2014 WIND POWER PROGRAM PEER REVIEW

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

Next Generation Wind Energy Technologies

March 25-29, 2014

PR-5000-62152

Contents

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

Advanced Turbine Controls R&D

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March 25, 2014

Budget, Purpose, & Objectives

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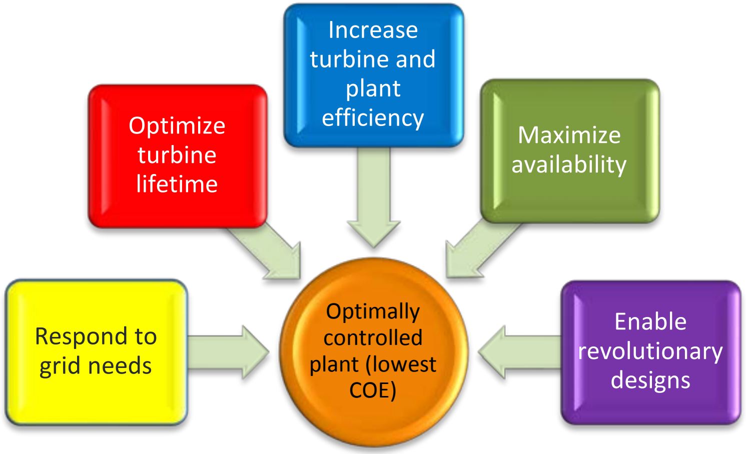
Total DOE Budget[1]: $2.250M

Total Cost-Share[1]:$1.050M

Problem Statement:

- Develop turbine controls that enable revolutionary new technologies and support optimized wind plants
- Demonstrate proof of concept through field testing
- Transfer these advanced control technologies to industry.



Impact of Project:

Optimize COE reductions for wind plants and supporting turbines.

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:**
  Reduce Wind Plant Levelized Cost of Energy (LCOE).

[1]*Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Technical Approach

1. Develop new integrated controls approaches using advanced state-space multi-variable control methods
   - Improved load mitigation (independent blade pitch)
   - Robust controls (robust to model errors)
   - Improved yaw controls
   - Extreme event controls.
2. Develop advanced feed-forward controls that use Light Detection and Ranging (LIDAR) wind-speed sensors to improve control.
3. Collaborate with LIDAR manufacturers (ZephIR, Avent-Leosphere, Michigan Aerospace) to demonstrate proof-of-concept LIDAR controls.
4. Demonstrate control algorithm performance through field testing on the Controls Advanced Research Turbines at NREL before implementation in large machines.

NREL has established the Controls Advanced Research Turbines (CARTs) as a world-class base for advanced controls research.

- Two 600-kW machines configured for advanced controls field-testing
- Variable-speed and independent pitch control actuation
- Public domain data
- Harsh turbulent wind inflow at NWTC
- Perfect for vetting new controls approaches
- Robust/rugged machines.

CART2

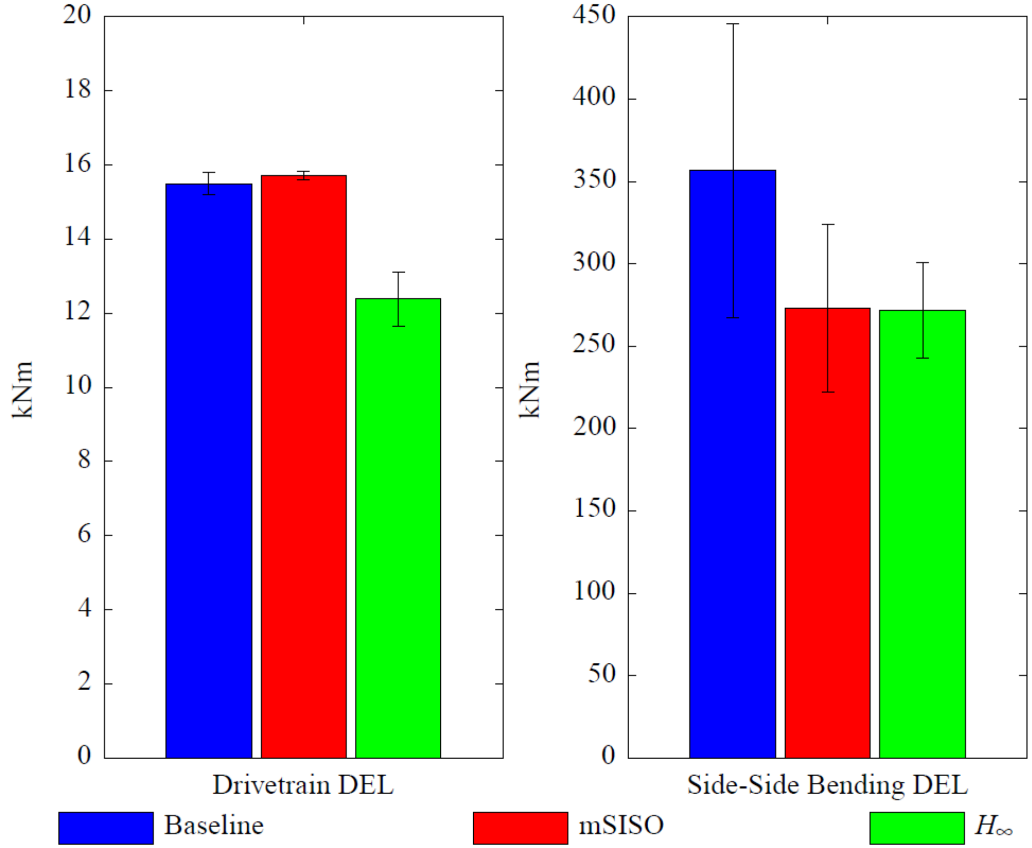
CART3

Left photo: NREL PIX 18278; right photo: NREL PIX 18279

CART3 Field tests of multi-variable robust controls (H∞ methods)

- Multivariable controller outperforms both baseline and multiple loop controllers

- Multivariable controller accounts for coupling between control loops and improves robustness to modeling error.



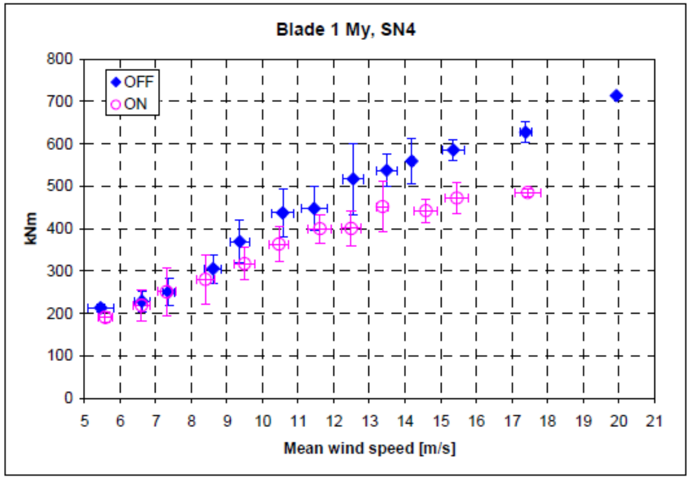
Partner: TU-Delft

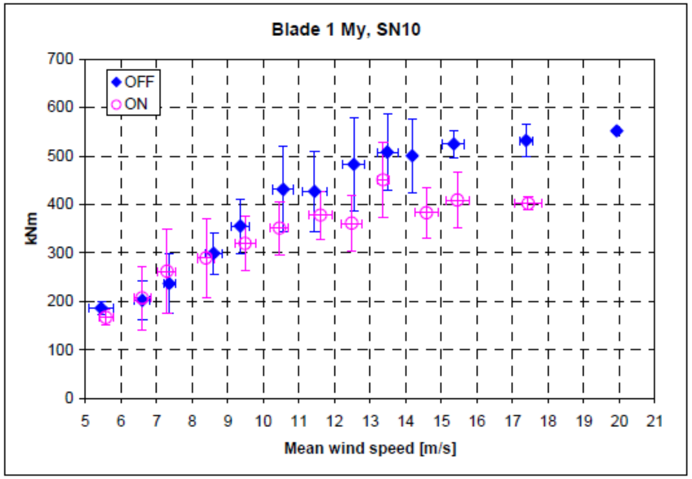
Accomplishments
CART IPC Field Tests

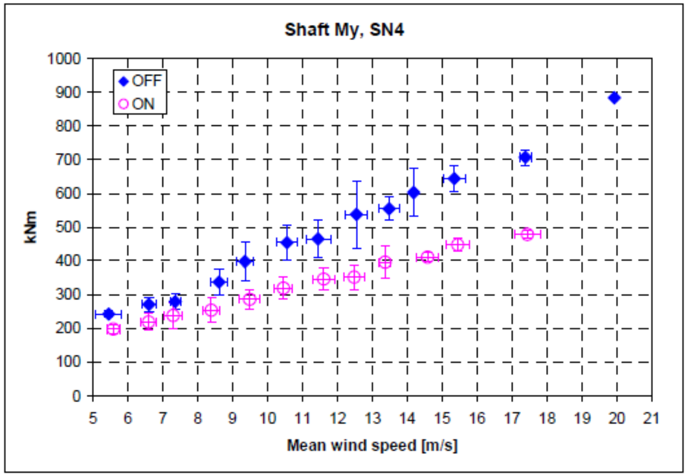
Reduction in fatigue loads when IPC is on (pink) versus off (blue)

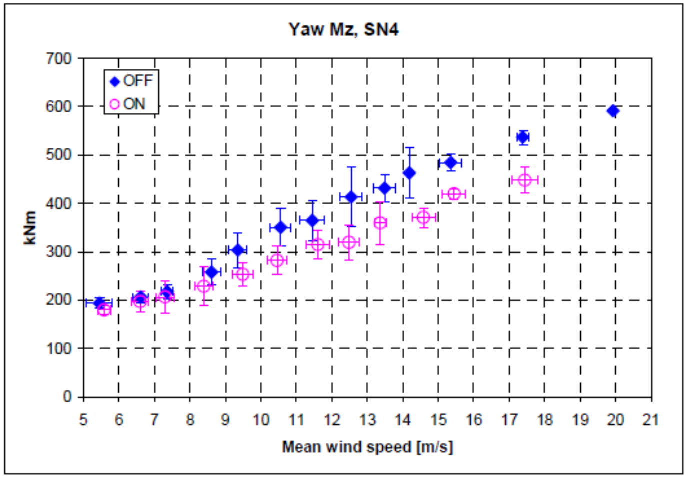
- Independent pitch control (IPC) reduces turbine loads by mitigating asymmetric rotor loads
- CART field tests demonstrate clear load reductions

Partner:
Garrad Hassan









Accomplishments
Advanced Yaw Control Tests

- CART3 field tests demonstrate improved yaw control resulting in enhanced power capture!
- With DTU-Wind, applied rotor-dependent nacelle vane corrections for improved power capture.

