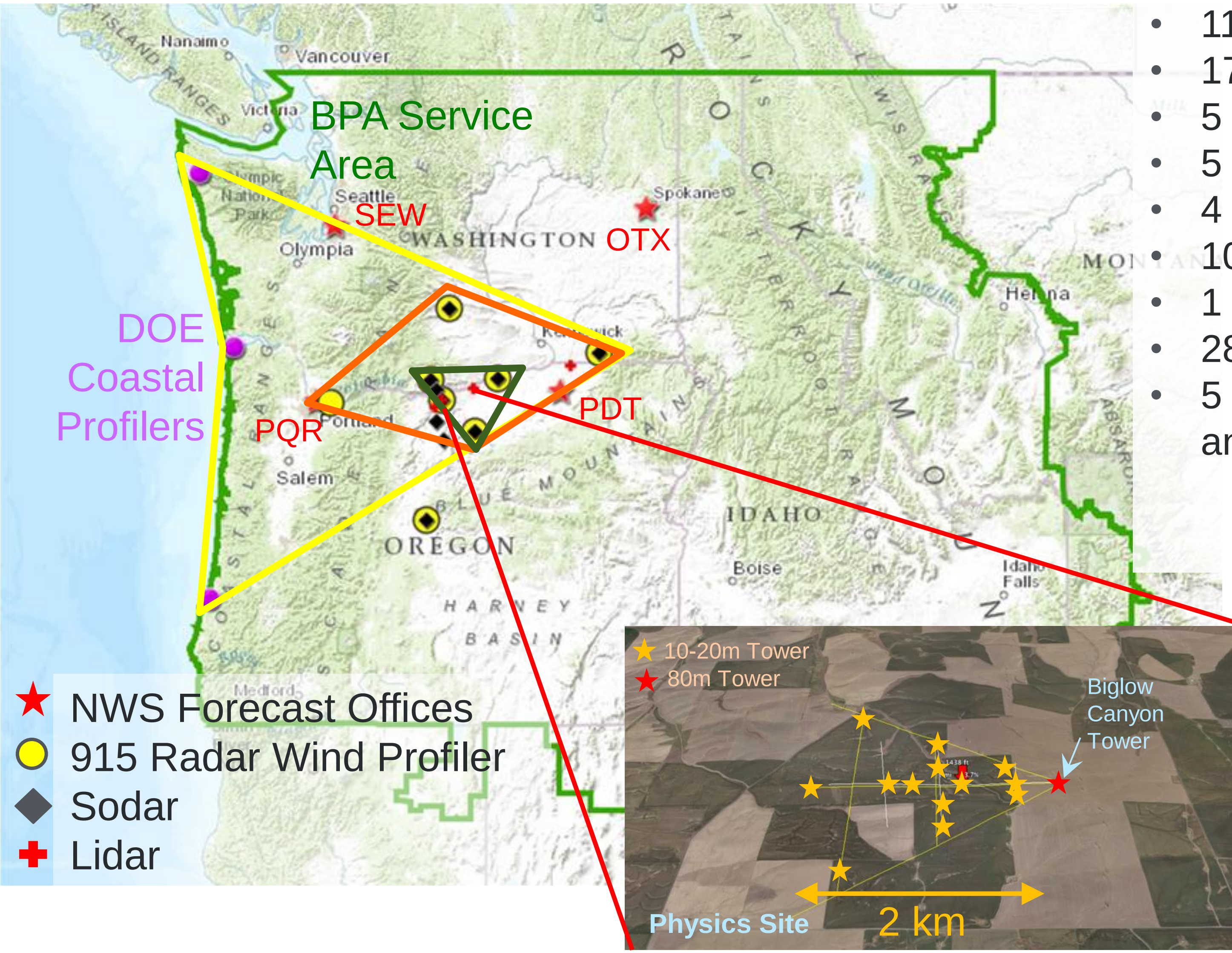

- 11 wind profiling radars
- 17 sodars
- 5 wind profiling lidars
- 5 scanning lidars
- 4 radiometers
- 10 microbarographs
- 1 Ceilometer
- 28 sonic anemometers
- 5 radiative flux systems and soil moisture

NWS radiosondes: 200 supplemental launches

WFIP 2 Study Area: Measurement Strategy

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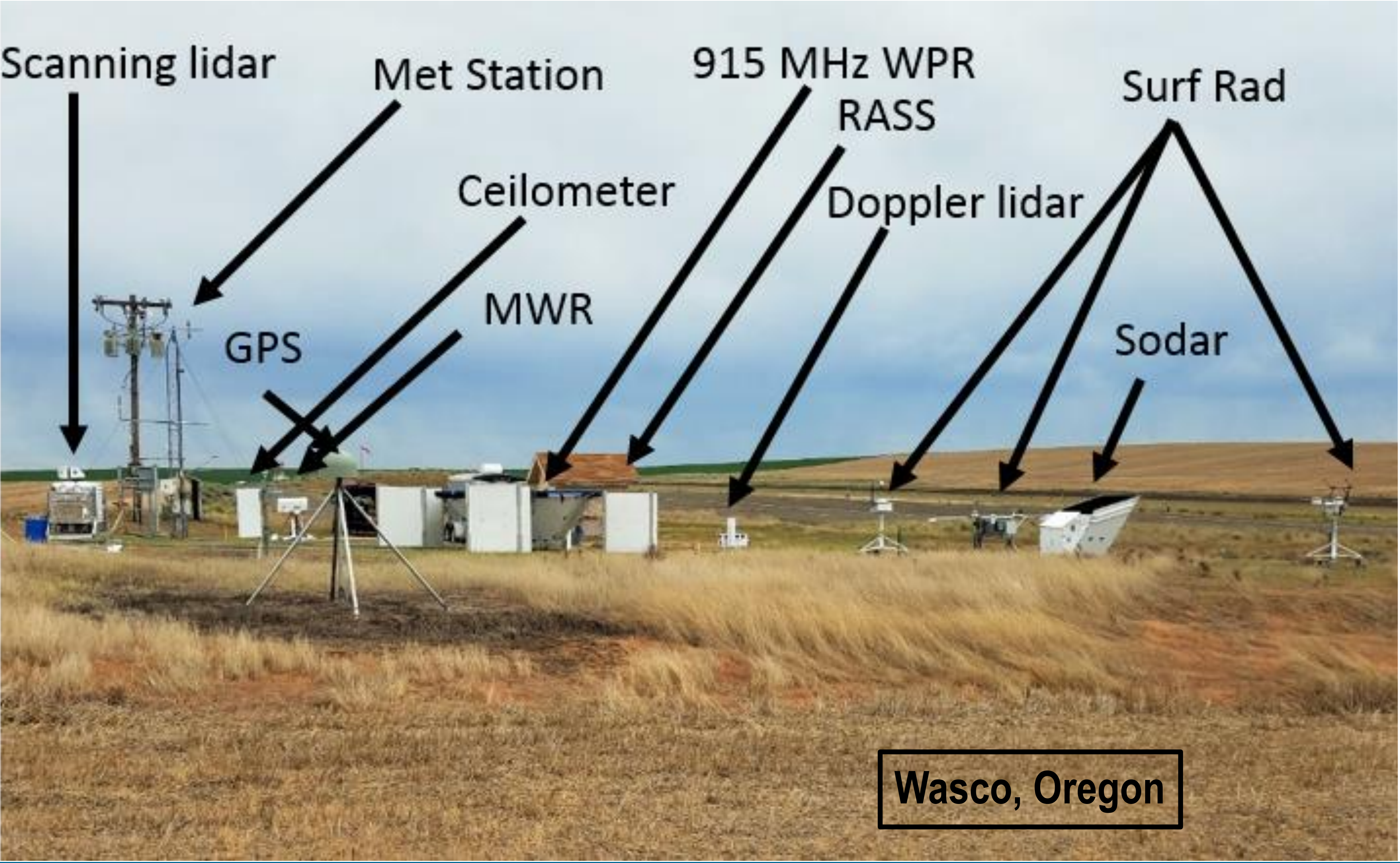

WFIP 2 Study Area: Complex Terrain of Columbia Basin

Primary Models (Hourly Updated)

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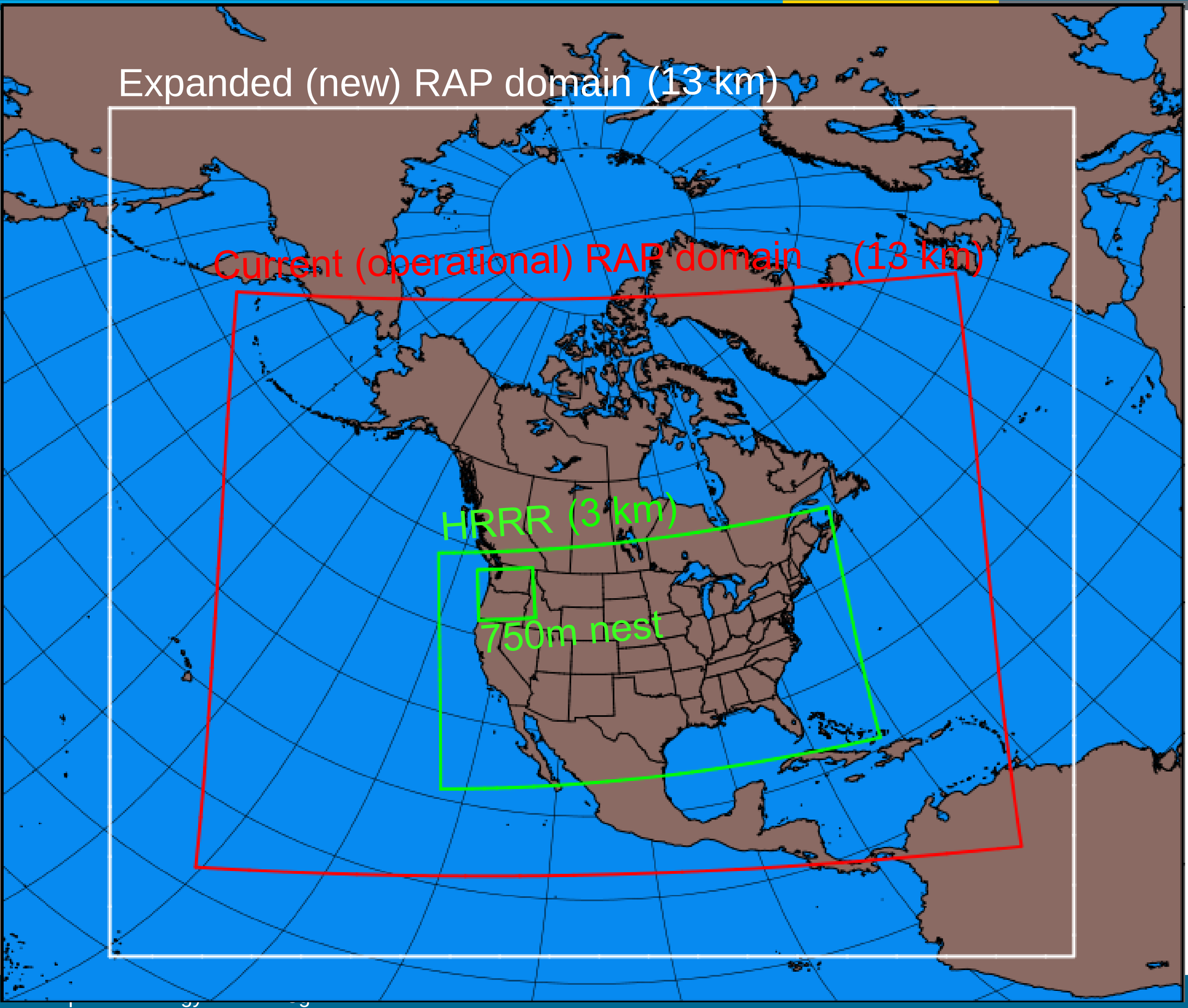

RAP (13km)
Rapid Refresh

HRRR (3km)
High Resolution
Rapid Refresh

HRRR Nest (750m)

Model – Obs Evaluation Webpage:

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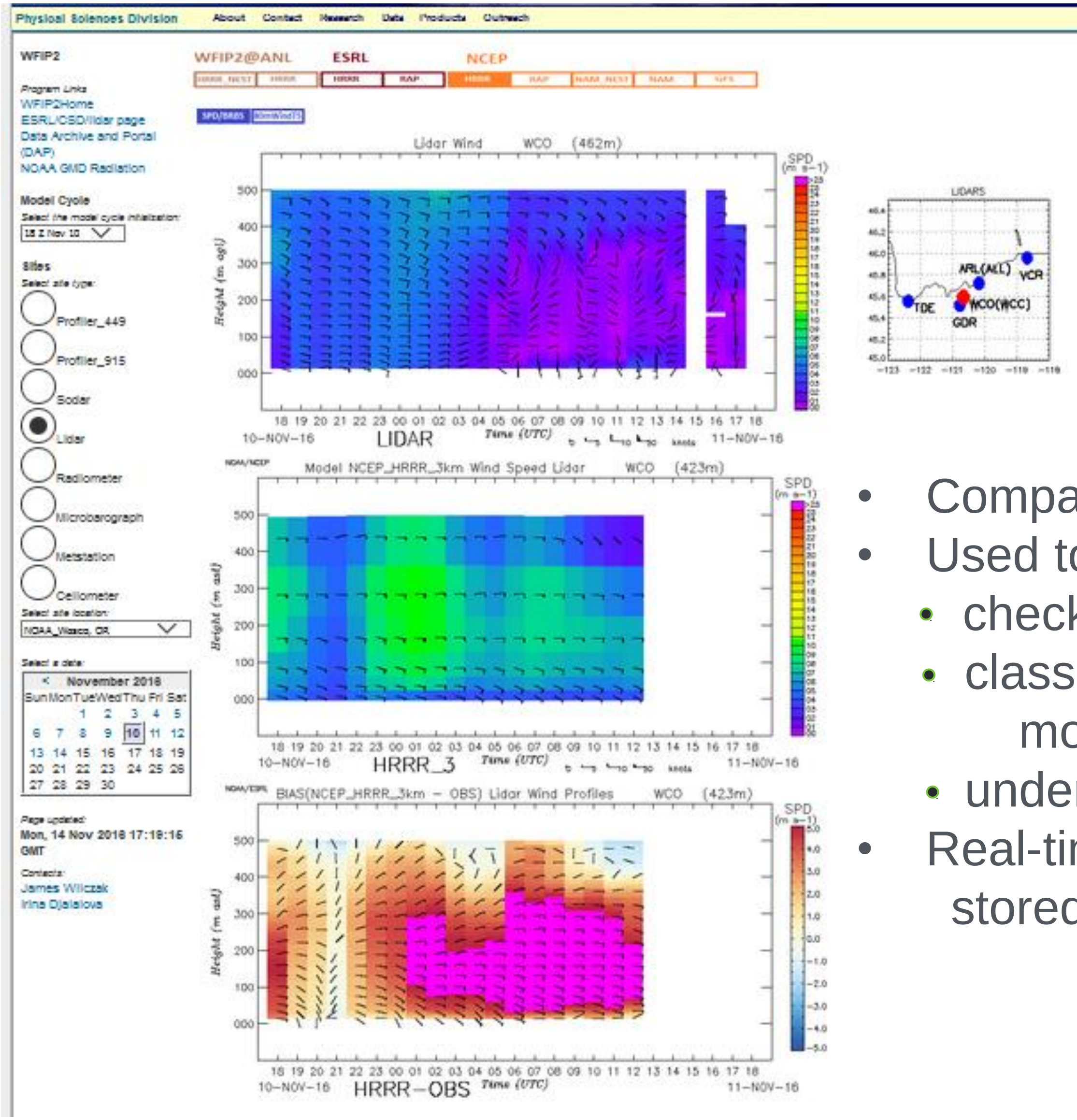
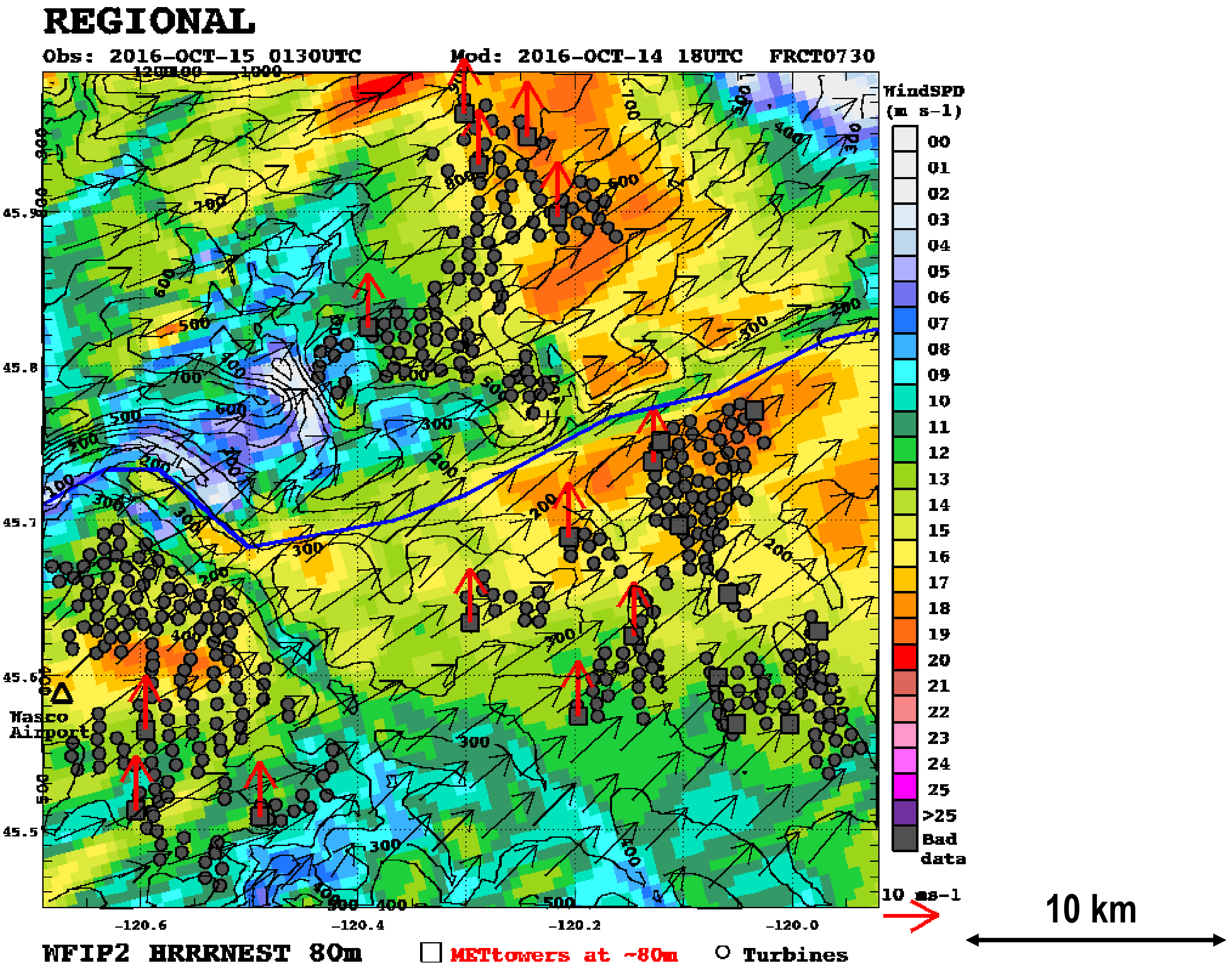


http://wfip.esrl.noaa.gov/psd/programs/wfip2/

- Compares observations with models
- Used to:
  - check if instruments running correctly
  - classify weather events when models fail
  - understand physical processes
- Real-time and final QC'd data is being stored on DAP at PNNL

WFIP 2 Study Area: Industry Wind Plant Data



Accomplishments—Data Collection and Organization

- Over 100 separate meteorological observing instruments at 38 separate field sites
- Turbine-level wind plant data from 13 facilities
- More than 2100 GB of observational data over a 14-month period to date (continues through March, 2017)
- Strong contributions from industry partners
  - Scanning LIDAR data from Siemens
  - Wind plant data from six operators

Data Partners:

IBERDROLA RENEWABLES
EDISON
PGE
Eurus Energy
NEXTera ENERGY RESOURCES
White Creek Wind
SIEMENS

Accomplishments—
Data Collection and Organization

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

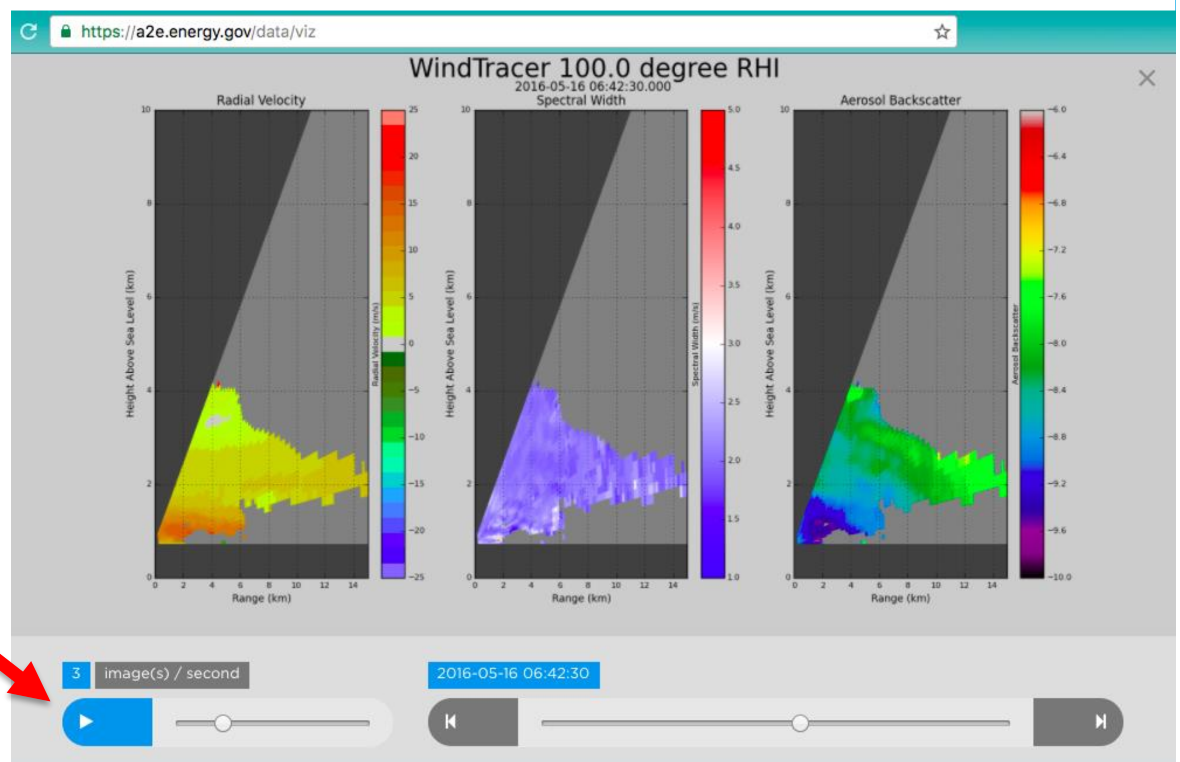
Data available at the A2e Data Archive and Portal (DAP)

(https://a2e.energy.gov/data#wfip2)

DAP provides data discoverability and access

Simple access to:

- Data types
- Dates
- Locations
- File types
- Downloads
- Image looping



Accomplishments—NWP Model Development

Parameterization	
PBL	• Mixing Length formulation (Scale-aware, Z-less) • Mass flux formulation for non-local transport • Blended 3D-TKE scheme • Mixing on x-y-z coordinates (instead of σ)
Surface Layer	Sub-grid turbine height variability Scale-aware
Land surface model	Impact of heterogeneity on heat and moisture fluxes
Wind Farm Parameterization	Sub-grid turbine height variability Scale-aware

Numerics	
Idealized Flow Analysis	Mesoscale interface for Immersed Boundary Method (IBM) (FY17)
Hybrid vertical coordinates	Flatter vertical coordinate system over complex terrain – numerical noise reduction.

Accomplishments—Verification and Validation

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The Phenomenon Identification and Ranking Table (PIRT)

The meteorological phenomena we are interested in:

- What, where, when?
- What are the dominant physics?
- How can we see this from measurements?
- What are the metrics we should use?

WFIP2 Weather Taxonomy

Meteorological phenomena that we observe in the study area

- Major categories
- Differentiates between formation, persistence, and dissipation
- Agreed between users

The WFIP2 Event Log

Time series of observed phenomena

- What, where, when?
- Uses the WFIP2 weather taxonomy
- Identifies case studies

Case Study Report Templates

Standardized report on case studies

- What did we look at and why?
- Model settings
- Comparison results
- Free--form results and explanations

Validation Tools

Standardized systems for comparisons

- Model to model
- Model to data

From Andy Clifton, NREL

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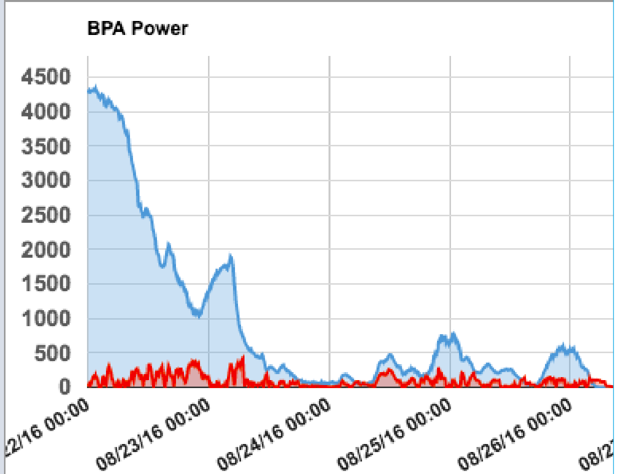
Event logging – central to curating the data

A	B	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	
		Regime Types														Significance Type		CS	Instructions (unhide row 2, or click mouseover this cell a
RRR-WFIP config																			
			CBS			Cold Pool													
Date (UTC)	DOW	CBT	+	ss	-	+	ss	-W	-C	-R	MW	TW	CO	EF	OT	Forecast Skill	Importance for Wind Energy	CS	Narrative
2016-08-21	Sun	1	2	2							3	2				POOR	HIGH		> 4 GW BPA up ramp, starting from ~ zero. Cold front sweeps stu through gorge. By late in the period, surface cyclogenesis ensues strong W-E syntopic-scale pressure gradient between developing magnitude around 23Z. Wakes and mountain waves are apparent Regarding forecast skill, 20/18Z run of HRRR-ESRL, -WFIP2, and forecast, 21/06Z run of HRRR-WFIP2 and nest were deficient in st Troutdale.
2016-08-22	Mon	1		2	1						3	2				POOR	HIGH		
2016-08-23	Tue				2										2	POOR	LOW		
2016-08-24	Wed	2												2	3	POOR	MEDIUM		
2016-08-25	Thu	2												2	3	POOR	MEDIUM		
2016-08-26	Fri		2													AVERAGE	MEDIUM		
																			Ramp to 1.5 GW by the beginning of 8/27 but pickup not seen at o



Next Steps and Future Research

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- Continuing model development
- Formal evaluation of model improvements using V&V process and year-long baseline and improved simulations
- Development of decision support tools:
  - Fully probabilistic alerts
  - Phenomenon-specific forecasts will carry significant uncertainty, which must then be communicated to users
  - Evaluation will require standard methods for verification of probabilistic forecasts of binary and possibly multi-category event types
    - Contingency analysis (hit, miss, and false alarm rates)
    - Event-based summary metrics (equitable threat score)

Example alerts

09:00 – 12:00: Wind Project: Klondike

ALERT: 7 in 10 chance of stable cold pool mix-out leading to *power up-ramp*

12:00 – 15:00: Wind Project: Klondike

ALERT: 3 in 10 chance of mountain wave induced *power volatility (up/down)*

ATMOSPHERE TO ELECTRONS
U.S. DEPARTMENT OF ENERGY

Data Archive and Portal

Chitra Sivaraman

Project Overview

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

Challenge

In 2014, the Wind Program lacked the capability to preserve, archive and provide access to data generated by projects or PIs. The data were stored in home institutions. The lack of standardized access to data was impeding R&D progress and, in some cases, led to duplicative laboratory and field measurements and was vulnerable to loss.

Vision

To provide **secure**, **timely**, **easy**, and **open** access to all laboratory, field, and benchmark model data produced by the Atmosphere to Electrons (A2e) Initiative.

Objectives

The Data Archive and Portal (DAP) will **collect, catalog, process, store, preserve, and disseminate** all significant A2E data while conforming to or helping define industry data **standards**.

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- **Information synthesis and dissemination**
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

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The Impact

- Provide centralized access to 11 projects – historical datasets, field studies, model output
- 100+ users
- Enables collaboration
- Enables scientific discovery
- Leverages existing best practices and standards
- Real-time analysis
- 81 TB of data
- Expected growth to PB's

DAP: Planning the Technical Approach

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Name	Organization
Tom Boden	Oak Ridge National Lab (ORNL)
Ann Brennan	National Renewable Energy Lab (NREL)
Mike Hagengruber	Sandia National Labs (SNL)
James Myers	University of Michigan
Alex Pothen	Purdue University
Rob Ross	Argonne
Chitra Sivaraman, Lead	Pacific Northwest National Lab (PNNL)
Dean Williams	Lawrence Livermore National Lab (LLNL)
Glenn Rutledge	National Oceanic and Atmospheric Administration (NOAA)/National Climatic Data Center

Planning Process

- Planning group a spectrum of national data management experts
- Weekly planning calls in 2014
- DAP Workshop at PNNL, July 28-29, 2014
- Formal Data Archive and Portal (DAP) strategy report: September 30, 2014.

Platforms Reviewed

ARM Climate Research Facility; Earth System Grid Federation; Globus; Open Energy Information; Sustainable Environment Actionable Data

Project Plan and Schedule - 2014

Sept. 2014 | **Dec. 2014** | **Spring 2015** | **Summer 2015**

Strategy Report

Field study registration

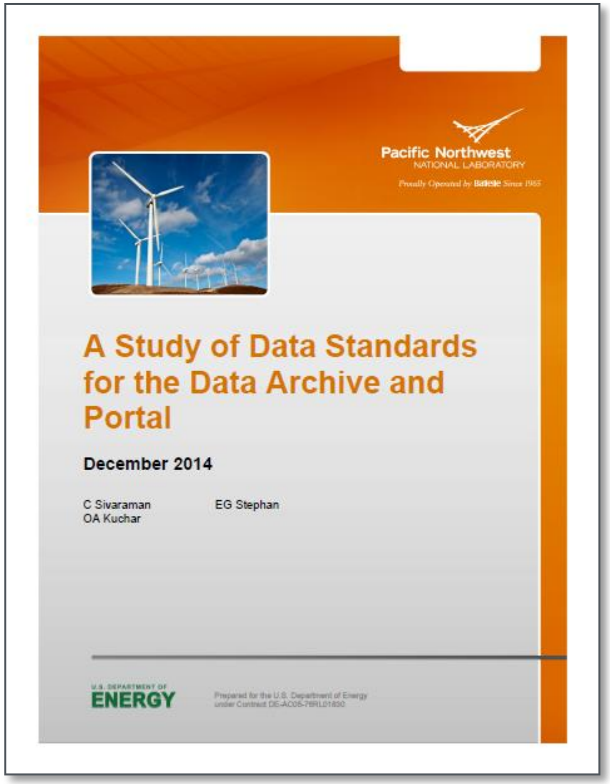
Upload and download data

Industry Standards Report

Providing leadership for field studies

No milestones were missed

DAP: First Step - Data Standards



Purpose: provide a review of the existing industry data standards.

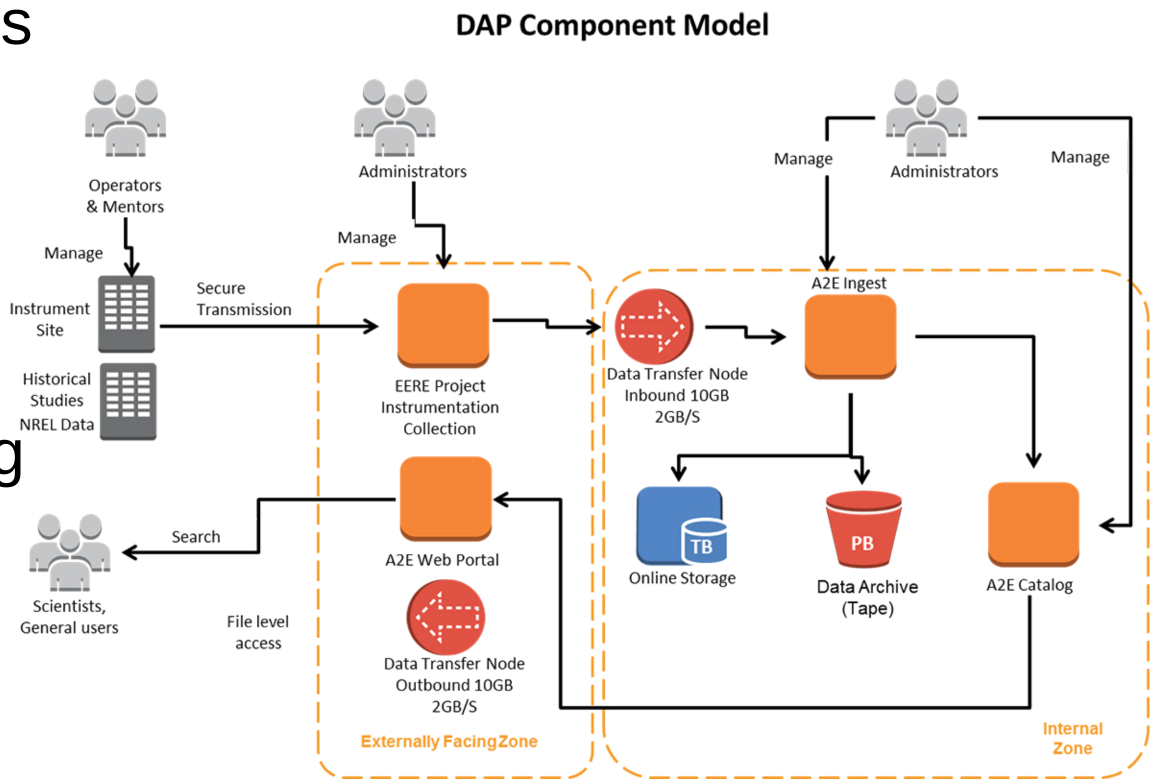
- Developing standards is crucial to providing interoperability among independently developed data to enable model runs and community interaction.

Summary of off the shelf standards that can be adopted

Requirement	Wind Energy Standards	Atmosphere Standards
Machine-readable format	Adopt	Adopt
Standardized format	Adopt	Adopt
Multiple representations	Identify	Identify
Metadata documentation	Adopt	Adopt
Community vocabularies	Adopt	Identify
Persistent identifiers	Identify	Identify
Data quality metrics	Adopt	Adopt
Data provenance availability	Adopt	Identify
Data security	Adopt	Identify
Data citable	Identify	Adopt
Data archival	Identify	Identify
Data catalog	Adopt	Adopt
Catalog search	Identify	Identify
Data usage	Adopt	Identify

DAP: Registry Model Features

- Definitions vetted by international standards bodies
- Customizable and extensible
- Low maintenance
- Allows for participating projects to provide either minimal or extensive information about the study.



Project Plan and Schedule - 2016

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December 2015	March 2016	June 2016	September 2016
• Support capability to upload and download data • Support WFIP 2 users	• 2-factor authentication for proprietary datasets and successful web penetration tests (security plan)	• Published open data to data.gov • Submitted wire frames for a2e.energy.gov	• Assigned DOIs for published data • Completed development of video by NREL team

Continuous monitoring of data flow and user support

No milestones were missed

DAP - Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$0	$0	$402.667k	$0	$631.819k	$0

- The FY15 budget was $402.667k. Of that amount, $101.819k carried over into FY16. The FY16 budget was $530k + $101.819k c/o = $631.819k. The unspent balance of $202.024k will carry over into FY17.
- 78.4% of the budget was spent through September 30, 2016.
- There are no additional funding sources.

Integration and Collaboration

Partners, Subcontractors, and Collaborators: University of Michigan, Amazon Web Services, NREL, Participants from field studies such as XPIA, MMC, WFIP2.

Users
- 83 Active users

Projects
- 15 projects – proprietary and open
- Seven sub-projects for WFIP2

Files
- 3,589,644 AWS
- 739,128 HRRR
- 18,593 WFIP 2 model

Volume
- 5 TB - AWS
- 25 HRRR
- 51 WFIP 2 model

Impact

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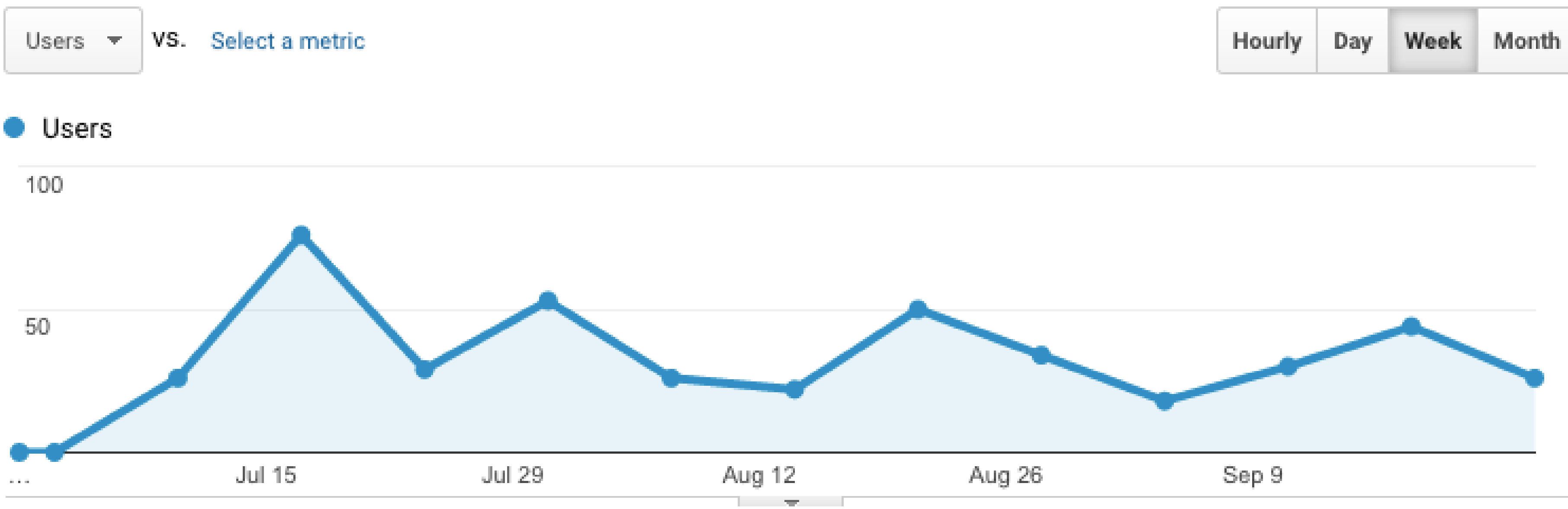

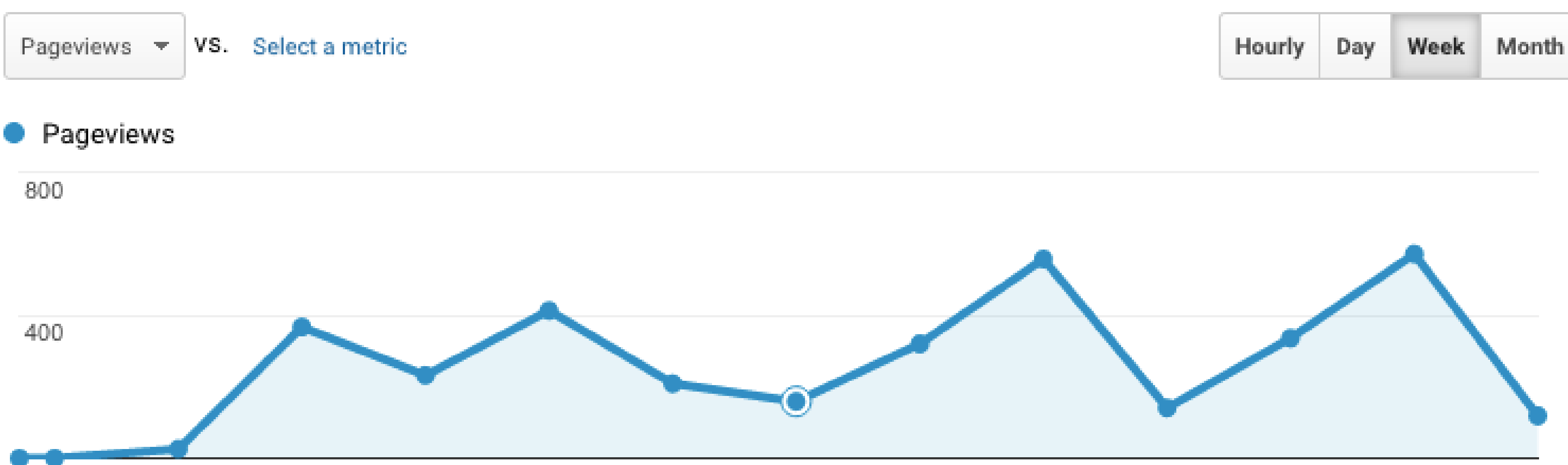

Future Capabilities

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- Convert data to standard format, and apply min, max, and delta quality checks
- Design framework for applications of advanced algorithm
- Install tools to document data quality
- Advanced search and discover capabilities
- Provide a mechanism to share data and information (Confluence/Google Drive)
- Create community to share success stories
- Code repositories
- EU Collaboration

Next Steps

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December 2016	March 2017	June 2017	September 2017
• Support WFIP2 to create standardized datasets as input to model • Develop metrics dashboard	• Support PRUF and WAKE Steering Experiment • Easier access to model data on Institutional Computing	• Additional easier method to download and upload data	• Search and discover capabilities

Day-to-day operations: manage versions of datasets, registration, missing metadata, user support, security patches, etc.

Long-term Goal

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

2016 — 2022

- 81 TB Data
- 15 Projects
- Upload/Download
- Web Presence
- Proprietary Data Collaborations

- PBs Data
- Advanced Data Capabilities
  - Extraction
  - Visualization
  - Analysis
  - Discovery
- Multi-site Data Store
- Active User Community

Distributed Wind Research, Development, and Testing

Patrick Gilman
Distributed Wind Team Lead

February 15, 2017

Enabling Wind Nationwide

Enabling U.S. Industry Growth and U.S. Competitiveness

- **GOAL**: Reduce the unsubsidized market levelized cost of energy (LCOE) for utility-scale land-based wind energy systems from a reference wind cost of $0.074/kWh in 2012 to $0.057/kWh by 2020 and $0.042/kWh by 2030.
- **GOAL**: Reduce the unsubsidized market LCOE for offshore fixed-bottom wind energy systems from a reference of $0.18/kWh in 2015 to $0.15/kWh by 2020 and $0.096/kWh by 2030.

Enhancing U.S. Energy Security and Independence

- **GOAL**: Accelerate widespread U.S. deployment of clean, affordable, reliable, and domestic wind power to promote national security, economic growth, and environmental quality.

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- **GOAL**: Expand the geographic development potential of wind power plants in the United States, particularly in offshore zones and the U.S. Southeast.

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- Communicating the costs and benefits of wind energy

Wind Energy Technologies Office *Structure*

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

Wind Energy Technologies Office (WETO)
Jose Zayas, Director
Jim Ahlgrimm, Deputy Director

- Wind Research and Development — **Mike Derby**
  - Manufacturing, Reliability, Testing and Facilities — **Megan McCluer**
  - Resource Characterization — **Joel Cline**
  - Aerodynamics and Components — **Vacant**
  - Offshore Demos and R&D — **Alana Duerr**
  - Distributed Wind — **Patrick Gilman**
- Modeling and Analysis — **Patrick Gilman**
- Market Acceleration and Deployment — **Jocelyn Brown-Saracino (acting)**
  - Siting, Radar, and Environmental — **Jocelyn Brown-Saracino**
  - Stakeholder Engagement — **Maggie Yancey**
- Grid Systems Planning and Operations — **Charlton Clark**
  - Grid Systems Planning and Operations — **Jian Fu**
- Project Management and Operations
  - Golden Field Office — **Gary Nowakowski**
  - Operations — **Shane Beichner**

What is Distributed Wind?

Some definitions

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

- Distributed wind (DW) competes with residential solar and retail electric rates.
- By units sold**, small wind technology** is most frequently deployed.