Partner: DTU-Wind

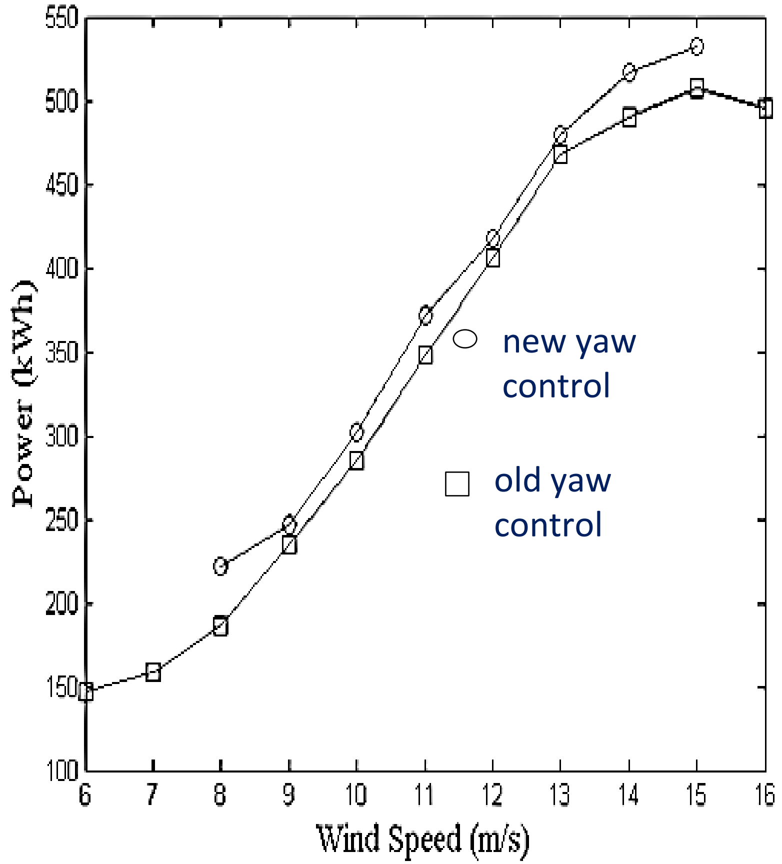
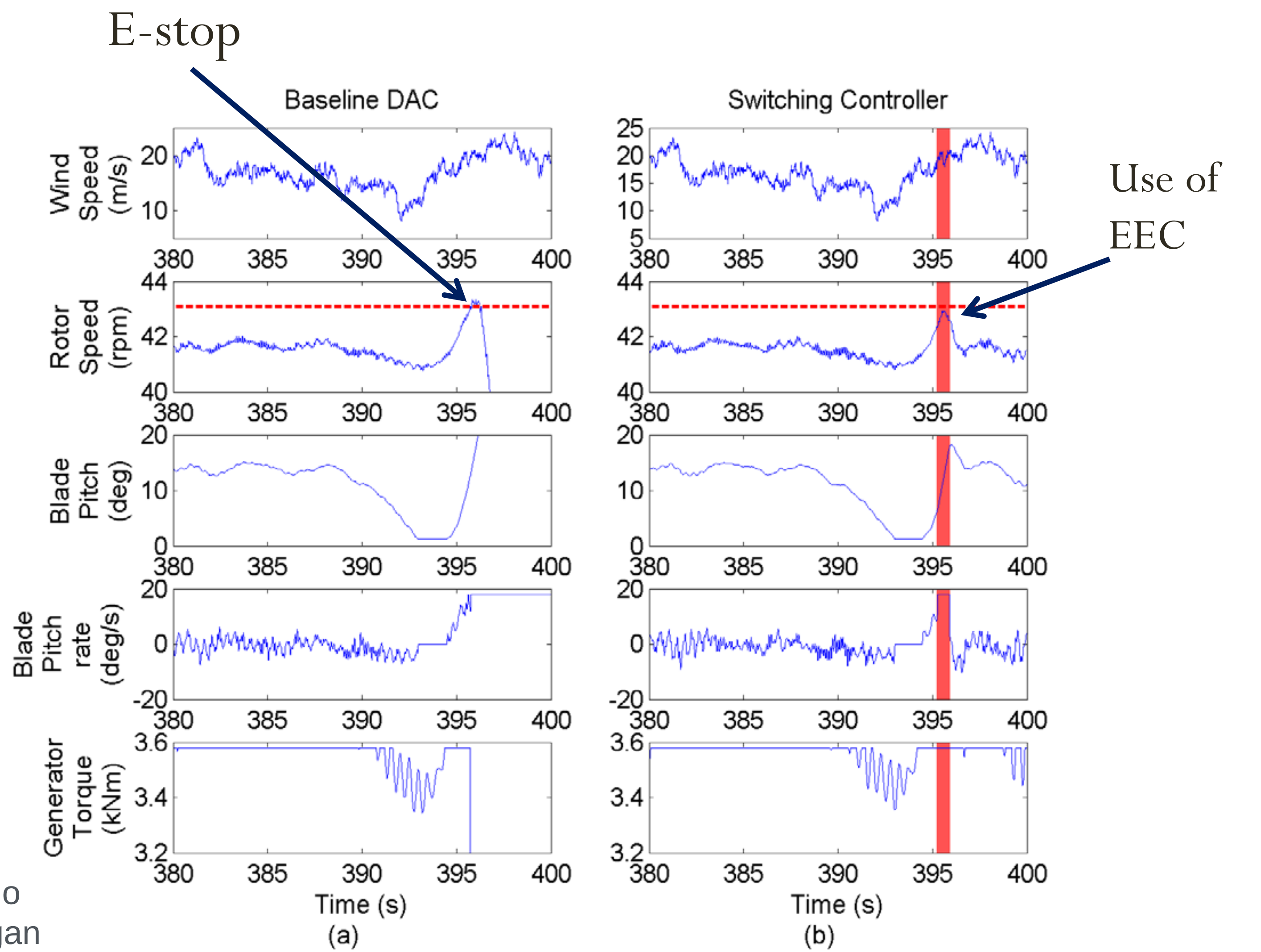


Figure 7 Power curve from the experimental data collected from the CART3 turbine during the Autumn of 2011. □: Original yaw controller, o: Updated yaw controller. Data is binned in bins with a width of 1 m/s.

Accomplishments
CART3 Extreme Event Control Simulation

Extreme Event Controls (EEC):

- Reduce loads due to extreme events
- Reduce turbine shutdowns due to extreme events

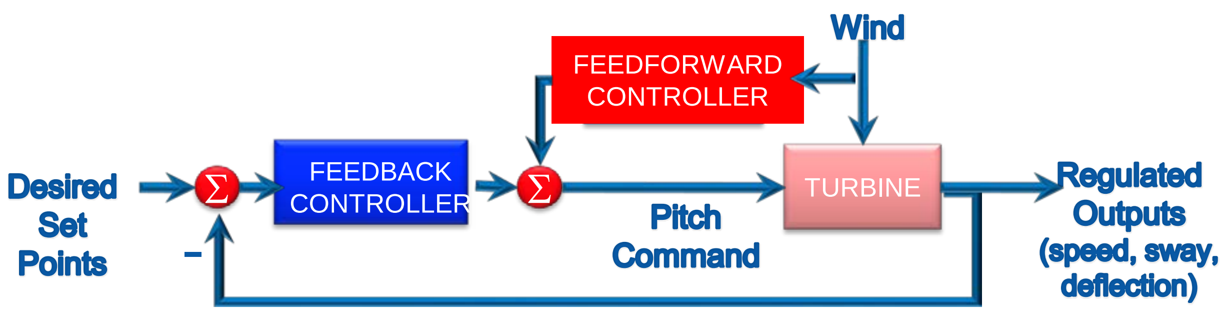


Partners: ECN, Colorado School of Mines, Michigan Aerospace (LIDAR)

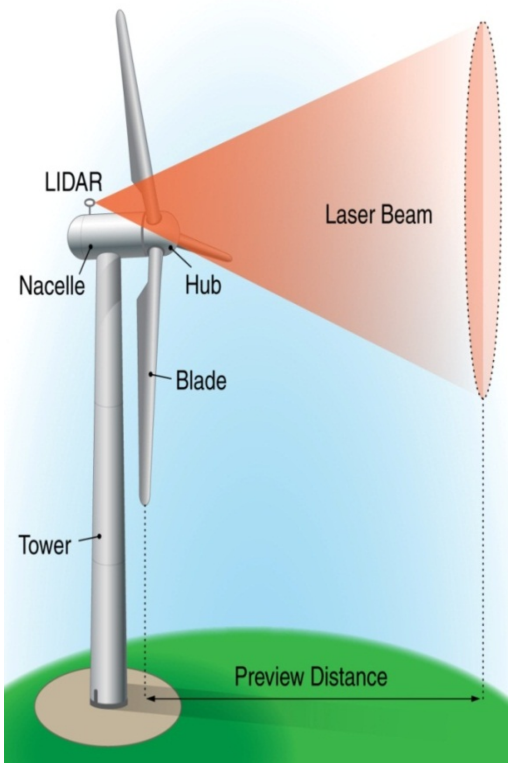
Technical Approach
Feed-Forward LIDAR Controls:

Approach

- Previous controls used only turbine measurements
- New feedforward control uses LIDAR-measured windspeed to improve control performance



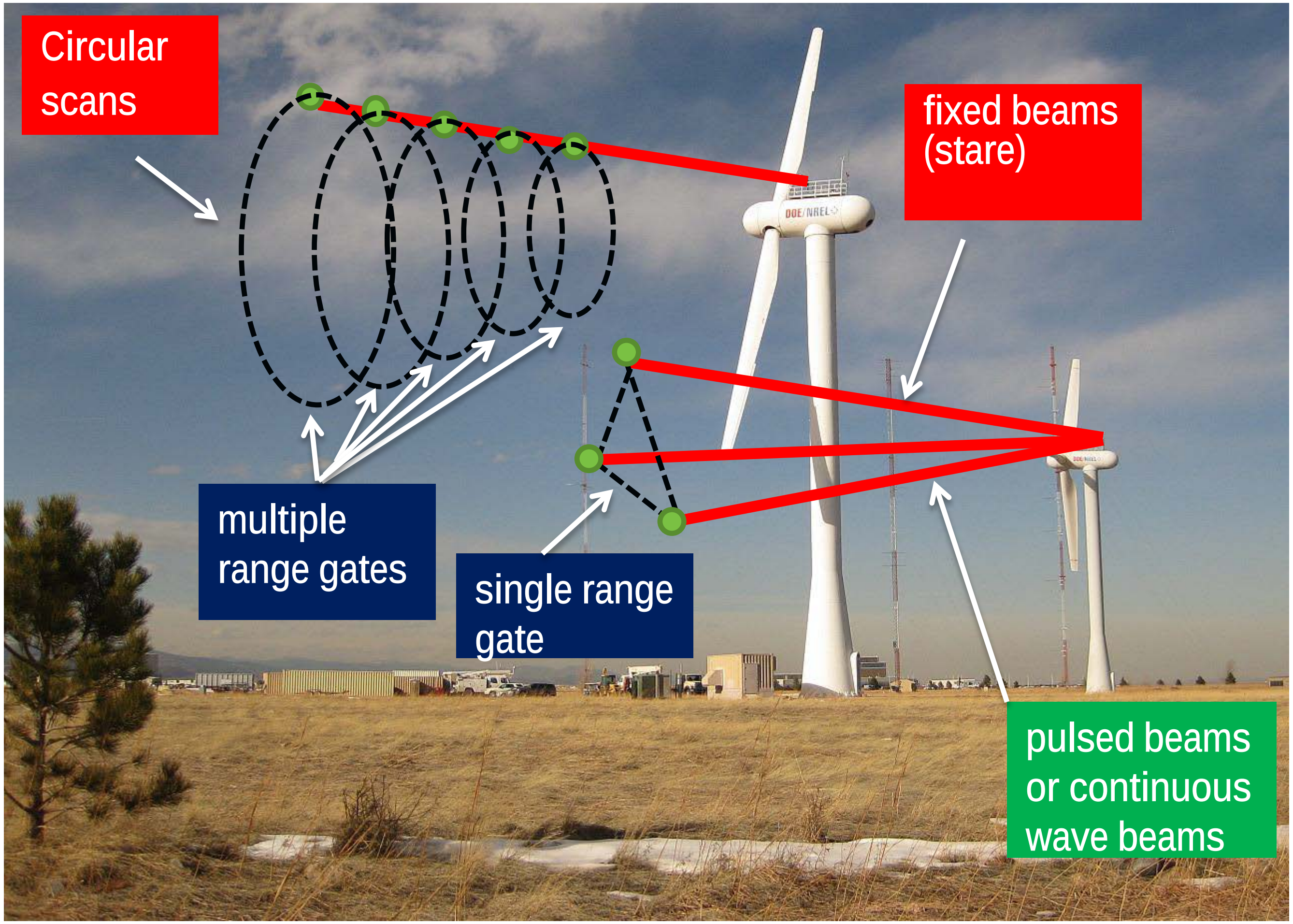
Courtesy Dr. Lucy Pao



Partners: Alstom, VESTAS, GE, University of Colorado, Colorado School of Mines, University of Stuttgart, BlueScout Technologies, DTU-Wind, Avent/Leosphere, Zephir

Technical Approach
Advanced Feed-Forward Controls

Important to evaluate different LIDAR configurations for turbine control



LIDAR configurations being tested:

Manufacturer	Type	Turbine location	Scan pattern	# Range gates used	Control being tested
Blue Scout*	Pulsed	nacelle	multiple-fixed beams	one	Collective pitch
Univ. Stuttgart	Pulsed	nacelle	circular scans – one beam	multiple	Collective pitch
Avent-Leosphere	Pulsed	nacelle	multiple fixed beams	multiple	Yaw calibration, collective pitch
ZephIR	CW	nacelle	circular scans – one beam	one	Collective pitch
DTU-Wind	CW	Hub/spinner	circular scans – one beam, other patterns possible	one	Collective and independent blade pitch

* Now in Chapter 7

Accomplishments
LIDAR Controls Field-Testing

University of Stuttgart (SWE) LIDAR - CART2

- Proof of concept feed-forward collective pitch control
- Two campaigns:
  - CART3: commercial pulsed LIDAR
  - CART2: SWE-Scanner LIDAR.
- Control objective: reduction of rotor speed variations in above-rated operation.

Blue Scout Technologies LIDAR – CART3

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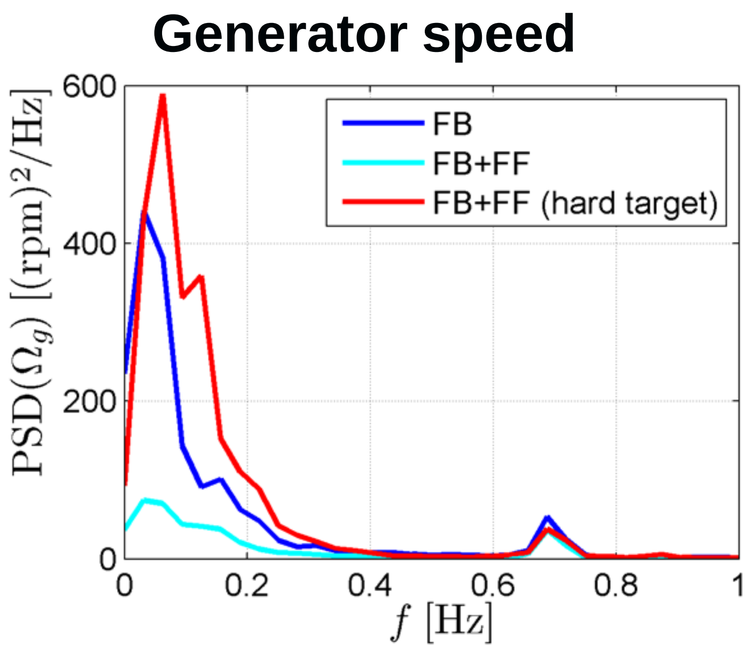
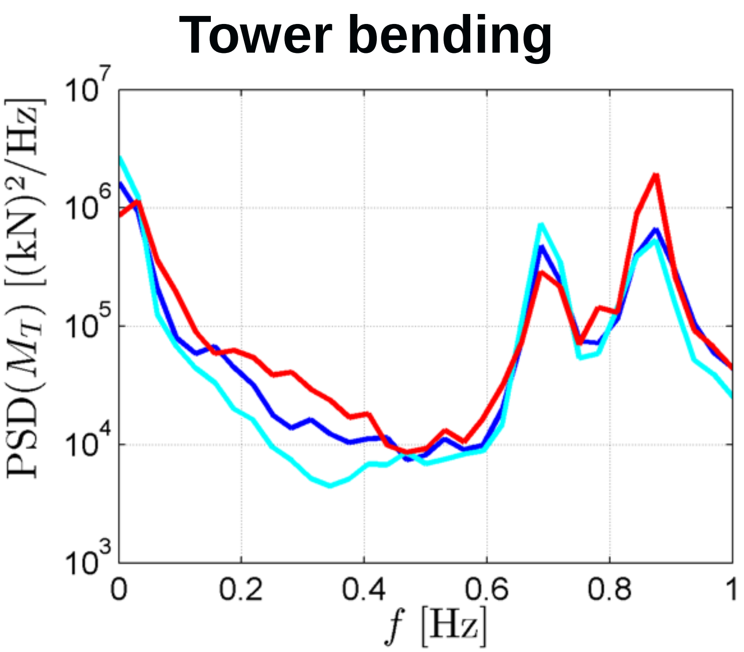
CART2 Test Results

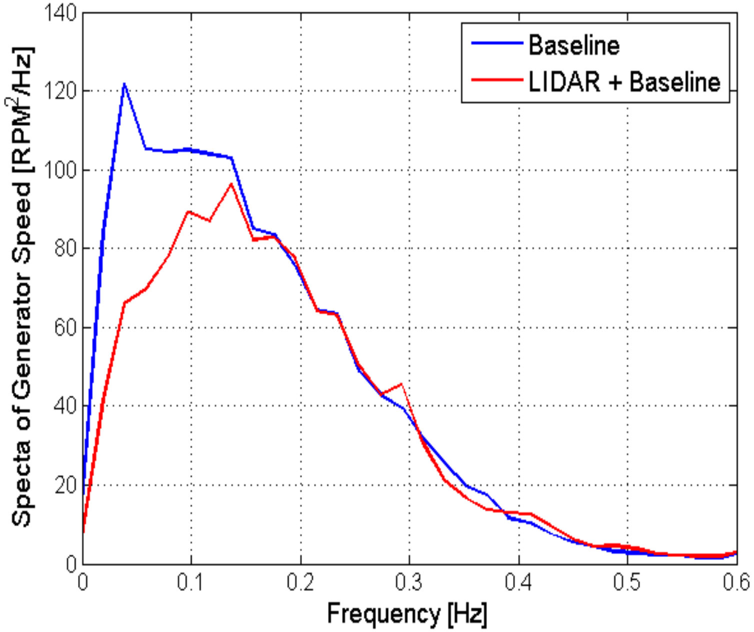




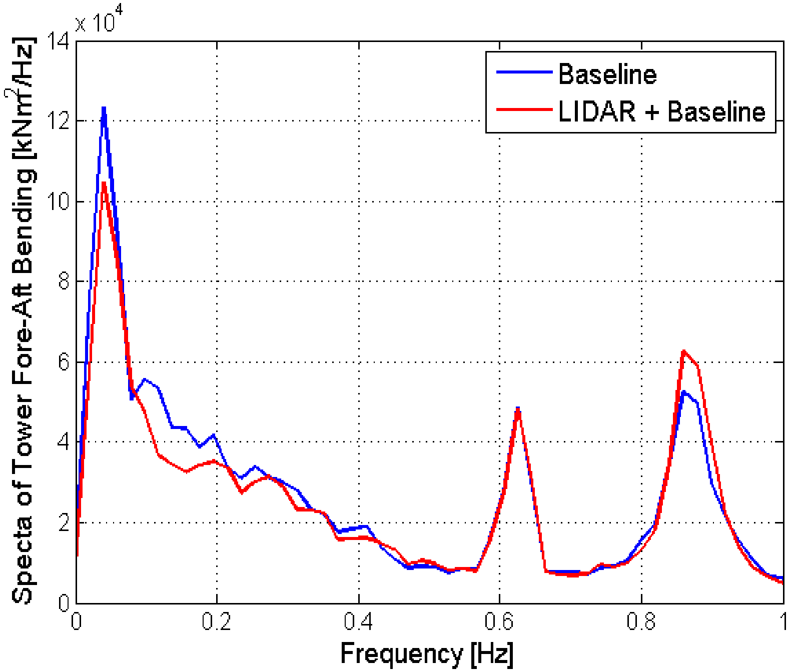
- Reduction in standard deviation of the generator speed of 30% at low frequencies
- But increase of 30% before solving the hard target problem
- Similar behavior for the tower base bending moment and other loads.

CART3 Test Results

Generator speed



Tower bending



- Reduction in standard deviation of the generator speed of 13.6% at low frequencies
- Some reduction in tower fore-aft bending at low frequencies
- Improved pitch control will lead to better regulation of the turbine's thrust.

CART2

Avent-Leosphere

Goals: Improved yaw control, improved rotor collective pitch

Project Plan & Schedule

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Summary	
WBS Number or Agreement Number	2.3.0.9
Project Number	Advanced Turbine Controls
Agreement Number	26862

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Advanced Turbine Controls												
Q1 Milestone: CART2 field tests comparing baseline and state-space controllers												
Q2 Milestone: Paper detailing CART3 test comparisons of baseline and advanced controller												
Q3 Milestone: Draft report on feed-forward controls simulation												
Q1 Milestone: Conference paper on Lidar feed-forward controls tests												
Q2 Milestone: Initial field tests of industry standard baseline and multi-variable torque controllers on CART3 (TU-Delft collab.)												
Q3 Milestone: Field tests of Extreme Event controls - CART3 (ECN collab.)												
Q4 Milestone: Field tests of system identification algorithm on CARTs (TU-Delft, CENER collab.)												
Current work and future research												
Develop strategy for developing Fault Tolerant controls and Fault Detection												
Field tests of baseline and advanced multi-variable independent blade pitch controls												
Feed-forward Lidar controls field tests on CART2 and CART3												
Field tests of updated system identification algorithms												

Comments

- Project original initiation date: 10/01/2011; Project planned completion date: 9/30/2014
- The FY13 Q2 milestone was delayed due to a rescheduling of controller field tests on the CART3 to test the ECN extreme event controller (Q3 milestone) during a visit to NREL by ECN controls researchers. As a result, the Q3 milestone was finished ahead of schedule and the Q2 milestone at end of Q3.
- Go/no-go decision points for FY12 and FY13: Completion of quarterly milestones.

Partners, Subcontractors, Collaborators

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Partner	Activity	CRADA	MOU	Subct
Alstom	Feed-forward controls and offshore systems	x		
VESTAS**	Feed-forward LIDAR controls collaboration with University of Colorado			
GE**	Feed-forward LIDAR controls	x		
Gamesa	Advanced controls development	x		
DTU Wind Energy	LIDAR evaluation and yaw control		x	
ECN	Extreme event controls	x		
TU-Delft	Controller comparison study, system identification, wind plant control	x		
CENER	Closed-loop system identification	x		
Garrad Hassan (GH)	Independent blade pitch controls + LIDAR feed-forward	x		
BlueScout Technologies*	LIDAR supplier	x		
Michigan Aerospace	LIDAR supplier			x
Avent-Leosphere	LIDAR supplier	x		
ZephIR**	LIDAR supplier			
U. Of Colorado (CU)	Advanced LIDAR feed-forward control algorithms			x
Colorado School of Mines(CSM)	Advanced LIDAR feed-forward control algorithms, fault tolerant controls			x
U. Of Stuttgart (U of S)	LIDAR feed-forward controls		x	
University of Minnesota**	Robust controls and wind plant controls			

** No formal agreement * Now in Chapter 7

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Select Collaborative Publications

Avent-Leosphere

- Fleming, P., Scholbrock, A., Jehu, A., Davoust, S., Osler, E., and Wright, A., "Field-test Results Using a Nacelle-mounted Lidar for Improving Wind Turbine Power Capture by Reducing Yaw Misalignment," accepted for presentation at the 2014 Science of Making Torque from Wind Conference, June 18-20, 2014, Copenhagen, Denmark.

Blue Scout Technologies, University of Stuttgart

- Scholbrock, A., Fleming, P., Fingersh, L., Wright, A., Schlipf, D., Haizmann, F., and Belen, F., "Field Testing LIDAR-Based Feed-Forward Controls on the NREL Controls Advanced Research Turbine." Presented at the 51st AIAA Aerospace Sciences Meeting and Exhibit, Grapevine, Texas, January, 2013.

Garrad Hassan and Partners

- Bossanyi, E., Fleming, P., and Wright, A., "Validation of Individual Blade Pitch Control by Field Tests on Two- and Three-Bladed Wind Turbines." *IEEE Transactions on Control Systems Technology* (Special issue: "To Tame the Wind: Advanced Control Applications in Wind Energy"), Vol. 21, no. 4, 2013.

DTU-Wind

- Kragh, K. A., and Fleming, P., "Rotor speed dependent yaw control of wind turbines based on empirical data." In Proceedings of the 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, January, 2012.

TU-Delft

- Gebraad, P., van Wingerden, J., Fleming, P., and Wright, A., "LPV Identification of Wind Turbine Rotor Vibrational Dynamics Using Periodic Disturbance Basis Functions." *IEEE Transactions on Control Systems Technology* (Special issue: "To Tame the Wind: Advanced Control Applications in Wind Energy"), Vol. 21, no. 4, 2013.

Colorado School of Mines

- Wang, N., Johnson, K., and Wright, A., "Comparison of Strategies for Enhancing Energy Capture and Reducing Loads Using LIDAR and Feedforward Control." *IEEE Transactions on Control Systems Technology* (Special issue: "To Tame the Wind: Advanced Control Applications in Wind Energy"), Vol. 21, no. 4, 2013.

University of Colorado

- Dunne, F., Schlipf, D., Pao, L., Wright, A., Jonkman, B., Kelley, N., and Simley, E., "Comparison of Two Independent LIDAR-Based Pitch Control Designs." 50th AIAA Aerospace Sciences, Nashville, TN, January 2012.

Next Steps and Future Research

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FY14/Current research:

- Complete CART feedback control field tests
- Complete CART LIDAR feed-forward control field tests as steps to commercial turbine implementations

ZephIR CW nacelle LIDAR

DTU-Wind CW spinner LIDAR

Goals: Higher wind measurement fidelity, improved pitch control

Next Steps and Future Research

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Proposed future research:

- Implement feed-back and LIDAR feed-forward controls on commercial machines (with collaborative partners)
- Initiate development and field testing of Fault Tolerant Controls on the CARTs
- Develop and field test optimized wind plant controls.