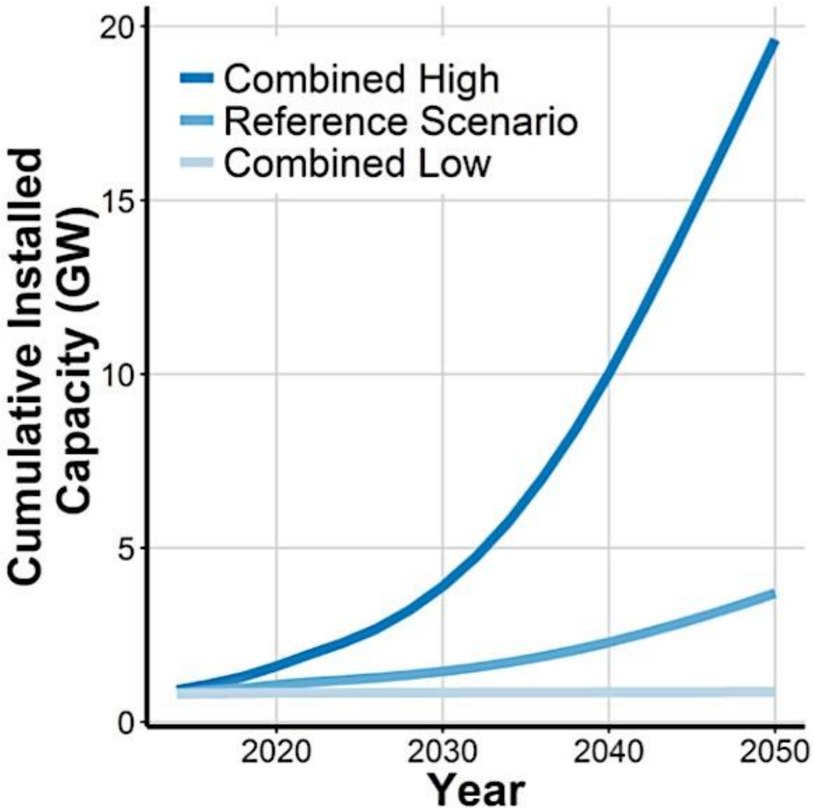
Courtesy of NREL

Courtesy of Pika Energy

Courtesy of Patsy McEnroe

Courtesy of Aegis Renewables

Distributed wind can play a significant role in the U.S. electricity sector.



Cumulative Installed Capacity (GW)

Scenario	2015	2030	2050
Low	0.9	0.9	0.9
Reference		1.5	3.7
High		3.9	20

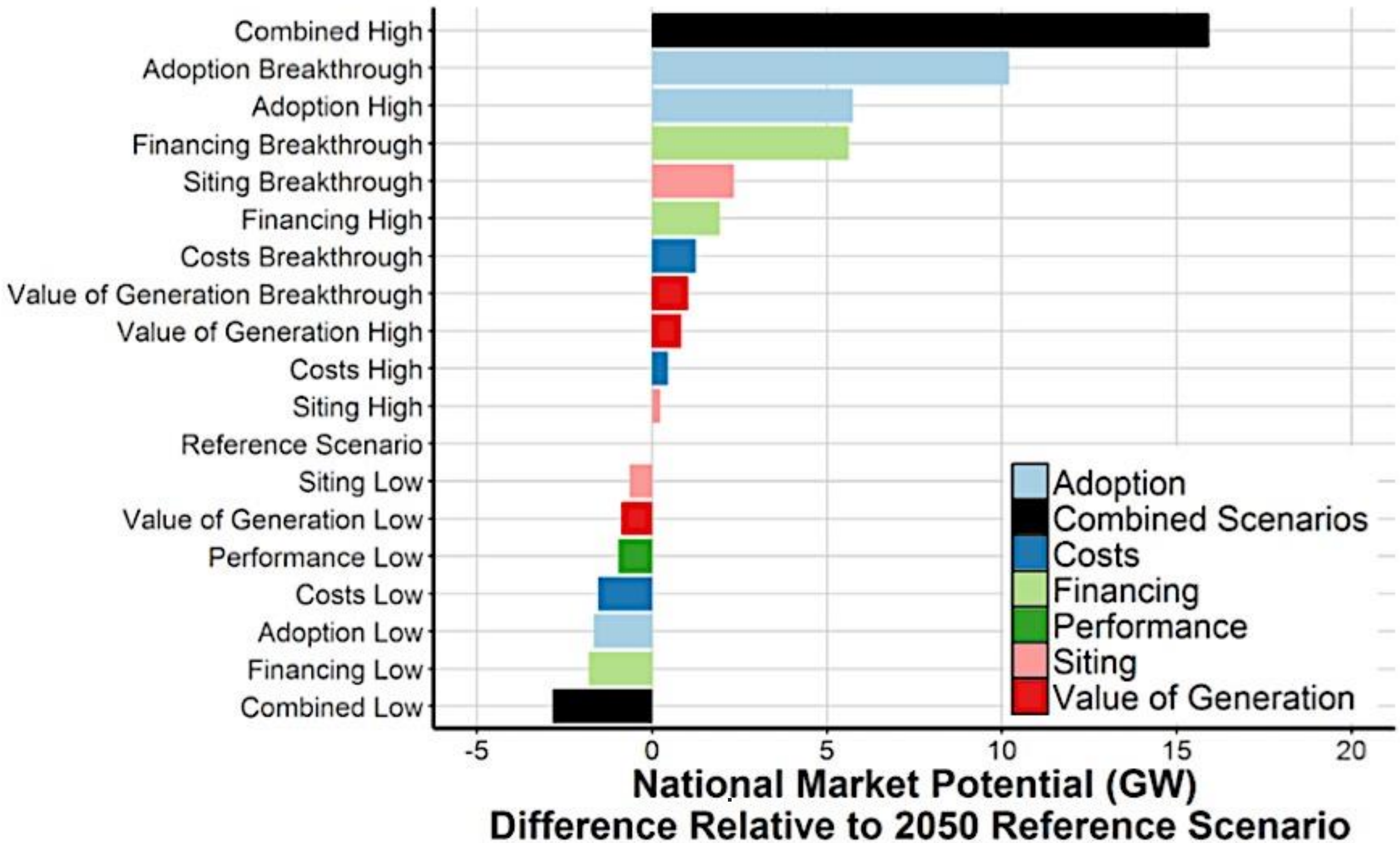
Assessing the Future of Distributed Wind: Opportunities for Behind-the-Meter Projects (NREL 2016)

The addressable resource potential for distributed wind turbines of less than 1 megawatt in size is estimated at 3 terawatts (TW) of capacity or 4,400 TW-hours (TWh) of generation—**more electricity than the United States consumes in a year.**

Achieving U.S. Market Potential

Levers

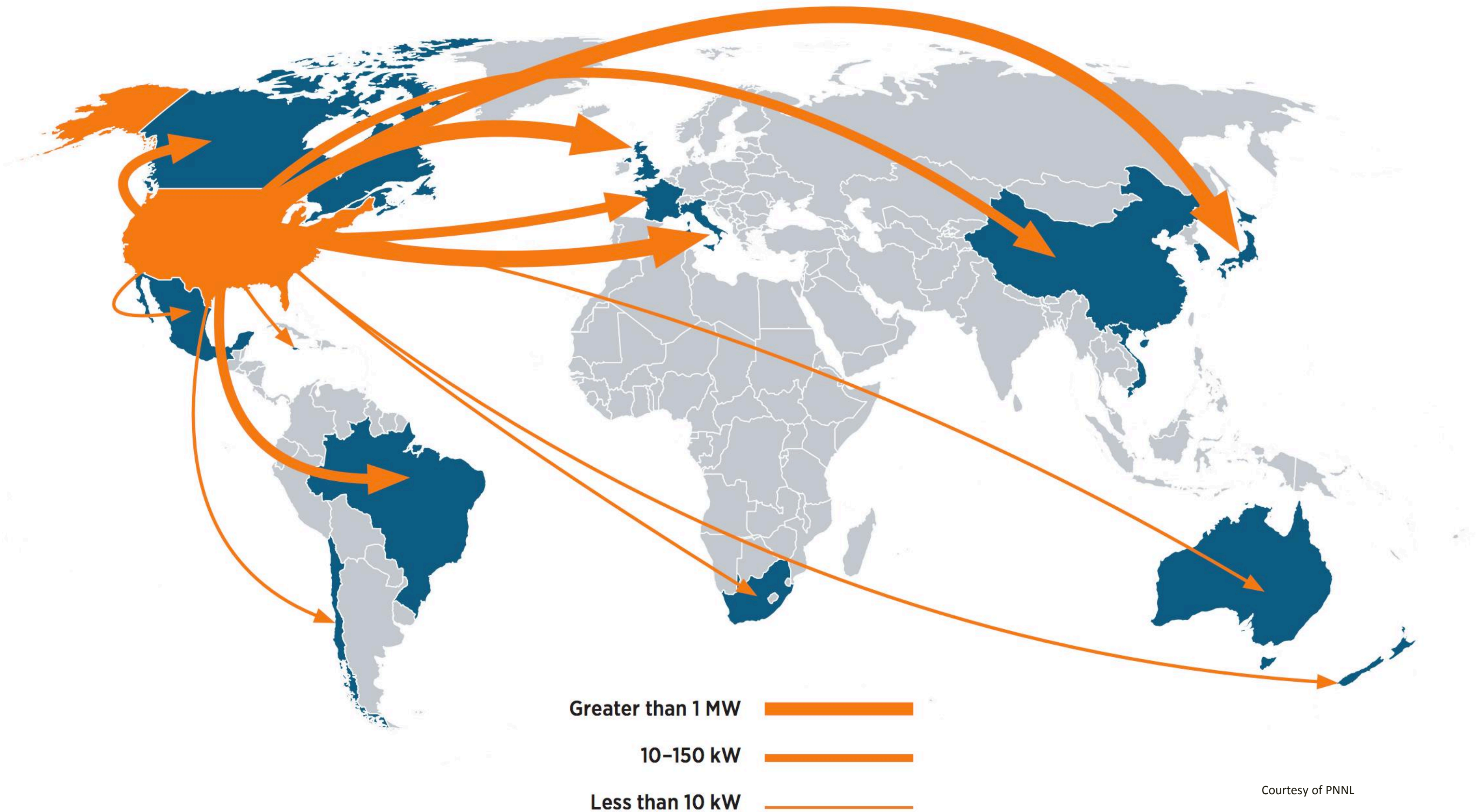
Analysis and stakeholder feedback shows action will be required across a number of strategic focus areas.



U.S. Distributed Wind Market

Small Wind Exports

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



U.S. small wind manufacturers are selling into markets with feed-in tariff programs. There is also potential in Asia Pacific markets and developing nations where there are tens of thousands of island and remote communities that require electrification; however, quality assurance and stable policy are risks.

Distributed Wind Portfolio

Strategic focus areas

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

Distributed Wind Research Development and Testing *(3:55pm)*	Ian Baring-Gould
Market Assessment & Analysis	
Annual Distributed Wind Market Report dWind Diffusion Model Development and Scenario Analysis	Alice Orrell Eric Lantz
Soft Costs	
Distributed Wind Costs Taxonomy Report Distributed Wind Costs Benchmark and Reduction Opportunities Report	Suzanne Tegan Tony Jimenez
Resource and Performance Assessment	
Deployment of Wind Turbines in the Built Environment: Risks, Lessons & Recommended Practice (NASA Building 12 & IEA Task 27) Small Wind Site Assessment Guidelines Distributed Wind Resource Assessment: State of the Industry	Jason Fields Heidi Tinnesand Tim Olson
Competitiveness Improvement Projects *(4:15pm)*	Ian Baring-Gould
Turbine Technology & Consumer Confidence	
Turbine Testing (prototype and certification) Advanced Manufacturing Component and System Optimization	Karin Sinclair Robert Preus

Strategic Focus Areas

Challenges, goals, and approach

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

Strategic Area	Challenges	Goals	Approach
Market Assessment and Analysis	**Consistent access to trustworthy data to inform future investment decisions. Inability to confidently quantify U.S. Distributed Wind market potential.**	Report annually on distributed market trends and confidently quantify market growth potential.	• **Collect, store and analyze market data** • **Diffusion model development and scenario analysis.**
Soft Costs	**Non-hardware or "soft" costs are not document for distributed wind systems and cost reduction opportunities are not well understood.**	Establish a baseline for distributed wind soft costs and identify cost reduction opportunities.	• **Establish DW Cost taxonomy** • **Interview installers to collect detailed project cost data.**
Wind Resource and Performance Assessment	**Utility-scale site assessment, specifically resource assessment, is too costly and time consuming for distributed wind project development leading performance assessments that are not bankable.**	Facilitate business models that access low cost capital by accurately predicting distributed wind system performance.	• **Convene industry experts to document state of the art** • **Reduce performance assessment error.**
Turbine Technology	**Small and medium wind turbine technology is not optimized distributed applications, outdated, and struggles to be cost competitive with other distributed generation technologies.**	Develop and certify low wind speed optimized, lower cost small and medium wind turbine designs.	• **Support design optimization** • **Facilitate utilization of advanced manufacturing.**
Consumer Confidence	**Adoption of distributed wind systems has been hindered by untested technologies, unverified claims about turbine performance, and equipment failures.**	Increase confidence in and appeal of distributed wind system to consumers beyond "early adopters".	• **Support turbine certification testing** • **Educate stakeholders.**

Budget Summary

Total Budget			
FY2014	FY2015	FY2016	**Total FY2014-FY2016**
$2.1M	$5.4M	$0.7M	**$8.2M**

Peer Reviewed Budget			
FY2014	FY2015	FY2016	**Total FY2014-FY2016**
$1.8M	$5.4M	$0.7M	**$7.9M**
85%	*100%*	*100%*	***96%***

Distributed Wind Portfolio

History of priorities, activities, and accomplishments

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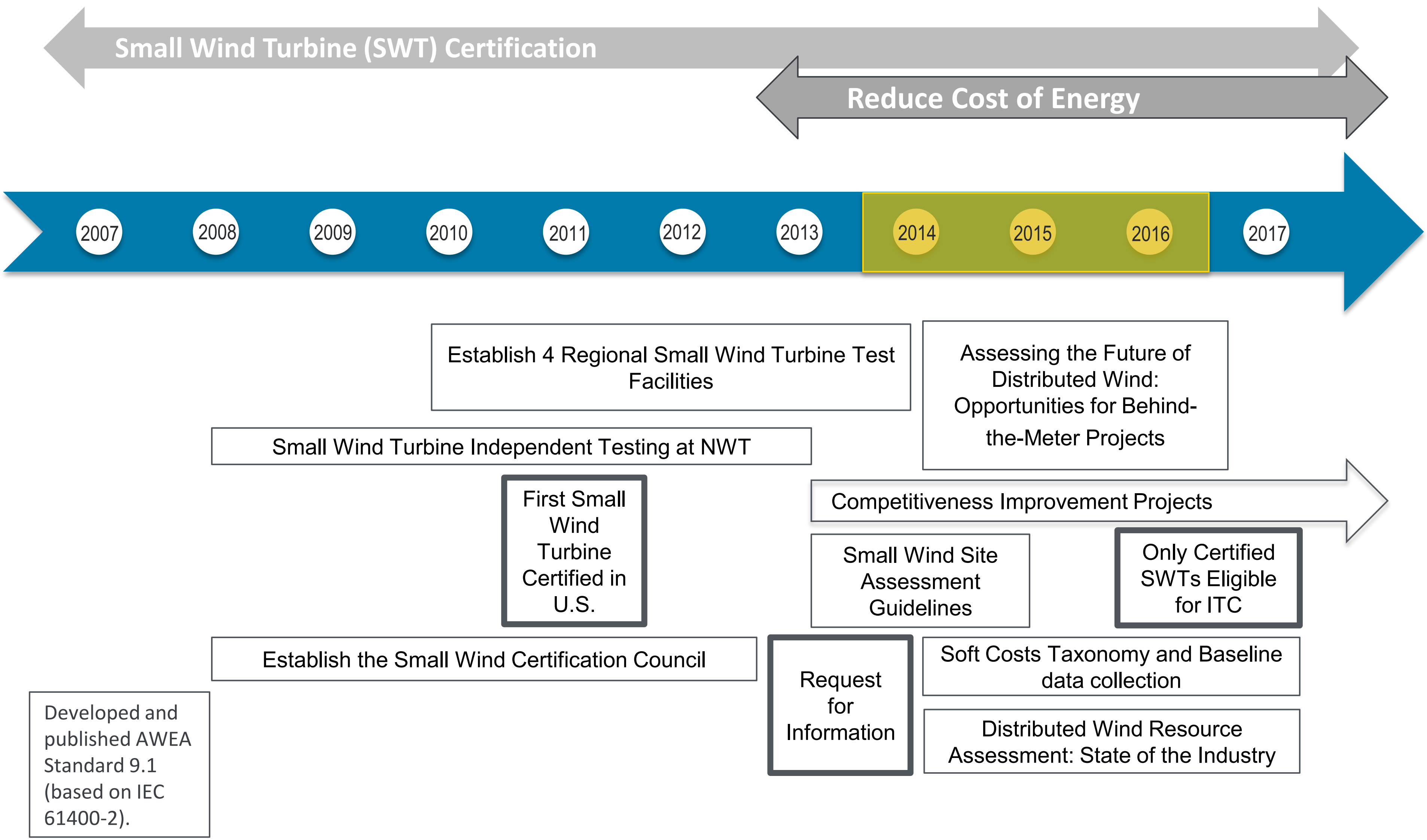

Photo from Robin and Duncan Ross, Arrowhead Spring Vineyards, NREL 26772

Photo from Northern Power Systems, NREL 16730

Photo from Pika Energy, NREL 33942

Distributed Wind Research Development and Testing

Ian Baring-Gould

National Renewable Energy Laboratory (NREL)

Ian.baring.gould@nrel.gov; (303) 384 7021

February 2017

Project Overview

Distributed Wind Research, Development, and Testing

Develop and implement activities, provide technical support, and conduct research in support of the wider distributed wind (DW) industry, focused on accelerating the appropriate deployment, expanding user confidence, and reducing the cost for DW systems.

Challenge: Technical, economic, and deployment barriers are limiting the contribution of DW systems to the domestic energy mix and U.S. manufacturers' ability to lead the competition in the expanding global market. The DW industry itself is primarily composed of small businesses that have significant resource limitations in terms of capital, staffing, and technical skills.

Partners: NREL works closely with DOE WETO and Pacific Northwest National Laboratory (PNNL) to implement research efforts and projects. Project leaders also collaborate very closely with the Distributed Wind Energy Association (DWEA) and wider DW industry to ensure that project efforts target industry needs.

Enabling Wind Energy Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- Reliability improvements
- Enabling access to better resources through tall wind
- **Distributed wind R&D**
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- **Information synthesis and dissemination**
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- Advanced technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- **Communicating the costs and benefits of wind energy**

Enabling Wind Energy Nationwide

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- NextGen component innovations

The Impact

Engaging with the distributed wind industry in efforts to reach cost parity across the wide range of DW technologies

Direct Impacts

- Direct support and leadership in industry initiatives such as the SMART Wind Consortium
- Updating and testing of design modeling tools, and better understanding of small turbine / tower operational dynamics
- Documenting the challenges of installing turbines in the built environment, including the difference in actual and estimated power output
- Support for IEA task 27, Small Wind Turbines in High Turbulence Sites, eventually leading to improved standards
- Support for IEEE 1547 standards development.

Indirect Impacts

- Reduced life-cycle cost products, expanding competitiveness.

Enabling Wind Energy Nationwide

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
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- Advancing grid integration

The Impact

Engaging with the distributed wind industry to better understand market benefits, challenges, potential, and costs, directing future research and supporting market adoption

Direct Impacts

- Development of the DW Jobs and Economic Development Impacts (JEDI) model
- Development of DW full system cost taxonomy, cost breakouts, and soft cost reduction opportunity assessment
- Developed "DW Resource Assessment: State of the Industry" report, highlighting current practices and recommendations to improve DW resource assessment (DWRA) and performance prediction
- Developed dWind, the first DW diffusion model enabling national assessment of the behind-the-meter market for DW.

Indirect Impacts

- More competitive U.S. products and installations, expanding manufacturing, exports, and U.S. leadership in the world market.

Enabling Wind Energy Nationwide

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- Advanced-technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- **Communicating the costs and benefits of wind energy**

The Impact

Engaging with the distributed wind industry and other national stakeholders from across the deployment space to increase DW market adoption

Direct Impacts

- Development of best practice guides for siting of DW technologies
- Drafting of the first behind-the-meter market assessment for DW, allowing a better understanding of long-term market potential and conditions under which that potential could be realized.

Indirect Impacts

- Providing resources to the DW industry to articulate the development potential of behind-the-meter DW deployment, potentially leading to a DW industry that provides good U.S.-based manufacturing jobs and local economic development, and enables American homes, small business, government, and industry to support locally deployed wind energy, leading to the potential deployment of 20 GW of locally installed wind by 2050.

DW Challenges

DW technology is not widely cost competitive or deployed in a great enough volume to allow industry growth and sustainability. The many challenges include the following:

- High technology development and certification costs relative to current sales volume **(It costs too much to innovate!)**
- Lack of knowledge of the DW market **(What and where are we deploying anyway?)**
- Lack of long-term DW market understanding and associated credible analysis tools **(How big is it and where do we focus?)**
- High hardware and non-hardware costs **(It just costs to much!)**
- Lack of understanding and design tools **(It's still to much of a trial-and-error industry!)**
- No "good" approach to cost-effective DW resource characterization and overall poor actual performance **(How good – or bad – is the wind resource really?)**

Core Principles

- Work in collaboration with partners to better understand the challenges and then address the "low-hanging fruit"
- Leverage, to the extent possible, industry knowledge, expertise, and funding through competitively awarded projects to increase impact
- Understand that resources are scarce in relation to the level of the problem, it's better to make small progress across a broad front rather than diving deeply into only one area and making no progress in others

Programmatic Approach

Based on a great deal of industry feedback, in 2015, NREL and PNNL in partnership with WETO developed a new programmatic plan to holistically address the challenges faced by the DW industry. These have been previously presented during the Program overview.

Previous DOE Investment to Establish Technical Quality Assurance

Standards

IEC
AWEA AMERICAN WIND ENERGY ASSOCIATION

Test Facilities

NREL
HIGH PLAINS Small Wind Test Center
WINDWARD ENGINEERING
aei
Intertek

Certification Bodies

SMALL WIND CERTIFICATION COUNCIL (SWCC)
Intertek

International Harmonization

iea

IREC Interstate Renewable Energy Council, Inc.

Certified Small Wind Turbine Model Ratings

Applicant	Turbine	Certifier	Rated Annual Energy[1] @ 5 m/s	Rated Sound Level[2]	Certified Power Rating[3] @ 11 m/s
Bergey Windpower	Excel 6	SWCC	9920 kWh	47.2 dB(A)	5.5 kW
Bergey Windpower	Excel 10	SWCC	13,800 kWh	42.9 dB(A)	8.9 kW
Eveready Diversified Products	Kestrel e400nb	SWCC	3,930 kWh	55.6 dB(A)	2.5 kW
Kingspan Environmental	KW6	SWCC	8,950 kWh	43.1 dB(A)	5.2 kW
Osiris Technologies	Osiris 10	Intertek	23,700 kWh	49.4 dB(A)	9.8 kW
Pika Energy	T701	SWCC	2420 kWh	38.3 dB(A)	1.5 kW
Sonkyo Energy	Windspot 3.5	Intertek	4,820 kWh	39.1 dB(A)	3.2 kW
Sumec Hardware & Tools Co	PWB01-30-48	Intertek	2,920 kWh	41.1 dB(A)	1.2 kW
Sumec Hardware & Tools Co	PWA03-44-48	Intertek	6,400 kWh	40.9 dB(A)	3.2 kW
Sumec Hardware & Tools Co	PWB02-40-48	Intertek	4,660 kWh	36.9 dB(A)	1.7 kW
Sumec Hardware & Tools Co	PWA05-50-280	Intertek	9,240 kWh	42 dB(A)	5 kW
Xzeres Wind Corp	442SR	SWCC	16,700 kWh	48.5 dB(A)	10.4 kW
Xzeres Wind Corp	Skystream 3.7	SWCC	3,420 kWh	41.2 dB(A)	2.1 kW

Courtesy of Interstate Renewable Energy Council

Distributed Wind
Next Generation Technology Development

Increased Energy Production

CIP *system optimization* awardee Northern Power Systems of Barre, Vermont, achieved a 15% energy production increase for the NPS-100 100-kilowatt turbine by increasing blade length and improving blade aerodynamics.

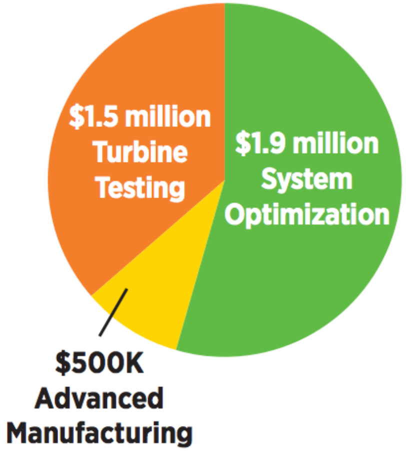
Reduced Hardware Costs

CIP *advanced manufacturing* awardee Pika Energy of Westbrook, Maine, reduced blade costs by approximately 90% by developing an innovative tooling and cooling strategy to produce blades using injection-molded plastic.

Certified Turbine Performance & Safety

Four CIP *turbine certification* awardees are testing their turbine designs to national standards. Turbine certification requires third-party verified testing for safety, function, performance, and durability to national standards.

As of May 2016, DOE and NREL awarded 16 subcontracts to nine manufacturers, totaling $3.9 million of investment across three topic areas



Endurance Windpower (Seattle, WA)

Northern Power Systems (Barre, VT)

Bergey Windpower (Norman, OK)

Pika Energy (Westbrook, ME)

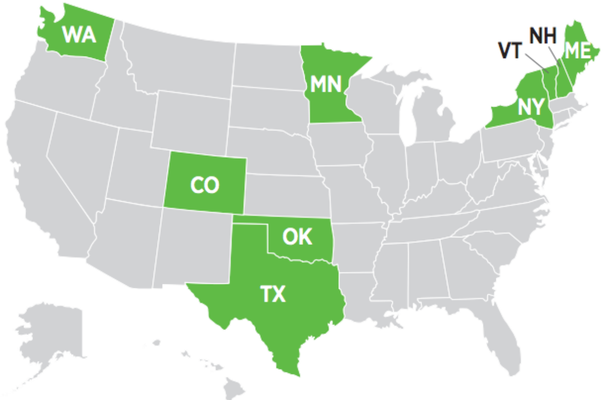
Primus Windpower (Lakewood, CO)

Ventera Wind (Duluth, MN)

Urban Green Energy (NYC)

Intergrid (Temple, NH)

Wetzel Engineering (Round Rock, TX)



Courtesy of NREL

Accomplishments

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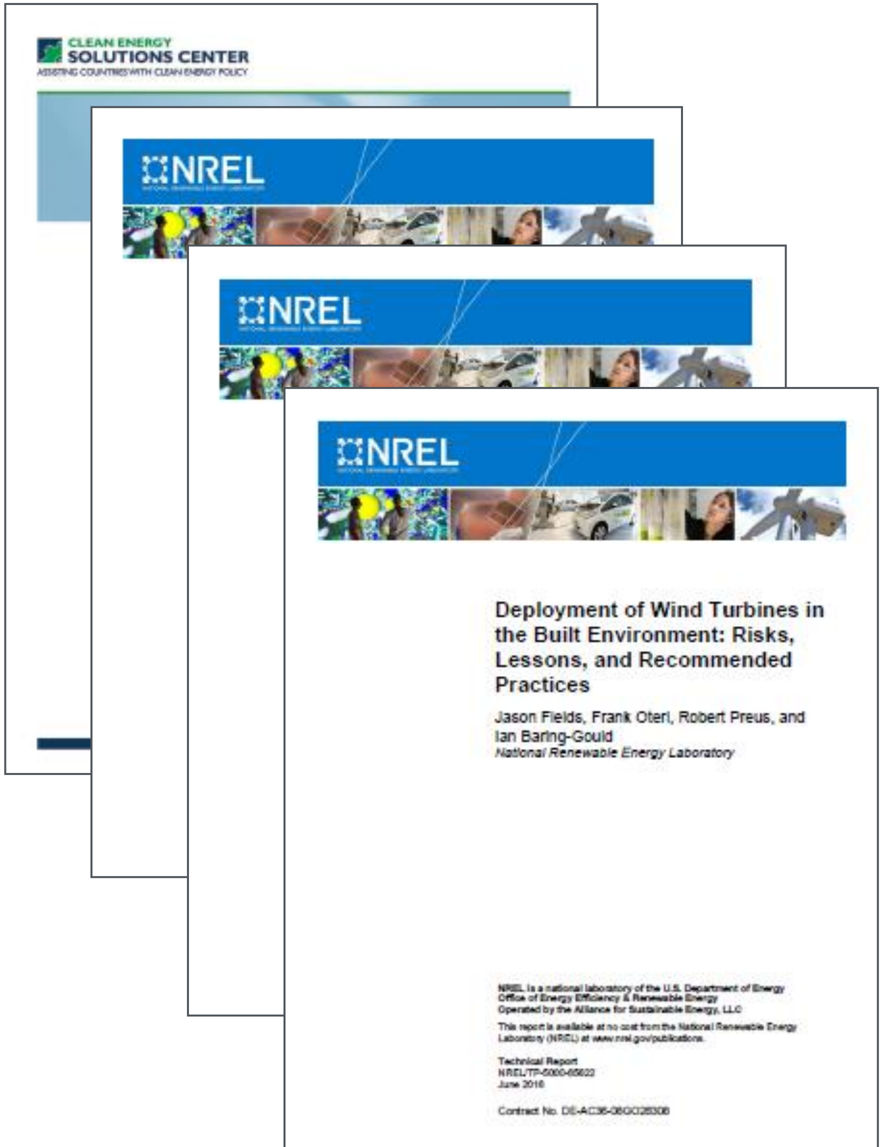
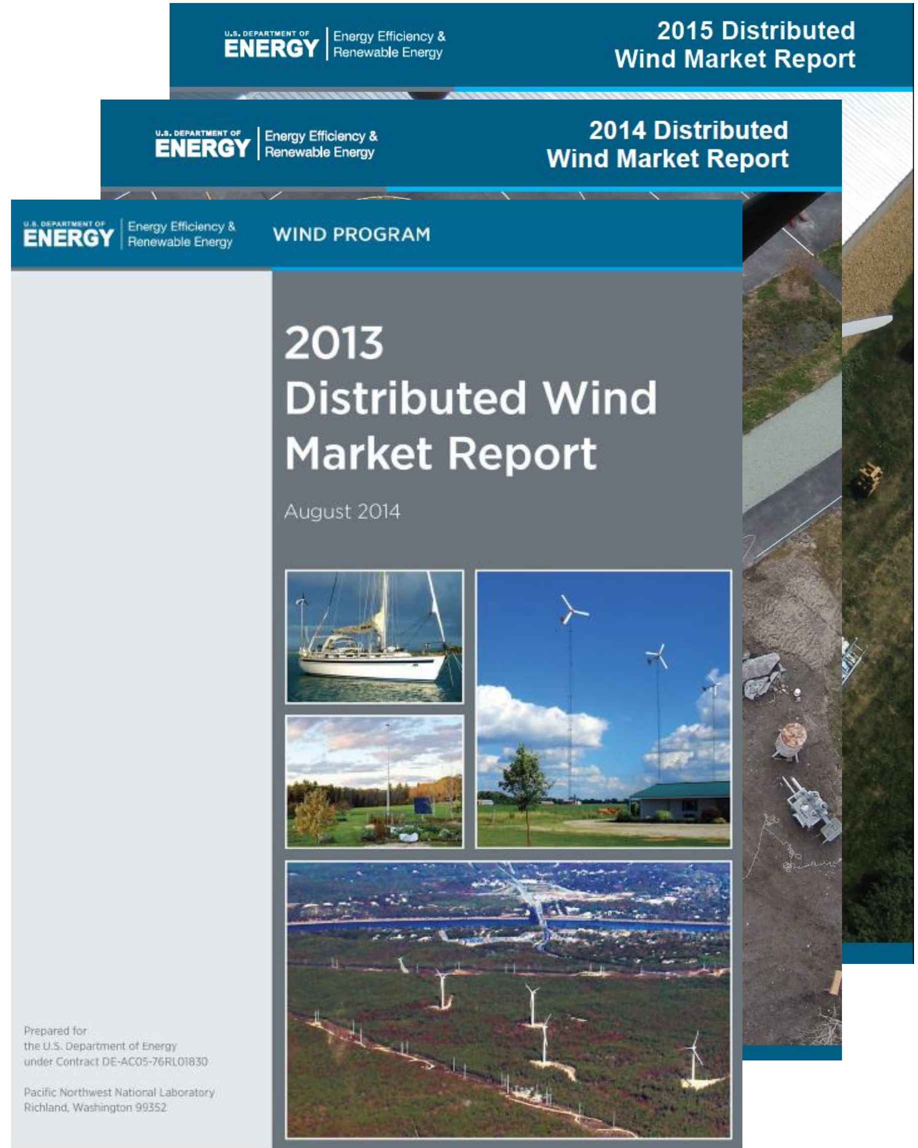




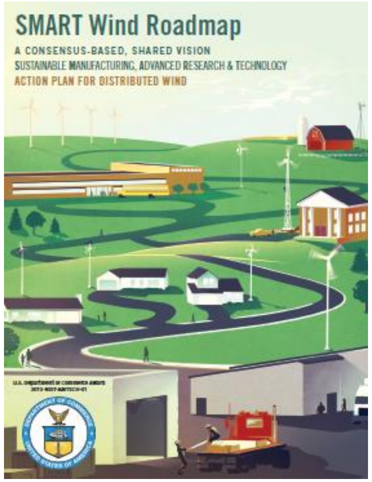
Progress – Developing Insight

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

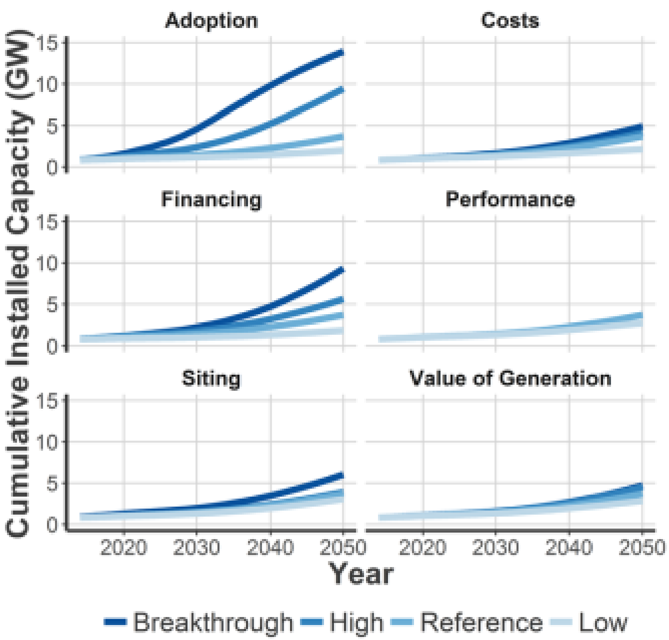
Knowledge about industry needs and paths forwards have been a focus for the last two years

DW Resource Assessment Needs and Impact Matrix

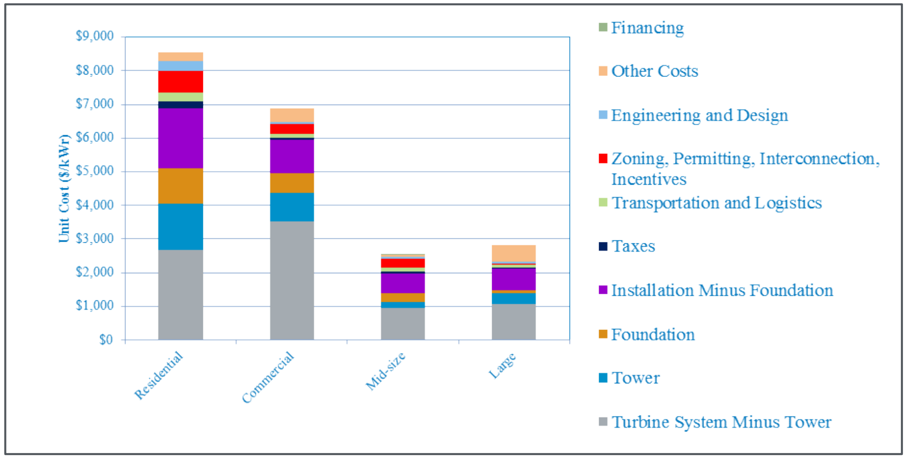
Tier	Improvement Opportunity	Cost of Assessment	Consumer or End User Confidence	Performance Estimation	Improving Characterization of Site Suitability	Level of Effort Required
Tier 1	Data Access	Major	Minor	Major	Major	Moderate
Tier 1	Validation & Benchmarking	Minor	Major	Major	Minor	Moderate
Tier 1	Education & Outreach	Major	Major	Major	Major	Low
Tier 2	Atmospheric Model Input Data	Major	Minor	Major	Minor	Low/Moderate
Tier 2	Measure-Correlate-Predict (MCP)	Minor	Minor	Major	Major	Low
Tier 2	Downscaling Methods	Minor	Minor	Major	Major	Moderate /High
Tier 2	Standardization	Minor	Major	Moderate	Moderate	Low
Tier 3	Site Suitability Assessment	Minor	Major	Major	Major	Moderate /High
Tier 3	Low-Cost Instrumentation	Minor	Major	Major	Major	High



Assessing the Future – Single Variable Sensitivities Low - Breakthrough Inputs



Detailed DW Cost Taxonomy and Initial Full System Cost Assessment



Project Plan & Schedule

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

Ongoing; project merit reviewed in FY15; expected completion in FY18, although ongoing work expected.

All milestones met, although some were delayed due to process and staffing issues. All FY16 milestones met and were within budget.

Go / No-Go milestones in relation to Regional Testing and Market Model Development were met and continued activities were recommended.

Project Budget

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

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-Share	DOE	Cost-Share	DOE	Cost-Share
$1,563.315k	$0	$ 872.252k	$0	$ 993k	$0

- Funding decrease in FY15 largely mitigated by carryover and the end of several projects
- 115% of budget expended between FY14 to FY16 due to a large amount of FY14 carryover
- Extensive industry collaboration, but limited formal cost-share. Industry cost-share expected to increase as more outward-focused work is implemented in future years.

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators

Subcontractors and Partners include: Marshall Goldberg (developer of JEDI modules), the Wind Advisors Team for data collection and analysis, eFormative Options, and the Small Wind Certification Council. The DW team collaborates with many other organizations including American Wind Energy Association, DWEA, New York State Energy Research and Development Authority (NYSERDA), and the broader distributed-wind industry.

Communications and Technology Transfer

Extensive outreach efforts have been undertaken throughout the project period, and multiple presentations given at several conferences each year, including the Small Wind Installers Conference, DWEA siting and business conference, and AWEA WINDPOWER. Workshops also have been held on market modeling, soft costs, and resource assessment to expand industry collaboration. Multiple webinars on industry topics, including the “DW Market Report,” held annually. Numerous technical reports have been developed, including the annual market report (< 8,100 downloads), siting guidelines and best practices (< 500), built environment (< 650), DW JEDI and national wind resource maps (< 42,000 pageviews in 2015).

Next Steps and Future Research

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

FY17 / Current Research

Many activities are planned for FY17 including the publication of a DW taxonomy and initial soft-cost benchmarking, publication of technical reports on the DW market projections identifying industry improvement needs, launching of a DW installers collaborative to help identify and then implement soft-cost reduction options, a DW workshop for federal agencies to support appropriate deployment, and implementation of near-term resource assessment tools to support project developers.

Planned Future Research

The path set out in 2015 remains solid, combining knowledge gained in markets, soft costs, manufacturing, and resource assessment, working jointly with the wider DW industry to address issues through a combination of laboratory and competitively solicited actions focused on addressing defined challenges. The program also will develop impact metrics for all research areas to aid understanding of the value of DOE's investment.

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

Competitiveness Improvement Project

Distributed Wind Research and Testing

E. Ian Baring-Gould

National Renewable Energy Laboratory (NREL)

Ian.baring gould@nrel.gov 303 384 7021

February 2017

Project Overview

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

Competitiveness Improvement Project: A competitive cost-shared solicitation for manufacturers of small and medium wind turbines to optimize their designs, invest in advanced component development, implement advanced manufacturing processes, and perform certification turbine testing.

The Challenge: The rapidly reduced costs of PV are hitting the U.S. distributed wind market hard, requiring rapid innovation in an industry that has limited resources to undertake that innovation independently.

Partners: NREL collaborates closely with the Wind Energy Technologies Office in the determination of specific technical focuses and then with the Distributed Wind Energy Association to insure that information about the Competitiveness Improvement Project (CIP) project is readily available and targets industry needs.

Program Strategic Priorities

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

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- Reliability improvements
- Enabling access to better resources through tall wind
- **Distributed wind R&D**
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

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Program Strategic Priorities

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The Impact

Direct programmatic goals:

- By 2020, increase the number of certified small and medium wind turbine models to 40 from a 2010 baseline of zero
- Reduce distributed wind (DW) system cost of energy to be competitive with retail electricity rates and other sources of distributed energy generation.

Industry impact: During the four cycles of CIP, solicitations and support for 16 awarded projects targeted at

- Certifying turbines for safety and performance
- Increasing energy production
- Reducing hardware hosts

Technical Approach

Technical Approach: Provide competitively selected cost-shared funding combined with direct technical support to the U.S. distributed wind industry, allowing technology innovation, advanced manufacturing, and turbine certification.

Key issue: Working with small, resource constrained companies has been difficult, especially around certification testing. Close contract monitoring and the provision of targeted technical assistance have addressed many of these issues, but it has been a learning process.

Unique Approach: To the extent possible, maintain an open solicitation process to allow original equipment manufacturers to propose innovative concepts.

Accomplishments and Progress

- 16 subcontracts over four rounds of CIP solicitations, engaging with nine companies
- $3.9 million in DOE finding, leveraging $2.3 million of industry cost share across three topical areas including turbine testing, system optimization and advanced manufacturing leveraging
- Early mutual discontinuation of two contracts due to technical complications

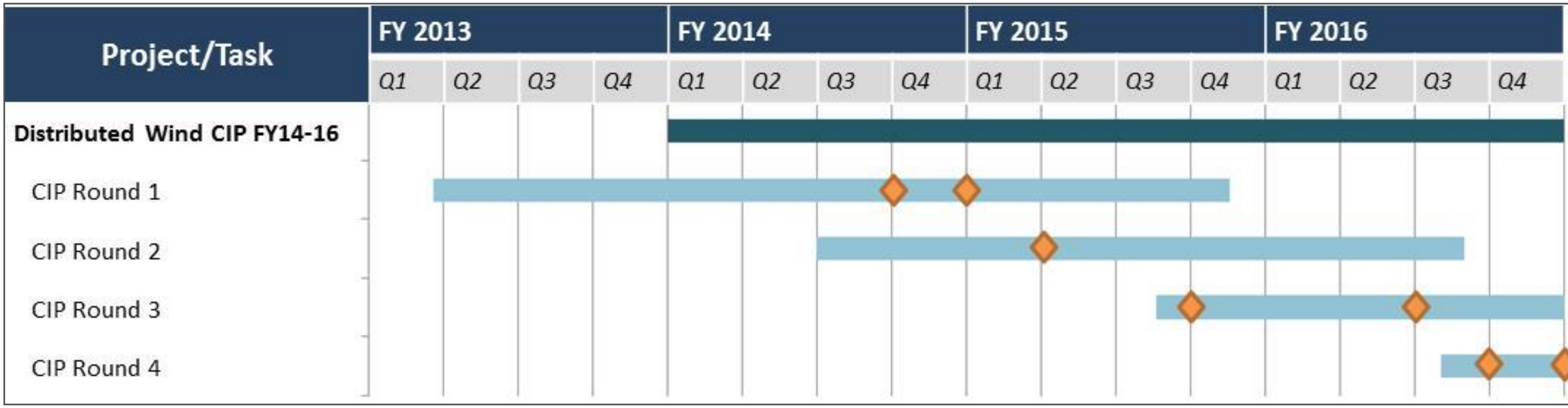
“The CIP program is helping us and other distributed wind original equipment manufacturers be more competitive and create more manufacturing jobs here in the United States.”
Michael Bergey, president, Bergey Windpower

Pika Energy of Westbrook, Maine, reduced blade costs by approximately 90% by developing an innovative tooling and cooling strategy to produce blades using injection-molded plastic.

Northern Power Systems of Barre, Vermont, achieved a 15% energy production increase for the NPS-100, 100 kW turbine by increasing blade length and improving blade aerodynamics.

Project Plan & Schedule

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



First round of CIP released in fall of 2012; Round 4 CIP projects expected to run through fall of 2017.

All process based milestones have been met.

Go/No-Go milestones have been process related, primarily decision points around holding additional rounds of the CIP project.

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$1,365.358k	$788.572k	$3,042.348k	$356.571k	$ 0.00	$828.931k

- End of FY15 funding allowed Round 4 CIP to be launched early in FY16.
- Each round of CIP is fully funded at the time of the solicitation.
- 85.9% of budget expended between FY14 to FY16. However, fiscal years do not match CIP contract expenditures.
- Levels of industry cost share dependent of solicitation cycle and topic area.

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

Subcontractors: Endurance Wind Power, Intergrid, Northern Power Systems, Pika Energy, Primus Wind Power, Urban Green Energy, Wetzel Engineering, Ventera Wind, Bergey Windpower Company.

Collaborators: Distributed Wind Energy Association

Communications and Technology Transfer:

Limited, but due to IP issues outreach generally needs to wait until after each CIP has been completed. Press releases and fact sheets have been the focus of current work but case studies will be developed in FY17.

Next Steps and Future Research

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

FY17/Current Research: Current FY17 plans expect to conduct a 5th round of solicitations. NREL will hold a formal industry forum in February to engage industry in future CIP efforts and increase outreach about the successes of the CIP efforts.

Planned Future Research: dWind modeling continues to show that life cycle cost reductions will be needed to enable the DW market. This points to ongoing rounds of competitive solicitations, potentially expanding areas of engagement as needed to support wider DW industry needs.

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Offshore Wind

Research, Development, Demonstration and Deployment; Technology; and Resource Characterization

Alana Duerr, Ph.D.
Offshore Wind Team Lead

February 16, 2017

Enabling Wind Nationwide

Enabling U.S. Industry Growth and U.S. Competitiveness

- **GOAL**: Reduce the unsubsidized market levelized cost of energy (LCOE) for utility-scale land-based wind energy systems from a reference wind cost of $0.074/kWh in 2012 to $0.057/kWh by 2020 and $0.042/kWh by 2030.
- **GOAL**: Reduce the unsubsidized market LCOE for offshore fixed-bottom wind energy systems from a reference of $0.18/kWh in 2015 to $0.15/kWh by 2020 and $0.096/kWh by 2030.

Enhancing U.S. Energy Security and Independence

- **GOAL**: Accelerate widespread U.S. deployment of clean, affordable, reliable, and domestic wind power to promote national security, economic growth, and environmental quality.

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- **GOAL**: Expand the geographic development potential of wind power plants in the United States, particularly in offshore zones and the U.S. Southeast.

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Wind Energy Technologies Office *Structure*

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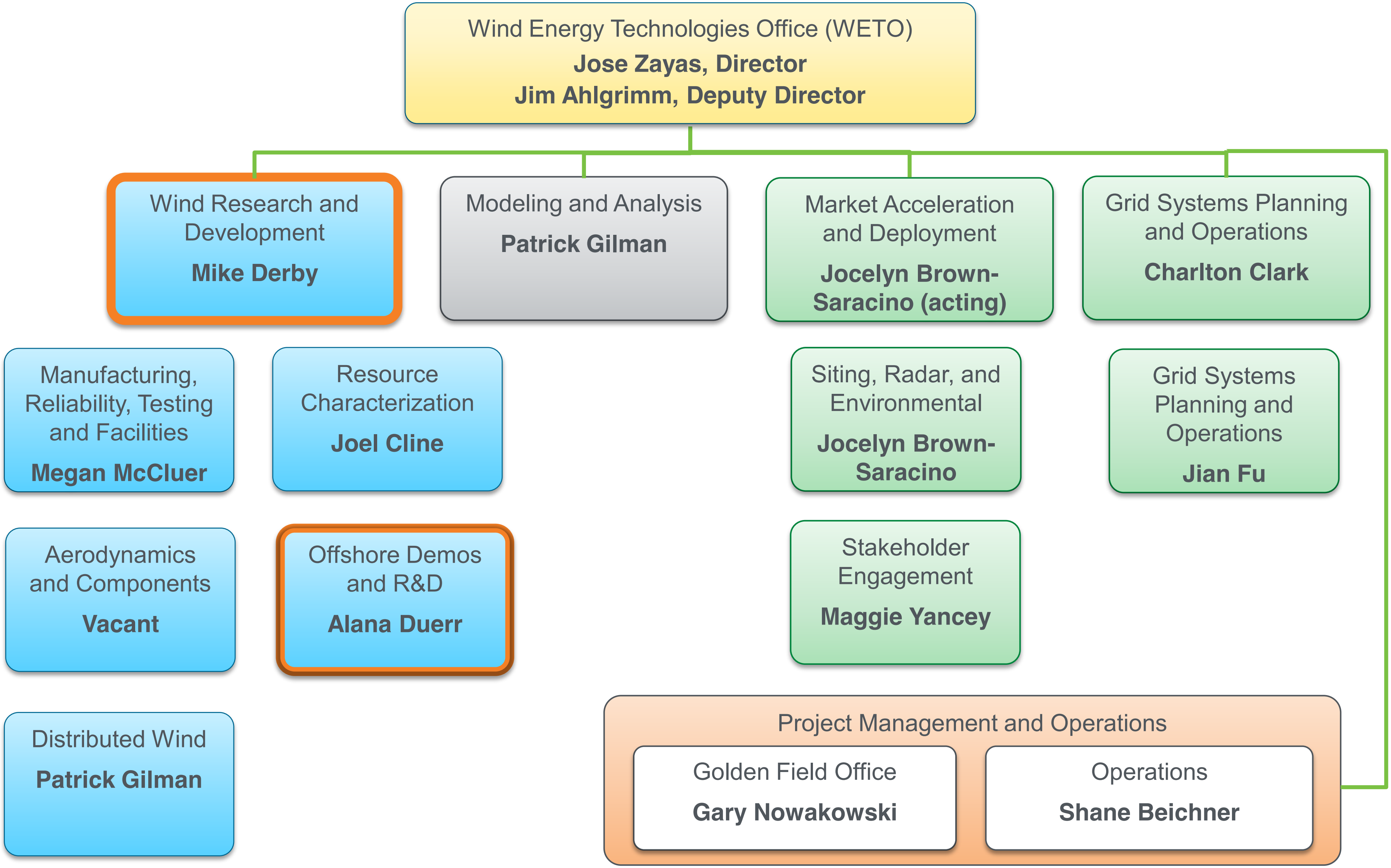
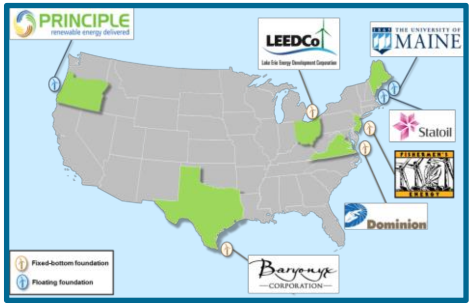


Key Projects Over Time

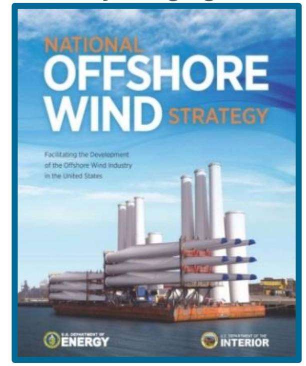
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Advanced Technology Demonstration Projects
FOA 410 (FY12-17)
Industry, Academia, National Labs



Deployment of 1:8 Scale VolturnUS
Academia, National Labs, Industry

National Offshore Wind Strategy (FY15-16)
DOE/DOI/NREL with Industry Engagement



Launch of Buoy Loan Program
(FY17)

Offshore Wind Consortium
(FY17 Budget Request)
Industry, National Labs, Academia

'12 '13 '14 '15 '16 '17

R&D and MA&D
FOA 414/415 (FY12)
Industry, Academia, National Labs

DOE Procures and Deploys Metocean Buoys (FY14)
National Labs

Deployment and Operation of the Demo Projects
(FY18+)

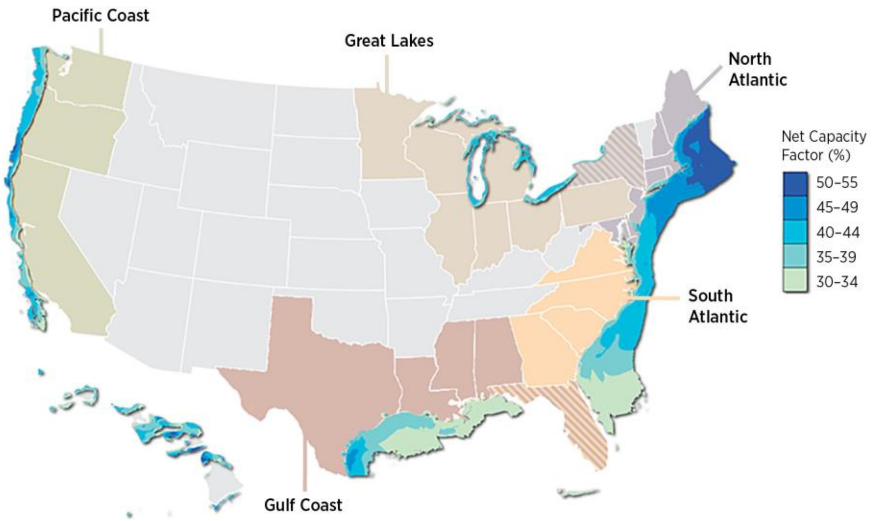
WETO's Role in Offshore

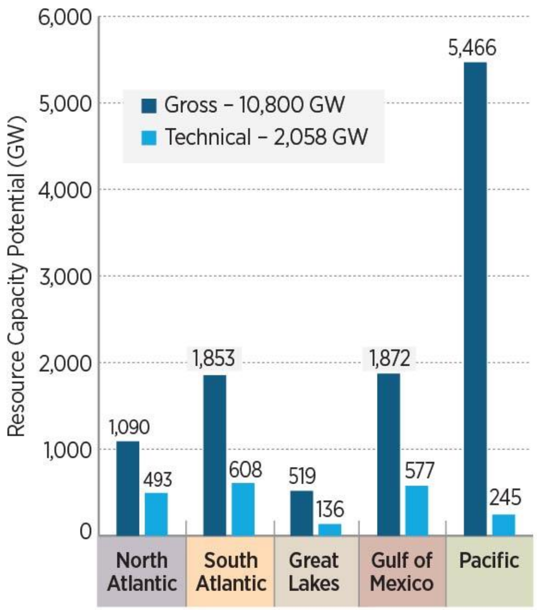
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

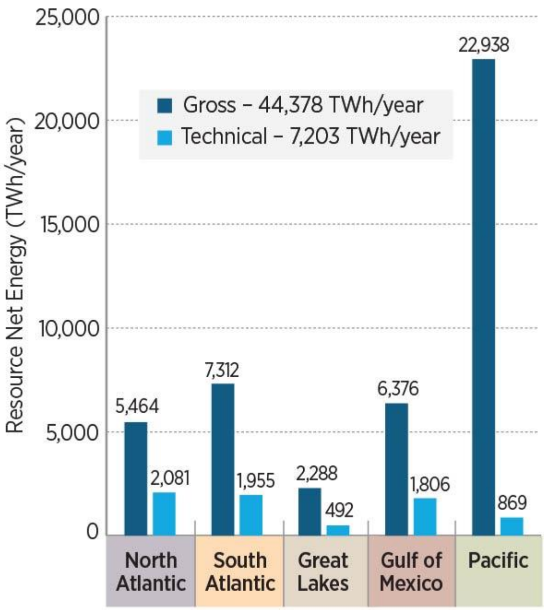
Facilitating the Development of the Offshore Wind Industry in the United States

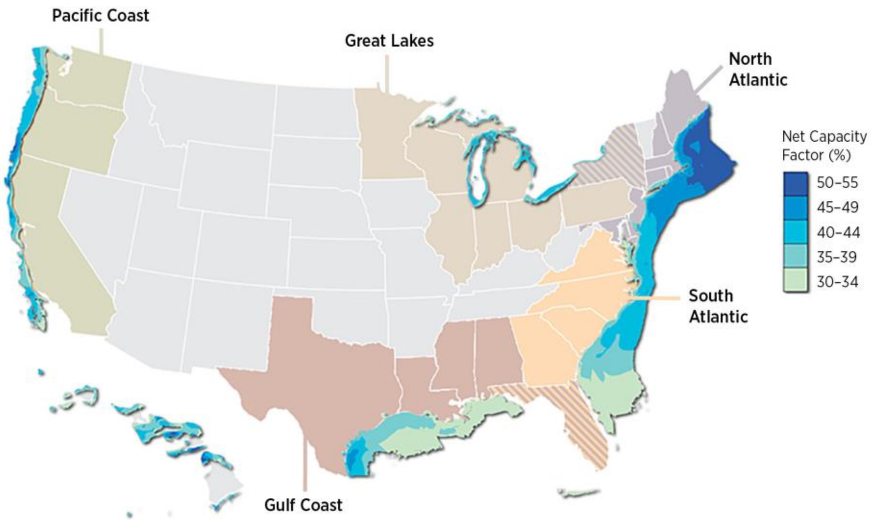
- **All-encompassing scope**: Fostering the industry—from development and validation of computer models to steel in the water
- **Buy down technology and market risks**: R&D and demonstration to showcase and validate innovative technologies; evaluation of the offshore wind resource; address market risk through analysis
- **Convene stakeholders and partners**: Request for Information, National Offshore Wind Strategy, workshops, roundtables, open door for industry
- **Disseminate data and results**: reports, conference participation, journal papers, etc.
- **Enabling offshore wind in all five U.S. offshore regions.**

Nationwide Resource

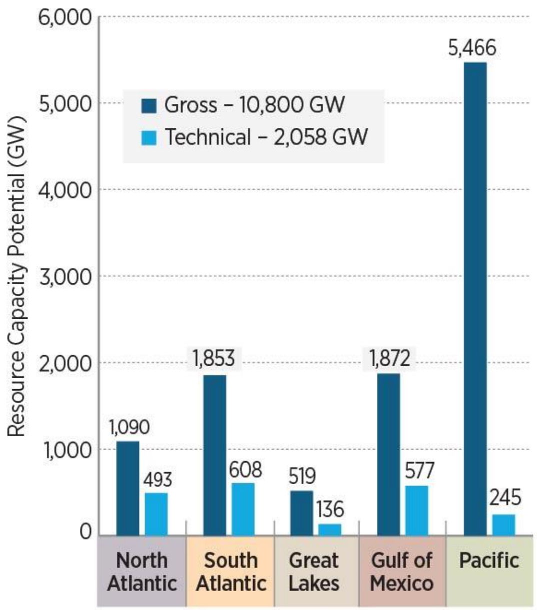


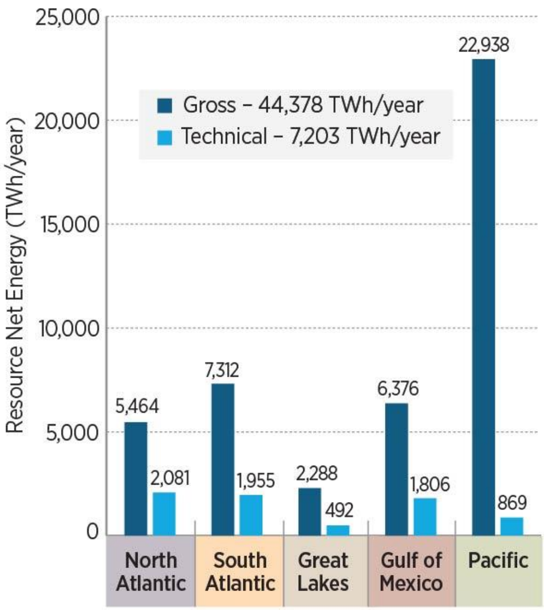




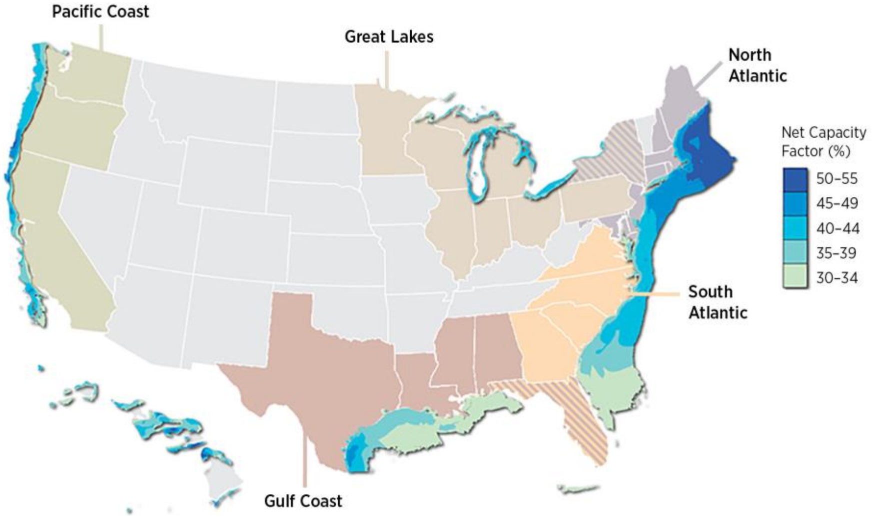


2,058 GW of offshore wind resource capacity technically accessible in U.S. waters using existing technology



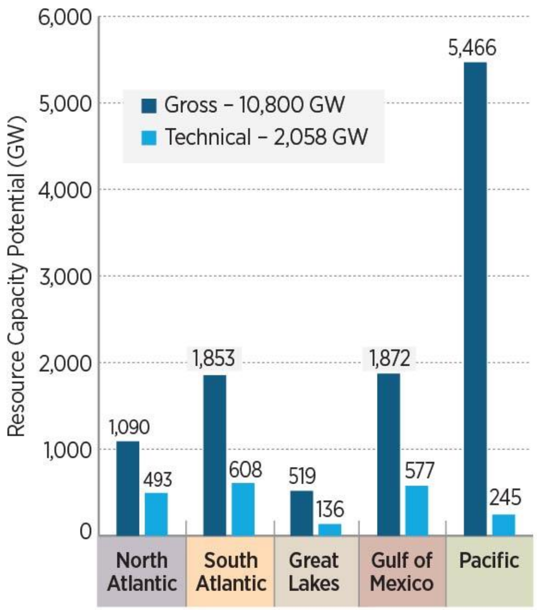


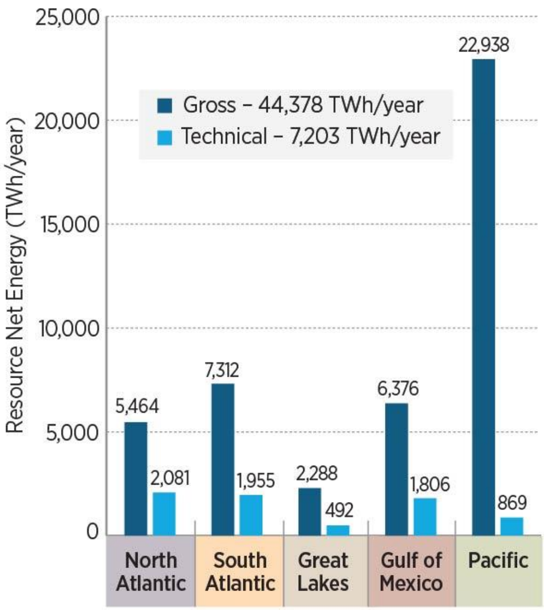
Nationwide Resource



2,058 GW of offshore wind resource capacity technically accessible in U.S. waters using existing technology

TWICE the current electricity generating capacity of the United States





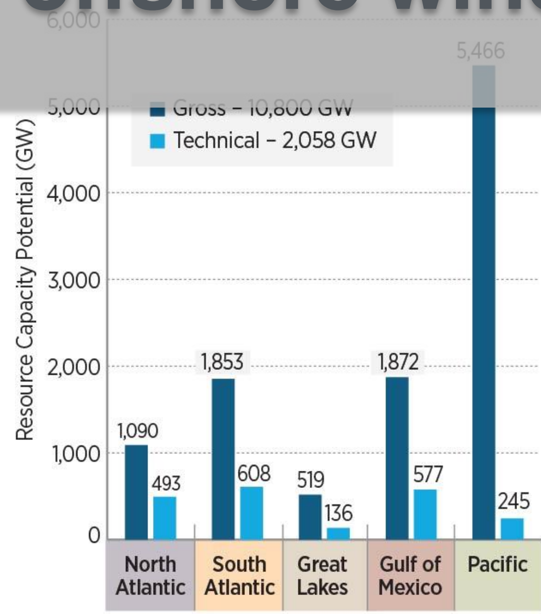
Nationwide Resource

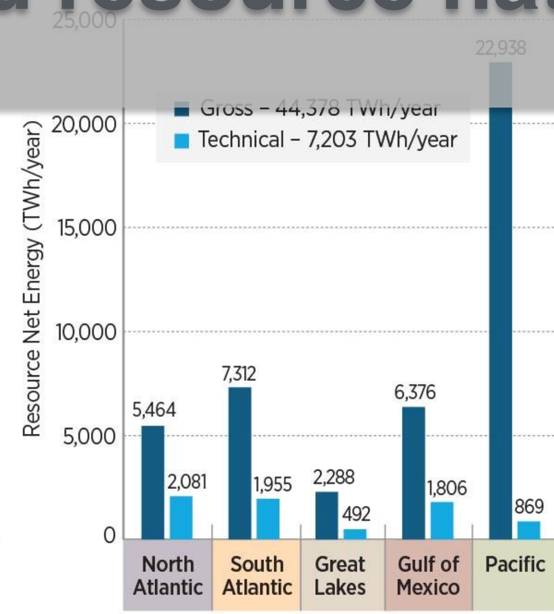
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

2,058 GW of offshore wind resource capacity technically accessible in U.S. waters using existing technology

TWICE the current electricity generating capacity of the U.S.

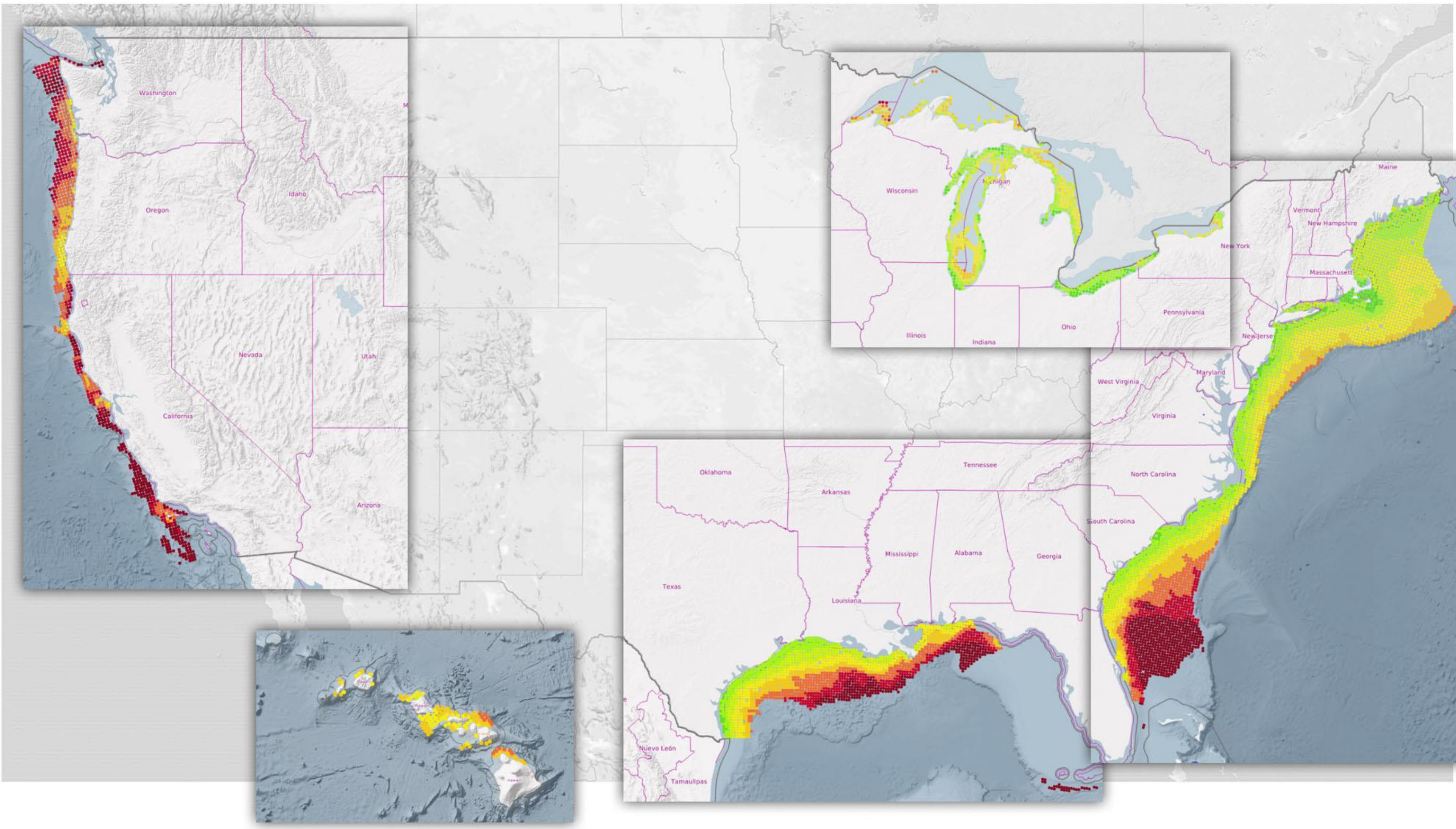
There is offshore wind resource nationwide.





Nationwide Cost Reduction

Commercial Operation Date – 2015



Levelized Cost of Energy ($/MWh)

● <=100 ● 100–125 ● 125–150 ● 150–175 ● 175–200 ● 200–225 ● 225–250 ● 250–275 ● 275–300 ● >300

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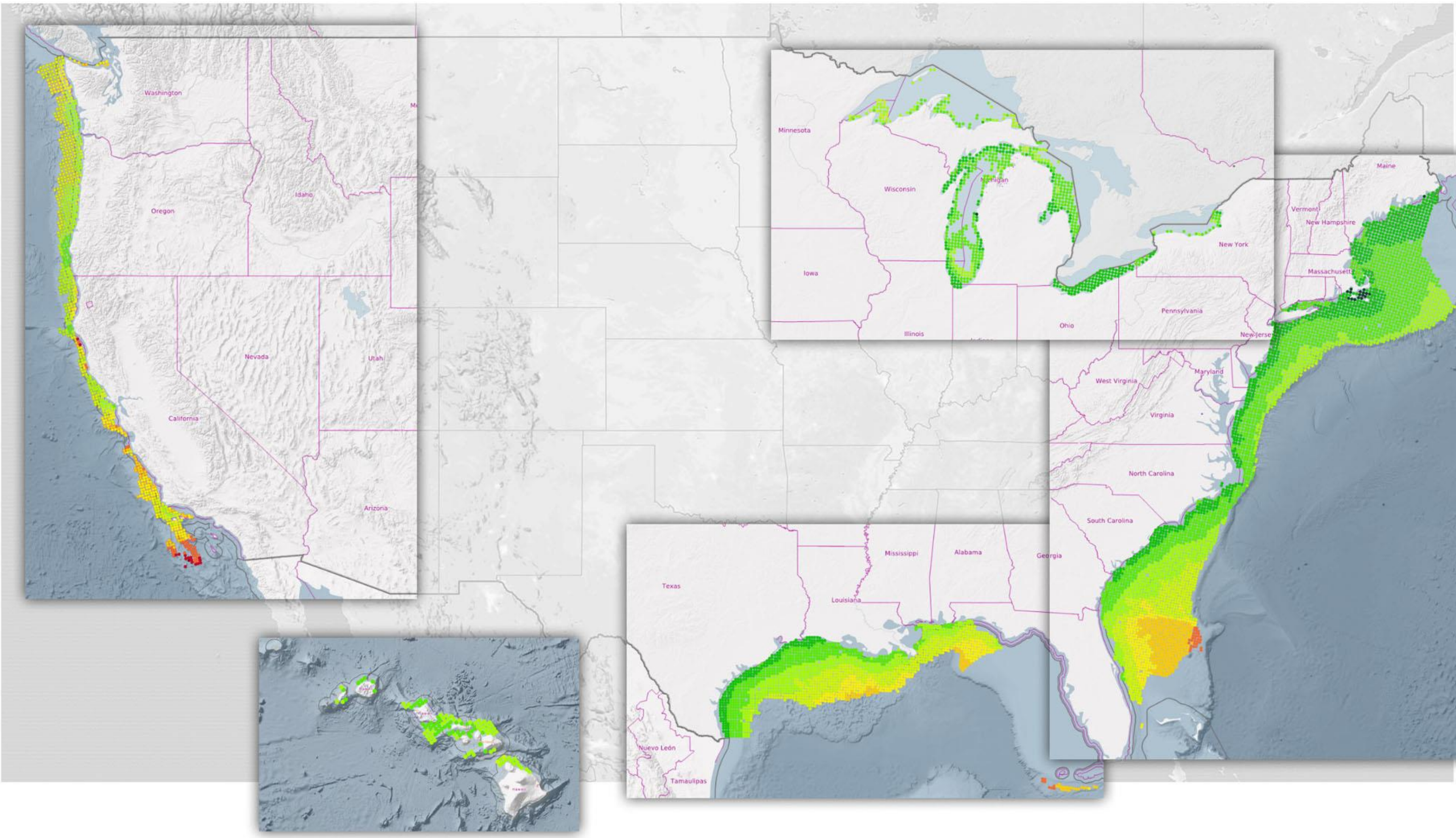
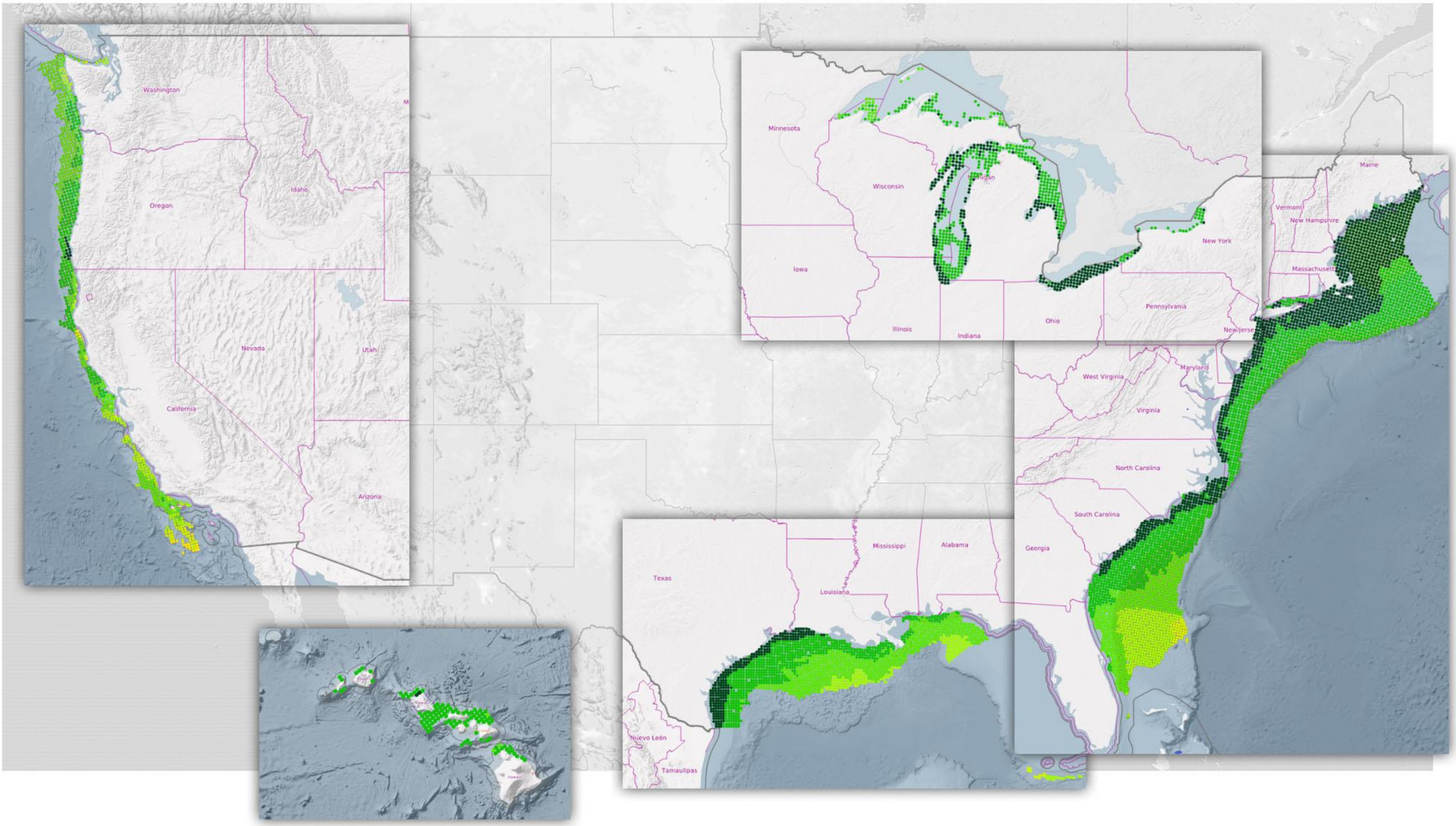
Commercial Operation Date – 2022



Levelized Cost of Energy ($/MWh)

<=100 · 100–125 · 125–150 · 150–175 · 175–200 · 200–225 · 225–250 · 250–275 · 275–300 · >300

Commercial Operation Date – 2027

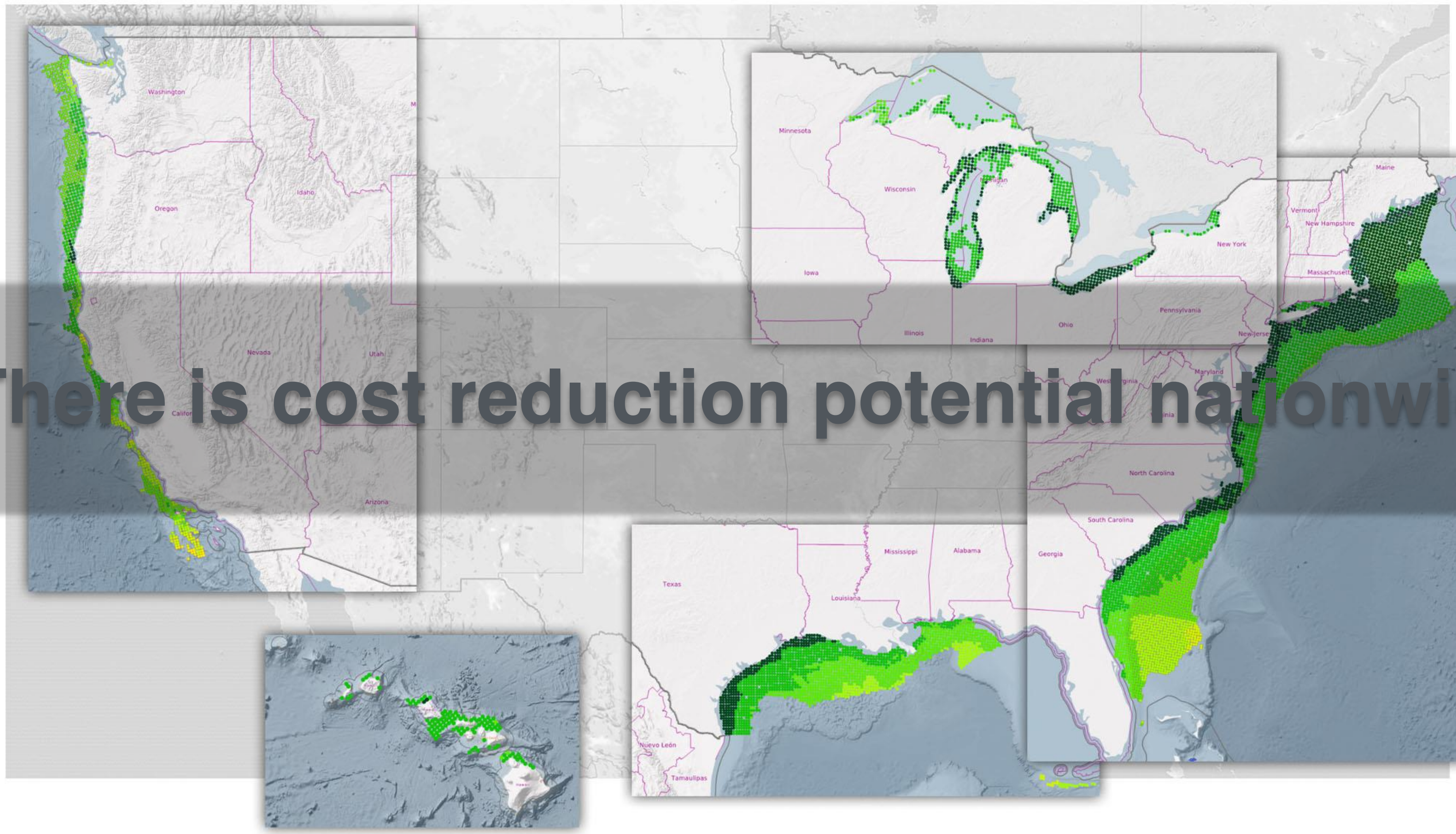


Levelized Cost of Energy ($/MWh)

<=100 | 100–125 | 125–150 | 150–175 | 175–200 | 200–225 | 225–250 | 250–275 | 275–300 | >300

Nationwide Cost Reduction

Commercial Operation Date – 2027



Levelized Cost of Energy ($/MWh)

<=100 · 100–125 · 125–150 · 150–175 · 175–200 · 200–225 · 225–250 · 250–275 · 275–300 · >300

Strategic Focus Areas

Challenges, Goals, & Approach

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

Strategic Area	Challenges	Goals	Approach
Offshore Wind Plant Technology Development	**Current estimated cost of offshore wind is too high to support widespread deployment.**	Achieve cost competitiveness in all five U.S. offshore regions by 2030 through the investment in technologies that have significant cost reduction potential.	• **Design next generation innovative large-scale turbines and foundations optimized for installation and O&M in the marine environment** • **Develop, validate, and verify engineering modeling and analysis tools required to lower overall offshore facility costs.**
Offshore Resource & Site Characterization	**There is a significant lack of data describing metocean and geologic conditions at potential offshore wind sites.**	To have publicly available site characteristic data to help stakeholders and decision makers.	• **Utilizing the DOE's offshore wind lidar buoys to collect and disseminate offshore wind resource characterization data.**
Advanced Technology Demonstration	**Innovative offshore wind technologies are expensive and potentially unproven at MW scale.** **Offshore wind permitting and approval processes have not been exercised.** **Securing grid interconnection is challenging.**	De-risk innovative technologies through demonstration scale deployment Exercise the permitting process with innovative technologies that have not been deployed elsewhere Secure PPA and grid interconnection.	• **Support the development of the offshore wind demonstration projects to be deployed in 2018-2020.**

Offshore Wind Overview

Unique Offshore Wind R&D, Resource Characterization and Analysis	
Modeling and Validation for Offshore Wind *(9:25am)*	Amy Robertson
Wave Impacts on Fixed Offshore Wind Foundations *(9:50am)*	Ralph Nichols
Sediment Transport Impacts on Offshore Wind Projects *(10:15am)*	Jesse Roberts
Instrument Planning for the Offshore Demonstration Projects *(11:00am)*	Walt Musial
Structural Health & Prognostic Management for Offshore Wind *(11:20am)*	Todd Griffith
DOE Offshore Wind Lidar Buoy Deployment Program *(11:40am)*	Will Shaw
National Offshore Wind Strategy Supporting Analysis *(12:05pm)*	Walt Musial
Floating Offshore Wind Research and Demonstration Projects	
Turbine Advanced Controls for Floating Offshore Wind *(1:40pm)*	Albert Fisas
The University of Maine's New England Aqua Ventus I Program *(2:00pm)*	Habib Dagher
Hywind Maine Project *(2:20pm)*	Andrea Nina Eugster
WindFloat Pacific Project *(2:45pm)*	Kevin Banister
Fixed Offshore Wind Demonstration Projects	
Fishermen's Atlantic City Wind Farm *(3:30pm)*	Chris Wissemann
Project Icebreaker *(3:55pm)*	Dave Karpinski

Budget Summary

Total Budget			
FY2014	FY2015	FY2016	**Total FY2014-FY2016**
25M	47M	48M	**120M**

Peer Reviewed Budget			
FY2014	FY2015	FY2016	**Total FY2014-FY2016**
19M	33M	35M	**87M**
76%	*70%*	*72%*	***72%***

Activities & Accomplishments (FY14-16)

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

Strategic Area	Accomplishments	Collaborators
Offshore Wind Plant Technology Development	• Publication of the DOE-DOI dual-sealed National Offshore Wind Strategy • Improved offshore wind modeling capabilities	• DOI/BOEM • National labs (NREL, SNL, SRNL)
Offshore Resource & Site Characterization	• Procurement and deployment of lidar buoys in Virginia and New Jersey	• PNNL
Advanced Technology Demonstration	• Advanced technology demonstration down-select	• Industry (Dominion, Fishermen's Energy, LEEDCo, Principle Power, University of Maine)

Photo by Robb Wallen NREL, 21966

Photo by Senu Sirnivas NREL, 27602

Photo by DHI [1]

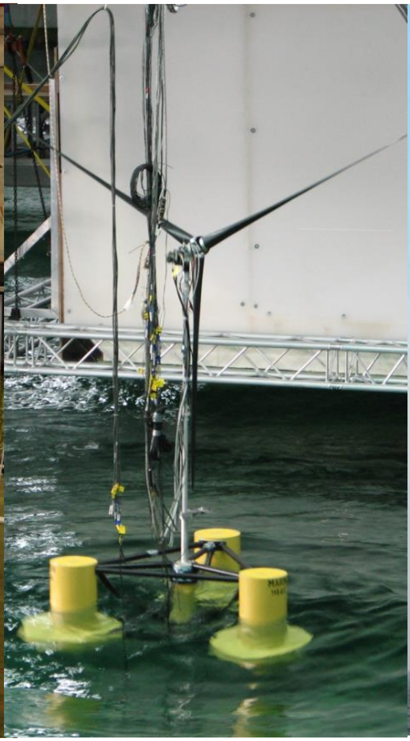


Photo by Andy Goupee Univ. of Maine, 19576

Photo by Gary Norton NREL, 27360

Modeling and Validation for Offshore Wind

Amy Robertson

National Renewable Energy Laboratory (NREL)

Amy.robertson@nrel.gov 303.384.7157

February 2017

Modeling and Validation for Offshore Wind:

To ensure the reliability of offshore wind systems and achieve cost effectiveness, ***offshore wind design tools*** need to consider the coupling between aerodynamic and hydrodynamic loading, and the tools need to be validated to ensure their accuracy.

The Challenge:

The methods and tools used to design today's existing installed offshore wind systems do not capture the dynamic coupling characteristics that need to be considered to ensure stability of a floating concept, or to achieve superior cost optimization for a fixed-bottom system.

Partners:

The main validation task in this project, "**OC5**", is an international research collaborative run under IEA Wind involving offshore wind designers, consultants, certifiers, developers, and research institutions.

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- **NextGen component innovations**

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- Advanced technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

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- Distributed wind R&D
- **NextGen component innovations**

The Impact:

- Enabling the design of next-generation offshore wind systems that will lower levelized cost of energy (LCOE):
  - Floating wind
  - Optimized fixed-bottom
- Improved industry offshore wind design tools and methods:
  - Validated and improved design tools for a variety of system configurations and conditions
  - Findings on capabilities and limitations of different modeling approaches
  - Set of public benchmark offshore designs, measurement data, and analysis results
  - Training analysts on how to accurately model offshore wind systems.

Technical Approach

- Coupled offshore wind design tools (OWDTs) are validated through a series of campaigns examining different configurations
- Validation achieved by comparing simulated loads/motion against measurements from a test campaign
  - **OC4** (2010-2014)
  - **OC5** (2015-2018)
- Results from different tools show advantages/ disadvantages of modeling approaches.