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Cost of Energy reduction for offshore Tension Leg Platform (TLP) wind turbine systems through advanced control strategies for energy yield improvement, load mitigation and stabilization

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03 / 25 / 2014

Budget, Purpose, & Objectives

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Total DOE Budget[1]: $0.391M

Total Cost-Share[1]:$0.134M

Problem Statement:

- The current Levelized Cost of Energy (LCOE) of floating offshore wind turbines (FOWT) combined with several technical-market barriers and the very little field validation experience are making it infeasible to commercially develop the vast deep-water wind resources in the US coast

Impact of Project:

- This project will demonstrate the value of advanced controls to reduce the LCOE of FOWT, advance the state of the art of the floating technology, and provide a validation strategy based on field testing performed on multi-MW turbines at several world class test facilities (NWTC, VOWTAP[1], Reese Technology Center, ETI offshore demonstrator[2])

This project aligns with the DOE Program objectives and priorities :

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Testing Infrastructure:** Enhance and sustain the world-class wind testing facilities at Universities and national laboratories to support mission-critical activities

[1] Advanced controls testing is planned for VOWTAP if Phase 2 down selection awarded to team lead by Dominion

[2] UK's Energy Technology Institute (ETI) has indicated support for use of its Floating Offshore Demonstrator, if constructed, for testing advanced controls

[1]***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

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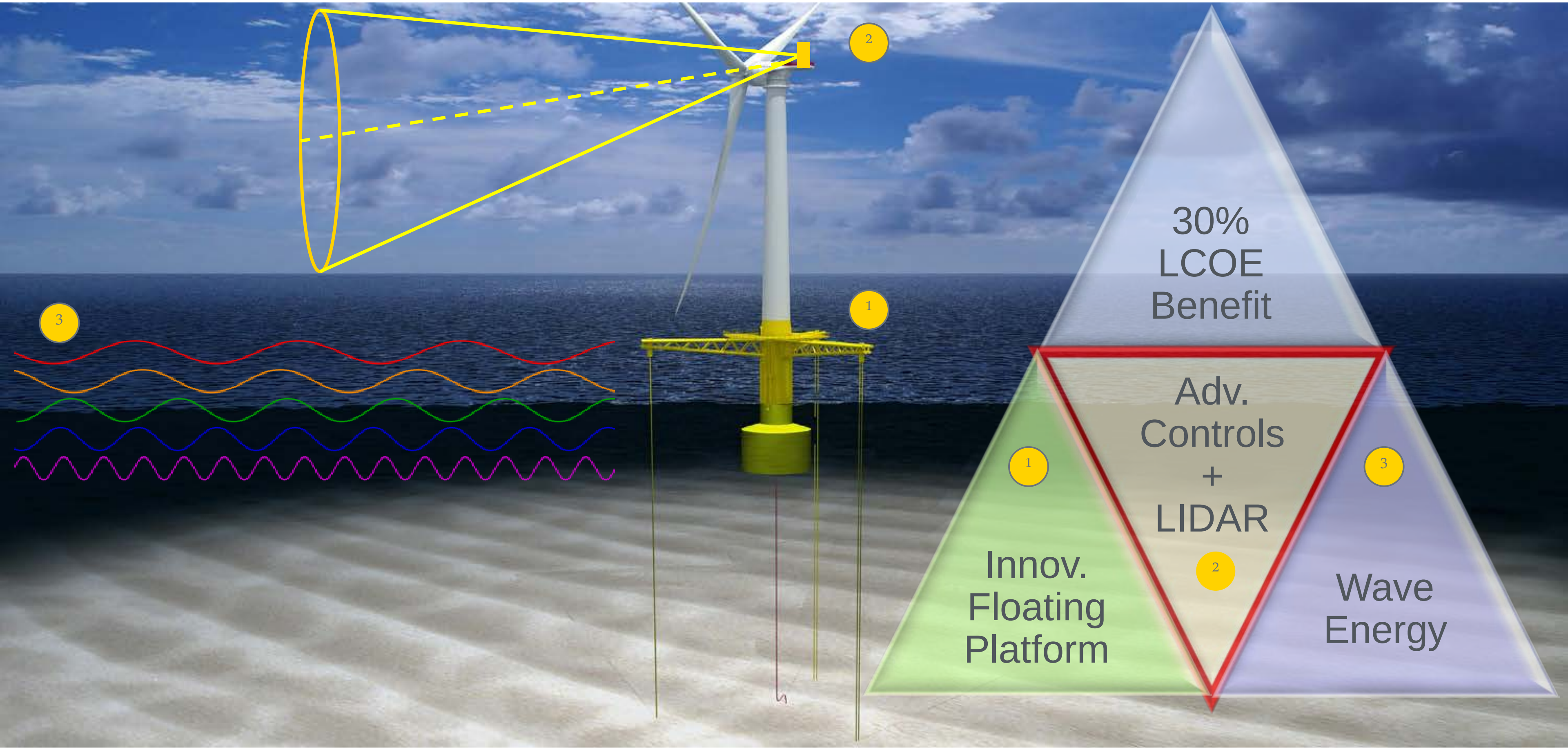
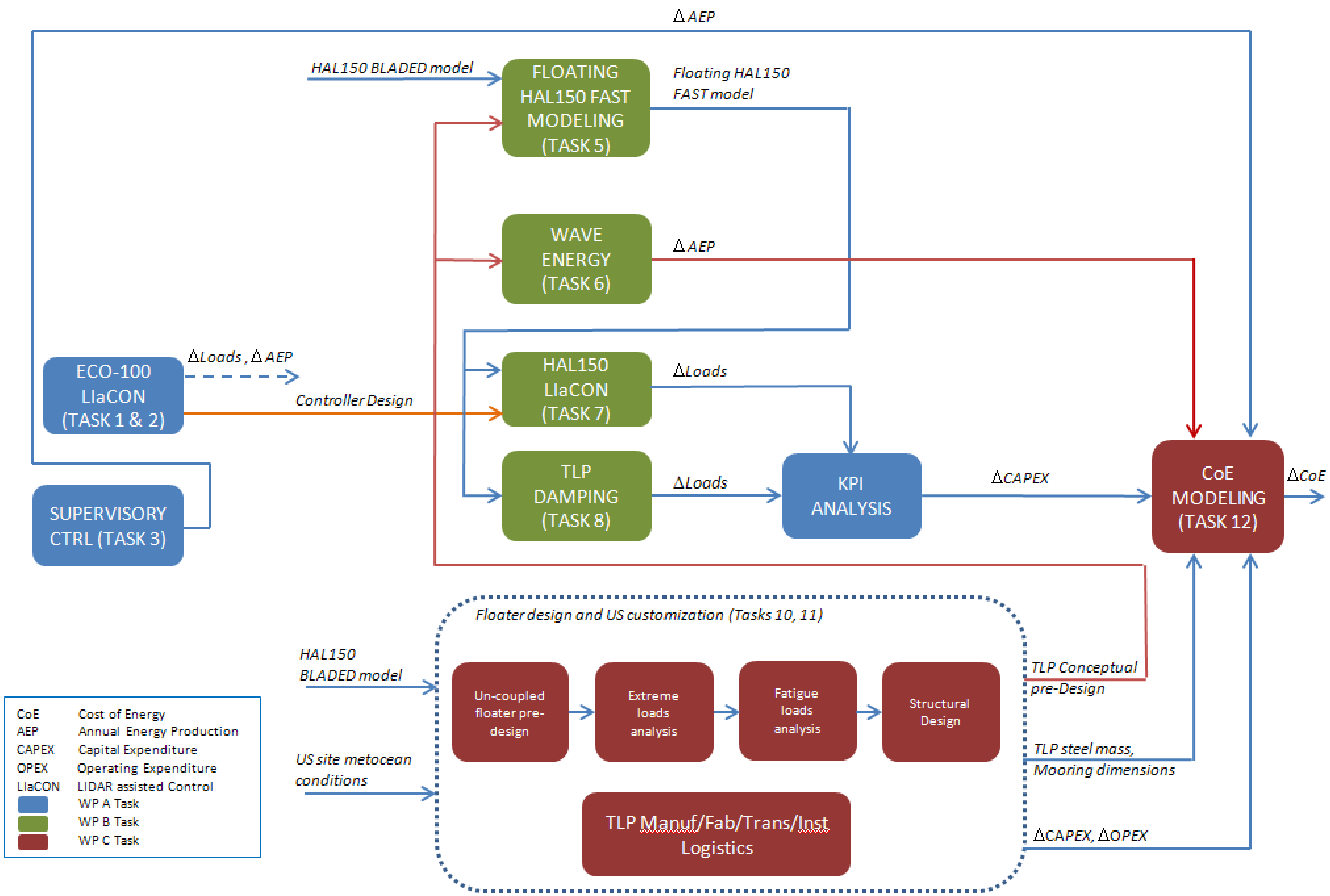
- Innovations to Reduce LCOE for FOWT



- Technical approach & methods : Overall flowchart

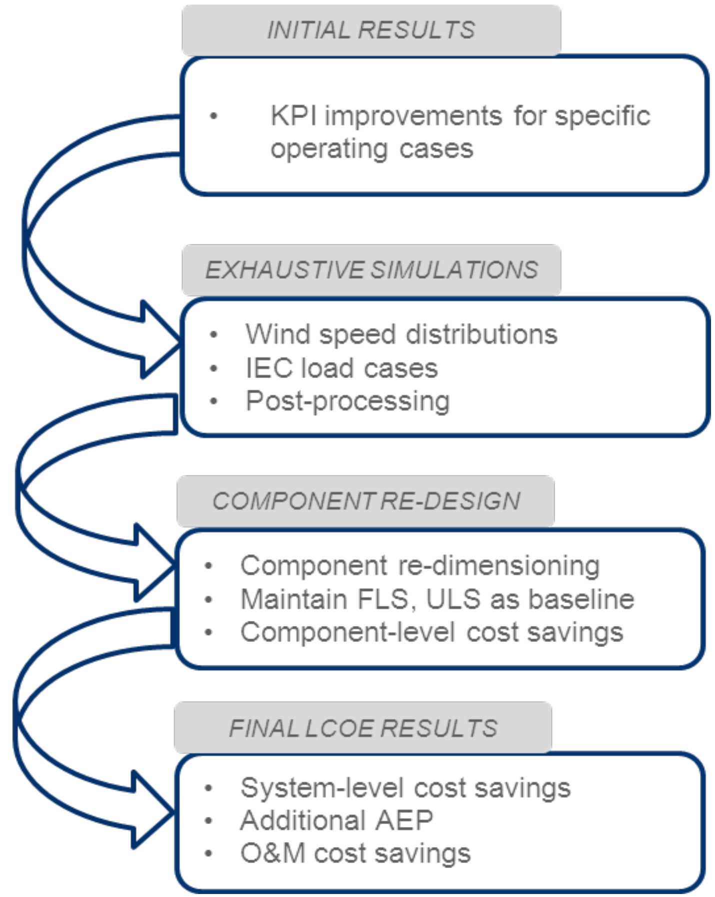


Technical Approach

- Key issues and unique aspects of the approach

Barrier	Description
Wave loading and system dynamics	➢ Increased fatigue drives tower weight up 50% compared to jacket foundations.
	➢ Heavy substructures due to the need of withstand extreme events.
System Stability	➢ Floating wind turbines have inherent instabilities that require specialized control
System Modeling	➢ Techniques for modeling of FOWT and substructures not well developed.
	➢ Little data available for validation of floating wind turbine modeling techniques.