OC5

Photo by DHI [1]

Phase I
2014–2015

Photo by Andy Goupee Univ. of Maine, 19576

Phase II
2015–2016

Photo by Gary Norton NREL, 27360

Phase III
2017–2018

All test data acquired from partners at no cost to DOE

OC5 Participants/Tools

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

OC5 guides the improvement of industry design tools

Wind Turbine Designers/Consultants:
- GE/Alstom
- Siemens
- Goldwind
- Knowledge Center WMC
- DongFang Electric Corporation

Offshore System Designers/Consultants:
- 4Subsea
- IFP Energies nouvelles
- PRINCIPIA
- WavEC offshore renewables

Wave Tank Testing/Research:
- MARINTEK
- MARIN
- Danish Hydraulic Institute

Certifiers:
- DNV GL
- ABS Consulting
- CGC

Research Institutes:
- NREL
- Fraunhofer IWES
- DTU
- Stuttgart Wind Energy
- Institute for Energy Technology
- CENTEC
- ECN
- Polytechnic Univ. of Milan
- Univ. of Maine
- Univ. of Ulsan
- Univ. of Tokyo
- Univ. of Catalonia
- Universidad de Cantabria
- Norwegian Univ. of Science and Technology

Tools:
- FAST
- Bladed
- HAWC2
- OrcaFlex
- FAST+OrcaFlex
- CHARM3D+FAST
- FAST v6+OPASS
- aNySIMPHATAS
- 3DFloat
- STAR CCM
- DeeplinesWind
- Samcef Wind Turbines
- Sesam
- UOU + FAST
- UPC + FAST
- NK-UTWind+AeroDyn
- FF2W
- OceanWave3D
- RIFLEX
- FEDEM
- SIMPACK+HydroDyn
- IH2VOF
- POLI-HydroWind
- Wavec2Wire
- FOCUS6 (PHATAS)
- CAsT

Technical Approach

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- Additional NREL projects examine theories and practices in more detail:
  - PPI, SWAY, and INNWIND validation
  - Advisement on other international research projects
  - Examination of load cases needed for floating design
- NREL participates in these projects through the development of **FAST,** an aerolastic computer-aided engineering tool:
  - Examine modeling theories/approaches
  - Make improvements based on findings
  - Validate tool capabilities
  - Make recommendations on best practices for designing floating systems.

Solutions to modeling challenges made accessible to all through implementation in Open Source FAST

SWAY


Photo by Robb Wallen NREL 21966

PPI WindFloat


Photo by Senu Sirnivas NREL 27602

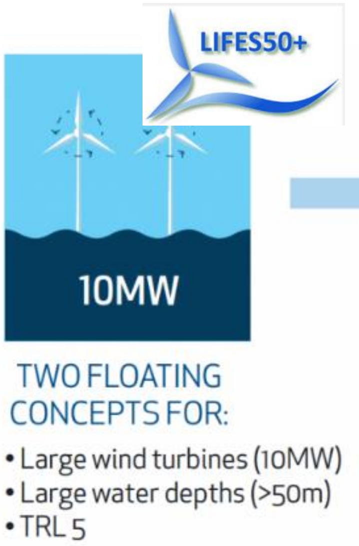


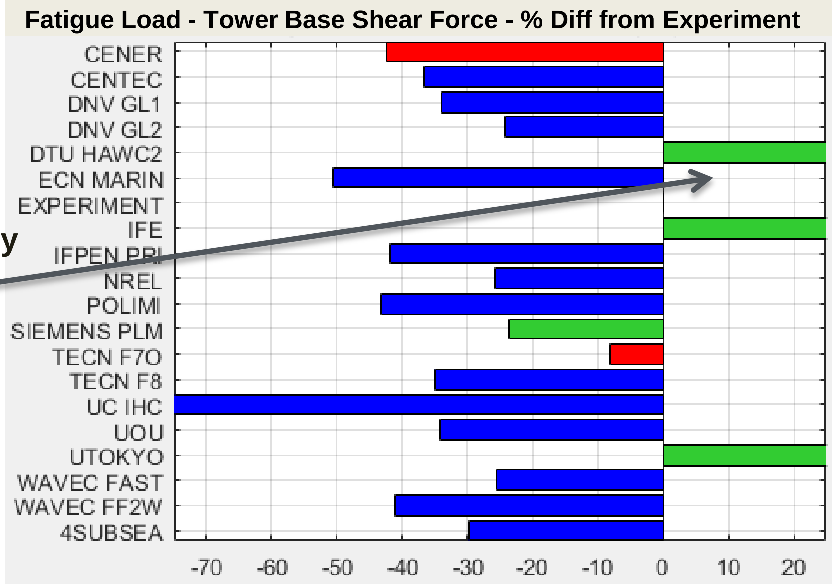

Photo by Henrik Bredmose [2]

Accomplishments and Progress

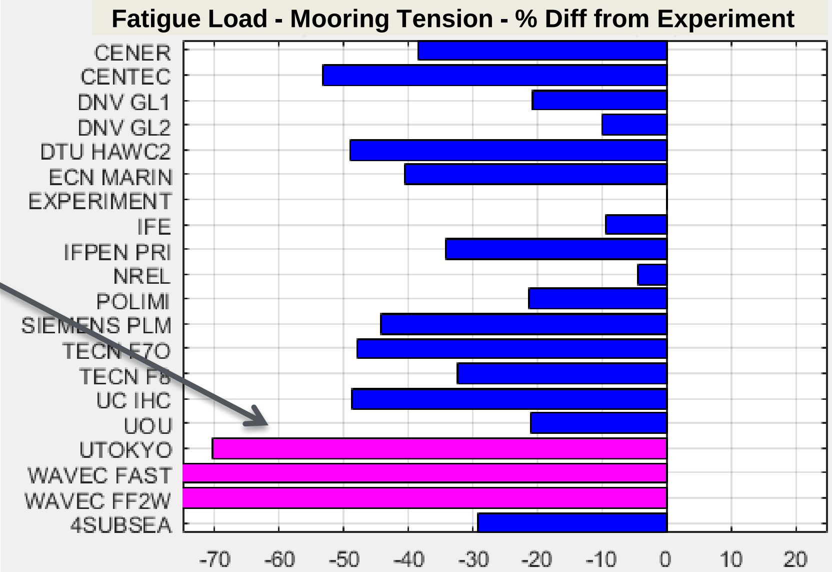
- Program has determined the following is needed to accurately capture extreme/fatigue loads of an offshore wind system:
  - Higher-order wave theory
  - Complex seabed models
  - Breaking wave models
  - Dynamic mooring models
  - Accurate loads on heave plates
  - Nonlinear hydrodynamic theory (wave stretching, 2nd-order)
  - Proper choice of hydro coefficients.
- Recommendations made on load cases needed for floating design, included in new IEC-61400-3-2.

Industry tools have been updated to address errors and include many of these components.

Morison-only model (green)



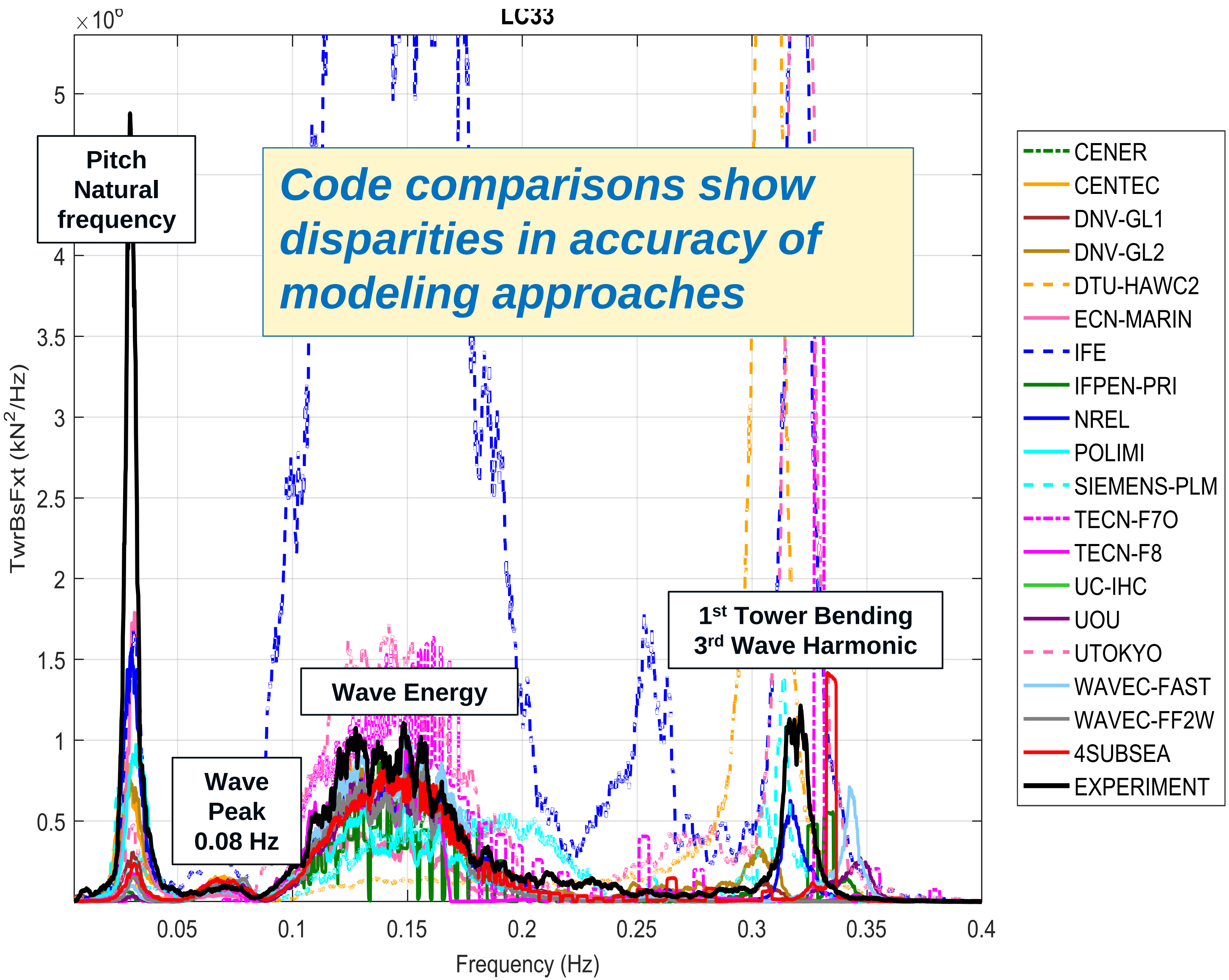
Quasi-static Mooring model (pink)



Accomplishments and Progress

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

Simulation responses interrogated to understand sources of errors



Project Plan & Schedule

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

- **All milestones met on schedule, with one exception:**
  - SWAY validation work—FY14 Q2 milestone to publish summary delayed to Q3
  - Delay due to difficulties in modeling unique dynamic characteristics of tensioned spar
- **OC4:**
  - Initiated: April 2010
  - Planned completion: April 2013
  - Actual completion: December 2013
    - Phase II analysis of floating semisubmersible more complex than expected
    - Required additional time to develop model properties
- **OC5:**
  - Initiated: January 2014
  - Planned completion: January 2018
  - Expected completion: June 2018
    - Addition of a second monopile dataset in Phase I
    - Difficulties in obtaining data for Phase III analysis of Alpha Ventus Jacket

Some delays in project, but no impact on deliverables

Project Budget

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

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost Share	DOE	Cost Share	DOE	Cost Share
$800K		$650K		$350K BA +$289K Carry-Over (from other projects)	

No formal cost-share, but in-kind contributions provided significant support to the project

- OC4/OC5 projects participants supported their own contributions
  - Estimated at 3 man-months per year per participant – about 25 participants per year
- Four Ph.D. students supported floating design method research and validation projects through internal funding at University
- For the validation projects, valuable design information and test data was supplied at no cost (SWAY, PPI, INNWIND, DeepCwind, DTU/DHI, MARINTEK test campaigns)
- ***Project is still on going; all funds spent except for carryover into future years.***

Partners, Subcontractors, and Collaborators:

- OC5 is run under IEA Wind Task 30
  - 146 people, 68 organizations in 18 different countries have participated, including offshore wind designers, consultants, certifiers, developers, and research institutions
- Advisors on European offshore wind research projects:
  - INNWIND**:** DTU, Ramboll
  - NOWITECH: Norwegian Univ. of Science and Technology, Statoil, Statkraft
  - Floating Wind JIP (recommended practice): DNV GL, EDF, Olav Olsen
  - LIFES50+: Ramboll, Statoil, Siemens
- Additional validation projects: PPI, SWAY, DeepCwind consortium

Communications and Technology Transfer:

- Improvement of industry design tools based on findings from project
- 14 conf. papers, five journal articles, one chapter, and two NREL publications
- Semi-monthly teleconferences and bi-annual meetings for OC4/OC5
- Public websites for work (model info/results) once finished:
  - **OC3:** https://drive.google.com/folderview?id=0B0KGNSHvXXgCMmVsU3RkZ3FHVlE&usp=sharing
  - **OC4:** https://drive.google.com/folderview?id=0B0KGNSHvXXgCSDBlREZLdDRxX2s&usp=sharing

Next Steps and Future Research

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FY17/Current Research:

- Upcoming FY17 Milestones (OC5)

Q1: Acquire needed design information to build model of Alpha Ventus jacket OWS for Phase III
Q2: Compile and summarize findings on validating global loads of floating semi for Phase II
Q3: Provide description to project participants to build model of Alpha Ventus jacket for Phase III
Q4: Complete initial models of Alpha Ventus jacket by participants in individual modeling tools

- Floating joint industry project: continue development of recommended practice
- Propose method for assessing uncertainty in floating wind tank tests
- Continue advisement on LIFES50+ and INNWIND

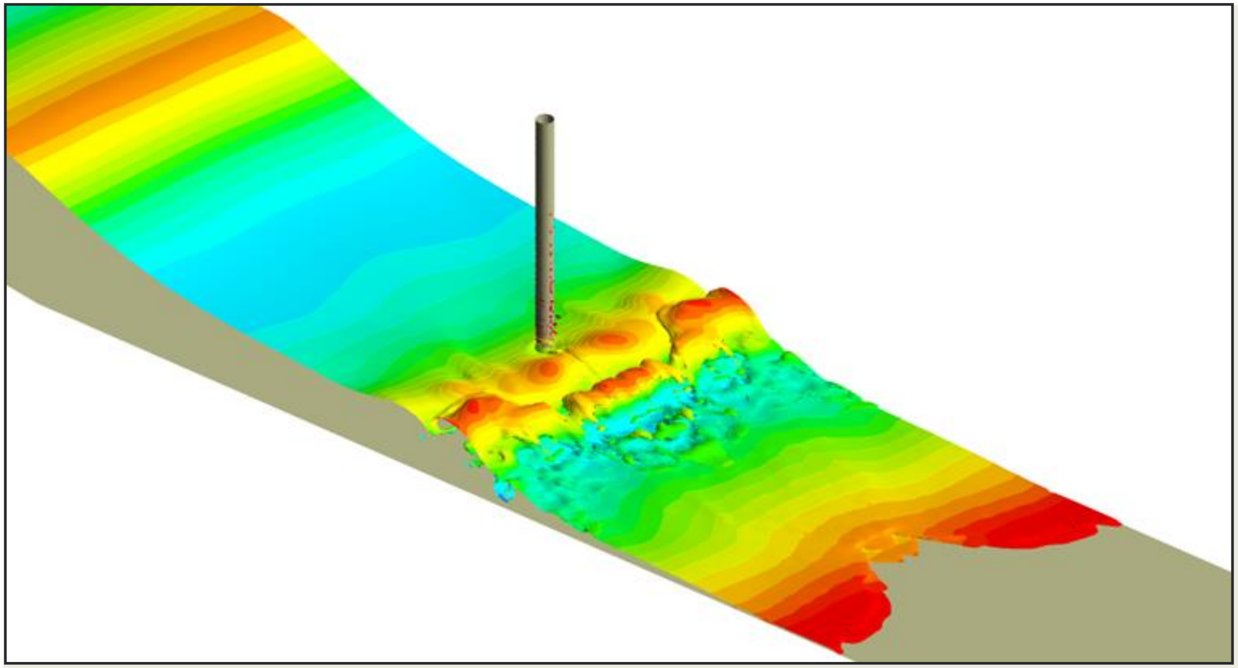
Planned Future Research:

- OC5 Phase III - full-scale, open-ocean offshore wind system
  - Validation work expected to be completed in June 2018
- Extend OC5 to perform own testing to obtain better data for validation
- Continue to advance tools so that they can be used to develop and assess innovative, cost-effective offshore designs

References

1. Bredmose, H ; Slabiak, P ; Sahlberg-Nielsen, L ; Schlütter, F (2013) “Dynamic Excitation of Monopiles by Steep and Breaking Waves: Experimental and Numerical Study”, *Proc. 32nd Int. Conference on Ocean, Offshore and Arctic Engineering* (OMAE 2013), 2013, Nantes, DOI: http://dx.doi.org/10.1115/OMAE2013-10948.

2. Bredmose, H ; Mikkelsen, RF ; Hansen, AM ; Laugesen, R ; Heilskov, N; Jensen, B; Kirkegaard, J (2015) “Experimental study of the DTU 10 MW wind turbine on a TLP floater in waves and wind”, Presented at *EWEA Offshore 2015 Conference*, 2015, Copenhagen



Wave Impacts on Fixed Offshore Wind Foundations

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February 16, 2017

Project Overview

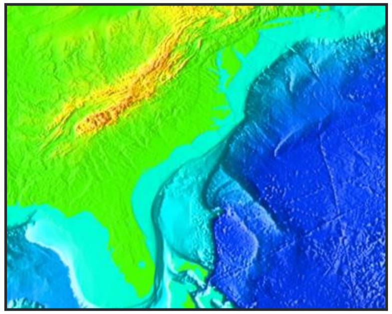
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

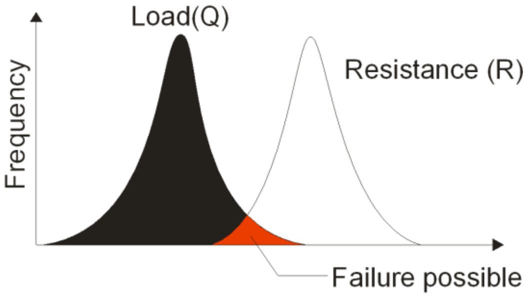
Wave Impacts on Fixed Offshore Wind Foundations

Approximately 70 percent of the United States' offshore wind energy resource exists along the east coast on the outer continental shelf in water <60m deep. This same area is highly susceptible to tropical cyclones with wind speeds ranging from 18m/s for tropical storms to >70ms for category 5 hurricanes.

The combination of high wind speeds and shallow water can lead to steep and breaking waves. Steep and breaking waves can produce large slam loads on offshore structures and can be the controlling factor in the design of fixed foundations for offshore wind turbines.

Partners: Coastal Carolina University, MMI Engineering, National Renewable Energy Laboratory





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Enabling Wind Nationwide

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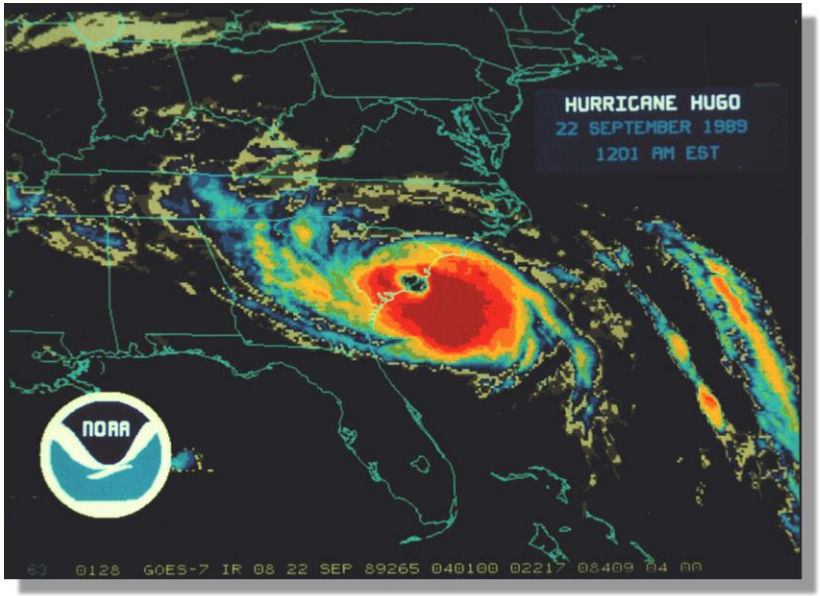
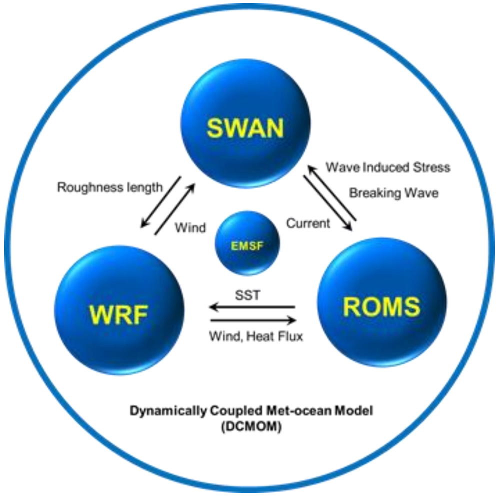
The Impact

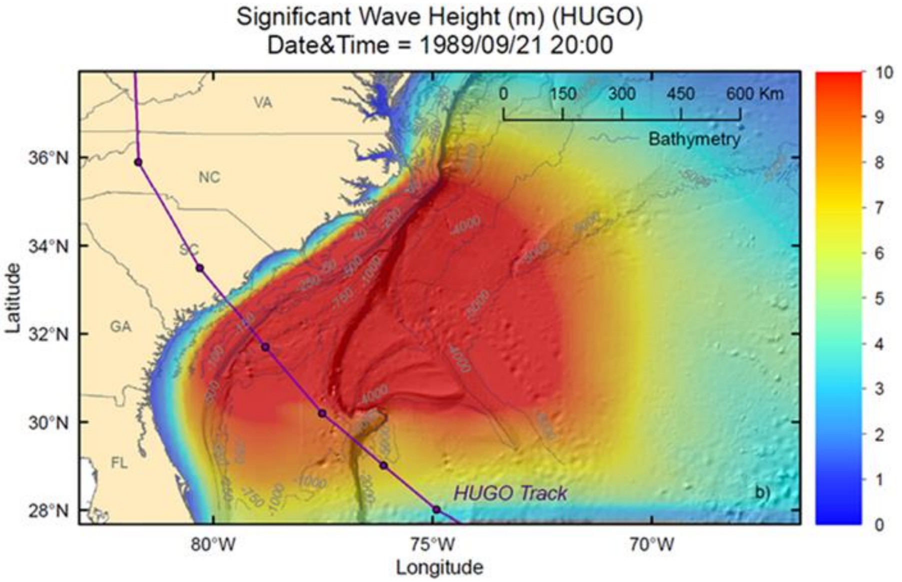
- Demonstrate spatial and temporal variability of parameters effecting the fixed foundation of wind turbines during tropical cyclones using computer models.



Technical Approach

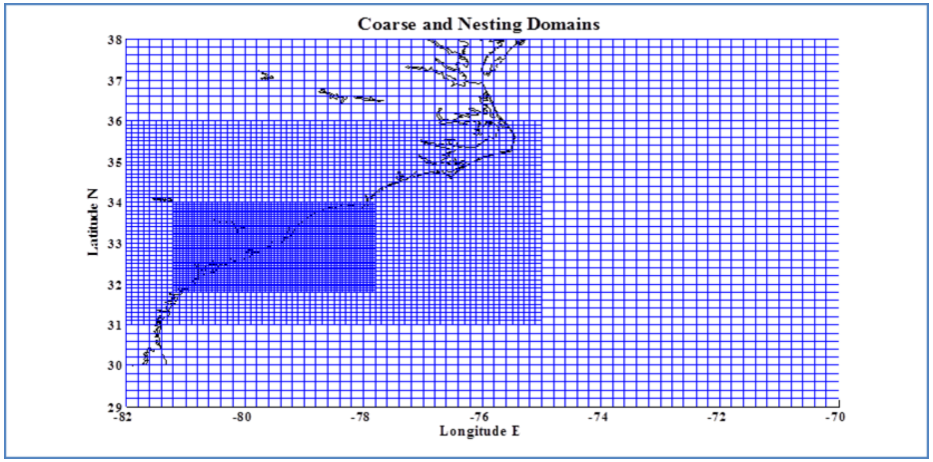
A dynamically coupled met-ocean model (DCMoM) was developed from open source models of the atmosphere, waves, and ocean using a software coupling tool Earth System Modeling Framework (EMSF) to simulate 2 hurricanes in the South Atlantic Bight of the AOCS) which extends from Cape Hatteras, NC USA to West Palm Beach, FLA USA.

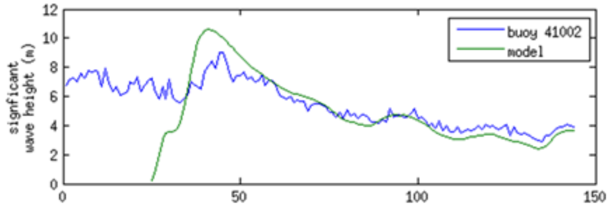




Technical Approach

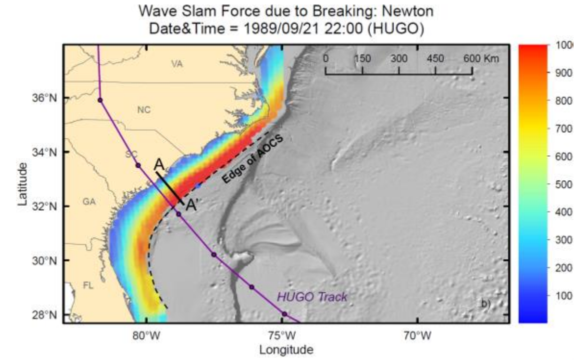
Data from observational buoys operated by the NOAA National Data Buoy Center was used to validate the model. A nested grid (18km->3.8km->0.72km) was used to increase the resolution of the model around to particular areas of interest for offshore wind energy development. The vertical discretization was 28 layers for the atmosphere and 13 layers for the ocean.

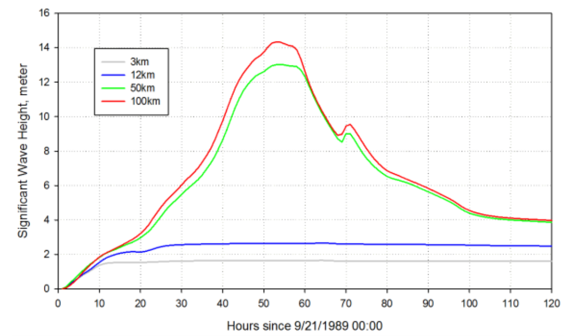


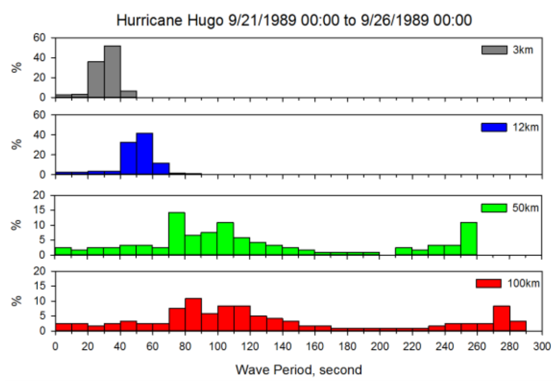


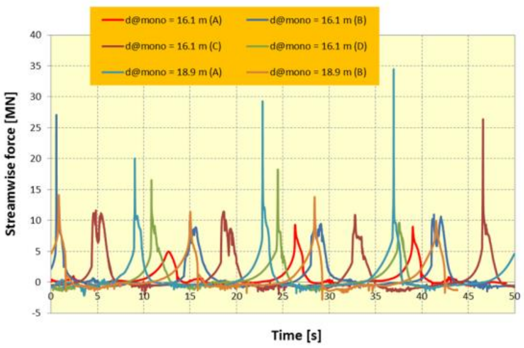
Accomplishments and Progress

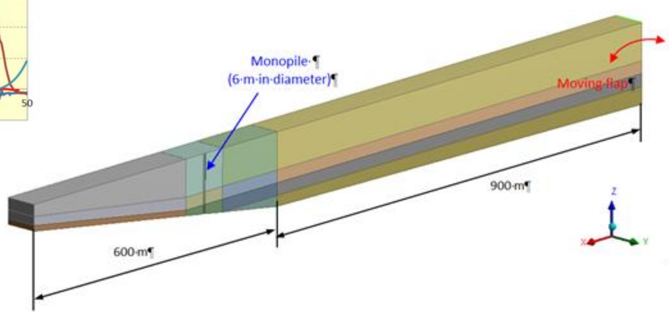
- Coupled open source codes
- Validated model with observations
- Simulated two hurricanes
- Prepared maps of engineering parameters related to hurricanes
- CFD modeling of wave loads on monopile with ANSYS/CFX











Project Plan & Schedule

- Awarded project submitted in response to FOA 414 in FY11
- 3-year project from FY12 thru FY14
- Project over 1Q FY15

Project Budget

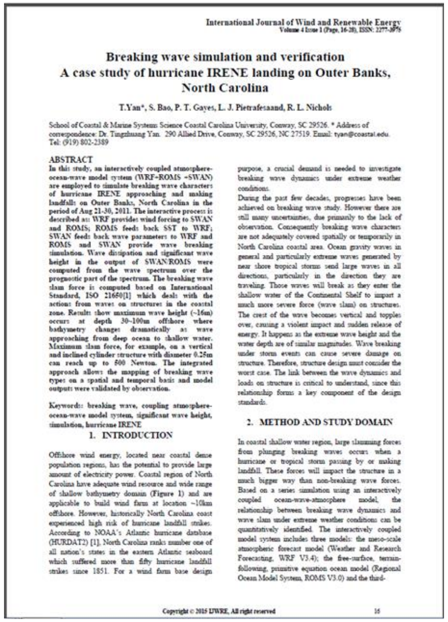
Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$304k	$0	$0	$0	$0	$0

Partners, Subcontractors, and Collaborators:

- Coastal Carolina University
- Moffatt & Nichol Engineering
- National Renewable Energy Laboratory

Communications and Technology Transfer.

- Poster at Offshore 2013 and Offshore 2015
- Participate in standards meetings
- Platform presentation at AGU Ocean Sciences 2014
- Publication in International Journal of Wind and Renewable Energy
- Presented at 2011 Offshore Technology Conference
- Presented at American Meteorological Society Annual Meeting 2014



International Journal of Wind and Renewable Energy
Volume 4 Issue 1 (Page, 16-20), ISSN: 2277-3975

Breaking wave simulation and verification
A case study of hurricane IRENE landing on Outer Banks, North Carolina

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ABSTRACT

In this study, an interactively coupled atmosphere-ocean-wave model system (WRF+ROMS +SWAN) are employed to simulate breaking wave characters of hurricane IRENE approaching and making landfalls on Outer Banks, North Carolina in the period of Aug 21-30, 2011. The interactive process is described as: WRF provides wind forcing to SWAN and ROMS; ROMS feeds back SST to WRF; SWAN feeds back wave parameters to WRF and ROMS and SWAN provide wave breaking simulation. Wave dissipation and significant wave height in the output of SWAN/ROMS were computed from the wave spectrum over the prognostic part of the spectrum. The breaking wave slam force is computed based on International Standard, ISO 21650[1] which deals with the actions from waves on structures in the coastal zone. Results show maximum wave height (~16m) occurs at depth 30~100m offshore where bathymetry changes dramatically as wave approaching from deep ocean to shallow water. Maximum slam force, for example, on a vertical and inclined cylinder structure with diameter 0.25m can reach up to 500 Newton. The integrated approach allows the mapping of breaking wave types on a spatial and temporal basis and model outputs were validated by observation.

Keywords: breaking wave, coupling atmosphere-ocean-wave model system, significant wave height, simulation, hurricane IRENE

1. INTRODUCTION

Offshore wind energy, located near coastal dense population regions, has the potential to provide large amount of electricity power. Coastal region of North Carolina have adequate wind resource and wide range of shallow bathymetry domain (Figure 1) and are applicable to build wind farm at location ~10km offshore. However, historically North Carolina coast experienced high risk of hurricane landfall strikes. According to NOAA's Atlantic hurricane database (HURDAT2) [1], North Carolina ranks number one of all nation's states in the eastern Atlantic seaboard which suffered more than fifty hurricane landfall strikes since 1851. For a wind farm base design purpose, a crucial demand is needed to investigate breaking wave dynamics under extreme weather conditions.

During the past few decades, progresses have been achieved on breaking wave study. However there are still many uncertainties, due primarily to the lack of observation. Consequently breaking wave characters are not adequately covered spatially or temporarily in North Carolina coastal area. Ocean gravity waves in general and particularly extreme waves generated by near shore tropical storms send large waves in all directions, particularly in the direction they are traveling. Those waves will break as they enter the shallow water of the Continental Shelf to impart a much more severe force (wave slam) on structures. The crest of the wave becomes vertical and topples over, causing a violent impact and sudden release of energy. It happens as the extreme wave height and the water depth are of similar magnitudes. Wave breaking under storm events can cause severe damage on structure. Therefore, structure design must consider the worst case. The link between the wave dynamics and loads on structure is critical to understand, since this relationship forms a key component of the design standards.

2. METHOD AND STUDY DOMAIN

In coastal shallow water region, large slamming forces from plunging breaking waves occurs when a hurricane or tropical storm passing by or making landfall. These forces will impact the structure in a much bigger way than non-breaking wave forces. Based on a series simulation using an interactively coupled ocean-wave-atmosphere model, the relationship between breaking wave dynamics and wave slam under extreme weather conditions can be quantitatively identified. The interactively coupled model system includes three models: the meso-scale atmospheric forecast model (Weather and Research Forecasting, WRF V3.4); the free-surface, terrain-following, primitive equation ocean model (Regional Ocean Model System, ROMS V3.0) and the third-

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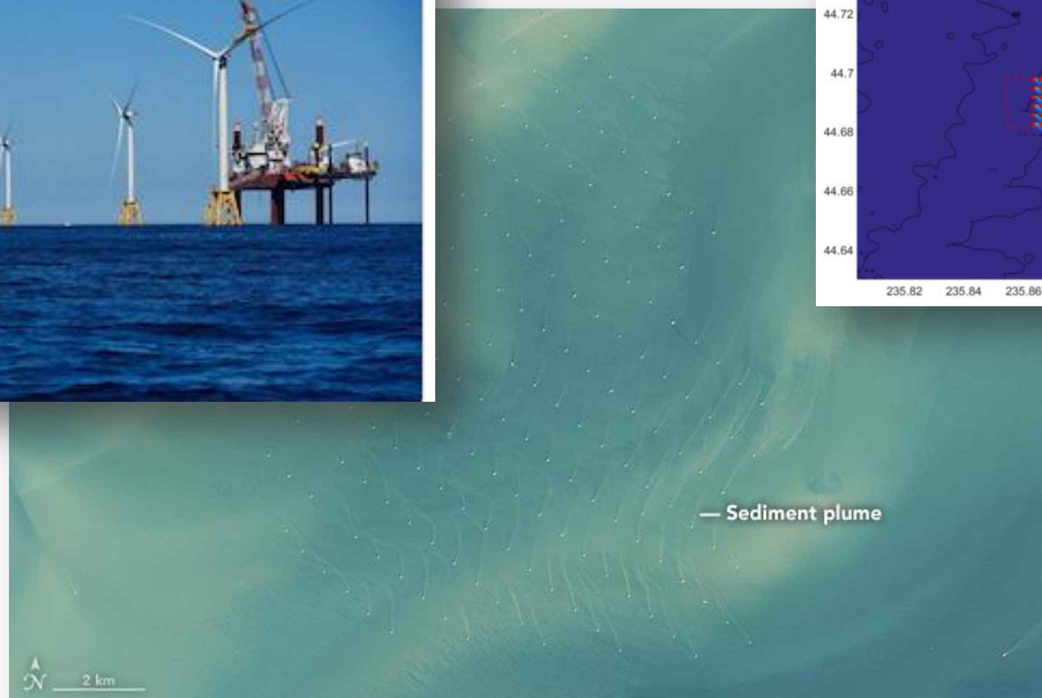

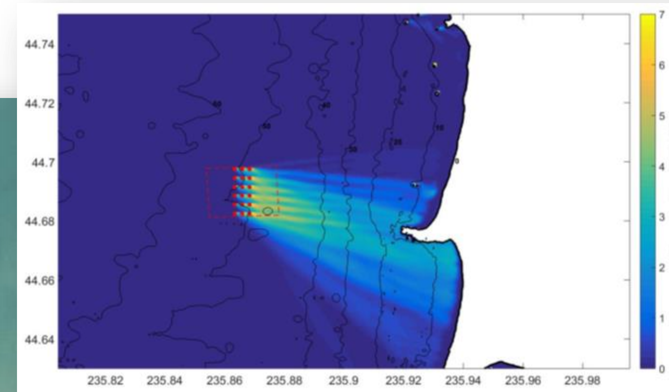

Sediment Transport Impacts on Offshore Wind Projects

Jesse Roberts & Craig Jones

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February 2017

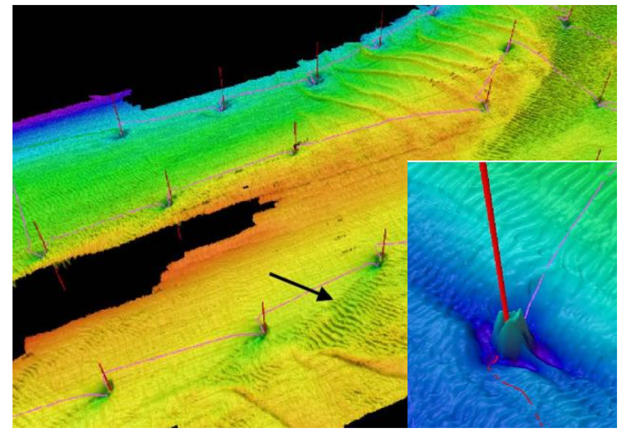
Sandia National Laboratories is a multi mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy s National Nuclear Security Administration under contract DE AC04 94AL85000.

Project Overview

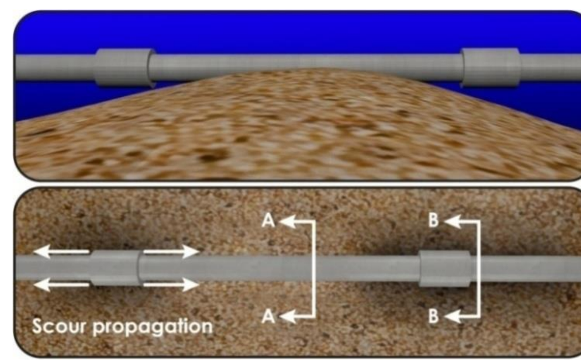
Sediment Transport Impacts on Offshore Wind Projects:

Purpose: Provide tools and guidance to quantify seafloor processes

- **Mitigate structural scour risk**
- **Retire/Mitigate environmental risk**



The Challenge: A primary risk driver for offshore wind (OW) projects is the harmful interaction between sub-structures, cables and the seafloor.



Reduce costs and risks due to:

- **Over/under design**
- **Environmental compliance**

Partners

integral consulting inc.

McNeilan & Associates

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- **Offshore wind environments**
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- Advanced technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

Enabling Wind Nationwide

Enhancing U.S. Energy Security and Independence

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The Impact

Reduce installation and lifecycle maintenance costs through intelligent siting and design of OW arrays

Reduce permitting time and costs by enabling prediction of site-specific environmental responses to OW farm designs

Final Product:

- **Offshore Wind Guidance Document:** Oceanography and Sediment Stability (Version 1: Development of a Conceptual Site Model)
- Methodology for linking near- and far-field physical dynamics

Technical Approach
Ocean and Sediment Dynamics

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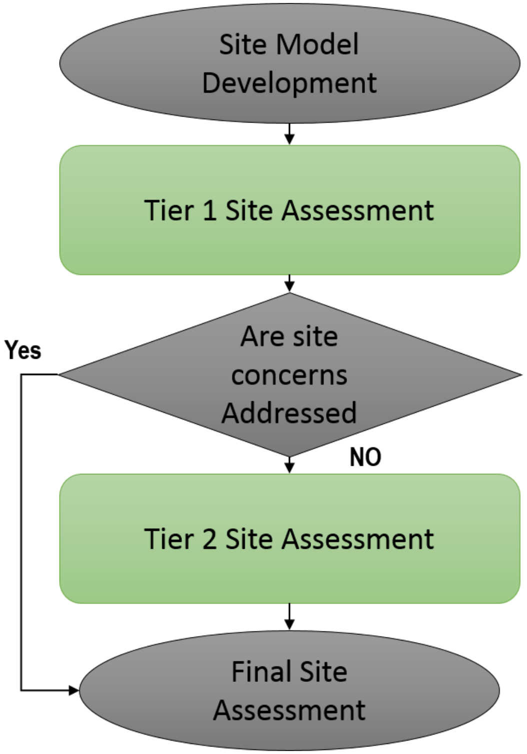
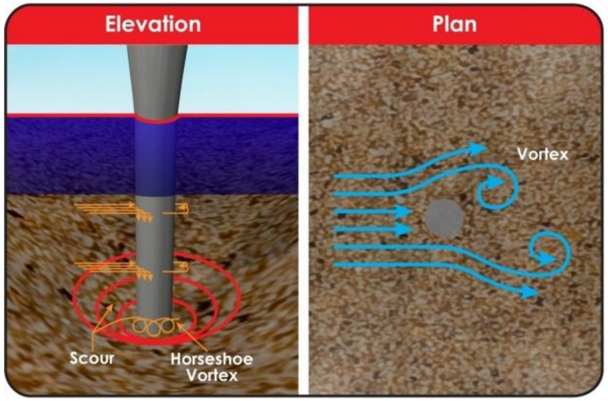
OW Infrastructure Sediment Stability and Environmental Risk

- **Develop and validate tools/methods** to create risk maps at OW sites
  - Use coupled hydrodynamic and sediment transport models to assess spatial patterns of likely sediment erosion, transport, and deposition
- **Industry Guidance** to identify key coastal processes and analysis techniques to support site evaluation and decision making
- **Transfer technology to industry**
  - Open source tools: SNL-SWAN and SNL-Delft3D

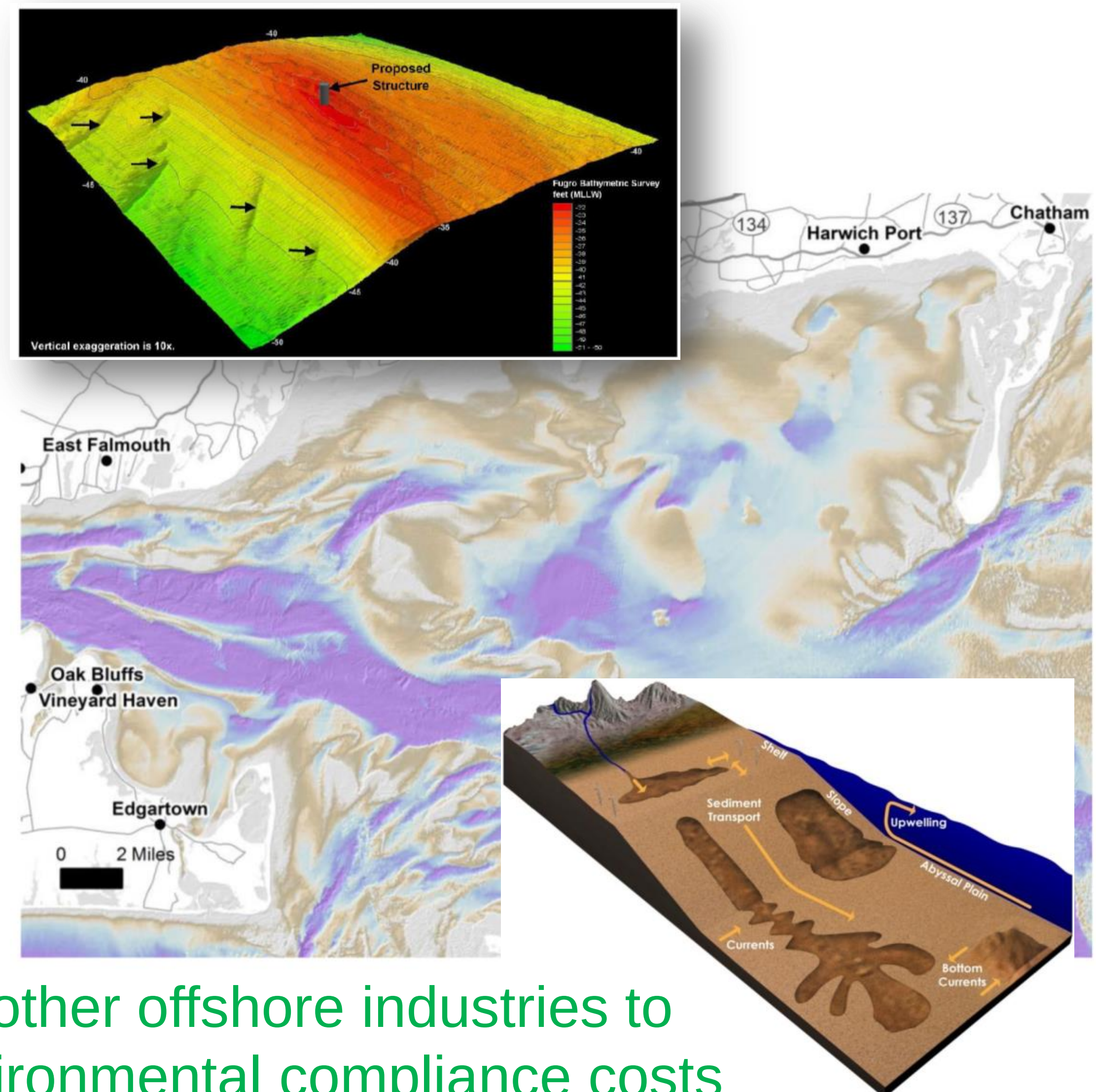


Develop, apply, and facilitate industry use of open-source OW-specific sediment mobility and environmental assessment tools/techniques



Offshore Characterization

- Numerous precedents for offshore site characterization and evaluation provide assessment foundation
- SNL guidance outlines geophysical and oceanographic data sets required for site evaluation
- Guidance provides example case studies

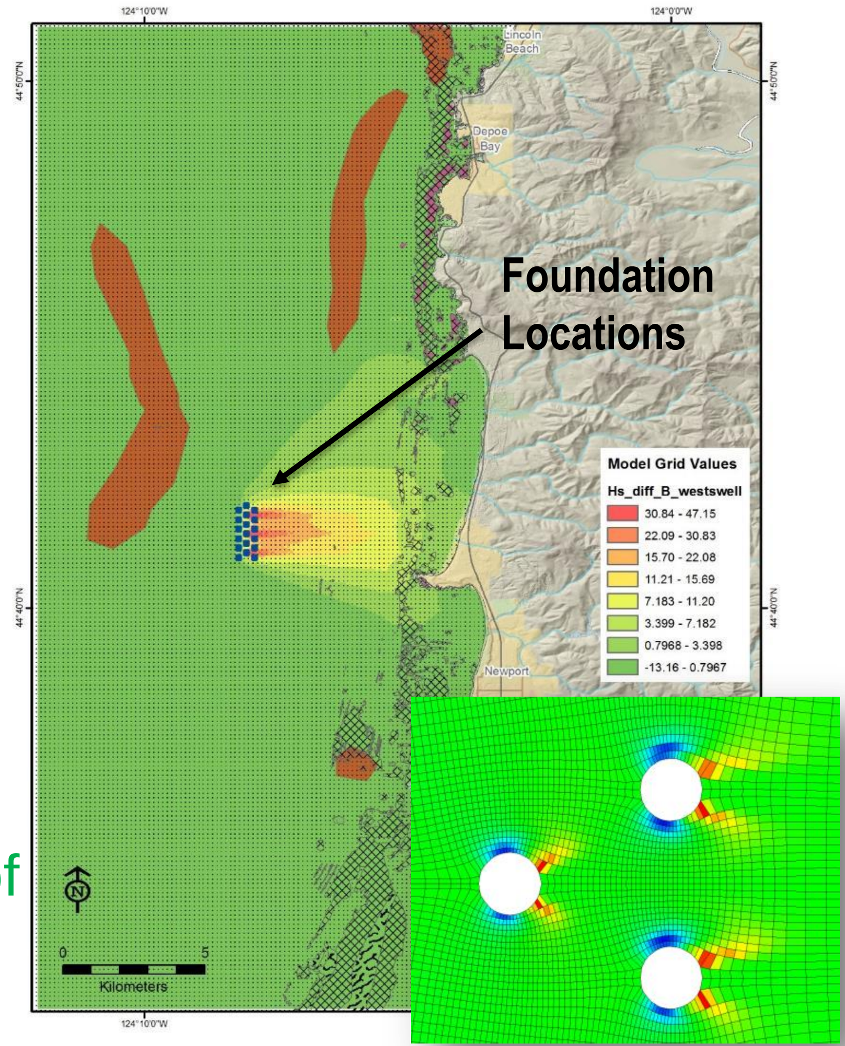


Apply lessons learned from other offshore industries to reduce engineering and environmental compliance costs

Accomplishments
Scour Model Studies

- Near- and far-field scour in the vicinity of wind farm infrastructure (foundation and cabling) is examined and baseline analysis methods are detailed

- SNL-Delft3D is being used for high resolution simulations of scour near foundations



Quantitative tools for the assessment of seafloor-infrastructure interaction

Leverage marine and hydrokinetic case studies

Offshore Array Modeling

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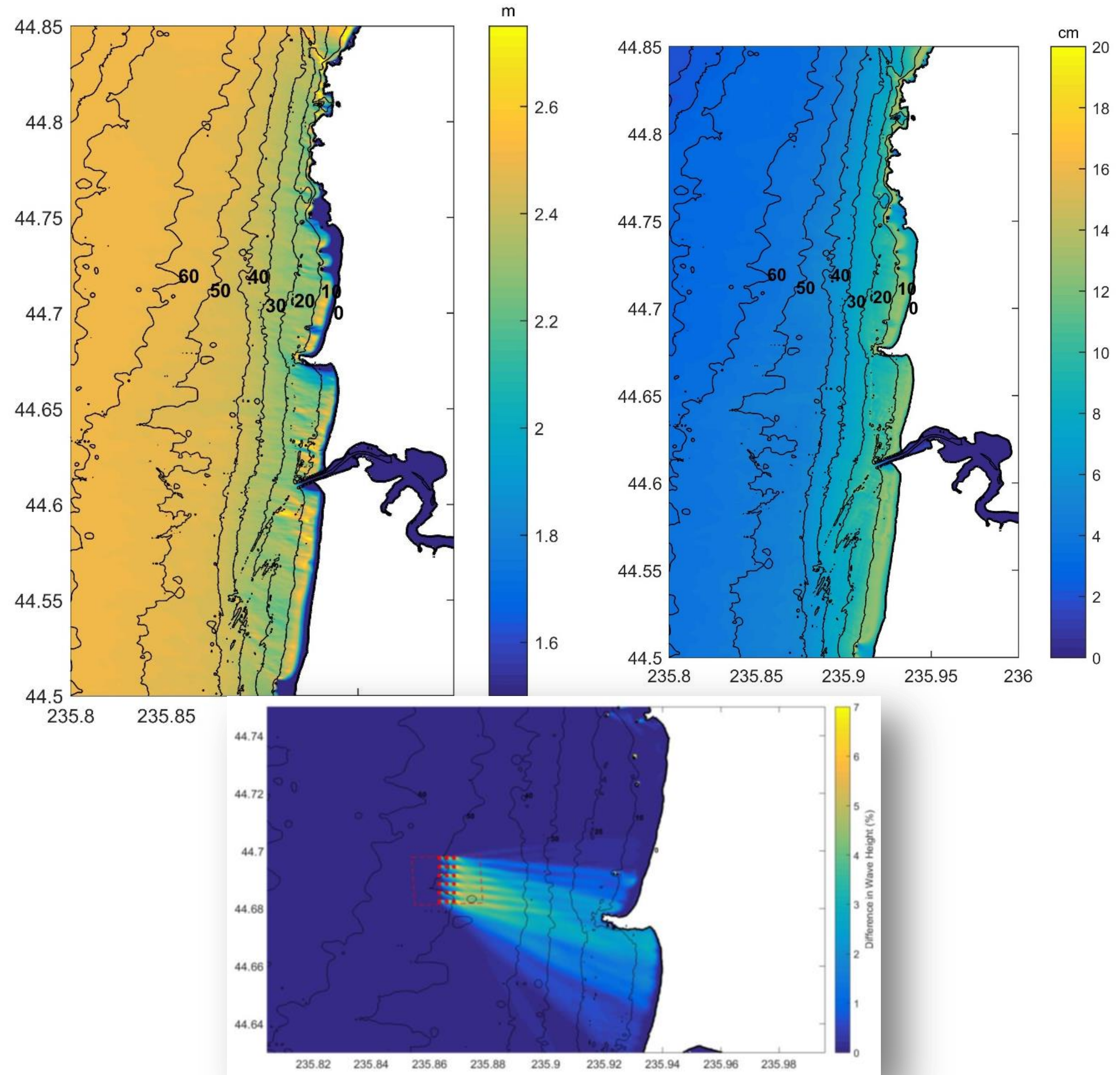
- Newport, Oregon was used as a test location for the offshore wind array modeling tools.

- Site Characteristics
  - 50m water depth
  - Four (4) miles offshore
  - 18 turbines

- The baseline hydrodynamic and wave models provide an excellent quantitative study.



Seabed Risk Assessment

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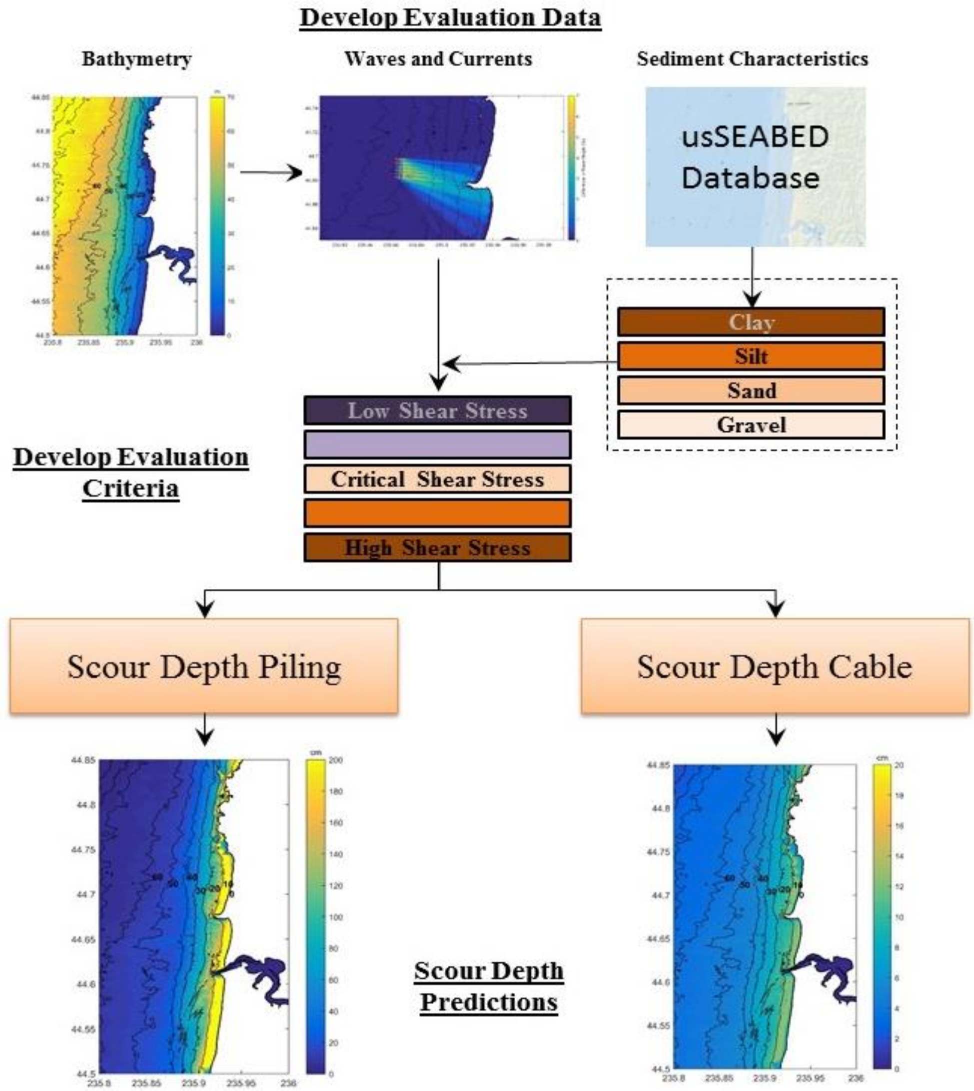
- Bathymetry, modeled waves and currents, and seabed characteristics are integrated in a classification system.
- A scoring criteria defines the risk to offshore environment and infrastructure.
- How big is the change?

Methodology provides quantitative site assessment to support engineering design and environmental compliance.



Project Plan, Schedule, Budget

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- Period of performance (FY11 – FY14,15)
- All milestones met on time and on budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$200K	-	$0K	-	$0K	-

- No variances from planned budget
- Carryover used in FY15

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators:

integral consulting inc.

McNeilan & Associates

Communications and Technology Transfer:

- Offshore Wind Guidance Document (SAND2014-15239):
  - Oceanographic and Sediment Stability (Updated)
- Technical Reports:
  - Five DOE/SNL technical reports
- Conference Proceedings/Presentations:
  - American Wind Energy Association Offshore Wind Conference 2015, Baltimore, MD
- Bureau of Ocean Energy Management (BOEM) and the National Oceanic Atmospheric Administration (NOAA) Washington, DC Seminar 2014, 2015
  - Tools and Techniques for OW Environmental Evaluation

Next Steps and Future Research

FY17/Current Research: N/A

Planned Future Research:

- Field demonstration and refinement of analysis tools
- Industry outreach and training

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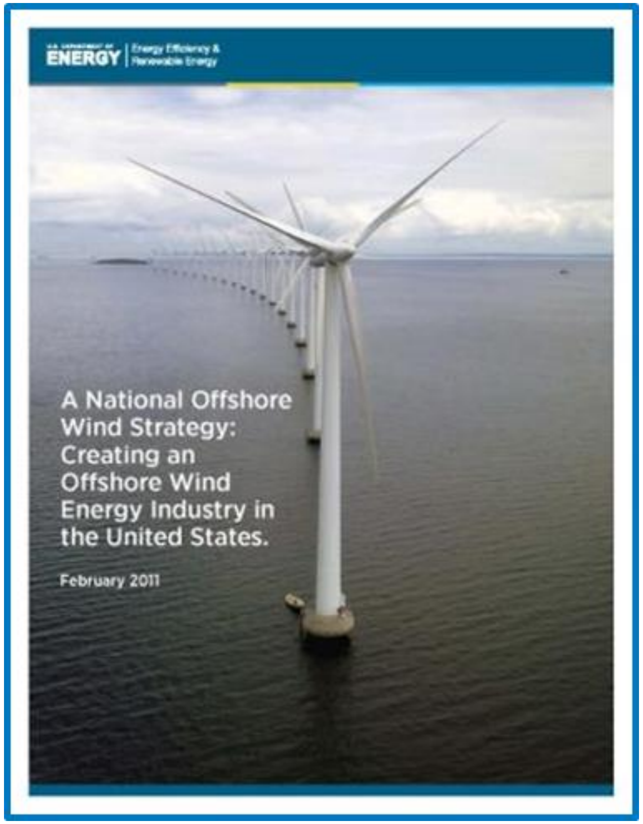

	Activities	Short-Term Testing (2 years)									Long-Term Testing (5+ years)				
		Power Performance	Rotor, Turbine and Tower Loads	Acoustic Noise	Power Quality	Safety and Function	Advanced Controls	Innovation Testing	Substructure and Foundation	Inflow and Wake Turbulence	Metocean Monitoring	Model Validation	Condition Monitoring	Wind Farm Performance	Ecosystem and Wildlife
1	Validation of the Metocean Design Basis										✓				
2	Type/Project Certification Process Validation	✓	✓	✓					✓	✓	✓	✓			
3	Turbine Design Validation and Standards Development	✓	✓			✓		✓	✓	✓	✓	✓		✓	
4	Design Methodology	✓	✓	✓				✓	✓	✓	✓			✓	
5	Wind Plant Evaluation and Optimization	✓	✓				✓	✓	✓	✓	✓	✓		✓	
6	Innovation Validation	✓					✓	✓	✓	✓	✓				
7	Long-Term Monitoring										✓	✓	✓	✓	
8	Ecosystem and Wildlife			✓							✓		✓		✓

Instrumentation Planning for the Offshore Wind Advanced Technology Demonstration Projects

Walter Musial
National Renewable Energy Laboratory
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February 2017

Project Overview

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Guidelines for Offshore Wind Advanced Technology Demonstration (ATD) Project Instrumentation, Data Collection, and Testing:

- DOE is investing up to $150M to demonstrate the latest offshore wind technology in U.S. waters under the ATD projects.
- A primary taxpayer benefit will be thorough dissemination of high quality near-term and long-term measurements and documented deployment experience for five years.
- This project provides recommendations that allow DOE and ATD project to coordinate testing activities and define ATD outputs.

The Challenge:

- Distinguishing ATD projects from commercial projects by securing near real-time data to maximize public benefit
- Obtaining high-quality data from ATD projects with uniformity that allow for cross-cutting analysis, accounting for site-specific differences
- Defining minimum requirements instrumentation and hardware, data quality, security, and storage.

Partners: None

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- **Advanced technology demonstration projects**
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

Green Text Indicates Subordinate Impacted Area

Program Strategic Priorities

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Enabling Wind Nationwide

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- **Advanced technology demonstration projects**
- Technical engagement initiatives
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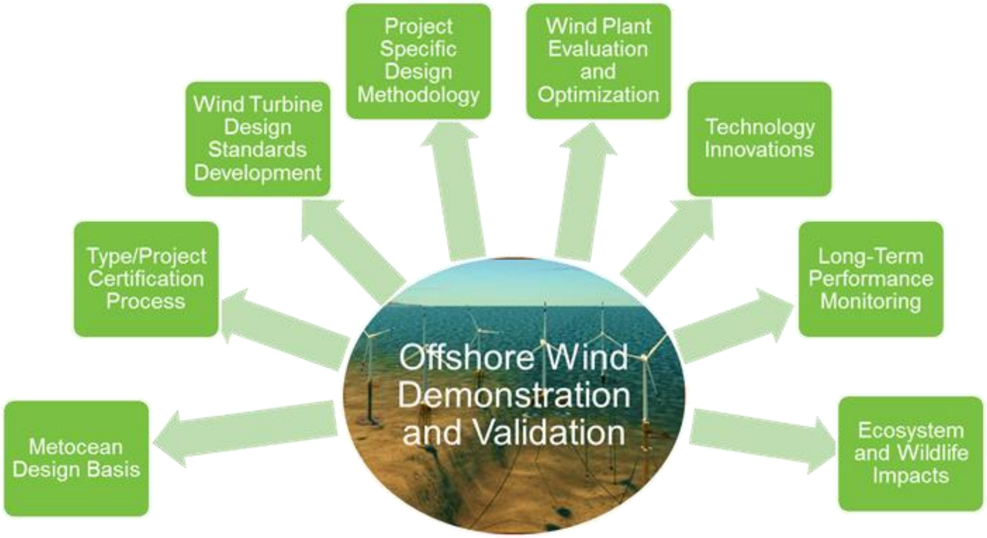
Green Text Indicates Subordinate Impacted Area

The Impact

- ATD projects set the bar for high quality crosscutting, traceable data sets over multiple disciplines
- Centralized data archiving and fast access by DOE will provide transparency to the public
- Distinguishes ATD projects from other commercial offshore wind projects (e.g. Deepwater Block Island)



Standard data collection, transmission, quality, storage, and cross-cutting testing methods for ATD projects

Technical Approach

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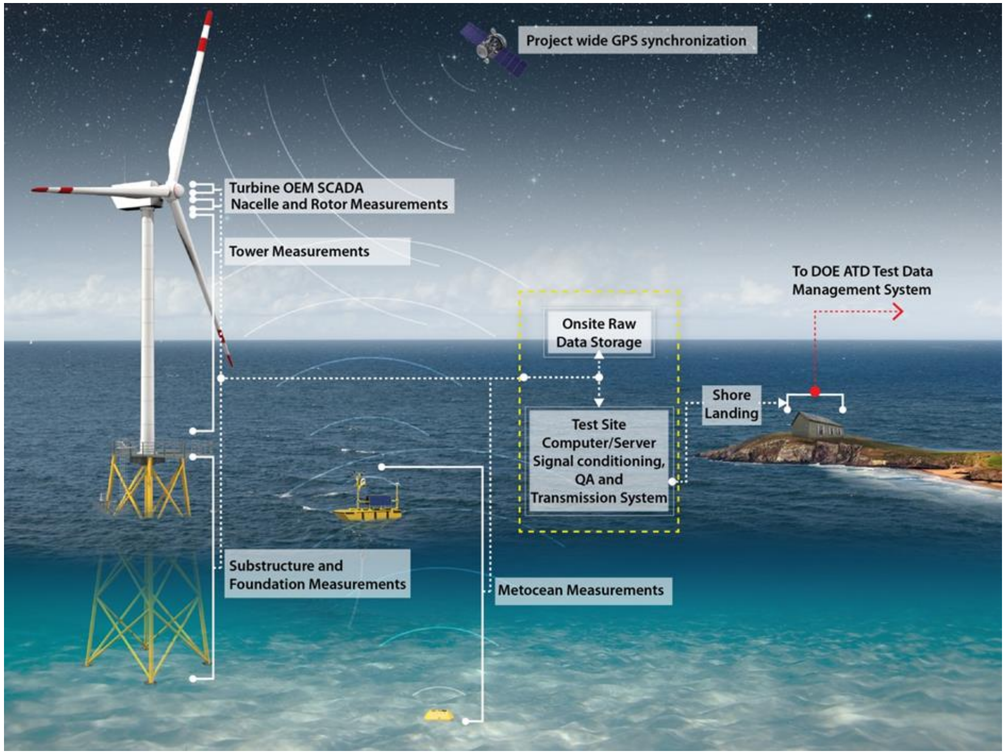
Develop a standard approach for testing and data dissemination on Advanced Technology Demonstration Projects

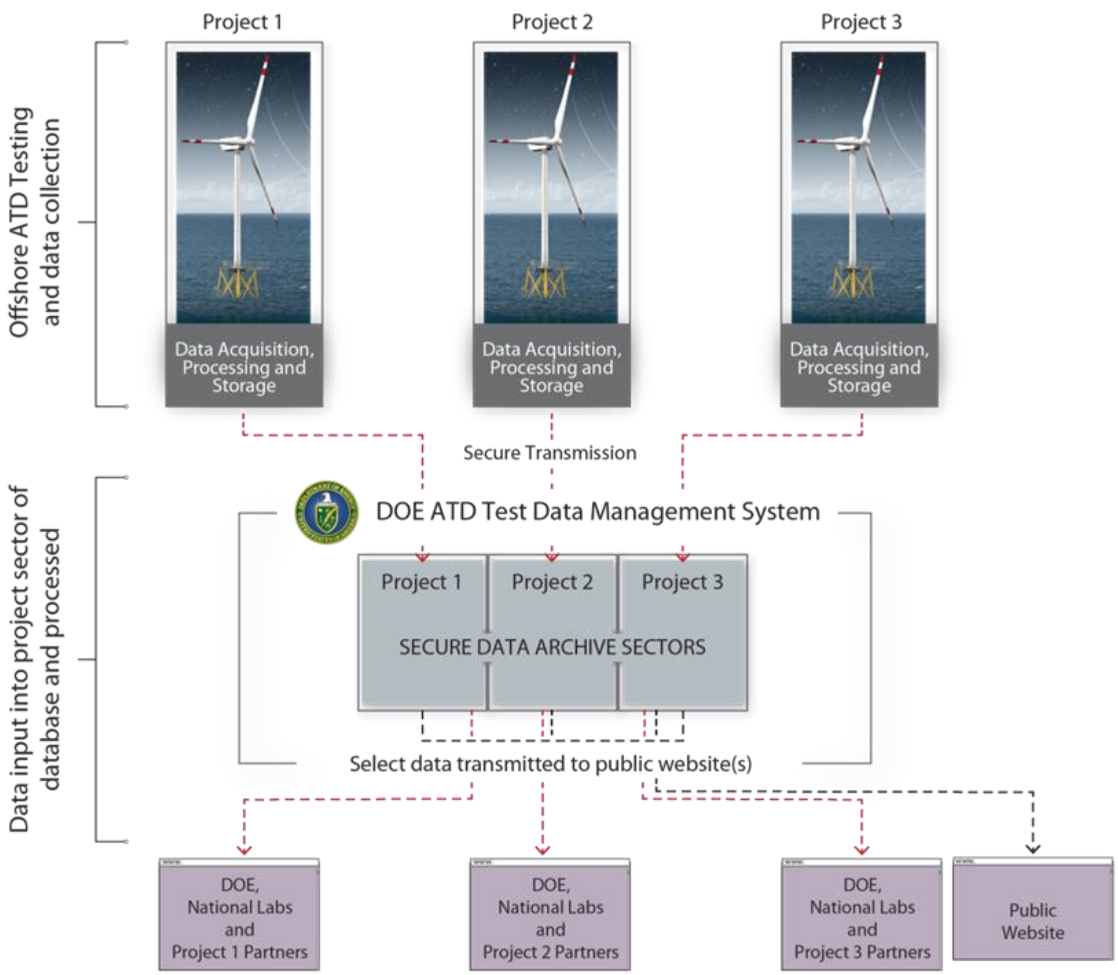
- Leverage NREL prior experience
- Consider broad range of data needs
- Consider hardware and instrumentation systems
- Integrate standards and guidelines
- Enable data dissemination
- Allow data access - near real time
- Maximize public transparency
- Five years of project data



Technical Approach

Key issues addressed, and their significance:

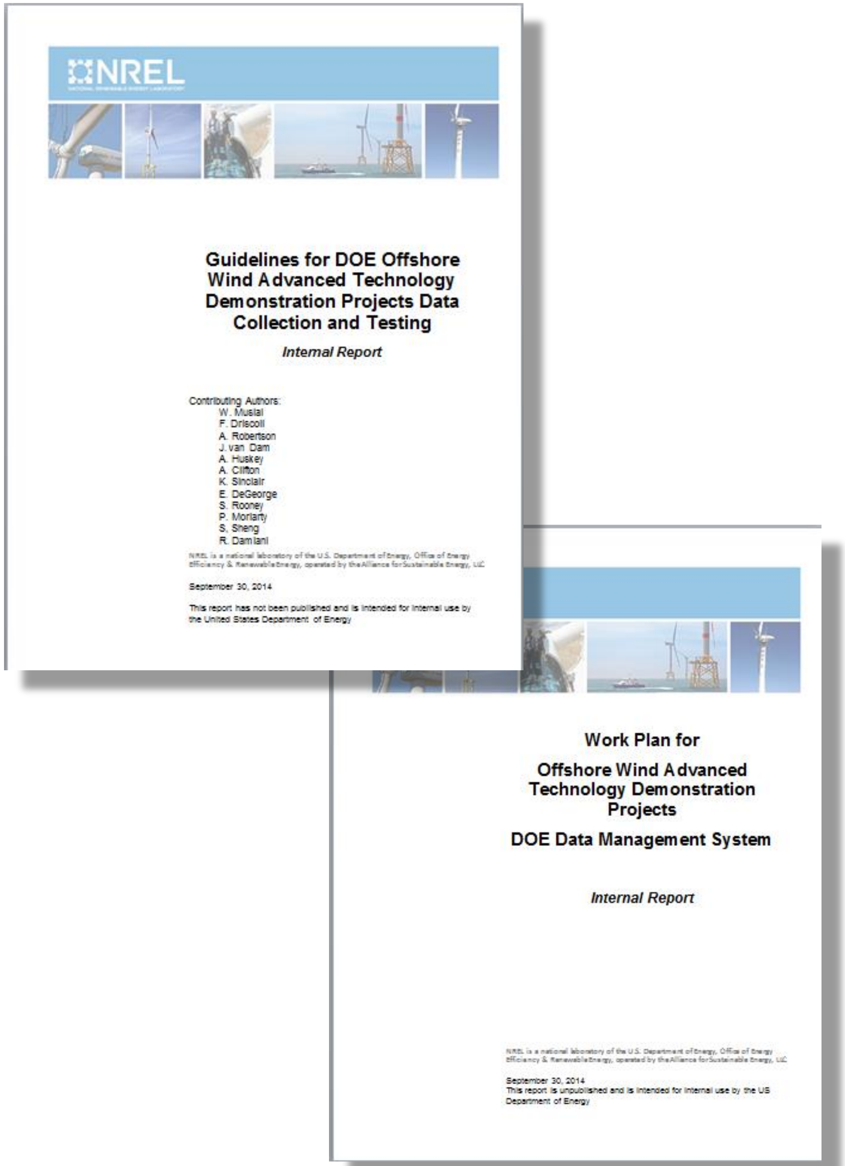
- Data sufficiency, consistency, quality, security, delivery, and dissemination
- Test planning and adherence to standards
- Hardware and instrumentation selection.



Accomplishments and Progress

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

- Webinar for DOE and the ATD projects on August 25, 2014
- Final report *Guidelines for DOE Offshore Wind Advanced Technology Demonstration Projects Instrumentation, Data Collection and Testing* was delivered to DOE on October 1, 2014
- Work plan for implementation of DOE data management system on advanced technology demonstration projects
- Project cost plan to implement DOE data management system on advanced technology demonstration projects.



Project Plan & Schedule

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The project was completed on-time and within budget

Project Start Date: 10/1/2013

Project Completion Date: 9/30/2015

Milestones and Completion Dates	Date Complete
Q1 Project Milestone Description: Draft an internal work plan that clarifies all of the DOE objectives for the project and present the findings via a webinar by December 31, 2013.	1/15/2014
Q2 Project Milestone Description: Submit draft recommendations to DOE for testing and instrumentation support for the three final awardees by March 31, 2014.	5/2/2014
Q3 Project Milestone Description: Submit draft recommendations to DOE for testing, instrumentation, data dissemination, analysis and storage requirements by June 30, 2014.	5/19/2014
Q4 Project Milestone Description: Submit a final report to DOE on the testing and instrumentation recommendations and host a webinar for a select audience to present the findings of the project by September 30, 2014.	9/30/2014

Project Budget

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

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$169k	$0	$0	$0	$0	$0

All funds were spent in FY14 and all milestones were completed on time.

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

Internal NREL Staff Contributors: Andy Clifton, Rick Damiani, Elise DeGeorge, Rick Driscoll, Arlinda Huskey, Christopher Mone, Pat Moriarty, Walt Musial, Amy Robertson, Samantha Rooney, Shawn Sheng, Karin Sinclair, Jeroen Van Dam

Communications and Technology Transfer:

- An 80-page internal report *Guidelines for DOE Offshore Wind Advanced Technology Demonstration Projects Instrumentation, Data Collection and Testing* was prepared and circulated to the ATD project teams and DOE.
- NREL prepared a summary PowerPoint presentation and hosted a webinar for DOE and the ATD project teams on August 25, 2014.

Next Steps and Future Research

FY17/Current Research:

- NREL participated in the ATD projects and assisted in the development of test and instrumentation plans under Budget Periods 1 and 2
- No current involvement during PPA and financial negotiations.

Planned Future Research:

- NREL is communicating with the ATD project teams and plans to re-engage with testing and data analysis teams as needed
- Implementation of ATD data management system is uncertain.

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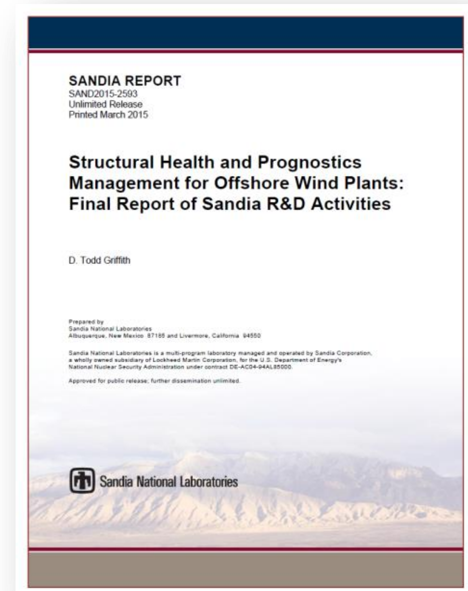

SANDIA REPORT
SAND2015-2593
Unlimited Release
Printed March 2015

Structural Health and Prognostics Management for Offshore Wind Plants: Final Report of Sandia R&D Activities

D. Todd Griffith

Sandia National Laboratories

Structural Health and Prognostics Management for Offshore Wind Projects

D. Todd Griffith, PhD

Sandia National Laboratories
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February 2017

Project Overview

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Structural Health and Prognostics Management (SHPM) for Offshore Wind Projects:

COE affected in three areas

$$COE = \frac{ICC*FCR + LRC}{AEP_{net}} + O\&M$$

ICC ↑
O&M ↓↓
AEP ↑↑↑

The Challenges: (1) Reliable sensing/monitoring of <u>blade</u> state of health and (2) detection early enough to make difference

- ✓ Reduce levelized cost of energy (LCOE) by increasing annual energy production (AEP) by avoiding complete shutdowns
- ✓ Reduce LCOE by planned maintenance and smaller (minor) maintenance
- ✓ Reduce LCOE through advanced warning to avoid major failures

Partners:

- Purdue/Vanderbilt University: Aero-elastic simulations of damaged turbines
- ATA, Inc.: Hi-fidelity simulations of damaged turbines
- Georgia Tech: Loads management (controls) for life extension

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

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- Resource assessment and characterization
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- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- **Commercialization of innovations and technology transfer**
- World-class test and user facilities
- Advanced technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

Enabling Wind Nationwide

Enabling U.S. Industry Growth and U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- **Reliability improvements**
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

The Impact

- LCOE reduction was the strategic target of this project (reduced O&M and increased AEP).
- If successful, this will impact the way that wind turbines are operated and how blades (and other major components) are maintained.
- The final product of this project was a comprehensive final report that detailed the following:
  - Damage detection studies
  - Detailed finite element analysis (FEA) of damaged blades
  - Loads management/controls for life extension
  - Technology roadmap for structural health monitoring and prognostics management (SHPM)
  - Economics analysis (value proposition).

Technical Approach

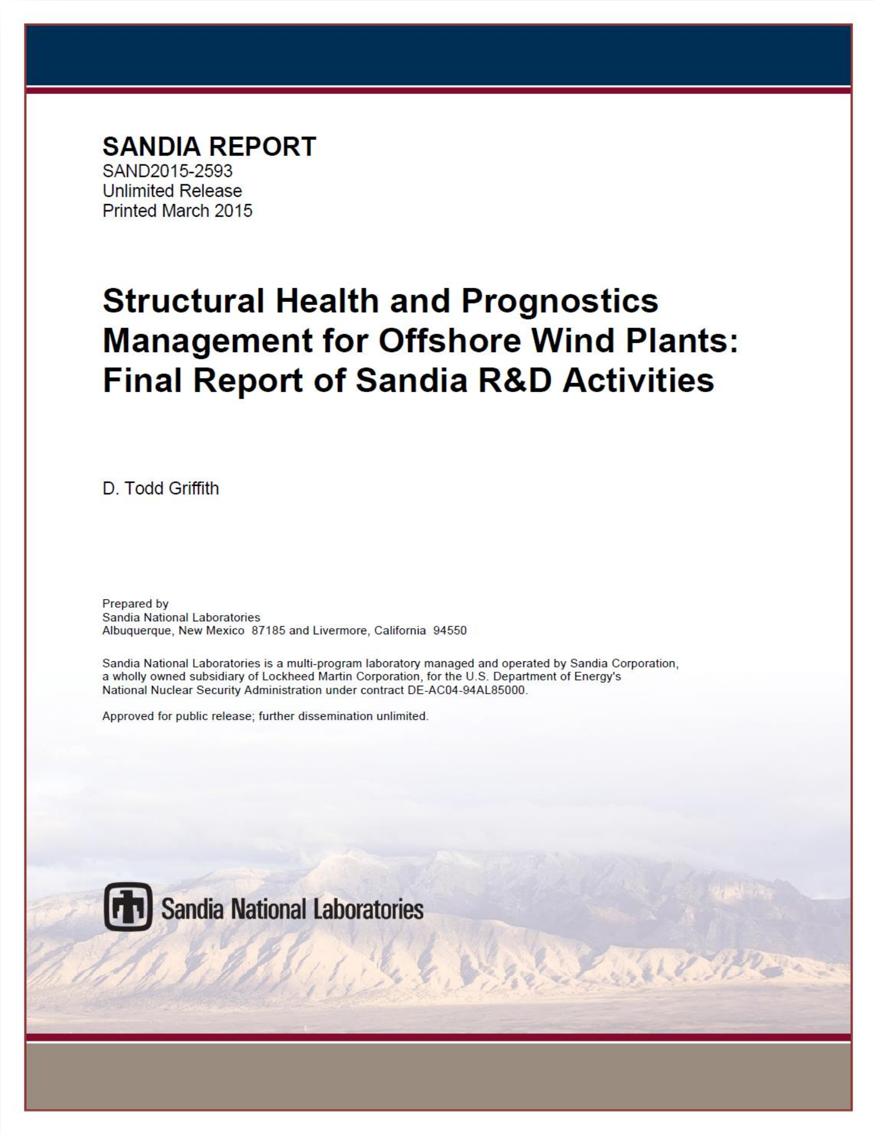
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY11 to FY13: Initial road mapping; simulation methods implemented and case studies performed

FY14+: Smart loads management was researched for extending turbine life and increasing AEP; damage detection was tested successfully (via simulations) under variable inflow conditions; a comprehensive final report was completed

A unique aspect of the technical approach was to tie two key elements: (1) damage detection and characterization, and (2) prognostics management where the state of health from #1 is used for revenue optimized decision making in #2.

Accomplishments and Progress



SANDIA REPORT
SAND2015-2593
Unlimited Release
Printed March 2015

Structural Health and Prognostics Management for Offshore Wind Plants: Final Report of Sandia R&D Activities

D. Todd Griffith

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.

Sandia National Laboratories

"Structural Health and Prognostics Management for Offshore Wind Plants: Final Report of Sandia R&D Activities,"

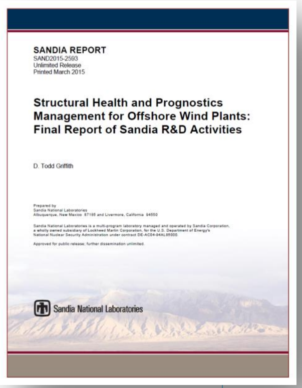
Sandia National Laboratories Technical Report,

SAND2015-2593, March 2015

(310 pages).

Project website:
http://energy.sandia.gov/energy/renewable-energy/wind-power/materials-reliability-standards/structural-health-monitoring/

Accomplishments and Progress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Sandia National Laboratories

Major Findings documented in the Final Report:

1. A Roadmap for SHPM Technology
2. Multi-scale Damage Modeling & Simulation Methodology
3. Damage Detection Strategies for Common Damage Types
4. State of Health of Damaged Turbines Assessment
5. Maturation of Damage Models for Wind Turbine Blade Analysis
6. Smart Loads Management (e.g. Derating, Damage Mitigating Controls)
7. Optimized Maintenance Process Concepts
8. SHPM Economics Calculations
9. Damage Detection Strategies Tested under Realistic & Variable Inflow Conditions
10. A Framework for SHPM Decision-making

[6] Smart Loads Management (e.g. Derating – an illustrative example)

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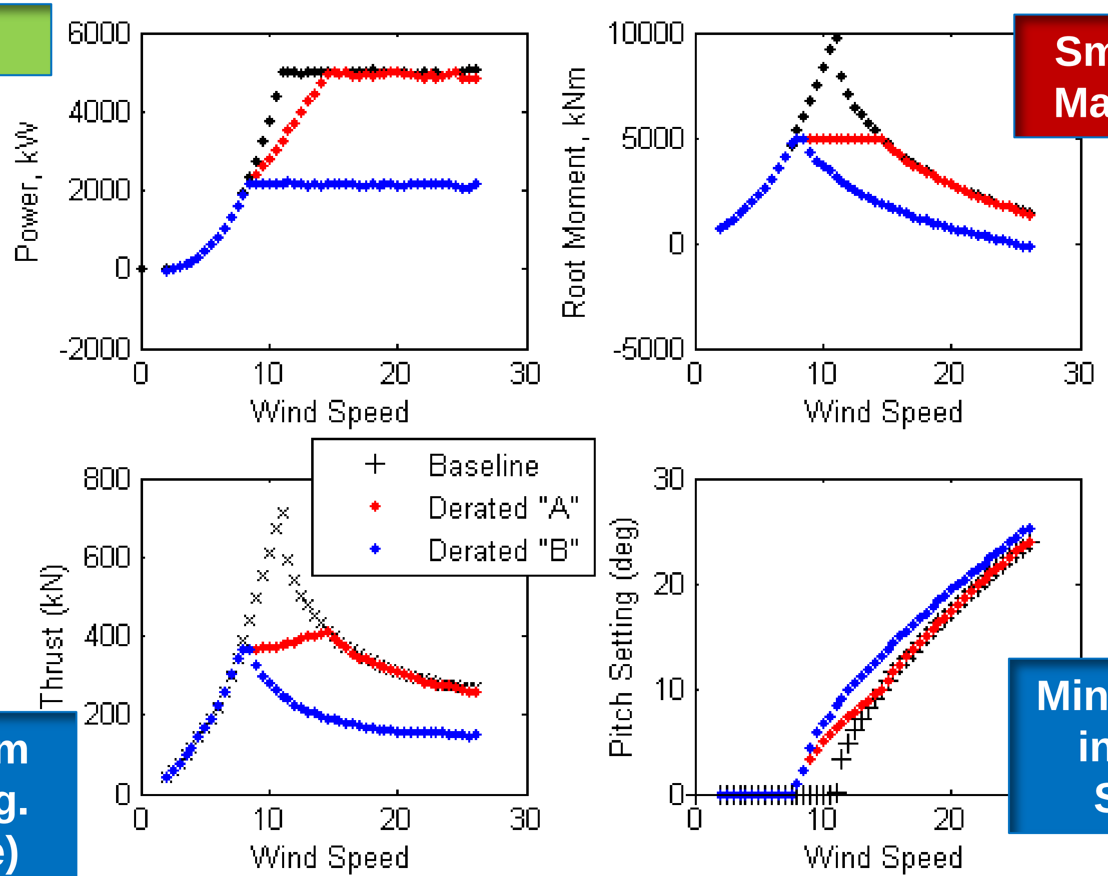
An illustration of 50% loads reduction (i.e. 50% derating) and the impact on revenue.

Revenue

Smart Loads Management

Derated A:
more aggressive

Derated B:
more conservative



Minor Change in Control Strategy

Secondary, System Level Benefits (e.g. support structure)

Increase energy capture and reduce O&M costs with planned maintenance

[9] Damage Detection Strategies Tested under Variable Inflow Conditions (1)

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➢ **Goal: Quantify effect of variable wind inflow on robustness of damage detection with a POD & POC simulations campaign**

Table 3: FAST Simulation Matrix for Each Blade Damage Type.

	Healthy	1m Dis-bond	2m Dis-bond	3m Dis-bond	4m Dis-bond	5m Dis-bond	10m Dis-bond
Wind Speed (3 - 25 m/s)	101	101	101	101	101	101	101
Horizontal Shear (30%, 60%, 90%)	303	303	303	303	303	303	303
Turbulence (A, B, KHTEST)	303	303	303	303	303	303	303

- **>16,000 simulations with varied extent of damage and varied inflow**
- **Sensitivities to varying inflow:**
  - **Wind speed, horizontal shear, and turbulence**
- **Effect on POD**
  - **POD improved in certain wind speed ranges**

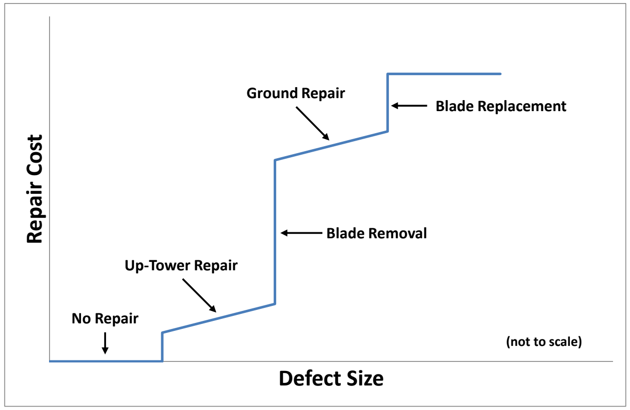
➢ **Waked flow is a subset of the varied inflow conditions: increased turbulence, horizontal shear, and velocity deficit**

POD = Probability of Detection

POC = Probability of Classification

[9] Damage Detection Strategies Tested under Variable Inflow Conditions (2)

Ex. SW Disbond Case



State 1 State 2 State 3 State 4

Table 5: POD and POC for shear web disbond. The POD values are shown under PRESENCE OF DAMAGE and the POC values are shown in the other columns.