Technical Barriers



LCOE calculation approach

Accomplishments and Progress

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- Milestones

Task 1 and 2 – LIDAR-based Feedforward Controls

- ✓ ECO100 aeroelastic modeling, implementation and verification in FAST;
- ✓ Feedforward control algorithm design and benchmarking;

Task 5 – Haliade and TLP FAST Modeling

- ✓ Floating model definition, implementation and validation in FAST
- ✓ Baseline controls adaptation in FAST to FOWT

Task 7.0 – Advanced Controls for Haliade150 and TLP

- ✓ Feedback/Feedforward controls development and FAST implementation
- ✓ Estimate KPI improvements

Task 8.0 – Structural Damping Controls

- ✓ Design and implementation of tuned mass dampers for FOWT in FAST

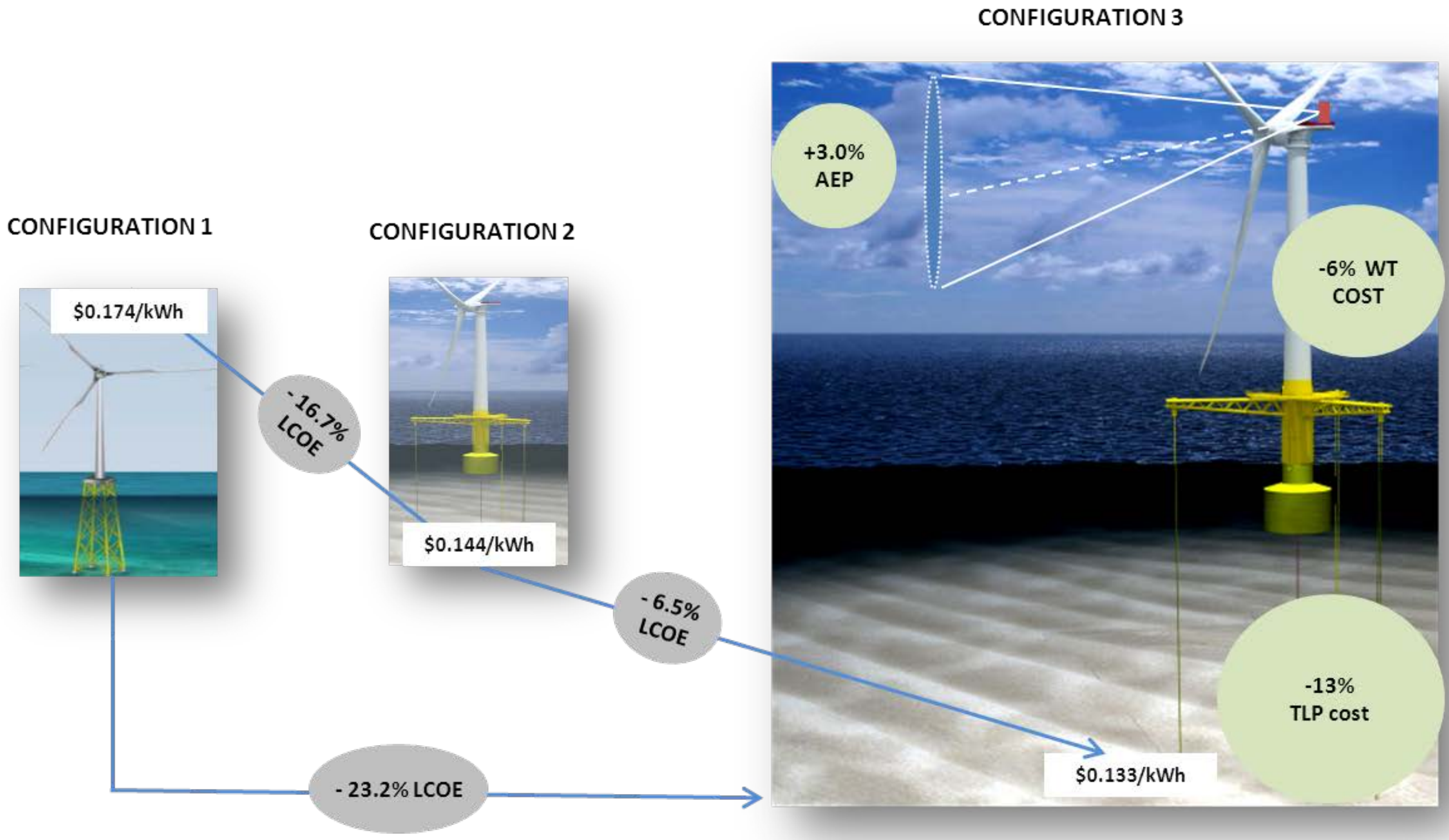
Task 10.0 – TLP Design and Analysis

- ✓ Design of TLP for Haliade for 100m water depth;
- ✓ Execution of full load simulations according to IEC-61400-3 in Bladed

Task 12.0 – LCOE modeling and evaluation

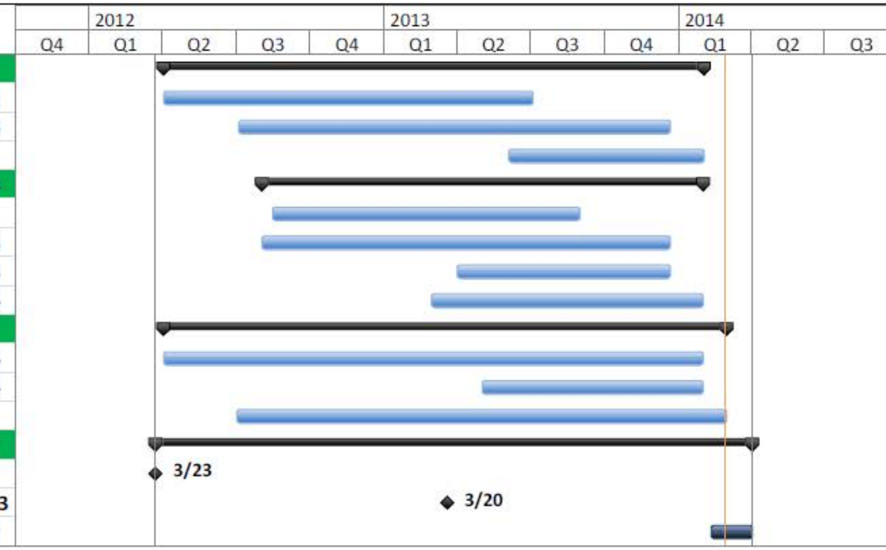
- ✓ LCOE reduction potential from Advanced Controls for Haliade on a TLP

- LCOE reduction actuals



Project Plan & Schedule

ID	Task Name	Start	Finish
1	Work Package A - Development of Innovative Control Systems	Mon 4/2/12	Fri 1/31/14
2	Task 1 - Control Strategies Design	Mon 4/2/12	Wed 7/3/13
5	Task 2 - Control Strategies Implementation	Wed 7/4/12	Fri 12/20/13
8	Task 3 - Improved Supervisory Control	Tue 6/4/13	Fri 1/31/14
10	Work Package B - Innovative Controls for TLP Offshore Wind Turbines	Thu 8/2/12	Thu 1/30/14
11	Task 5 - Baseline for Stabilization	Wed 8/15/12	Fri 8/30/13
15	Task 6 - Feed-forward Control for Energy Yield Increase	Thu 8/2/12	Fri 12/20/13
19	Task 7 - Feed-forward Control for Loads Reductions	Mon 4/1/13	Fri 12/20/13
22	Task 8 - Development of Advanced Active Damping Systems	Thu 2/28/13	Thu 1/30/14
25	Work Package C - Development of TLP Floating System for a 6MW WT	Mon 4/2/12	Fri 2/28/14
26	Task 10 - Detailed development of a TLP	Mon 4/2/12	Thu 1/30/14
29	Task 11 - TLP Upgrade and customization for Haliade 150	Thu 5/2/13	Thu 1/30/14
30	Task 12 - Cost-of-Energy Modeling	Mon 7/2/12	Fri 2/28/14
34	Work Package D - Project Management	Fri 3/23/12	Wed 4/2/14
35	Kickoff Meeting	Fri 3/23/12	Fri 3/23/12
36	Technical Specification Gate Review	Wed 3/20/13	Wed 3/20/13
37	Task 16 - Technical Concept Gate Review	Mon 2/10/14	Wed 4/2/14



Comments

- Originally scheduled start: 10/30/11
- Originally scheduled end date (BP1): 1/30/14
- Actual start date: 3/23/12 (staff availability issues)
- Final BP1 end date: 3/31/14 (no cost extension)
- Specification Gate Review originally schedule for roughly 9/30/13, conducted on 3/20/13 (6 month slip roughly corresponding to slip in start date)

Partners, Subcontractors, and Collaborators:

John Schroeder
Delong Zuo

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Alan Wright
Jason Jonkman
Paul Fleming
Kathryn Johnson (CSM)