		PRESENCE OF DAMAGE		STATE 2 (1-2 m DISBOND)		STATE 3 (3-5 m DISBOND)		STATE 4 (>= 10 m DISBOND)	
		3 - 25 m/s	8.5 - 17.08 m/s	3 - 25 m/s	8.5 - 17.08 m/s	3 - 25 m/s	8.5 - 17.08 m/s	3 - 25 m/s	8.5 - 17.08 m/s
LAMINAR	Raw	84.16%	100.00%	84.16%	100.00%	83.33%	100.00%	84.16%	100.00%
	Weibull Weighted	77.24%	100.00%	77.24%	100.00%	77.16%	100.00%	77.24%	100.00%
30% SHEAR	Raw	74.26%	100.00%	72.79%	100.00%	69.11%	100.00%	72.79%	100.00%
	Weibull Weighted	78.07%	100.00%	77.95%	100.00%	77.55%	100.00%	77.95%	100.00%
60% SHEAR	Raw	44.55%	100.00%	35.73%	100.00%	36.61%	100.00%	36.17%	100.00%
	Weibull Weighted	60.18%	100.00%	58.30%	100.00%	58.61%	100.00%	58.46%	100.00%
90% SHEAR	Raw	15.84%	32.50%	10.82%	32.50%	11.29%	32.50%	10.98%	32.50%
	Weibull Weighted	25.19%	39.18%	23.21%	39.18%	23.58%	39.18%	23.34%	39.18%
A TURBULENCE	Raw	37.62%	75.00%	34.27%	75.00%	29.80%	75.00%	27.94%	75.00%
	Weibull Weighted	50.49%	74.99%	50.03%	74.99%	48.31%	74.99%	47.91%	74.99%
B TURBULENCE	Raw	45.54%	85.00%	42.39%	85.00%	36.07%	85.00%	33.82%	85.00%
	Weibull Weighted	62.86%	84.98%	61.73%	84.98%	59.38%	84.98%	59.65%	84.98%
KHTEST TURBULENCE	Raw	45.54%	80.00%	33.82%	80.00%	34.72%	80.00%	28.41%	76.00%
	Weibull Weighted	68.43%	88.06%	64.93%	88.06%	65.41%	88.06%	60.51%	85.76%

Detection probability reduced with turbulent inflow.

But, small reduction in detection in "optimized" wind speed range

Project Plan & Schedule

- This project started in FY11 and was completed during FY15.
- There were a few slipped milestones due to delayed receipt of subcontractor reports. Otherwise, the project schedule was on-track as planned.

Offshore Wind RD&T Structural Health

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

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$300k		$0		$0	

- Budget was carried from FY14 to FY15 to complete the project final report, which was completed and presented to DOE in FY15/Q2.

Partners, Subcontractors, and Collaborators:

Subcontracts:

- ATA Engineering, Inc.
- Purdue University / Vanderbilt University
- Georgia Tech

Communications and Technology Transfer:

Publications: SAND reports, journal, and conference papers

Patent: Provisional filed, non-provisional to be filed.

Working Group: An industry and academic group was engaged to disseminate results.

Website: http://energy.sandia.gov/energy/renewable-energy/wind-power/offshore-wind/#structure_health

Research Integration & Collaboration

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

Publications: [SAND (4) Journal (5) Conference (4)]

1) Griffith, D.T., Yoder, N., Resor, B.R., White, J., Paquette, J., Ogilvie, A., and Peters, V., "Prognostic Control to Enhance Offshore Wind Turbine Operations and Maintenance Strategies," Proceedings of the European Wind Energy Conference Annual Event (Scientific Track), April 16–19, 2012, Copenhagen, Denmark.
2) Griffith, D.T., Yoder, N.C., Resor, B.R., White, J.R., and Paquette, J.A., "Structural Health and Prognostics Management for Offshore Wind Turbines: An Initial Roadmap," Sandia National Laboratories Technical Report, December 2012, SAND2012-10109.
3) Myrent, N., Kusnick, J., Barrett, N., Adams, D., and Griffith, D.T., "Structural Health and Prognostics Management for Offshore Wind Turbines: Case Studies of Rotor Fault and Blade Damage with Initial O&M Cost Modeling," Sandia National Laboratories Technical Report, April 2013, SAND2013-2735.
4) Myrent, N.J., Kusnick, J.F., Adams, D.E., and Griffith, D.T., ""Pitch Error and Shear Web Disbond Detection on Wind Turbine Blades for Offshore Structural Health and Prognostics Management" 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April 8–11, 2013, Boston, MA, USA, AIAA-2013-1695.
5) Griffith, D.T., Yoder, N.C., Resor, B.R., White, J.R., and Paquette, J.A., "Structural Health and Prognostics Management for the Enhancement of Offshore Wind Turbine Operations and Maintenance Strategies," Wind Energy, September 2013 (DOI: 10.1002/we.1665).
6) Myrent, N., Griffith, D.T., et al., "Aerodynamic Sensitivity Analysis of Rotor Imbalance and Shear Web Disbond Detection Strategies for Offshore Structural Health Prognostics Management of Wind Turbine Blades," 32nd ASME Wind Energy Symposium, National Harbor, MD, USA, January 2014.
7) Kusnick, J., Adams, D.E., and Griffith, D.T., "Wind Turbine Rotor Imbalance Detection Using Nacelle and Blade Measurements," Wind Energy, January 2014 (DOI: 10.1002/we.1696).
8) Richards, P.W., Griffith, D.T, and Hodges, D.H., "Structural Health and Prognostic Management: Operating Strategies and Design Recommendations for Mitigating Local Damage Effects in Offshore Turbine Blades," 70th American Helicopter Society Annual Forum & Technology Display, May 20–22, 2014, Montreal, Quebec, Canada.
9) Richards, P.W., Griffith, D.T., and Hodges, D.H., "High-fidelity Modeling of Local Effects of Damage for Derated Offshore Wind Turbines," Journal of Physics Conference Series, Science of Making Torque from Wind Conference, June 18–20, 2014, Lyngby, Denmark.
10) Myrent, N.J., Barrett, N.C., Adams, D.E., and Griffith, D.T., "Structural Health and Prognostics Management for Offshore Wind Turbines: Sensitivity Analysis of Rotor Fault and Blade Damage with O&M Cost Modeling," Sandia National Laboratories Technical Report, SAND2014-15588, July 2014.
11) Griffith, D.T., "Structural Health and Prognostics Management for Offshore Wind Plants: Final Report of Sandia R&D Activities," Sandia National Laboratories Technical Report, SAND2015-2593, March 2015.
12) Myrent, N, Adams, D., Griffith, D.T., "Wind turbine blade shear web disbond detection using rotor blade operational sensing and data analysis," Philosophical Transactions of the Royal Society A, January 2015.
13) Richards, P., Griffith, D.T., and Hodges, D., "Smart Loads Management for Damaged Offshore Wind Turbines," Wind Engineering, Vol. 39, No. 4, August 2015, pp 419-436, DOI: http://dx.doi.org/10.1260/0309-524X.39.4.419.

Next Steps and Future Research

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

FY17/Current Research:

This project was completed in FY15.

Planned Future Research:

No future DOE project is planned at this time; however, the published SHPM technology roadmap can be used to identify future research steps to further develop and demonstrate this technology.

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

Demo Project Buoy Deployment

WJ Shaw

Pacific Northwest National Laboratory

will.shaw@pnnl.gov (509) 372 6140

February 2017

OSW Environmental Research and Support – Project Overview

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

Demo Project Buoy Deployment:

Pacific Northwest National Laboratory (PNNL) manages deployment of two lidar buoys to provide previously unavailable long-term, hub-height winds in support of offshore wind energy in the United States.

The Challenge:

The marine environment is expensive for operations. There have been no previous multi-seasonal wind measurements to support resource model validation and offshore demonstration projects.

Partners and their Role:

Buoy deployments are managed by PNNL with support from site-dependent offshore marine contractors.

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- **Resource assessment and characterization**
- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
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- NextGen component innovations

The Impact

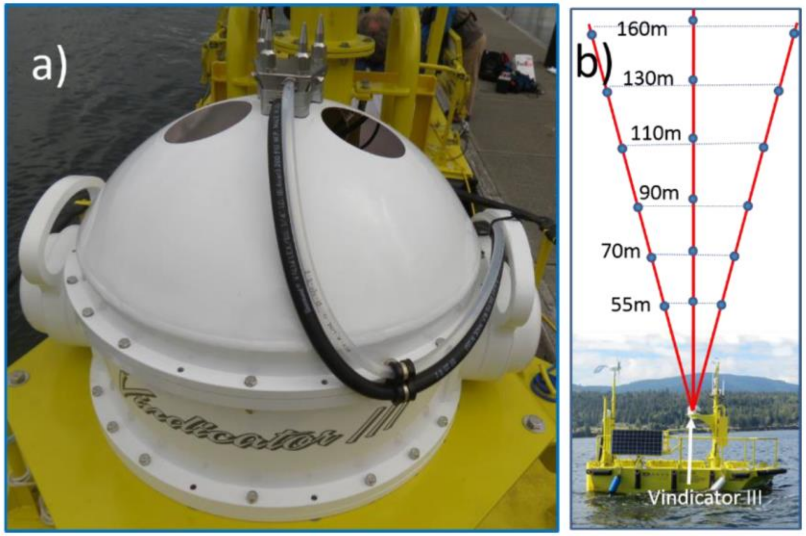
- Provides previously unavailable hub-height winds in the U.S. Outer Continental Shelf
- Provides data on station over full annual cycle, covering range of atmospheric conditions
- Allows validation of resource characterization models offshore
- Is far less expensive than offshore towers
- Is federally funded, so data are available to all interested parties
- Is a multi-year resource for the development of offshore wind energy in the United States

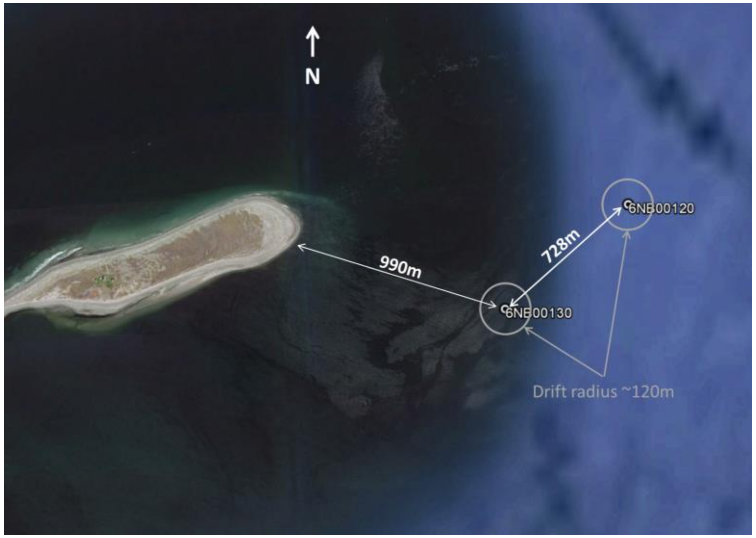
Develop Procurement Specification and Execute

- Review state of the art in floating lidar systems
- Engage PNNL expertise in instrumentation, marine deployments, contracting

Perform Acceptance Testing

- Engage PNNL's Marine Science Laboratory in Sequim, Washington





Buoy Comparison Locations near MSL

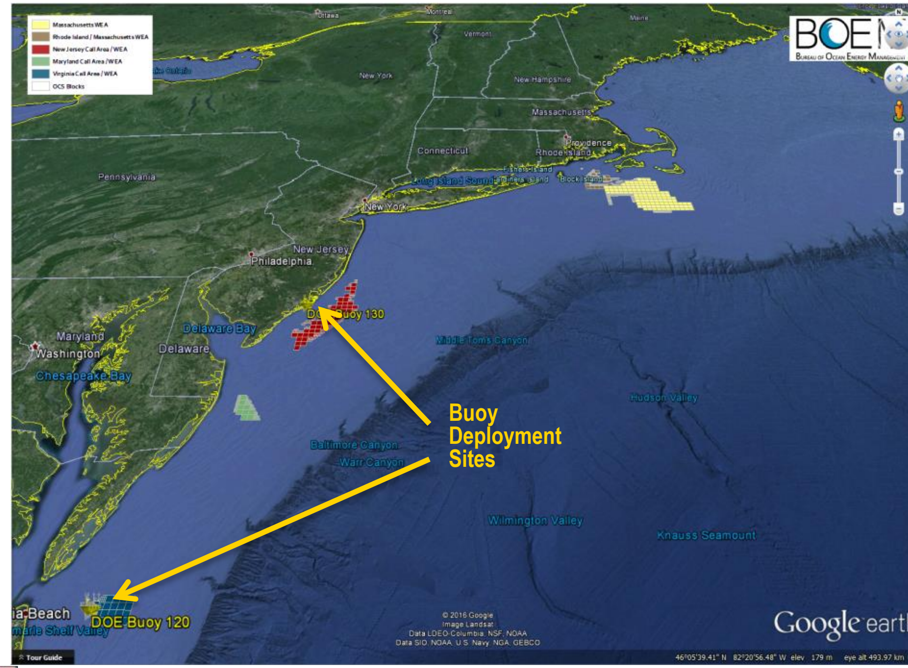
Technical Approach

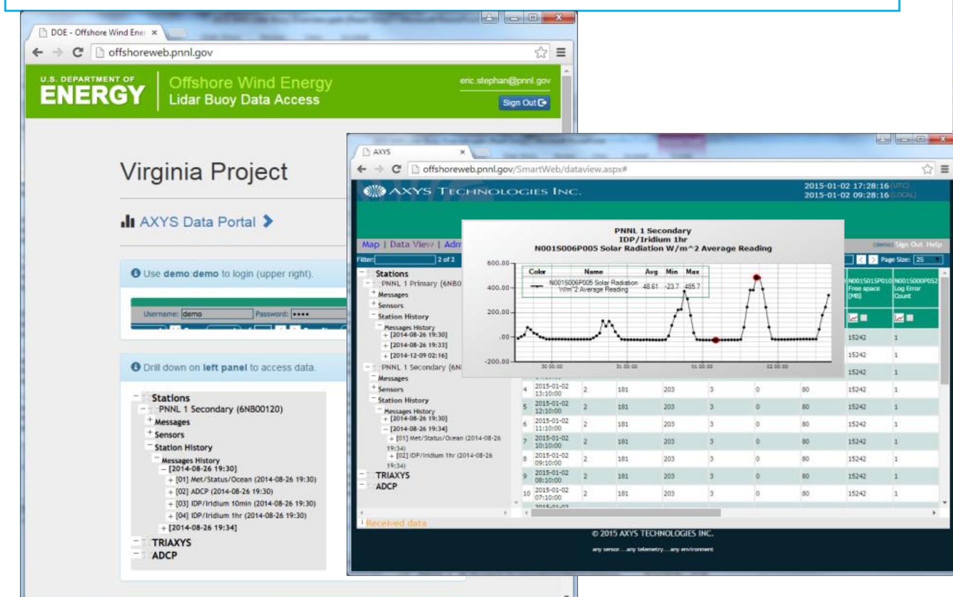
Develop Data Management Plan

- Host vendor data portal
- Use Atmosphere to electrons (A2e) Data Archive and Portal as permanent repository

Execute Deployments

- Develop deployment plans for DOE Offshore Wind Demo Sites
- Deploy at selected sites





Buoy 120 42 km off Virginia shore

Accomplishments and Progress

- Two WindSentinel buoys procured from AXYS Technologies in FY 2014
- Acceptance testing carried out at PNNL's Marine Sciences Laboratory in Sequim, Washington
- Deployment in Virginia (near Dominion demonstration project)
  - December 12, 2014
    - Deployed by PNNL staff with Cape Henry Marine Services
  - 17 months of data delivered to the A2e Data Archive and Portal
  - June 15, 2016
    - Recovered by Offshore Technical Services and Cape Henry
- Deployment in New Jersey (near Fishermen's demonstration project)
  - November 4, 2015
    - Deployment by OTS under contract
  - On station through November 2016

Project Plan & Schedule

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

- Project Initiation Date: October 2014
  - Project life: three years
  - Anticipated ongoing oversight of DOE buoy program
- Explanation for Slipped Milestones
  - One FY16 minor milestone slipped due to redirection of funds to emergency recovery of New Jersey buoy after it broke free from its mooring.
- There were no Go/No-Go Decision Points

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$3,500k	—	$793K	—	$286K	—

- Initial deployment costs were underestimated
  - Original plan was one East Coast and one West Coast deployment
  - West Coast logistically problematic
  - Project plan modified to do both deployments on East Coast
- All project funds, except mandated 25% carryover, have been expended
- Other funding
  - Commonwealth of Virginia through Virginia Tech provide $70K to document lidar behavior

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

Subcontractors

- Cape Henry Marine Services (Virginia)
- Offshore Technical Services (New Jersey and Virginia)

Collaborator

- Dr. George Hagerman, Virginia Tech

Communications and Technology Transfer:

- American Meteorological Society (AMS) Sixth Conference on Weather, Climate, and the New Energy Economy, 2014: 2 presentations
- AMS Seventh Conference on Weather, Climate, and the New Energy Economy, 2015: One presentation
- Newsom, RK, 2016: Optimizing Lidar Wind Measurements from the DOE WindSentinel Buoys, Technical Report, PNNL-25512.
- BOEM Virginia 2016 Task Force Meeting: One presentation
- Data publicly available
  - Visualization and low-bandwidth downloads: offshoreweb.pnnl.gov
  - Full data sets: a2e.energy.gov/data

Next Steps and Future Work

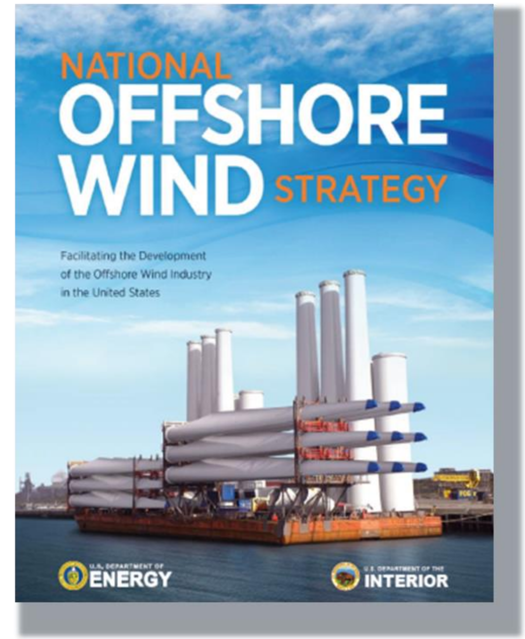
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY17/Current Work:

- Oversight of refurbishing of buoy recovered from Virginia deployment
- Oversight of recovery and refurbishing of buoy deployed off New Jersey
- Development of a buoy loan program
  - Multiple requests to DOE and expressions of interest
  - Will allow DOE to leverage user interest to advance offshore wind energy in the U.S.

Planned Future Work:

- Continuation of management oversight of buoy maintenance and loans
- Continuation of data archival and dissemination



National Offshore Wind Strategy Supporting Analysis

Walt Musial

National Renewable Energy Laboratory

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303 384 6956

February 2017

Project Overview

National Offshore Wind Strategy Supporting Analysis:

- Quantifies the value proposition for offshore wind in the United States
- Includes quantitative details on:
  - Resource class and assessment
  - Opportunity space for offshore capacity additions
  - Site-specific cost and cost reduction potential
  - Economic potential
  - Non-levelized-cost-of-energy (LCOE) value adders
- Provides detailed documentation in four Offshore Wind Strategy back-up publications

The Challenges:

- To provide data and analysis that enable the U.S. Department of Energy (DOE), Department of Interior, and industry to assess the business case for offshore wind in the United States
- To create a tool that can be used to assess cost trade-offs for future cost scenarios

Partners: DOE and U.S. Department of the Interior

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- Successful coexistence with radar systems
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Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
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- Communicating the costs and benefits of wind energy

The Impact

- Provides a credible basis for the U.S. offshore wind value proposition described in the 2016 national offshore strategy
- Enables targeted research and development and technology investments to accelerate industry advancement .

Five Published Reports Evaluate the Case for Offshore Wind:

U.S. Department of Energy. 2016. *National Offshore Wind Strategy:* *Facilitating the Development of the Offshore Wind Industry in the United States*, http://energy.gov/sites/prod/files/2016/09/f33/National-Offshore-Wind-Strategy-report-09082016.pdf .

Beiter, P. et al . ***A Spatial-Economic Cost Reduction Pathway for U.S. Offshore Wind Energy Development from 2015–2030*** (Technical Report). NREL/TP-6A20-66579. http://www.nrel.gov/docs/fy16osti/66579.pdf.

Beiter, P. and W. Musial. 2016. ***Terminology Guideline for Classifying Offshore Wind Energy Resources*** (Technical Report), NREL/TP-6A20-65431. http://www.nrel.gov/docs/fy16osti/65431.pdf.

Musial, W. et al. ***2016 Offshore Wind Energy Resource Assessment for the United States*** (Technical Report). NREL/TP-5000-66599. http://www.nrel.gov/docs/fy16osti/66599.pdf.

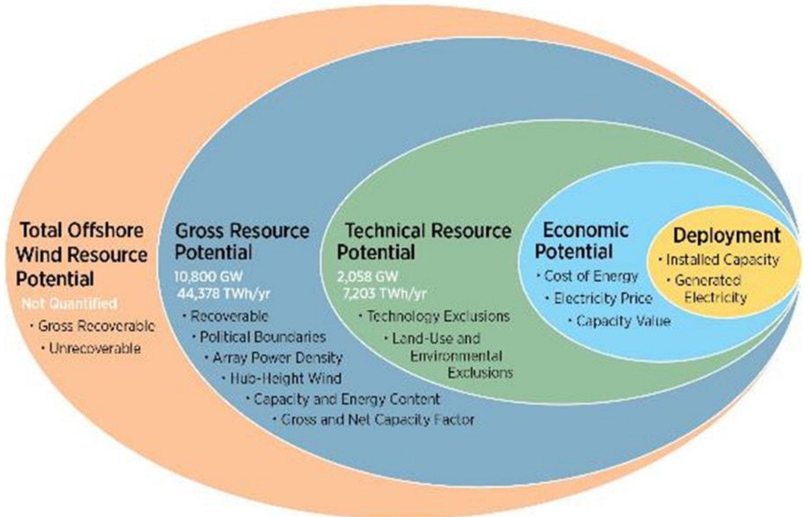
Marcy, C. and P. Beiter. 2016. ***Quantifying the Opportunity Space for Future Electricity Generation: An Application to Offshore Wind Energy in the United States*** (Technical Report). NREL/TP-6A20-66522. http://www.nrel.gov/docs/fy16osti/66522.pdf.

Technical Approach – Resource Assessment and Opportunity Space

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

Updated Resource Assessment

- New method of classification (top figure)
- More realistic estimates of technical potential
- Clear separation between the gross and technical potential
- Energy potential.



Terminology Framework for Resource Classification

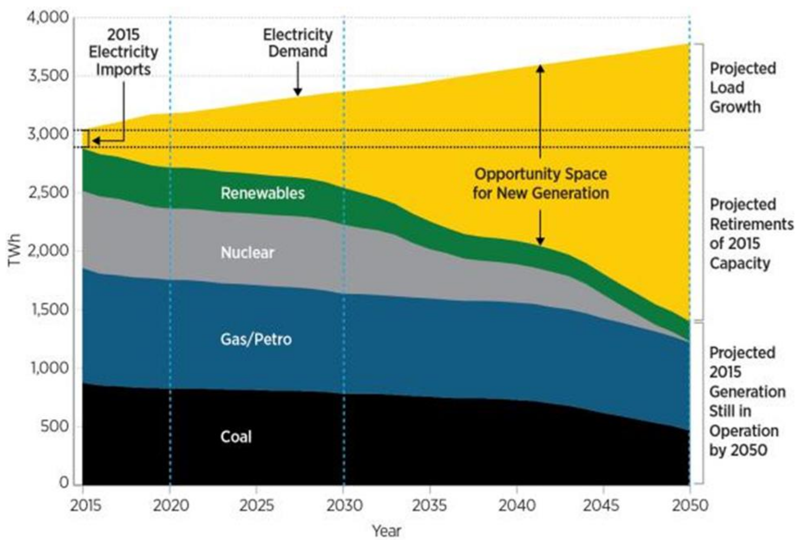
The Opportunity Space

(yellow wedge in bottom figure)

- Load growth
- Power plant retirements in the coastal states.

Load Compound Annual Growth Rate (CAGR) 0.66% per year (2015–2050) (Source: Regional Energy Deployment System/Energy Information Administration)

Announced retirements (EIA Form-860)

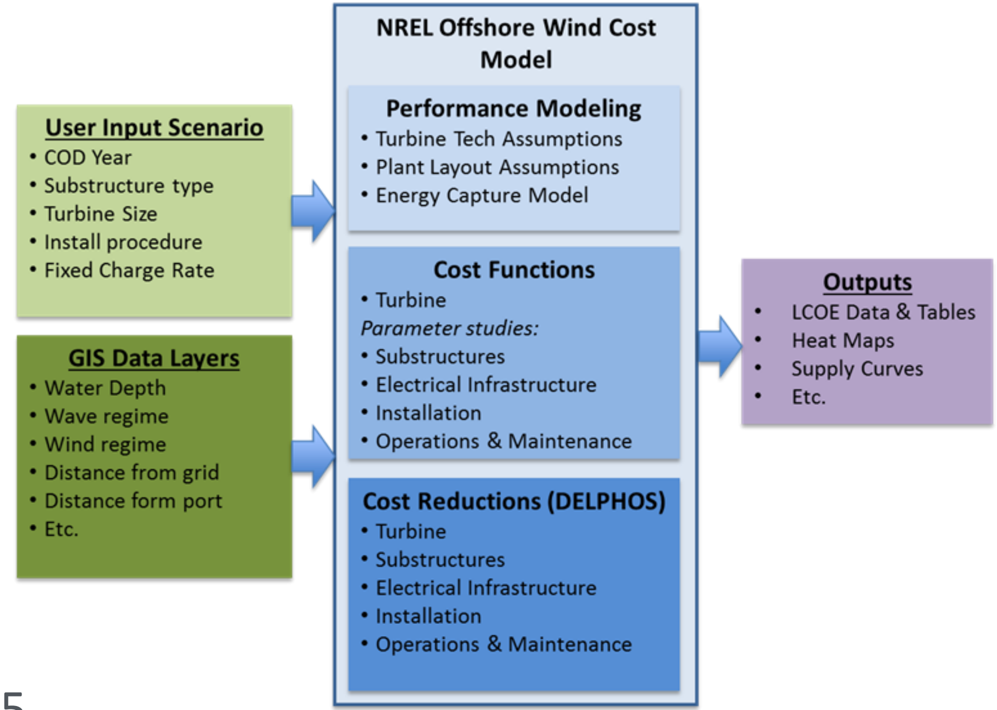


Opportunity Space for Offshore Wind in The USA

Technical Approach – Cost Modeling

Provide Higher-Fidelity Insights on LCOE and Cost Reduction Potential

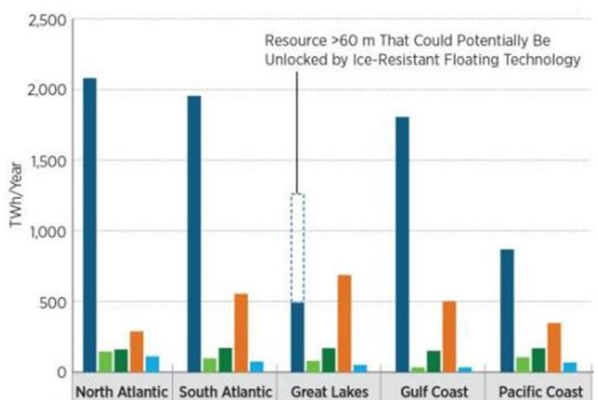
- Advance offshore wind geospatial economic model for the Outer Continental Shelf
- Integrate future cost prediction methods (Delphos) into NREL model
- Leverage open-source tools from KIC InnoEnergy/BVG Consulting (Delphos)
- Increase capabilities of Delphos to:
  - Extend from 2025 to 2030
  - Create capability for floating costs
- Model LCOE for 7,000+ sites from 2015 to 2030
- Calculate economic potential introduced using levelized avoided cost of energy.



Modeling approach showing inputs (green), NREL Offshore Wind Cost Model (blue), and model outputs (lavender)

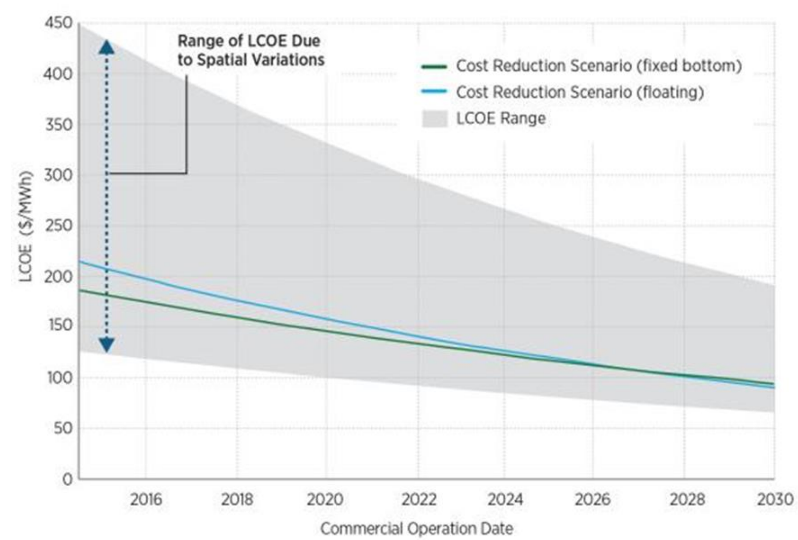
Some Key Findings and Takeaways

- **Available technical offshore wind resource exceeds development requirements**
- **About 2,300 terawatt hours (TWh) of opportunity space opens by 2050**
- **Need 14% of opportunity space for *Wind Vision* scenario of 86 gigawatts.**
- **Geographic variations result in wide range of LCOE; technology innovation can mitigate cost**
- **Floating wind can reach fixed bottom costs by 2030; $100/megawatt hour (MWh) is achievable by 2025**
- **Cost reductions depend on supply chain growth and maturity.**



	North Atlantic	South Atlantic	Great Lakes	Gulf Coast	Pacific Coast
Technical Resource Potential	2,081	1,955	492	1,806	869
2020 Opportunity Space	145	98	80	33	106
2030 Opportunity Space	161	170	170	151	168
2050 Opportunity Space	289	555	688	502	348
2050 Wind Vision Scenario	112	75	51	34	68

Opportunity Space by U.S. Region



NREL Geospatial Offshore Wind Cost Model

Project Plan and Schedule

- Project duration was from July 2015 to September 2016.
- All milestones are complete for the current task.

Photo by Dennis Schroeder, NREL

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-Share	DOE	Cost-Share	DOE	Cost-Share
$0	$0	$150k	$0	$0	$0

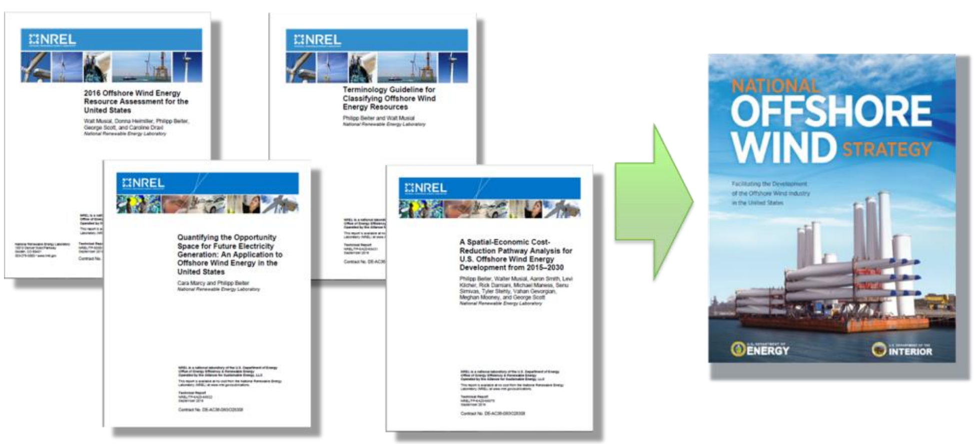
- $335K of total funds available (~$185K funds were reallocated from other projects)
- Project is complete and all of the project budget has been expended

Partners, Subcontractors, and Collaborators

- **<u>NREL Staff</u>**: Walt Musial, Philipp Beiter, Donna Heimiller, Caroline Draxl, Cara Marcy, Eric Lantz, Levi Kilcher, Senu Sirnivas, Tyler Stehly, Mike Maness, Aaron Smith, Sheri Anstedt
- **<u>DOE Wind and Water Power Program Staff</u>**: Jose Zayas, Mike Derby, Alana Duerr, Greg Matzat, Patrick Gilman, Rich Tusing, Dan Beals, Luke Feinberg, Ben Maurer
- **<u>Bureau of Ocean Energy Management</u>**: Abby Hopper, Darryl Francois, Doug Boren, Jennifer Golladay, Annette Moore

Communications and Technology Transfer

- Presentations at DOE Strategy Workshop—December 10, 2015
- ***Offshore Wind Strategy Session*** at International Partnering Forum—Oct 2–5, 2016, Newport, RI
- American Wind Energy Association WINDPOWER 2016–Philipp Beiter et al. (poster).



Five publications available online

Secretary Moniz Announces the release of the 2016 offshore wind strategy on September 9, 2016.

Biannual Market Reports
(separate funding from Strategy support)

2014-2015 Market Report Covers Global and Domestic Offshore Wind

- Recent market developments and drivers
- Deployment status and projections
- Technology trends
- Economic trends
  - Cost
  - Performance
  - Finance
- LCOE reduction progress.

Reference: Smith, A., T. Stehly, and W. Musial. 2015. *2014-2015 Offshore Wind Technologies Market Report* (Technical Report), NREL/TP-5000-64283. NREL, Golden, CO (US).
http://www.nrel.gov/docs/fy15osti/64283.pdf

FY17 report update is planned;
Basis for economic trends and projections

Next Steps and Future Research

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

FY17/Current Research

- Project has ended but new analysis work is beginning
- FY17 offshore wind strategy follow-on analysis:

  Task 1. Offshore wind system benefits analysis

  Task 2. Offshore wind technology pathways and innovation analysis

  Task 3. Market, risk, and resource analysis

Long-Term Goals

- Enable implementation of 2015 *Wind Vision*
- Quantify benefits of offshore wind by U.S. region
- Validate cost models
- Use models to guide research and technology investment opportunities.

Turbine Advanced Controls for Offshore Wind Floating Applications

Dhiraj Arora

GE Renewable Energy

Dhiraj.arora@ge.com 804 763 7732

February 2017

Levelized cost of energy (LCOE) reduction for offshore TLP wind turbine systems

Goals:

- Demonstrate value of advanced controls to reduce the LCOE of Floating Offshore Wind Turbines (FOWT)
- Advance the state-of-the-art of the floating technology
- Field demonstration of Advanced Controls on multi-MW turbines

Challenges:

- High LCoE of FOWT
- Several technical and market barriers
- Little field validation experience

Partners: Glosten Associates, National Renewable Energy Laboratory (NREL), Massachusetts Institute of Technology (MIT), Texas Tech University (TTU), University of Massachusetts

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- **Wind plant optimization**
- Resource assessment and characterization
- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- **World-class test and user facilities**
- **Advanced technology demonstration projects**
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

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- Distributed wind R&D
- NextGen component innovations

The Impact

- Advanced Controls to enhance energy capture and lower structural loads in wind turbine and sub-structure to lower LCoE
- Next generation of turbine controls using innovative sensors and actuators
- Development and validation of advanced controls for offshore wind turbines

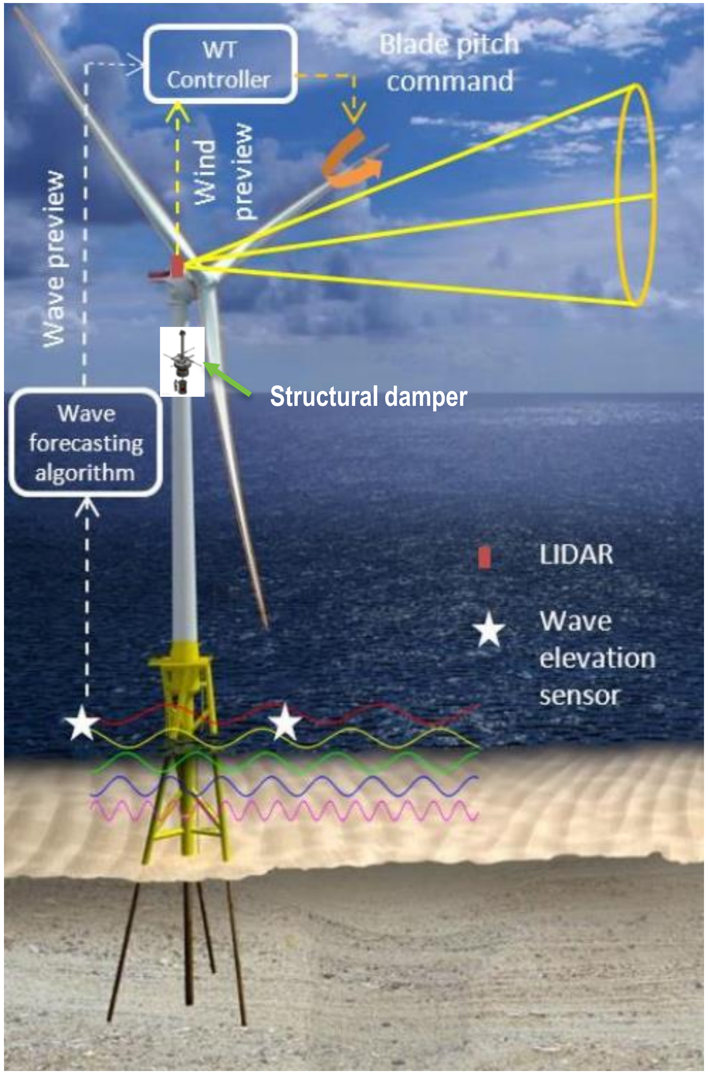
• Technical Approach – Overview

PROJECT FOCUS:

- ✓ Advance technology readiness of turbine controls with following objectives:
  - Fatigue and extreme loads reduction
  - Energy capture enhancement
  - Design optimization for US-specific wind/wave conditions
- ✓ Mature design tools and validate with measurement campaigns:
  - Simulation codes
  - Prototype testing
- ✓ Demonstrate LCOE reduction

TECHNOLOGIES CONSIDERED:

- ✓ LiDAR controls
- ✓ Yaw controls
- ✓ Floating turbine controls
- ✓ Dampers
- ✓ U.S. atmospheric characterization
- ✓ Wave forecasting



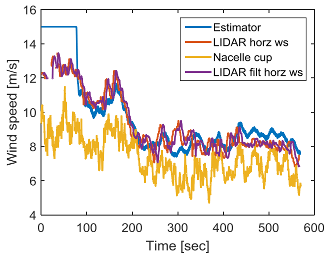
Technical Approach & Accomplishments

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

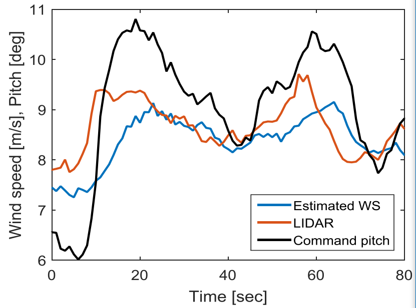
LiDAR Controls – Development and Validation of Feedforward Controls

Installation

Calibration

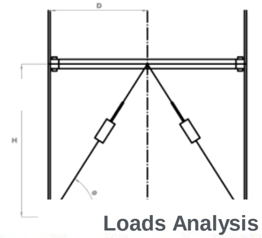


Closed-loop control

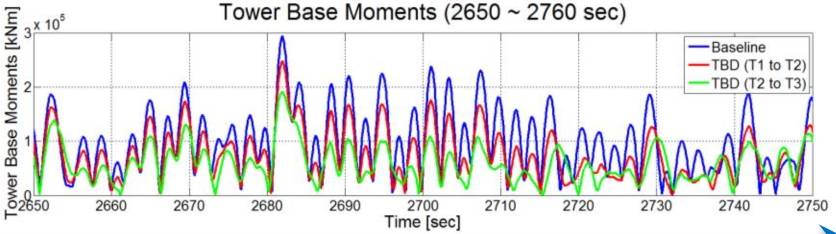


Dampers – Modeling and Assessment of Various Structural Damping Solutions

Toggle-Brace Damper



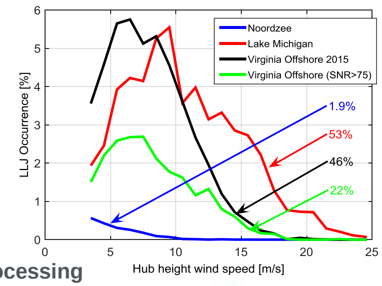
Loads Analysis
Tower Base Moments (2650 ~ 2760 sec)



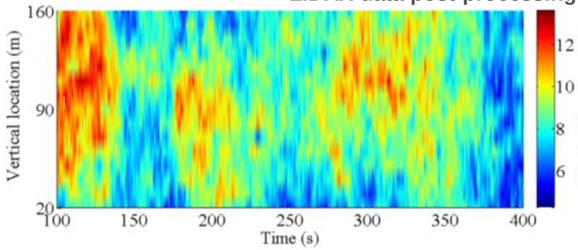
Atmospheric Characterization –Analysis & Modeling of met-ocean data from 2 US offshore sites

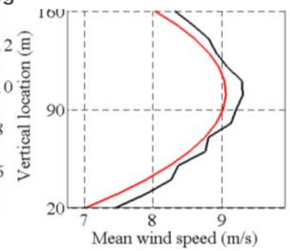
Virginia Offshore LIDAR Location
12/2014 ~ 06/2015, Range: 55m~160m

Low Level Jets Occurrence



LiDAR data post-processing

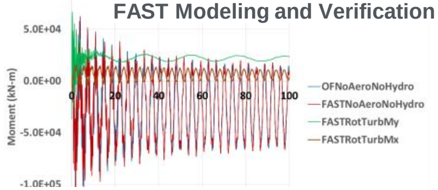




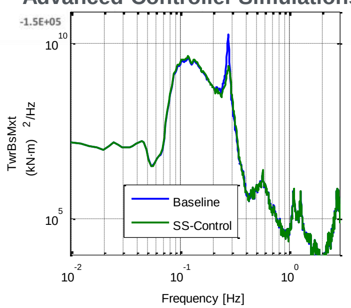
Floating Controls – Modeling, Controls Development and KPI Assessment of 6MW Turbine on Floating TLP

Floating System

FAST Modeling and Verification



Advanced Controller Simulations



Technical KPIs

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

<table>
<tr><th rowspan="2">Technology</th><th>Control Objective</th><th colspan="3">Loads /RMS Reduction</th><th colspan="2">Yield Increase</th><th rowspan="2">Progress</th></tr>
<tr><th>Fatigue (F) / Ultimate (U)/ Energy (E)/ Regulation (R)</th><th colspan="2">Maximum</th><th>Accumulated fatigue</th><th>Max. power increase</th><th>Annual energy yield</th></tr>
<tr><td rowspan="2">LIDAR controls</td><td rowspan="2">F, U, E, R</td><td colspan="2">15% (FA)</td><td>2.6% (FA)</td><td>2.5%</td><td>1%</td><td rowspan="2">Successfully completed field testing; Significantly improved rotor speed regulation</td></tr>
<tr><td>29% (FA)</td><td>52% (GEN)</td><td>10% (FA)</td><td>2.1%</td><td>0.7%</td></tr>
<tr><td rowspan="2">Yaw correction</td><td rowspan="2">E</td><td colspan="3" rowspan="2">-</td><td rowspan="2">-</td><td>0.55%</td><td rowspan="2">Field testing comple; field testing; Site dependent benefits</td></tr>
<tr><td>1%</td></tr>
<tr><td rowspan="2">Wave forecasting</td><td rowspan="2">R</td><td colspan="3"><5%</td><td colspan="2" rowspan="2">-</td><td rowspan="2">Forecasting algorithm development complete; Limited success</td></tr>
<tr><td colspan="3">>20%</td></tr>
<tr><td rowspan="2">Floating controls</td><td rowspan="2">F, R</td><td colspan="2">35%</td><td>20%</td><td colspan="2" rowspan="2">-</td><td rowspan="2">Significant Fatigue loads reduction with Advanced Controls</td></tr>
<tr><td colspan="2">20 % (FA), 30% (SS)</td><td>TBD</td></tr>
<tr><td rowspan="2">Dampers</td><td rowspan="2">F, U, R</td><td colspan="3">27% (EXT) , 30% (NAC. ACC)</td><td colspan="2" rowspan="2">-</td><td rowspan="2">Significant Fatigue and Extreme loads reduction</td></tr>
<tr><td colspan="2">35% (MP, EXT), 13% (TLP, EXT))</td><td>66% (MP SS) , 28% (TLP SS)</td></tr>
</table>

Target | Actual

Project Plan & Schedule

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

- Project duration: 04/01/2014 – 04/30/2017

- Slippage:
  - Contract execution delay
  - Securing full-scale demonstration turbines for field testing

- Mitigation:
  - Delays are being managed; project spending 12% below the plan
  - Seeking no-cost extension

- Go-No-Go Decisions
  - Q4 2014 - KPI and Robustness Evaluation of Preview Controls - Complete
  - Q2 2015 - Improved Yaw Control Development – Complete
  - Q2 2016 - Advanced Controller Implementation and Characterization in Bladed – in progress

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$99K	$25K	$1,035K	$259K	$880K	$220K

- Tasks and subtasks have been executed within current budget allocations.
- 58% of the budget has been spent to date.
  - Planned spend for this period is 70%.
- There are no other funding sources for this project.