Massachusetts Institute of Technology

Paul Sclavounos

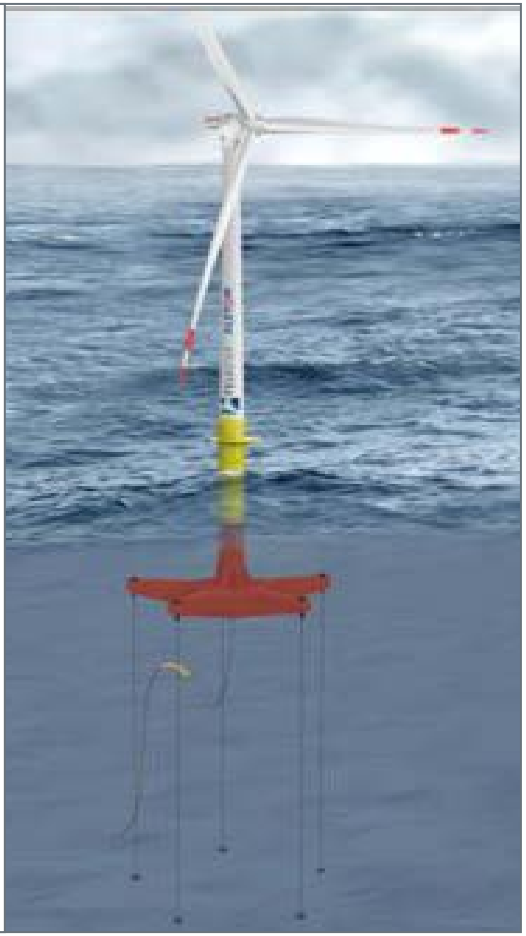
Communications and Technology Transfer

Title	Author	Conference	Status
Advanced Controls of Next Generation Floating Wind Turbines	Dhiraj Arora (Alstom)	AWEA 2013	Done
Floating Wind Turbines	Paul Sclavounos (MIT)	OMAE 2013	Done
Advanced Controls and Innovative Support Structure for FOWT	Dhiraj Arora (Alstom)	AWEA Offshore 2013	Done
LIDAR-assisted Preview Controllers Design for a MW-scale Commercial Wind Turbine Model	Na Wang (CSM) Kathryn Johnson (CSM)	Conference on Decision and Controls 2013	Done
Controller stability of floating wind turbines	Paul Fleming (NREL) Alan Wright (NREL)	OMAE 2014	Accepted
Preview-based Multi-region Control for the Alstom ECO-100	Na Wang (CSM) Kathryn Johnson (CSM)	IEEE Transactions on Control Systems Design	Submitted

Proposed future research : Budget Period 2 continuation proposal

Advanced Controls for TLP Wind Turbines

- Project Management Activities
  - Task 27 - Project Management
- **WP D – ADVANCED CONTROLS TESTING (ONSHORE)**
  - **TASK 17** – CART3 LIDAR Testing – *Validation: CART3 Testing*
  - **TASK 18** – Preview Controller Testing – *Validation: NWTC ECO 110*
  - **TASK 19** – Yaw Controller Testing – *Validation: Resse Tech Ctr. ECO 86*
- **WP E – ADVANCED CONTROLS TESTING (OFFSHORE)**
  - **TASK 20A** – Adv. Controls Testing (TLP Foundation) – *Validation: ETI*
  - **TASK 20B** – Adv. Controls Testing (Fixed Bottom Fdn) – *Validation: TBD Haliade*
  - **TASK 21** – Tank Testing of Wave Forecast Algorithms – *Validation: Tank testing*
- **WP F – TRL ADVANCEMENT**
  - **TASK 22** – Integrated TLP Design & Controls – *Validation: Simulation*
  - **TASK 23** – Wave Forecasting Techniques Dev. – *Validation: Tank tests*
  - **TASK 24** – Offshore Atmospheric Char. & Controls – *Validation: Simulation*
- **WP G – LCOE & COMMERCIAL VIABILITY**
  - **TASK 25** – Baseline COE evaluation of Haliade + PelaStar
  - **TASK 26** – LCOE reductions with innovations



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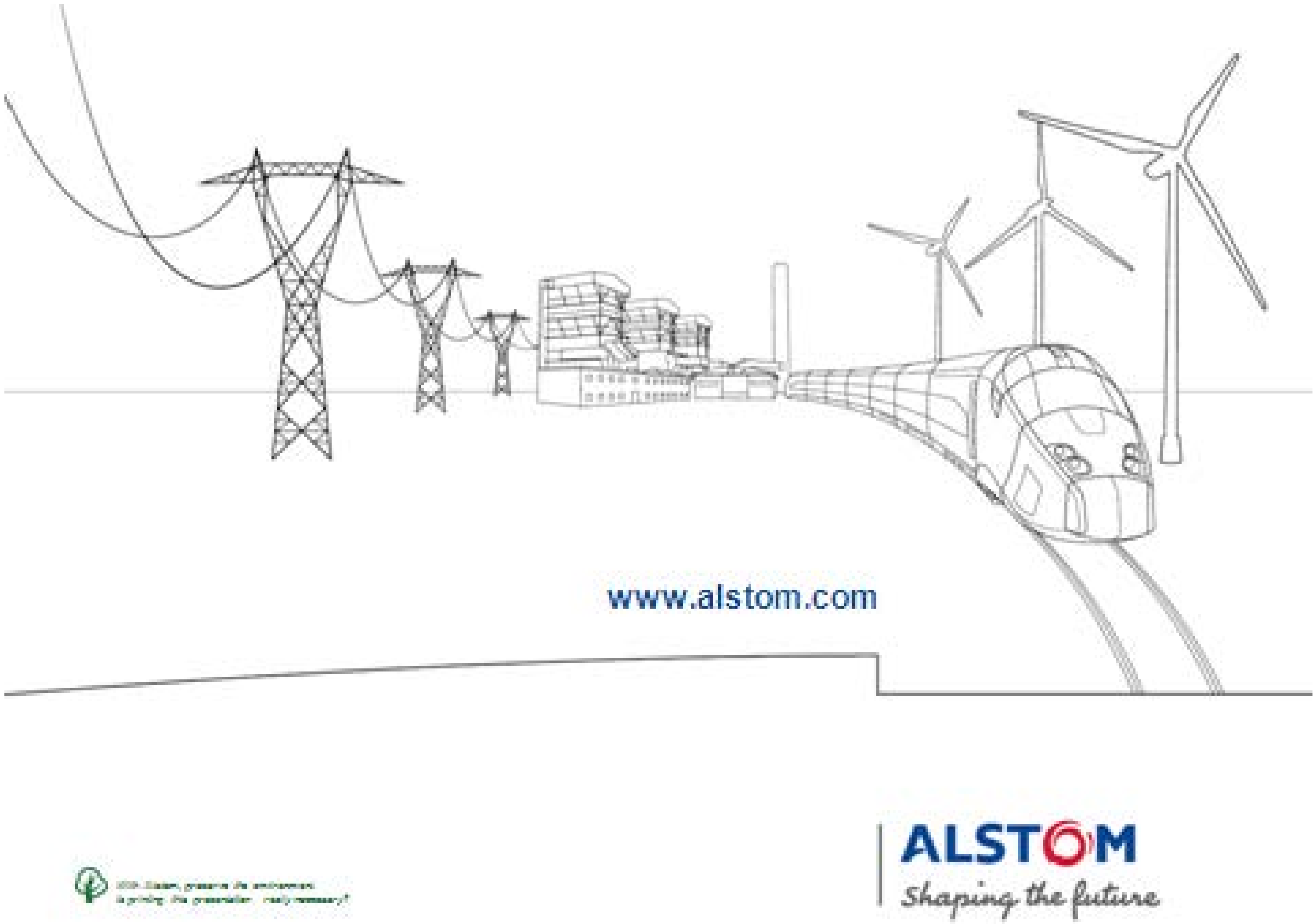
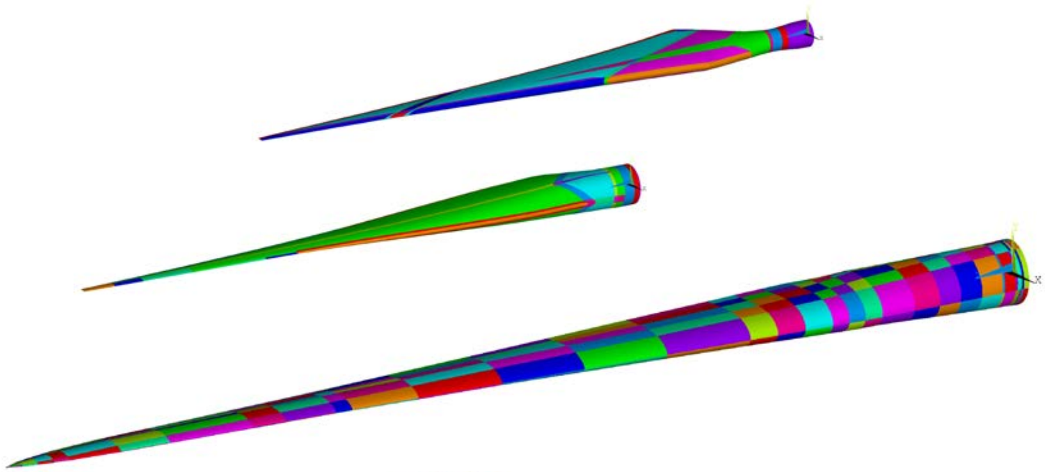
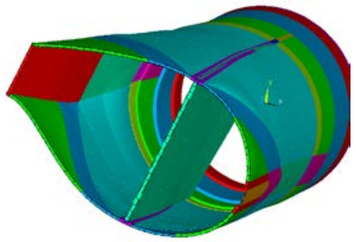
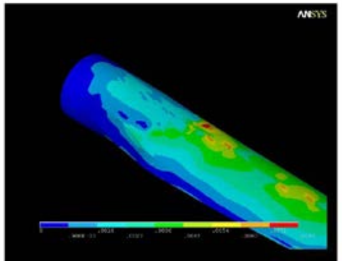
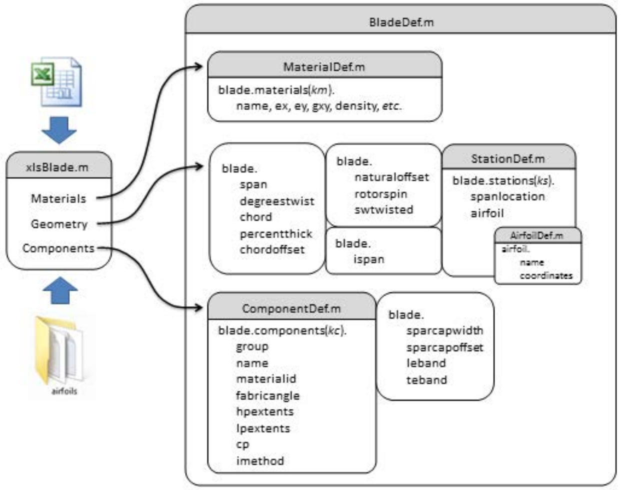










Blade Design Tools and System Analysis

Jonathan Berg

Sandia National Laboratories

jcberg@sandia.gov / 505-284-0905

25 March 2014

Budget, Purpose, & Objectives

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

Total DOE Budget[1]: $.400M

Total Cost-Share[1]:$0.000M

Problem Statement:

Provide open-source state-of-the-art simulation and analysis tools that researchers need to meet the technical challenges of multi-disciplinary rotor projects.