Research Integration & Collaboration

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

Commercial and Federally Funded Research Partners / Collaborators

THE GLOSTEN ASSOCIATES — Consulting Engineers Serving the Marine Community

- Supervision of TLP R&D activities
- Modeling of Haliade / Pelastar system
- TLP Cost of Energy modeling
- Wave basin test planning & execution
- ETI prototype management

GE

- Project Management
- Supervision of Turbine R&D activities
- Hardware-in-the-loop testing
- ECO110 / ECO86 prototype management
- Full scale test planning & execution

NREL

- OptoAtmospherics LIDAR assessment
- FF Ctrls for AEP increase + load reduction
- Advanced Ctrls for turbine / TLP system
- Extreme load mitigation strategies
- CART 3 prototype management

UMass

- Design of Tuned Mass Damper system for load reduction during extreme wind & wave events

MIT — Massachusetts Institute of Technology

- Wave loading estimation & prediction
- Pitch ctrls for extreme load mitigation

Texas Tech University

- Offshore wind characterization
- Complex phenomena mitigation strategies

Publications	Event	Type
Development, Field Testing, and Evaluation of LIDAR –Assisted Controls	AWEA Onshore 2015	Poster
Turbine-mounted LIDAR Validation	NAWEA 2015 Symposium	Presentation
Floating Offshore WTC Integrated Load Analysis & Optimization Employing a Tuned Mass Damper	AWEA Offshore 2015	Poster
Smart Novel Semi-Active Tuned Mass Damper for Fixed-Bottom and Floating Offshore Wind	OTC 2016 Conference	Paper
An Investigation of Passive and Semi-Active TMD for a TLP Floating Offshore Wind Turbine in ULS Conditions	OMAE2016	Paper
Atmospheric Characterizations of the US Offshore Sites and Impact to Turbine Performance	AWEA Offshore 2016	Poster

Next Steps and Future Research

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

FY17/Current Research:

- Complete Damper evaluation in simulations and KPI assessment
- Complete LCOE evaluation with Advanced Controls innovations
- Finalize field testing plans
    - *Challenge: Securing full or scaled turbines for field testing*
- Final reporting and project closure

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

New England Aqua Ventus I

Dr. Habib Dagher, PE
University of Maine
hd@maine.edu 207-581-2138
February 14, 2017

Project Overview

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

The Challenges:

- Design first commercial scale concrete floating wind turbines
- Receive ABS approval for concrete hull
- Confirm cost advantages of concrete floating hulls with independent estimates

Key Partners:

UMaine: Lead, floating concrete hull modeling and design, permitting, site data, outreach

Emera: Project financing

DCNS: CM, Project wrap

Cianbro: Hull construction

Enabling Wind Nationwide

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- Advanced technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

The Impact:

- Demonstrate two x 6MW floating concrete turbines by 2019
- Floating concrete wind technology:
  - 60% of U.S. offshore wind resourc
  - Less sensitive to site specifics
  - Easier to mass produce
  - Levelized cost of energy (LCOE) for utility-scale <10 c/kWh
- 100% Hull FEED approved by ABS
- Northeast - dense population, high electricity costs

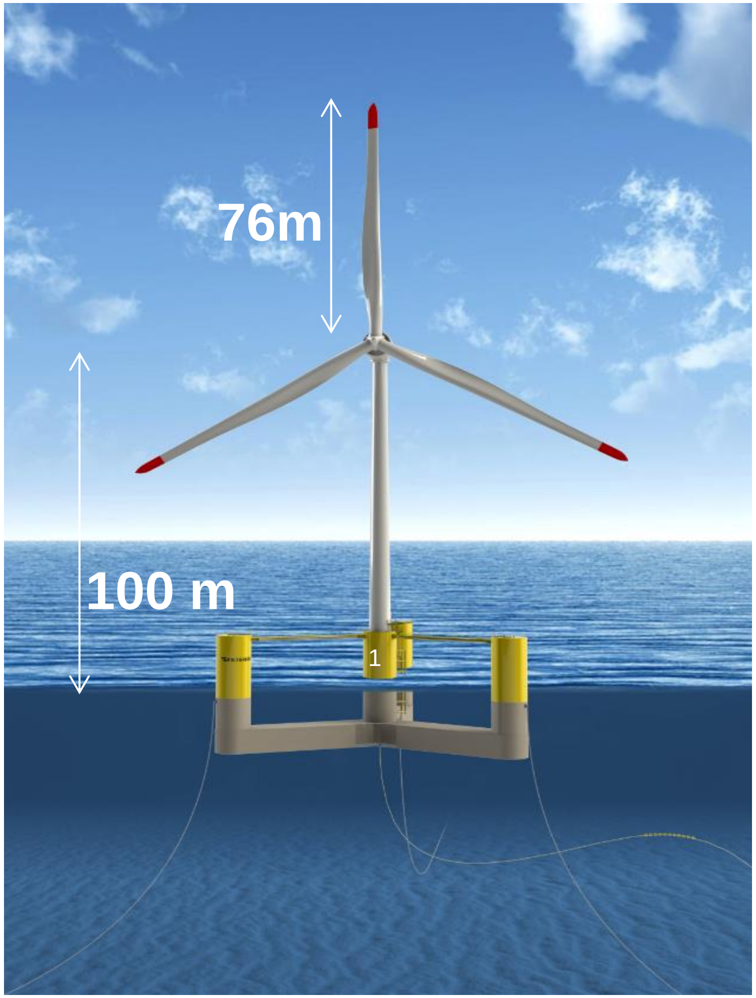
Technical Approach

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

1. **100% FEED for turbine, tower, hull, mooring, anchors, and dynamic cable:**
   - 65 reports and papers, and 96 dwgs.
   - Two third-party reviews of hull design
2. **Independent cost estimates:**
   - Concrete v. steel hulls
   - Composite v. steel towers
3. **Independent LCOE Analyses:**

   12MW and utility-scale projects
4. **Dissemination:**

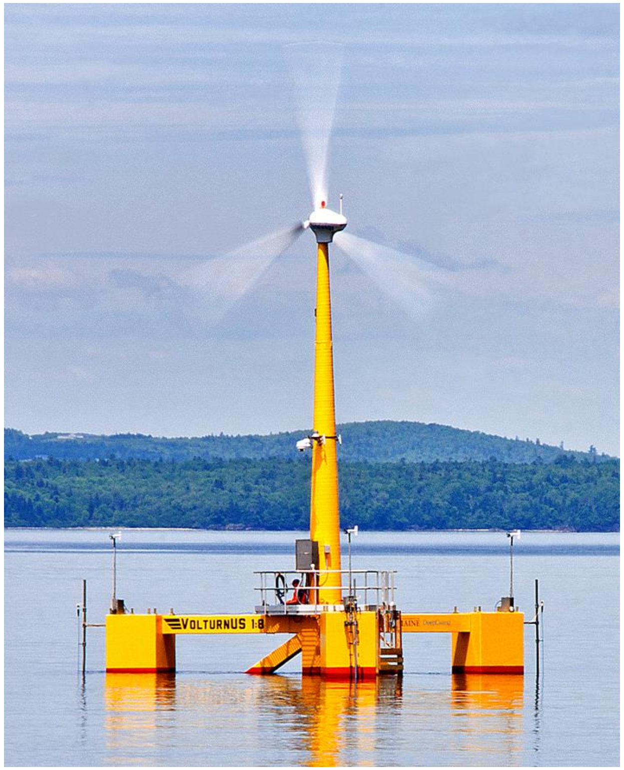
   Eight peer-reviewed papers and conference presentations



VolturnUS Floating Concrete Hull (6MW WTG)

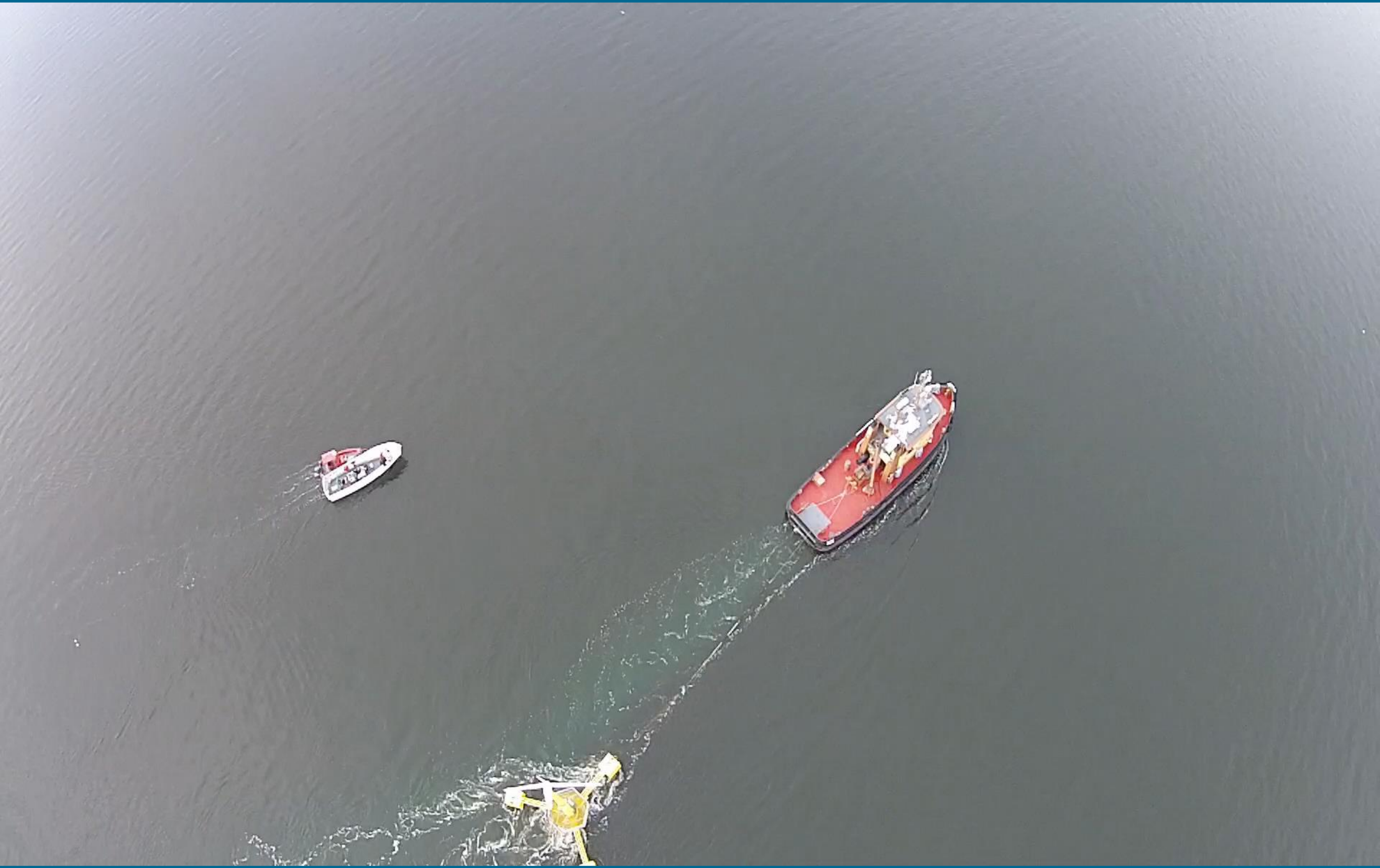
Accomplishments and Progress

- Successful of 1:8 scale pilot deployment in 2013–14 led to significant optimization of hull.
- Cost reductions independently established:
  - Concrete hulls < ½ the cost of U.S. steel hulls (nine steel and four concrete quotes)
  - National Renewable Energy Lab (NREL) study shows 28% LCOE reduction over steel hulls.



- Two third-party design reviews of concrete hull completed May 2016
- 6MW turbine suitability study

VolturnUS 1:8 Tow-Out



VolturnUS 1:8
Jan 25th, 2014 1:38pm

- ABS Load Case 1.6, 22.6m max wave height
- Rated wind speed

1:50 Scale Test of 6MW Hull At UMaine W2 Wave-Wind Basin

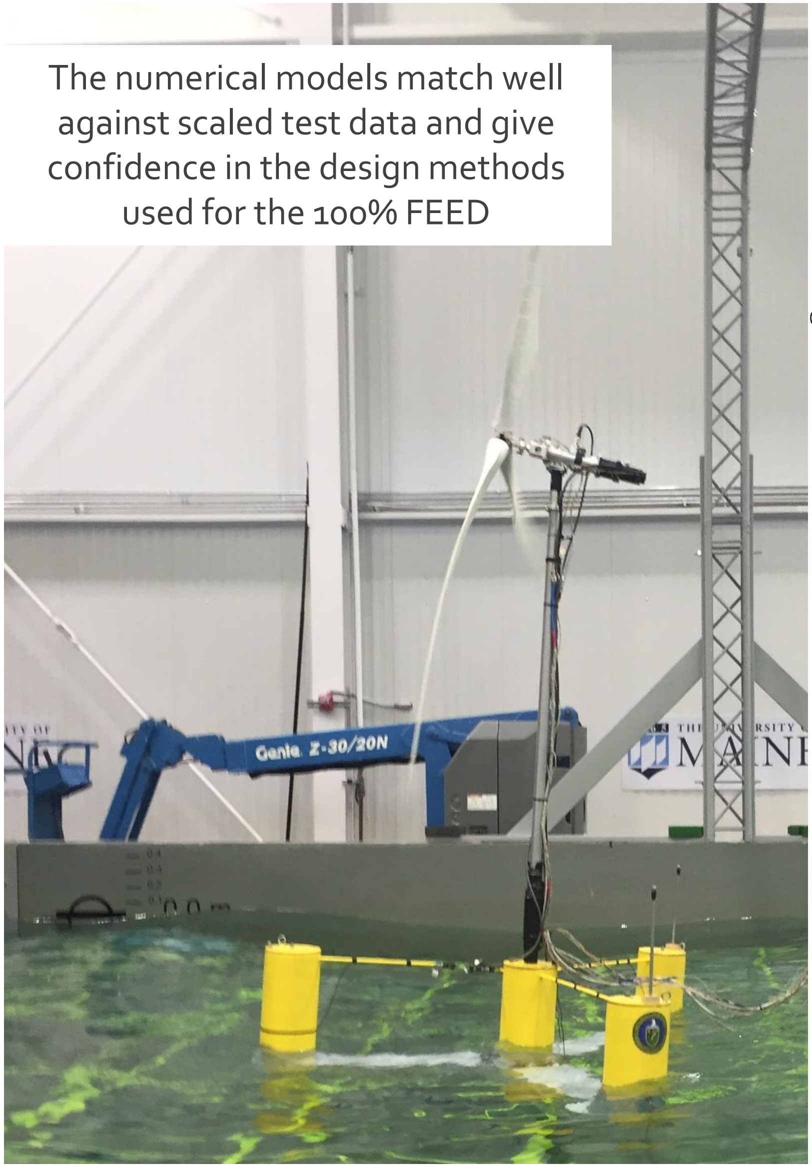
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

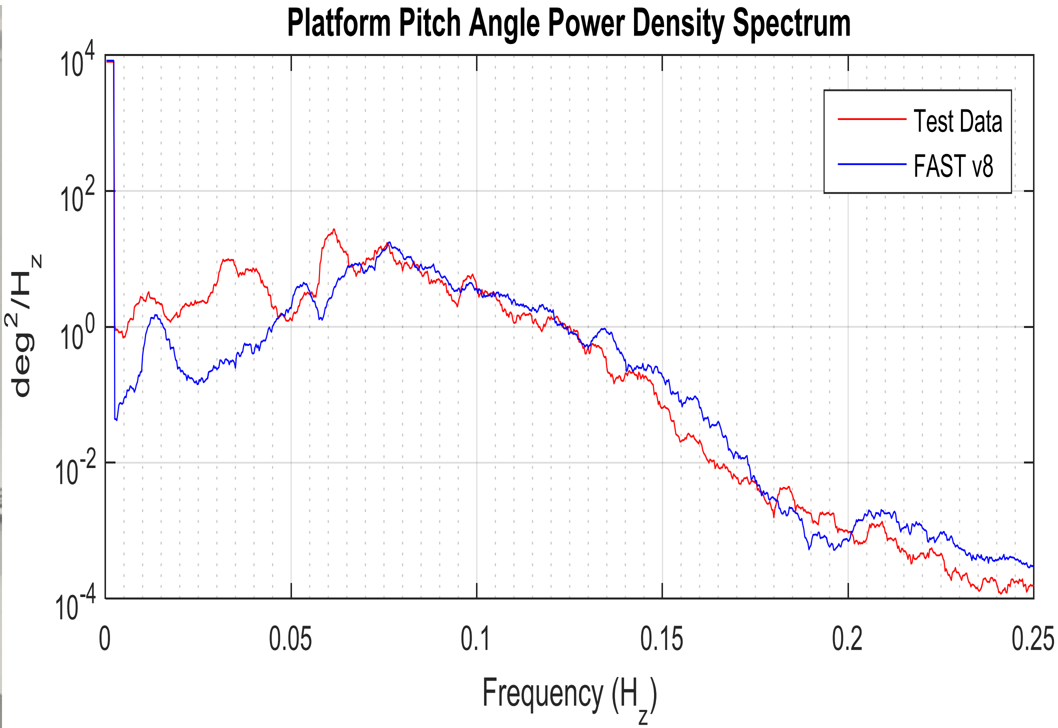
Objective: Final Design Confirmation of 100% FEED

Dr. H. J. Dagher hd@maine.edu

Sample Data from ABS DLC 1.6
50-year significant wave height- 9.8m, 14.2s Peak Period
Turbine operating at 12m/s-Rated Wind Speed

The numerical models match well against scaled test data and give confidence in the design methods used for the 100% FEED





Tower Base Bending Moment (kN-m)			
	Test Data	FAST v8	% Diff
Max. Mag.	1.68E+05	1.71E+05	-1.6%
Platform Pitch Angle(deg)			
	Test Data	FAST v8	% Diff
Mean	4.1	4.2	-1.8%

ABS Hull Design Review Complete

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

- **ABS has reviewed 28 design reports and 96 drawings and approved the 100% Hull FEED**

- **Primary Standards:**
  1. ABS Guide for Building and Classing Floating Offshore Wind Turbine Installations", 2013/14
  2. ABS Guide for Building and Classing Gravity-Based Offshore LNG Terminals, American Bureau of Shipping. November 2010.
  3. ABS Guide for Building and Classing Bottom-founded Offshore Wind Turbine Installations. American Bureau of Shipping. July 2014.

Monhegan Island Test Site

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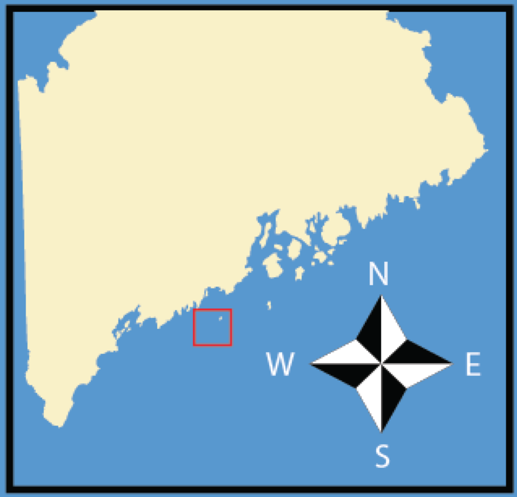
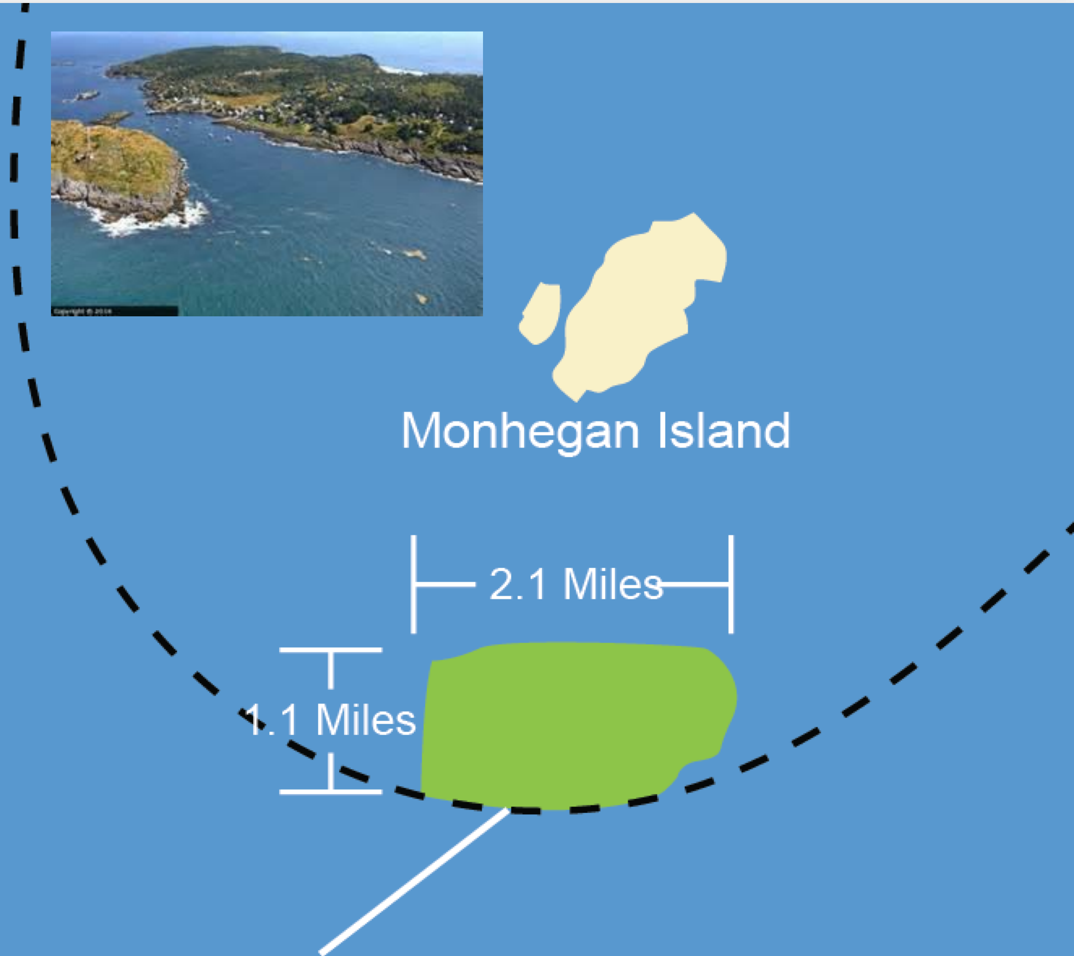


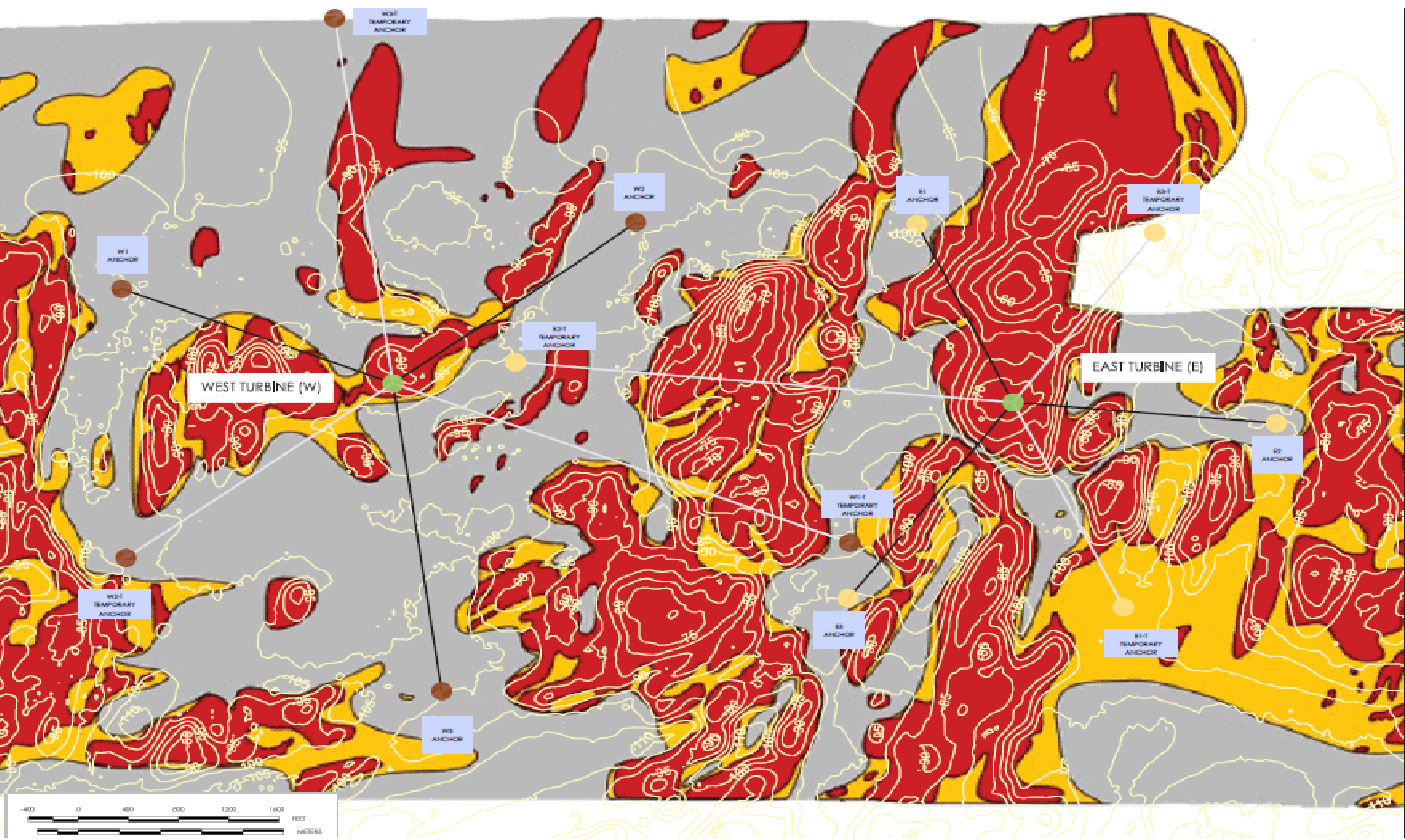
Latitude and Longitude of Site

Northern Boundary	43° 43’ 18.231”
Eastern Boundary	69° 20’ 16.759”
Southern Boundary	43° 42’ 15.436”
Western Boundary	69° 17’ 39.544”



University of Maine Deepwater Offshore Wind Test Site

Mooring and Anchor Layout Determined Based on Geophysical Survey and Locations of Deep Sediment Deposits



DeepCLiDAR Buoy Validated off Monhegan Island

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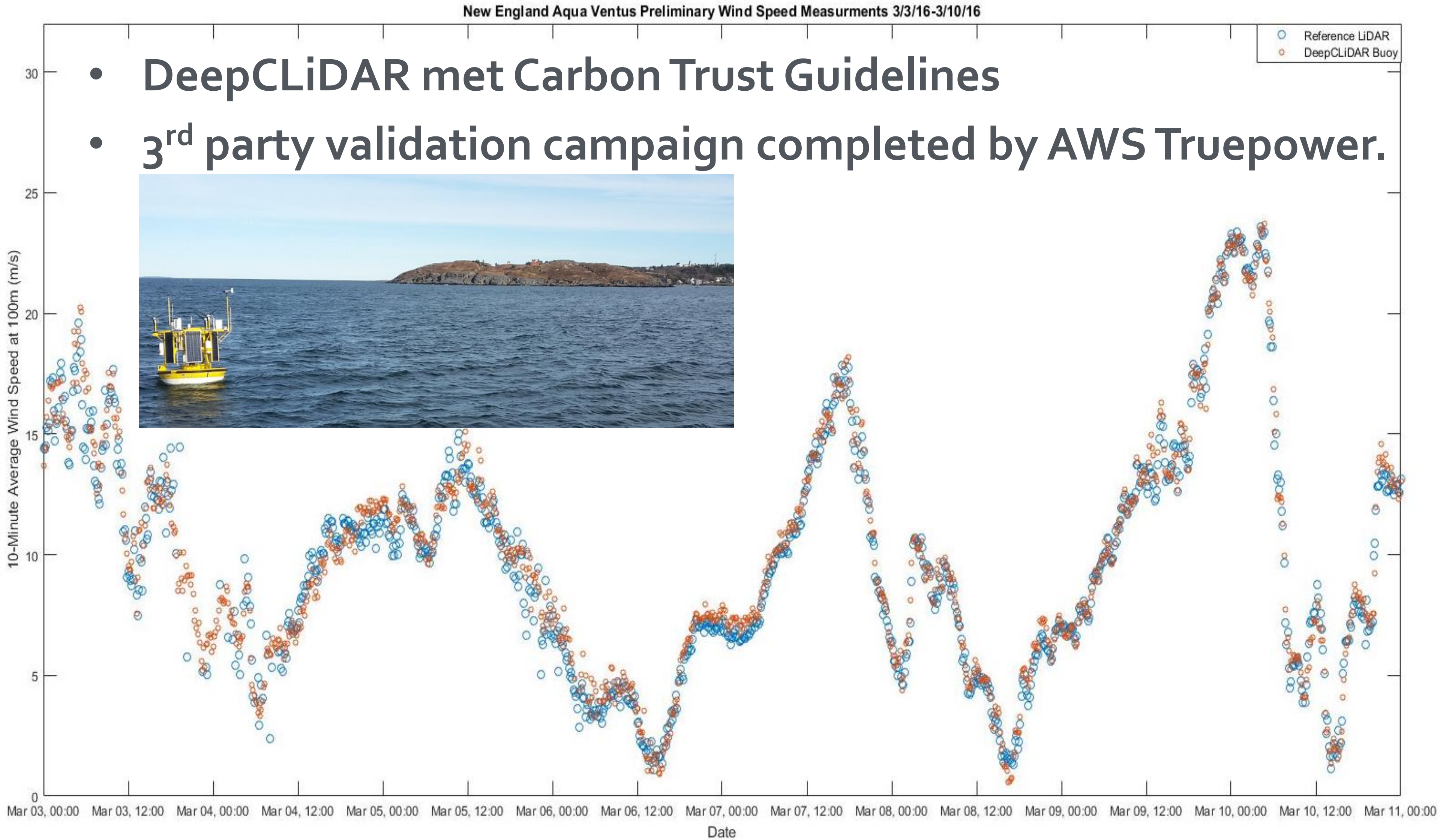
- DeepCLiDAR met Carbon Trust Guidelines
- 3rd party validation campaign completed by AWS Truepower.



Project Plan and Schedule, Next Steps

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Selected Milestones:

- Q1/2 2017 – Convert Power Purchase Agreement Term Sheet Into Contract
- Q2 2017 – Preliminary Investment Decision reached
- Q3 2017 – Submit Environmental Assessment
- Q1 2018 – Grid Interconnection Agreement
- Q1 2018 – All Permits Received
- Q1 2018 – Final Investment Decision/Financial close
- Q2 2018 – Start Construction
- Q4 2019 – Commercial Operating Date

Project Budget

Budget History			
FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share
$3,000k	$970.77k	$3,700k	$925k
100% Expended		25 % expended	

Award #6713 – End date 3/31/18.

Project is on schedule for 2019 Commercial Operations Date

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

- Cianbro
- Emera
- DCNS
- NREL National Wind Technology Center
- BergerABAM
- Ocean Renewable Power Company
- Houston Offshore Engineering
- SGC
- HDR
- Kleinschmidt Associates

Communications and Tech Transfer (Eight peer-reviewed papers and presentations)

- American Wind Energy Association (AWEA) Wind Conference
- AWEA Offshore Wind
- Offshore Wind Academy
- European Wind Energy Association
- Conference on Ocean, Offshore and Arctic Engineering (OMAE)
- International Society of Offshore and Polar Engineers
- Society of Naval Architects and Marine Engineers (best paper award)
- New York Times

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

Hywind Maine

Floating Offshore Wind Project   Budget Period 2

Andrea Eugster

Statoil ASA

aeu@statoil.com; +479 410 3223

February 13th   17th 2017

Hywind Maine Floating Offshore Wind Project (BP2):

Technology development and upscaling of the Hywind floating wind concept and exploration of floating wind potential in the United States

The Challenge:

WP1 Design and Analysis: IEC Ultimate and Fatigue Load Assessment

WP2 Wake modeling and wind power plant optimization

WP3 Resource assessment: Spatio-Economic Potential of Hywind Technology in the United States

Partners:

National Renewable Energy Laboratory (NREL) – execution of studies

Hywind Floating Concept

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- Robust slender cylinder substructure design
- Design and dimensions optimized for mass production and installation
- Standardized mooring system with three mooring lines
- Standard offshore turbine
- Inshore assembly and pre-commissioning

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- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

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- NextGen component innovations

The Impact

WP1 and 2 – Design, Analysis and Wake Modelling

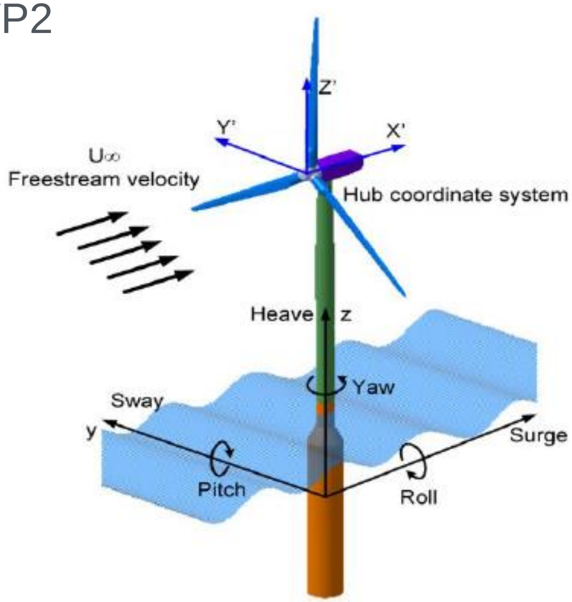
- Impact: Demonstrate top-class state-of-the-art integrated modelling of floating offshore wind turbines and arrays and understand floating wind turbine behavior in arrays
- Final Products: Reports, models and modelling output results used in further research.

WP3 – Spatio-Economic Analysis

- Impact: Provide targeted insight into the U.S. offshore wind resource area to inform strategic decisions about how to commercialize and market the Hywind technology
- Final Products: Report and GIS tool for site assessment and evaluation in U.S. waters.

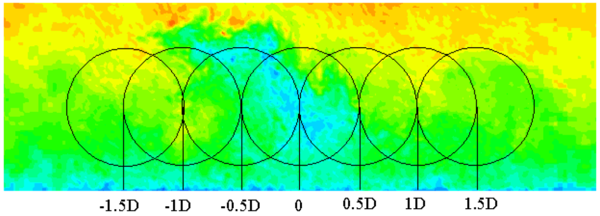
WP1 Design and Analysis

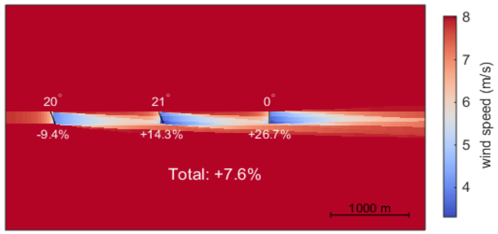
- Building of Hywind 6-MW turbine in FAST7
- Loads and fatigue analysis using the floating turbine simulation software FAST
- Identification of ultimate and fatigue limit design load cases in an integrated modelling approach
- Input to WP2



WP2 Wake Modelling

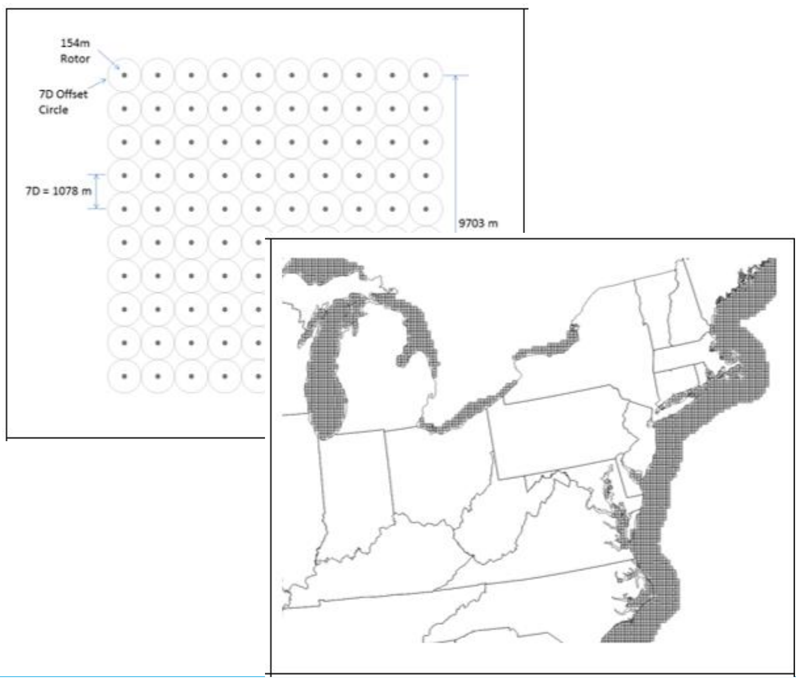
- Investigation of the influence of the wake generated from an upstream turbine on a downstream turbine using SOWFA (coupling of CFD and FAST)
- Performing two-turbines One-Way Coupling (OWC), three-turbines Two-Way Coupling (TWC)
- Investigation of power plant optimization with wake control with FLORIS





WP3 Spatio-Economic Potential of Hywind Technology in the United States

- New developed spatio-economic methodology to assess variability in spatial parameters and their effects on levelized cost of energy (LCOE)
- Combination of wind plant performance modeling, economic modeling, and national geospatial data layers to estimate the cost of potential projects using Hywind technology covering Atlantic Ocean, Gulf of Mexico, Pacific Ocean, and the Great Lakes.



LCOE

Hywind Unit CAPEX

Cost models, data, and experience

- **Turbines**
  - NREL offshore wind project database
  - Statoil internal database
  - Apply volume discounts (per literature)
- **Substructure**
  - NREL Offshore Wind FST
  - Cost estimates based on quotes from U.S. fabricator (Gulf of Mexico)
  - Cost reduction factor to reflect economies of scale associated with a 100-unit order (per literature)

Balance of System CAPEX

NREL Tools and Analysis

- **Offshore Wind BOS Model (data source only)**
  - Modified for floating projects
  - Electrical System
  - Development
  - Port and Staging
- **Hywind Installation Cost Estimator (ICE) Tool**
  - Developed for BP1 1 Economics Report
  - Models marine operations for Hywind technology
- **PSCAD**
  - Commercial software for simulating power system performance
  - Used to evaluate system suitability and estimate **electric system losses**

Annual Operation and Maintenance (OPEX)

ECN Offshore Wind O&M Tool

- Industry standard Offshore Wind O&M Tool purchased from ECN (designed for fixed-bottom)
- Estimates waiting time for repair strategies given site-specific wind and wave conditions; estimates **wind farm availability** and **OPEX**
- Modified to represent Hywind maintenance philosophy
- Multiple O&M strategies:
  - Close to shore
  - Close to shore(+)
  - Medium Distance
  - Far shore

Fixed Charge Rate (FCR)

Simplified Representation

- Simplified approach combining a capital recovery factor with a term to capture value of taxes and depreciation
- Standard values that NREL views as long term average for power plant investments in the United States
- 8.9% Discount Rate reflects Weighted Average Cost of Capital (all rates nominal):
  - 13% return on equity
  - 8% debt interest rate
  - 50% debt to equity ratio
  - 40% effective federal and state tax rate
  - MACRS depreciation schedule
  - 20 year business case

Annual Energy Production (AEP)

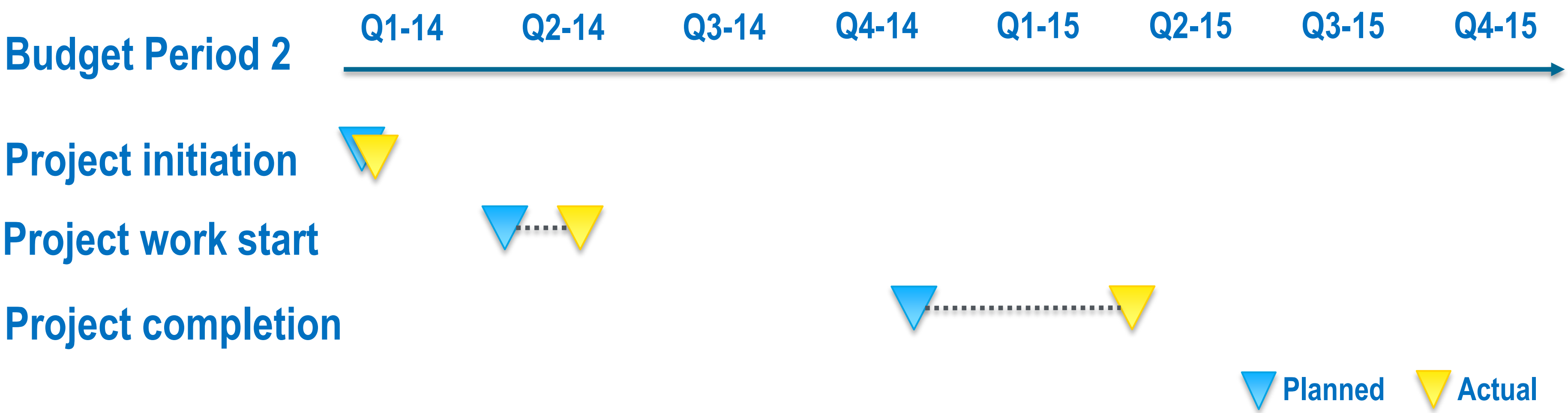
openWind Enterprise Software

- National WRGs derived from AWS Truepower data
- Generic project layout
  - 100 6 MW turbines
  - 10 x 10 square grid
  - Spaced at 7 rotor diameters (1,078 m)
- openWind modified to automatically evaluate AEP at all potential wind project locations
  - Gross AEP
  - Wake Losses
- Other system losses
  - Electric system losses from PSCAD
  - Availability losses from ECN O&M tool
  - Other losses set to 2%

Accomplishments and Progress

- Successfully completed work packages as originally defined:
  - WP1
    - Creation of a Hywind 6-MW turbine model for the floating turbine simulation software FAST
    - Performance of load and fatigue analysis for a set of design load cases for different combinations of wind and wave conditions.
  - WP2
    - Investigation of impact of fatigue loads in relation to the various spacing and lateral offset positions for downstream turbines, which mimicked partial and full waking scenarios for three different wind speeds
    - A series of simulations were performed with a 1x3 array of turbines spaced at 9D subjected to the same three inflows with varying mean hub-height wind speeds, along with five different wind directions
    - The FLOW Redirection and Induction in Steady-state (FLORIS) model was run to study optimized yaw setting of wind turbines in a wind power plant for improved energy production by redirecting the wake.
  - WP3
    - A study was conducted using NREL's newly developed spatio-economic methodology to assess how variability in spatial parameters can influence LCOE as related to the Hywind technology. The scope of the study covered the major offshore regions within the contiguous United States.

Project Plan & Schedule



- Slipped Milestones
  - Project work start: Contracting issues
  - Project completion: Modelling and computational issues

- Q1-2015 Finalization of Project Work with NREL
  - 2015-08 Submission of Public Reports to the DOE
  - 2015-09 Final presentations to the DOE

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$1,476.537k	$336.005k	$61.146k	$5.32k	$0	$0

- The entire budget has been spent. Project work was finalized in Q3 2015.
- The award was closed in 2016.

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

NREL:
Frederick Driscoll, Andrew Platt, Senu Sirnivas, Jim Green, Sang Lee, Matthew Churchfield, Pieter Gebraad, Aaron Smith, Zachary Parker, Tyler Stehly, Donna Heilmiller, George Scott, Walter Musial, Paul Fleming, Rick Damiani and Karen Atkison

University of Colorado:
Michelle Burns and Nick Wimer

Statoil ASA:
Eirik Byklum, Andrea Eugster, Finn Gunnar Nielsen and Bjørn Skaare

Communications and Technology Transfer:

Published
- S Lee, M. Churchfield, S. Sirnivas, P. Moriarty, F. G. Nielsen, B.Skaare, and E. Byklum (2015): Coalescing Wind Turbine Wakes. Journal of Physics: Conference Series 625 (2015) 012023, doi:10.1088/1742-6596/625/1/012023

Pending Publications
- S. Lee, M. J. Churchfield, F. Driscoll, P. Fleming, S. Sirnivas, P., Moriarty, B. Skaare, F.G. Nielsen, E. Byklum: Load Estimation of Offshore Wind Turbines (To be submitted to either Renewable Energy or Wind Energy)
- M. Burns, University of Colorado; F. Driscoll, S. Sirnivas, A. Platt, National Renewable Energy Laboratory: Loads Analysis of a 6 MW Wind Turbine on a Floating Spar Platform

Approaches and tools that were developed through both BP1 and BP2 are being applied in wider research by NREL (i.e. floater sizing tool, spatio-economic analysis of offshore wind etc.)

Next Steps and Future Research

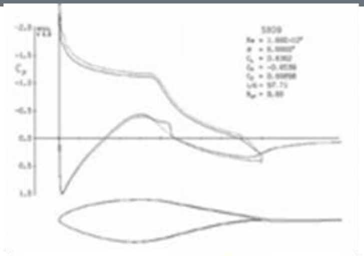
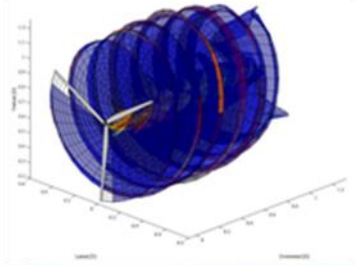
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

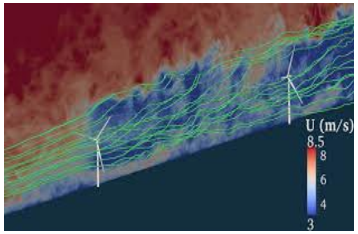
FY17/Current Research:

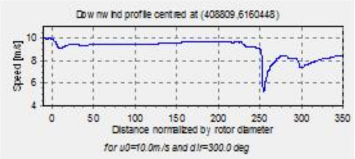
- Project completed
- Currently no ongoing DOE-funded projects

Planned Current and Future Research:

- Continuation of dynamic analysis of floating wind farms (building upon of WP1 and 2)
  - Simulation of a floating multi-MW offshore turbine in normal and extreme operational conditions using NREL's SOWFA model (today's most advanced multi-physics simulation model for offshore wind turbines)
- Collaboration with NREL on floating wind market potential (building upon WP3).





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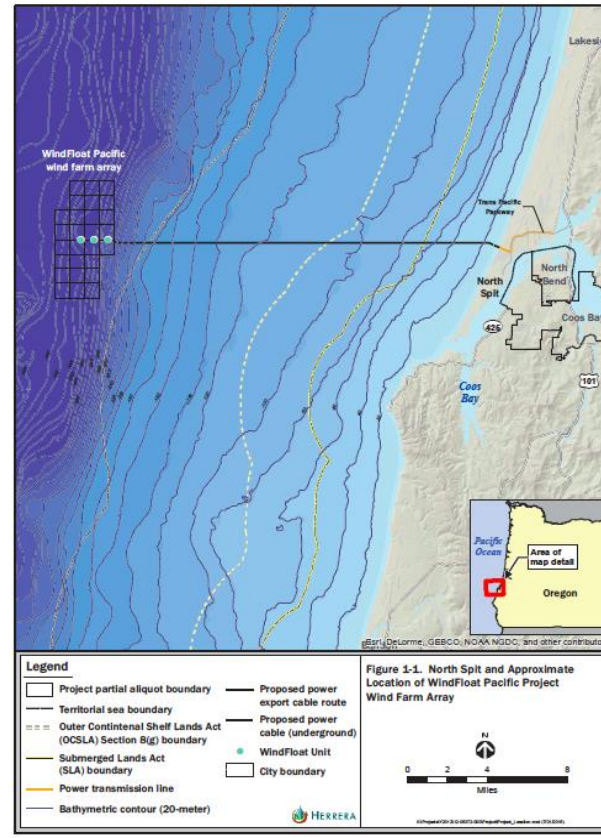

Figure 1-1. North Spit and Approximate Location of WindFloat Pacific Project Wind Farm Array

WindFloat Pacific

Floating Offshore Wind Demonstration Project

Kevin Banister

Principle Power, Inc.

kbanister@principlepowerinc.com +1 971.255.2391

February 2017

Project Overview

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

WindFloat Pacific: Floating Offshore Wind Demonstration Project

The Challenge: To engineer for and permit the deployment of a large scale, floating offshore wind (OSW) solution in deep water, in a new market, utilizing a conventional project finance scheme

	PARTY	ROLE
Prime Recipient	Principle Power, Inc. (PPI)	Engineering, Project Development and Management
Project Partners Providing Cost Share	Houston Offshore Engineering (HOE)	Engineering Support
	RPS Evans Hamilton	Offshore Surveys
	Herrera Environmental	Permitting Support
	Forristal Ocean Engineering	MetOcean/Design Basis
	C+C Technologies (Oceaneering)	Offshore Surveys
	American Bureau of Shipping (ABS)	Classification Society
Working Partners and National Laboratory Participants	International Port of Coos Bay	Local Stakeholder Support
	Siemens Wind Power	Turbine Integration Engineering
	National Renewable Energy Laboratory (NREL)	Economic Analysis and Support
	Pacific Northwest National Laboratory (PNNL)	Permitting and Study Plan Development Support
	Northwest National Marine Renewable Energy Center (NNMREC)	Permitting and Study Plan Development Support

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- Wind plant optimization
- Resource assessment and characterization
- Reliability improvements
- **Enabling access to better resources through tall wind**
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- Advanced technology demonstration projects
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

Enabling Wind Nationwide

Enabling U.S. Industry Growth and U.S. Competitiveness

- Commercialization of innovations and technology transfer
- World-class test and user facilities
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- Standards and certification
- Communicating the costs and benefits of wind energy

The Impact

- Install innovative offshore wind systems in U.S. waters in the most rapid and responsible manner possible
- Expedite the development and deployment of innovative offshore wind energy systems with a credible potential for lowering the levelized cost of energy (LCOE) so that offshore wind can compete with other regional generation sources without subsidies
- Access to new and better wind resources; reduction in cost and risk to deployment; more efficient O&M philosophies; reduced environmental impacts; enhancement and use of existing U.S. coastal infrastructure
- World-first floating offshore wind demonstration array (~ 30MW).

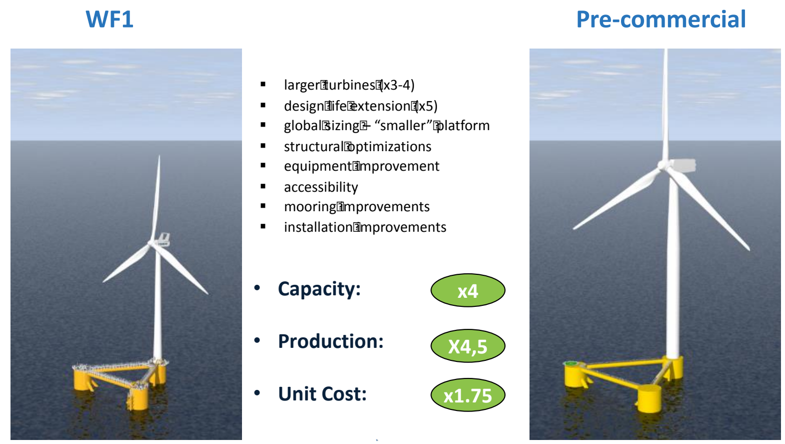
Technical Approach

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

1. WindFloat Design (100% Front End Eng. Design)

✔ Approval in Principle Issued by Class (ABS)

- Stability
- Wind Turbine Integration
- Structural Design
- CVA Review
- Vendor Quotes



2. Installation and Operations and Maintenance

✔ Strategy Focused on West Coast infrastructure

- Quayside fabrication and assembly
- Tow to site philosophy
- Operations and maintenance (O&M) efficiency

Technical Approach

3. National Environmental Policy Act and Permitting

✔ First OSW Farm proposed for West Coast; first floating

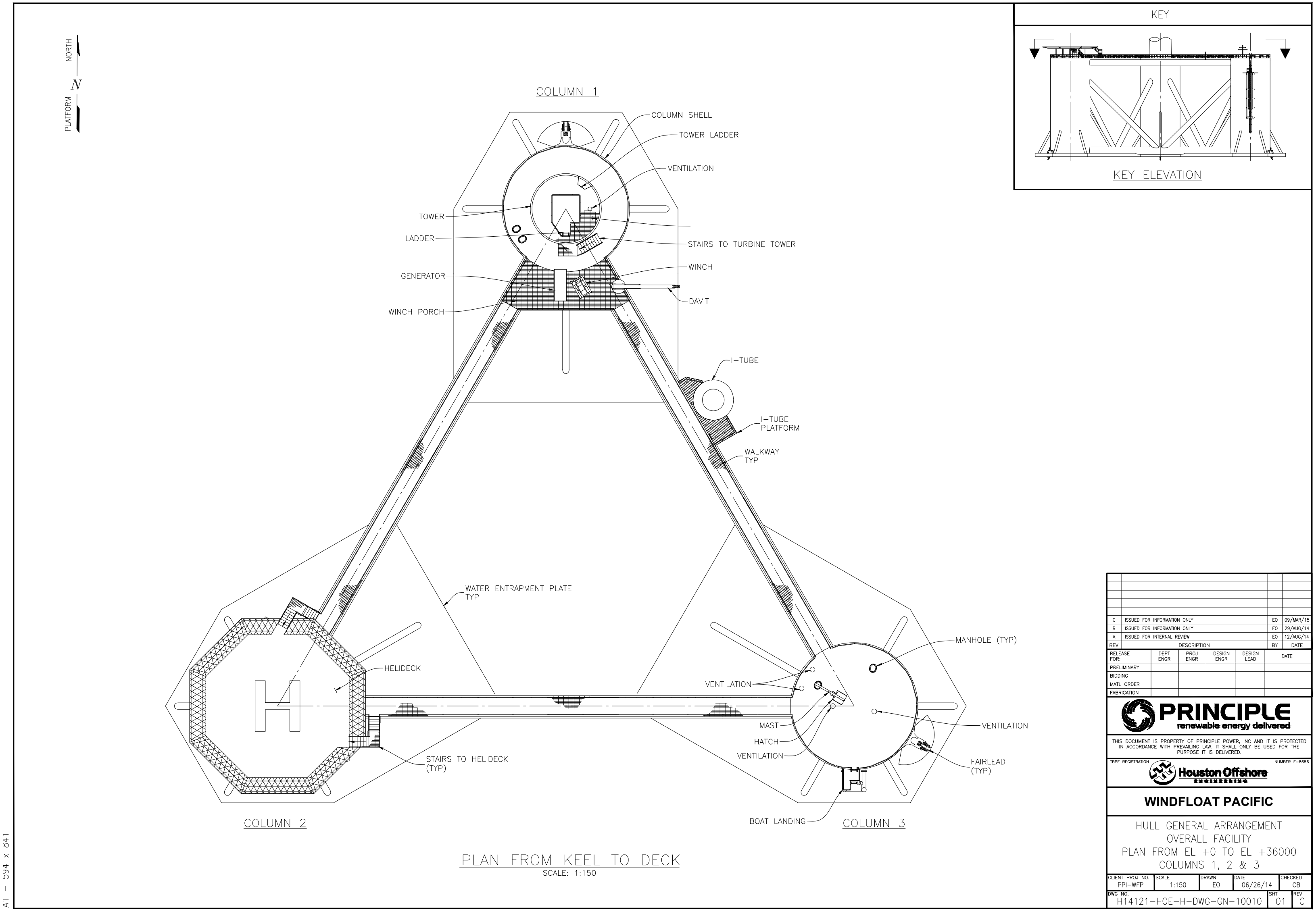
- Project siting and stakeholder engagement
  - >350 m water depth; 18 miles from shore
- Bureau of Ocean Energy Management (BOEM) leasing and permitting
  - Unsolicited Lease Request
  - Construction and Operations Plan developed
- Pre/Post installation monitoring planning

4. Grid Interconnection and Power Purchase Agreement

✔ Demo scale project required legislation to achieve a Power Purchase Agreement (PPA)

- Straightforward utility interconnection process
- Evolved strategy for PPA

Technical Approach



Accomplishments and Progress

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Engineering

- Design adapted to harsh Pacific conditions while featuring state of the art offshore turbines (6MW+)
- Approval in Principle achieved for first-of-its-kind project
- Plan developed relying on existing West Coast infrastructure

Permitting

- BOEM process initiated in earnest and ‘exercised’
- Offshore and onshore surveys completed
- Environmental Report and COP largely completed

Commercial

- PPA enabling legislation written, debated and considered
- Economic analysis concludes *at scale* offshore wind a viable option for the West Coast

Project Plan & Schedule

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

- Project Initiation Date: February 15, 2013
- Project Completion Date: May 31, 2016

BP1 (Feb 15, 2013 – May 14, 2014)	BP2 (up to May 31, 2016)	BP3 - 5
Completion of: • 50% FEED ✔□ • Preliminary Installation/O&M plans ✔□ • Initiation of studies/Path of compliance ✔□ • Initiation of grid connection, PPA ✔□	Completion of: • 100% FEED ✔□ • Detailed Installation/O&M plans ✔□ • NEPA/COP completion ✘ • PPA/Financing plan ✘	• Procurement • Construction • Installation • Commissioning • Monitoring

Project Budget

Budget History					
Budget Period 1		Budget Period 2		TOTALS	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$4,000.002k	$1,144.388k	$6,666.357k	$3,089.823k	$10,666.363k	$4,295.937k

- Notable variances from original budget(s) include:
  - Inter-array cable work retracted from Contractor and brought in-house (Budget Period 1 [BP1])
  - Pacific Northwest National Laboratory scope reduction (BP2)
  - Geo-physical survey timing (BP2)
- 100% budget expended
- Oregon Wave Energy Trust provided: $99.35k

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

Project partners providing cost share	Working partners and national labs
Houston Offshore Engineering RPS Evans Hamilton Herrera Environmental Forristal Ocean Engineering C+C Technologies (Oceaneering) American Bureau of Shipping (ABS)	International Port of Coos Bay Siemens Wind Power NREL,PNNL,NNMREC **Contractors** SHN Consultants, EnTranTec, S360, others

Communications and Technology Transfer: Dozens of meetings were held with various stakeholder groups and a paper developed describing regulatory processes and agency roles (presented at Offshore Technology Conference 2016). The project was presented at numerous conferences, and website was established (www.windfloatpacific.com) to assist with dissemination and outreach.

Next Steps and Future Research

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

FY17/Current Research: N/A

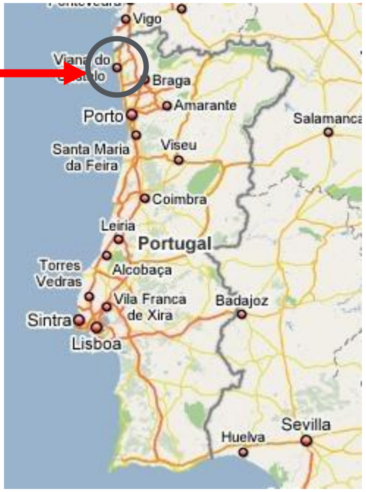
Planned Future Research: N/A

Future Project: Portugal

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

Project Overview

- **Total capacity: 25MW capacity**, (3 X Vestas V164),
- **Location: 20 km off the coast of Viana do Castelo**, in water depth of ~ 100m
- **Interconnection: to be constructed by REN**, allowing a direct connection at 60kV
- **Construction: shipyards in Portugal (same as WF1)**. Turbine installation quayside
- **Floating structure certification: designed for 25 years,** certified throughout design, construction and installation by ABS, an independent party
- **Detail design 90% completed** Q2 2016 by PPI Engineering



First Non-recourse financed FOW project

- **Equity financing completed in 2015;** 7 project partners
- **Non recourse financing expected completion Q2 2017**
  - European Investment Bank – Selected for InnovFin Programme
  - Export Agencies; Commercial Banks
- **Strong Institutional Support:**
  - EU: NER 300; Portugal: Feed-in Tariff, APA

edp renewables powered by nature | ENGIE | Mitsubishi Corporation | REPSOL | PRINCIPLE POWER | Marubeni | CHIYODA CORPORATION

European Commission | GOVERNO DE PORTUGAL

Future Project: France

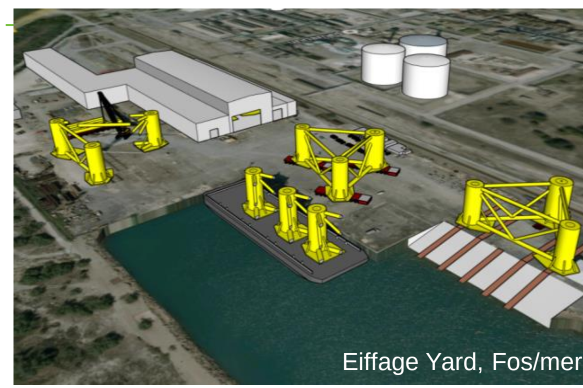
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Project Overview

- **Total capacity: 24MW capacity**, (4 X GE-Alstom Haliade 6MW)
- **Location: 18 km off Leucate, French Mediterranean coast**, in water depth of ~ 70-100m
- **Interconnection: to be constructed by RTE**, allowing a direct connection at 66kV
- Construction by EIFFAGE at Fos/Mer. Turbine installation at quayside in Port-La-Nouvelle.
- **Floating structure certification: designed for 20 years,** certification by BV
- **Operational Q4 2020**

French Call For Project

- **3 other Projects Awarded**
  - EOLFI/CGN – DCNS/VINCI in Groix (Atlantic)
  - EDF-EN – SBM/IFP in Faraman (Med)
  - QUADRAN/Bouygues-IDEOL in Gruissan (Med)
- **Up to 50M€ funding/project** by the Ministry of the Environment, the Energy and the Sea
- **Feed-In** between **150-275€/MWh** (TBC) for 20 years



Eiffage Yard, Fos/mer

ENGIE | edp renewables | Groupe Caisse des Dépôts 1816-2016 | GE | EIFFAGE | MINISTÈRE DE L'ENVIRONNEMENT, DE L'ÉNERGIE ET DE LA MER

Fishermen's Energy
Atlantic City Wind Farm

Chris Wissemann

Fishermen s Energy

Chris.Wissemann@FishermensEnergy.com

Tel: 917 838 1591

February 2017

Fishermen's Energy Atlantic City Wind Farm

Summary:

- Nation's second offshore wind farm
- Six turbines
- 2.8 miles off of Atlantic City
- Highly visible location with full local support
- Very accessible to public
- Empirical laboratory to lower costs by commercializing technology and improving regulations

Challenges:

- Perseverance
- Engineering is the lesser of the challenges
- #1 challenge is selling power

Key Partners:

Keystone Engineering Inc. (foundation Engineering)

SIEMENS (turbine supply, erection, service)

Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- **Wind plant optimization**
- Resource assessment and characterization
- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

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- World-class test and user facilities
- **Advanced technology demonstration projects**
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

Enabling Wind Nationwide

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

The Impact

- **Primary Goal:** Demonstrate pathway to lower cost of energy

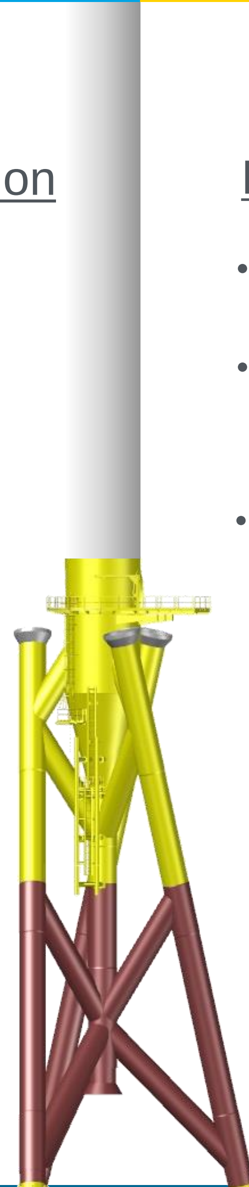
  On target to achieve 40% lower energy price than the only existing offshore wind farm operating in the United States

- **Primary Driver:** Capital Cost
- **Secondary Driver:** Optimizing wildlife protection regulations to *both* increase energy output and mitigate risks
- **Products:**
  - Demonstration that new foundation type is cost effective, logistically efficient and investment-grade (true commercialization - allowing project finance and wide deployment)
  - Regulatory protocols that would (a) protect marine mammals during construction, (b) protect birds & bats during operations, and (c) eliminate unnecessary curtailment

(1) *Driving Down Capital Cost*

Commercialize Promising Foundation

- Selected design that won UK Climate Trust Competition: Keystone's Inward Battered Guide Structure (IGBS)
- Completed initial designs vs industry standard monopile foundation and solicited fabrication & installation quotes to prove cost thesis (30% less weight)
- Key issues:
  1. Lender acceptance (ie. not proven)
  2. Turbine supplier acceptance
  3. Proof of fabrication costs
  4. Proof of installation efficacy
  5. Unique monitoring of performance post-construction to verify against design
- Fundamentally validate that this is a significantly better mouse trap



Demonstrate Installation Efficacy

- Goal: Achieve "European Cycle Times" for offshore installation
- Light weight of foundation allows for use of *one* specialty vessel for installation rather than two (500 ton lift vs 1,100 tons for a monopile)
- Target: Complete offshore work in 60 days

Technical Approach

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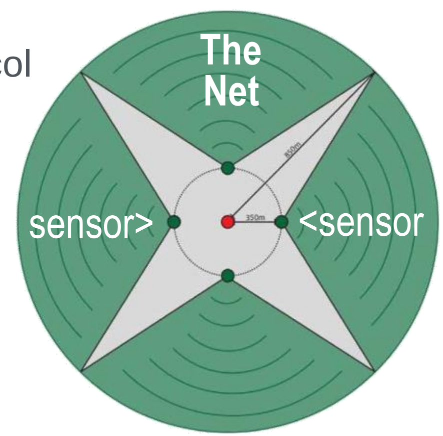
(2) Improving Regulations & Reducing Curtailment

Marine Mammals *During Construction*

- **Challenge:**
  - Permits require visual detection
  - No construction at night
  - Significant cost penalty
- **Solution:** *Deploy state-of-the-art technology*
  - Design and implement an acoustic "net" around the construction site
- **End result:**
  - Construct 24/7 unless detection
  - Better wildlife protection
  - Basis for new regulatory protocol
  - More cost effective installation
  - Lower cost of energy



Birds & Bats *During Operation*

- **Challenge:**
  - Permits require curtailment when low cloud ceiling is low or visibility
- **Solution:** *Deploy state of the art technology*
  - *Install LIDAR on windward turbine*
- **End result:**
  - Operate unless detection
  - Better wildlife protection
  - Basis for new regulatory protocol
  - More energy output
  - Lower cost of energy

Accomplishments and Progress

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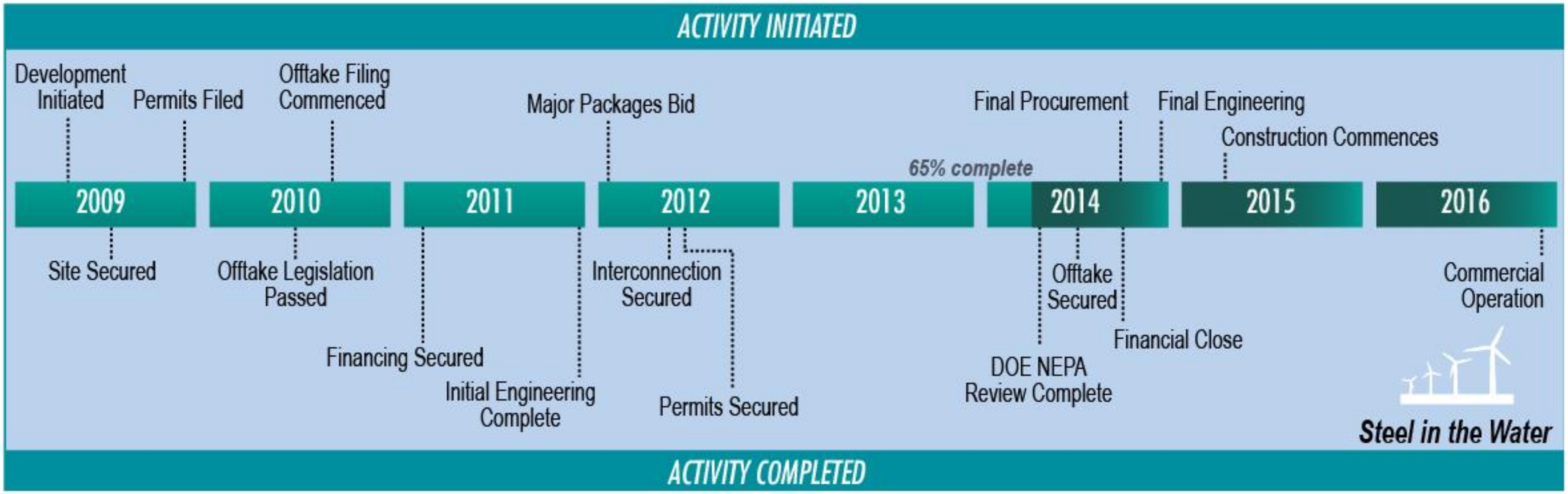
- **Foundation** progressed from concept to detailed design. Cost thesis validated.
- Developed **Jones Act-**compliant installation procedures
- Planned European style **rapid installation** procedures
- Developed and built innovative foundation **access ladder** prototype that improves worker safety and is OSHA-compliant
- Developed marine **mammal detection** system concept to reduce construction curtailment
- Advanced **avian detection** system to reduce operational curtailment
- Drafted Project Management Plan and all required supporting documents.

Project Plan & Schedule

- Original installation timeline: Operational in 2016



- Slipped milestone was securing an agreement to sell our power
- New Jersey said "no"
- Had to secure alternate buyer

- Go/No-Go:
  - FY14 = Down-select
  - FY15 = power offtake +
  - FY16 = power offtake extension

Project Budget

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

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$1,013k	$253k	$5,385k	$1,347k	$1,282k	$490k

- Slowed technical development of the project in late 2015 and 2016 to focus on obtaining a power purchase commitment. Total DOE funding was not modified.
- 100% of the Budget Period 2 federal funding has been expended (as of summer 2016)
- Additional private funds utilized to fund the non-federal portion of the ongoing development budget

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

- **Siemens**: Turbine and tower supply, erection
- **MPI**: Foundation transport and install
- **Marmon Utilities**: Cable supply and install
- **National Renewable Energy Lab**: Wake modeling, detection system design
- **DCO Energy**: Substation design and construct
- **Mott MacDonald**: Project management
- **ABS**: Certification verification agent
- **Keystone Engineering**: Foundation design

Communications and Technology Transfer:

- **Communication of past activities**: Conferences, workshops, educational meetings with state and federal elected officials, policy makers, trade groups, and public relations.
- **Prototype:** Designed & built prototype of OSHA-compliant access ladder and held multi-agency demonstration workshop[1].
- **Publications**:
  - Oct 2016, "Innovative OSW Substructure Access Ladder"
  - May 2015, "Wind Turbine Wake-Redirection Control at Fishermen's Energy AC Windfarm"
- **Future**: disseminate findings via publications and web site regarding:
  - Foundation performance, Cost of energy and capital cost
  - Marine Mammal and avian detection results and protocol

[1](http://energy.gov/eere/articles/thanks-energy-department-funding-safer-access-offshore-wind-turbine-platforms

Next Steps and Future Research

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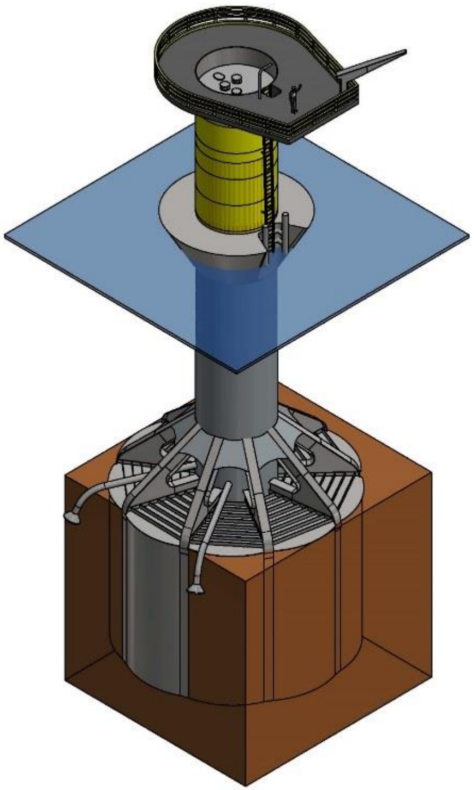
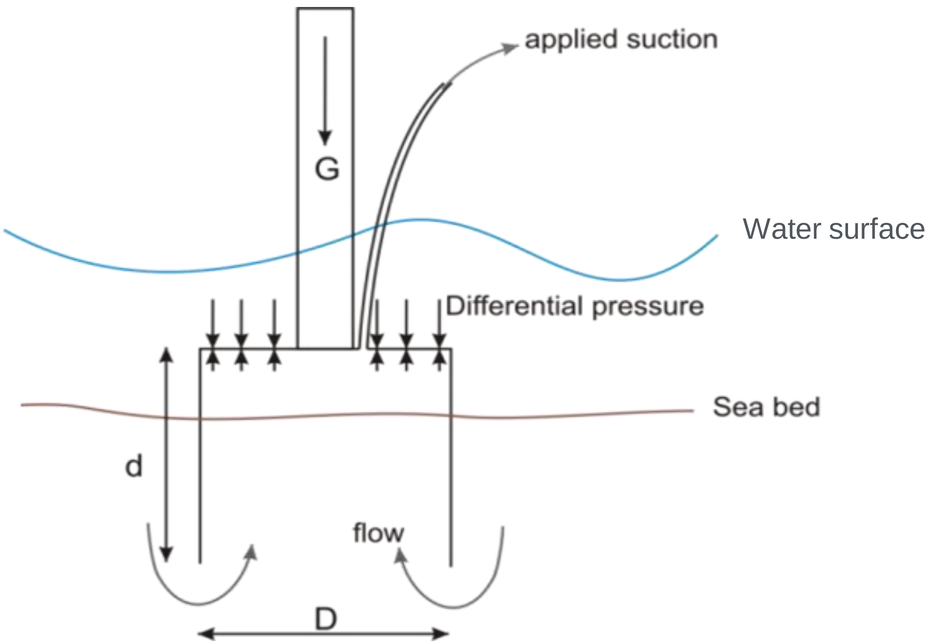
FY17/Current Research:

- Reach financial close
- Finalize design
- Finalize vendor/installer contracts
- Initiate fabrication
- Complete installation planning
- Finalize foundation instrumentation design
- Finalize marine mammal and avian detection systems.

Planned Future Research:

- Foundation instrumentation for structural loading
- Marine mammal detection system implementation
- Avian/bat detection system implementation.





Project Icebreaker

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LEEDCo

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February 14 17, 2017

Project Overview

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

Icebreaker Foundation Engineering & Assessment:

- Identify innovative wind turbine generator (WTG) foundations and determine the most cost-effective solution for the Icebreaker project; complete the engineering design
- Construct and operate a commercially viable six-turbine offshore wind (OSW) demonstration project utilizing the optimal foundation; sell the power output to secure non-recourse project debt and attract equity investor to fund the project.

The Challenge:

- Incumbent solutions are not cost effective and thus are obstacles to reducing levelized cost of energy (LCOE)
- Power price of small scale, first-of-its-kind project is several multiples of current market price.

Partners: Design Engineer - **Universal Foundation**; Owners Engineer – **Offshore Design Engineering**; Certified Verification Agent (CVA) – **DNV GL**; Supply Chain Development – **GLWN;** Research - **Case Western Reserve University;** Lead Power Purchaser – **Cleveland Public Power;** Equity Investor – **Fred. Olsen Renewables;** Project Debt - **KeyBank**

Project Overview

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Icebreaker OSW Demonstration Project

Six (6) Vestas V126-3.45 turbines

8 – 10 miles offshore

Water depth ≈ 60 feet

20.7 MW capacity

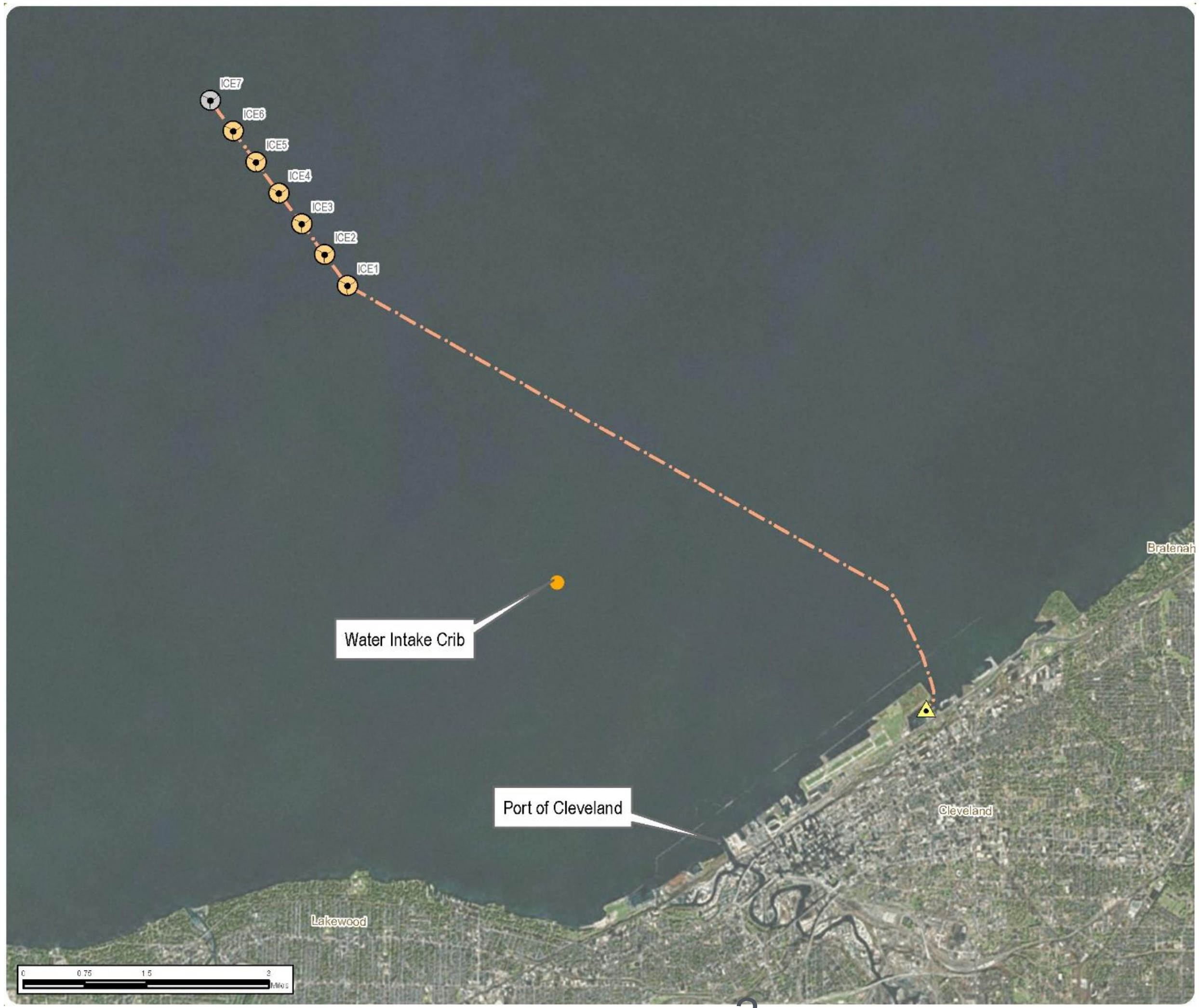
Power for 7,000 homes

Mono Bucket foundations

Grid connection at CPP Lake Road substation

Port of Cleveland staging and assembly site

Construction planned to begin in 2018



Enabling Wind Nationwide

Enabling U.S. Industry Growth and Enabling U.S. Competitiveness

- **Wind plant optimization**
- Resource assessment and characterization
- Reliability improvements
- Enabling access to better resources through tall wind
- Distributed wind R&D
- NextGen component innovations

Enhancing U.S. Energy Security and Independence

- Facilitating coexistence between wind energy and wildlife
- Offshore wind environments
- Information synthesis and dissemination
- Successful coexistence with radar systems
- Wind energy workforce and education development
- Advancing grid integration

Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

- Commercialization of innovations and technology transfer
- World-class test and user facilities
- **Advanced technology demonstration projects**
- Technical engagement initiatives
- Standards and certification
- Communicating the costs and benefits of wind energy

Enabling Wind Nationwide

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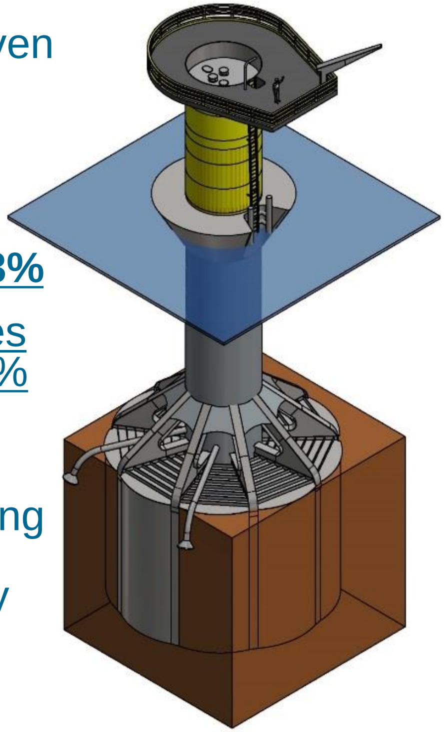
- Distributed wind R&D
- NextGen component innovations

The Impact

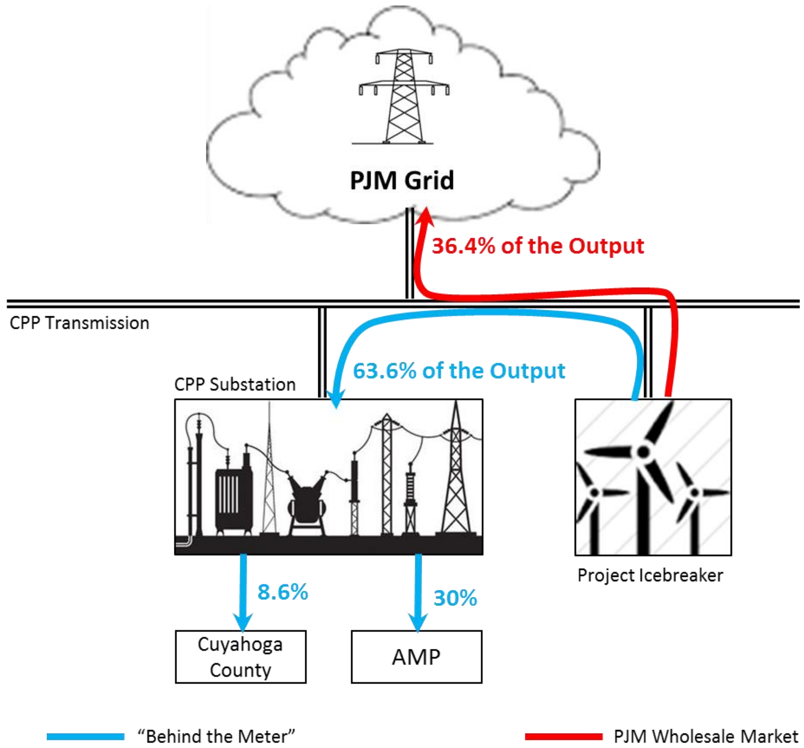
- **REDUCES BALANCE OF SYSTEM CAPEX, SUBSTRUCTURE**
- Introduces an innovative but proven (Technology Readiness Level 7) new foundation type to the U.S. market: the **Mono Bucket**
- For Icebreaker Wind – **Reduces CAPEX of the foundation by 33%**
- For East Coast markets – reduces CAPEX of the foundations by 10% to 30%, depending on soil conditions and water depth
- No pile driving required, eliminating a major environmental impact in ocean waters and potential costly delays related to curtailment.



Enabling Wind Nationwide

The Impact

- Creative solution to the Power Purchase Agreement (PPA) challenge



Strengthening Domestic Manufacturing and Providing Local Economic Value in all 50 States

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- **Advanced technology demonstration projects**
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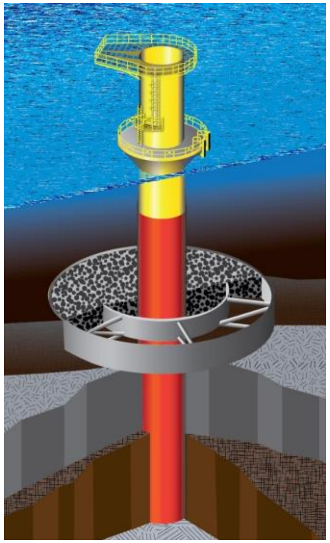
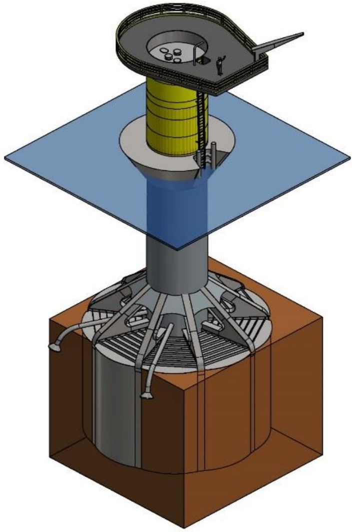
Technical Approach





- Established Basis of Design for the comparison
- Separate teams completed conceptual designs of both concepts
- Third team monitored and reviewed the two design streams to ensure consistency
- Both concepts had to meet design criteria
- Established fabrication and installation cost models to evaluate cost performance
- Assessed comparative risk of each concept
- Mono Bucket emerged as clear choice as best cost performance and equivalent risks.

Technical Approach

- Executed a geotech exploration program of the WTG sites tailored to the Mono Bucket requirements
- Finalized WTG selection
- Updated and initiated verification of Basis of Design (BOD)
- Updated the Mono Bucket conceptual design per BOD and WTG loads
- Performed first iteration coupled loads analysis with original equipment manufacturer (OEM)
- Explored U.S. fabrication supply chain and developed 10 prospects
- Executed competitive bid process based on primary steel and short-listed the field of U.S. fabricators

Accomplishments and Progress

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- Completed objective comparison and identified a new innovative foundation concept for the U.S. market
- Demonstrated superior cost performance of the Mono Bucket in Lake Erie and East Coast sites
- Completed coupled loads analysis with WTG OEM
- Developed many U.S. fabricators capable of and interested in manufacturing the Mono Bucket
- Demonstrated ability to achieve fabrication cost targets through competitive bid process
- Developed creative solution to the PPA challenge to keep the project commercially viable.

Project Plan & Schedule

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- Project start date: December 2014
- Planned completion: March 2016 (BP1); July 2017 (BP2)
- Construction: Beginning in 3Q 2018
- Completion of BOD verification delayed due to underestimated effort to resolve the verification issues
- Geotech final report delayed due to introduction of advanced cyclic tests that were not planned which delayed BOD
- Decision point achieved March 2015: Mono Bucket selected over Monopile with Friction Wheel.

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$195k	$95k	$2,162k	$1,337k	$824.040k	$631k

- Added geotech program in 2015 which increased budget and required additional cost-share
- Award extended by $3,700k in July 2016 to complete engineering for all CAPEX and complete permitting
- 75% budget spent as of October 31, 2016

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators:

Universal Foundation – Mono Bucket design engineer; **Offshore Design Engineering** – Owners engineer; **DNV GL** – CVA; **Fred. Olsen Windcarrier** – Installation engineer; **GLWN** – Supply chain development; **Case Western Reserve Univ.** – Research; **U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory**– Ice research

Communications and Technology Transfer:

Presented at International Partnership Forum, 28-Sep-15 and American Wind Energy Association Offshore Windpower on 30-Sep-15

Published two papers: 1) "Lake Erie Ice Ridges" by Dr. Steven Daly, CRREL and 2) "Engineering & Technology Reference – Case Study, A Foundation for Lowering the Cost of Offshore Wind Power" by Dr. Lorry Wagner, LEEDCo

Next Steps and Future Research

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FY17/Current Research: Complete detailed engineering for all aspects of the project; verify design; negotiate agreements for all CAPEX scopes of work; obtain all state and federal permits; prepare for financial close

Planned Future Research: Complete the PRE-CONSTRUCTION PHASE, then the CONSTRUCTION PHASE, and finally transition to OPERATIONS PHASE

Monitor the performance of the Mono Bucket during operations