Impact of Project:

- Enable Sandia projects to have access to cutting edge simulation capabilities
- Inform and enable the entire research community in cutting edge methodologies and algorithms for effective simulation and analysis

This project aligns with the following DOE Program objectives and priorities

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach

- Complementary and Efficient
  - Utilize a hybrid of existing external design codes and in-house developments
  - Complement the NREL NWTC Design Codes and commercially available codes with software toolboxes to increase our efficiency
  - Create new capabilities only when needed capabilities do not exist
- Modular and Object-Oriented
  - Enable highly effective and flexible **parametric systems analyses** by creating capabilities that can be connected and utilized as needed to fit the problem
  - "Object-oriented" is more than a buzzword; this programming convention **logically breaks down problems** and **manages how data and methods interact**

NuMAD Blade Design Tool

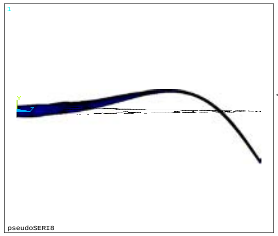
- Information manager for blade geometry, materials, and layup.
- Enables many types of analysis, including Finite Element Analysis in ANSYS

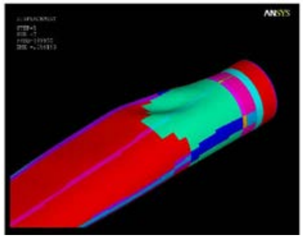
NuMAD is an example of complementing existing codes with needed capabilities.

ANSYS

ANSYS Analysis

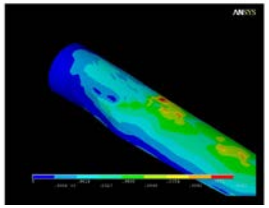
Modal





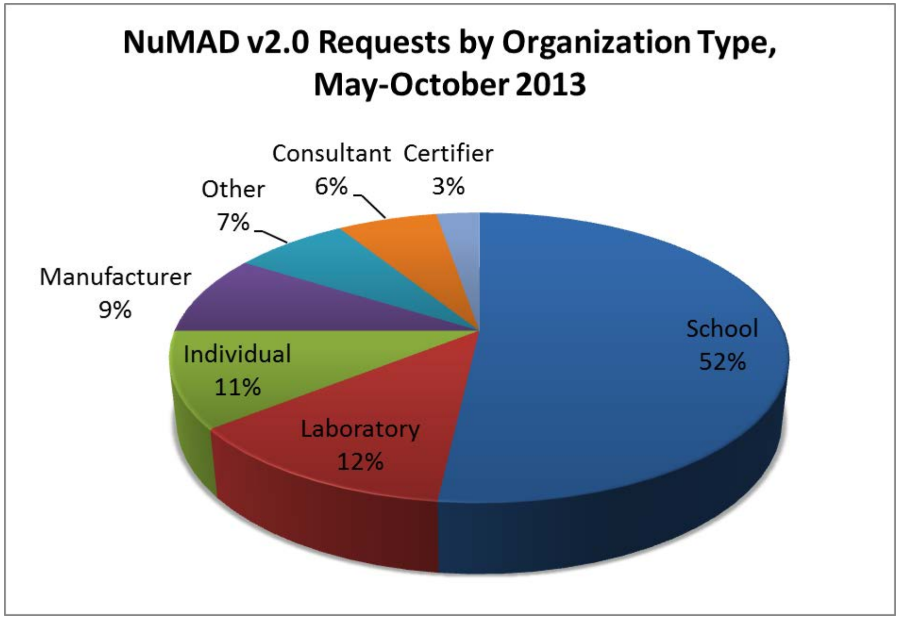
Buckling

Stress & Strain



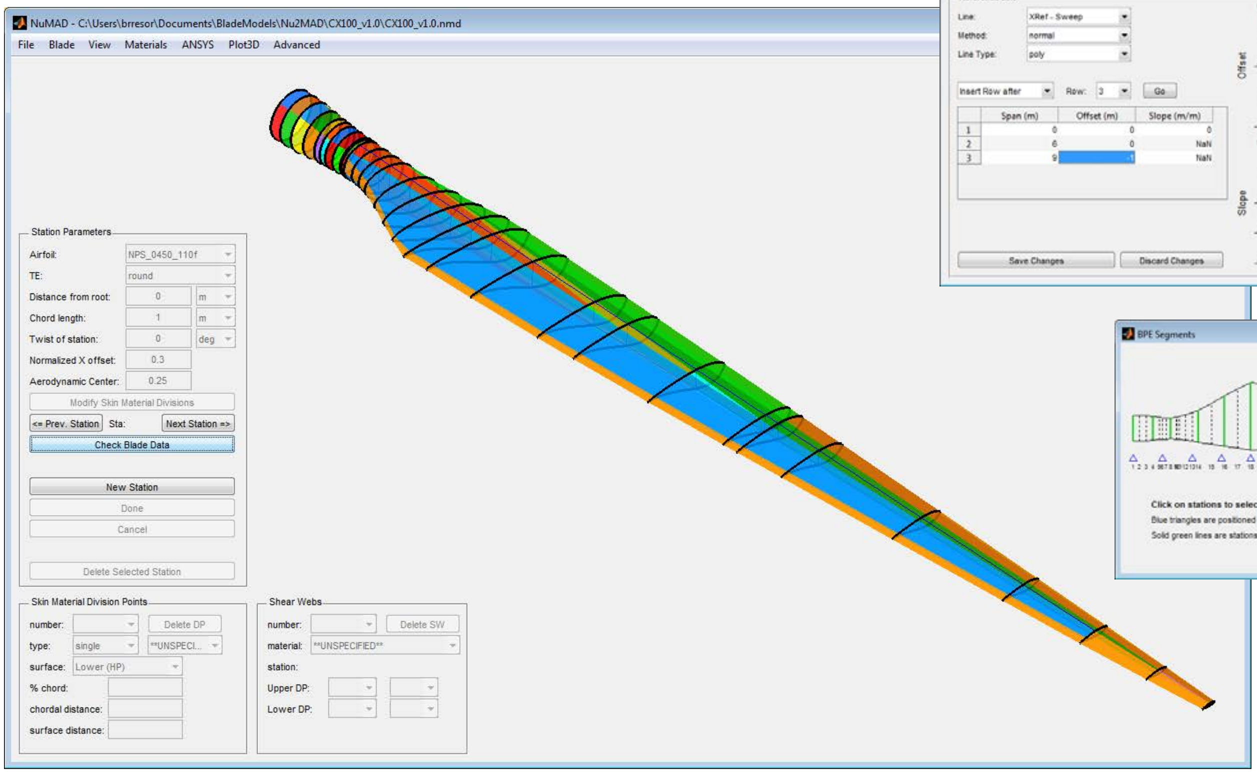
Accomplishments and Progress

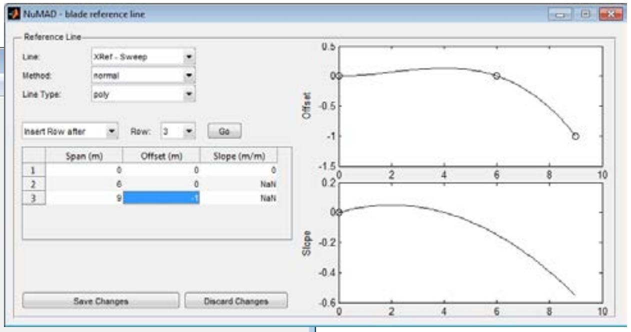
- Publicly Released NuMAD v2.0
  - Sandia's NuMAD tool began a complete overhaul in 2010.
  - It has been used internally since then with huge success.
  - It was released publicly in April 2013.
- Download Statistics
  - Requested by 112 users during 6 month timeframe (May-October)
  - 52% of requests from Academia
  - 12% of requests from Laboratories
  - Remaining 36% split between Individuals, Manufacturers, Consultants, Certifiers, and Other

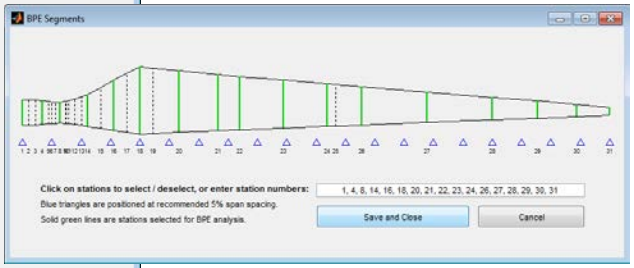


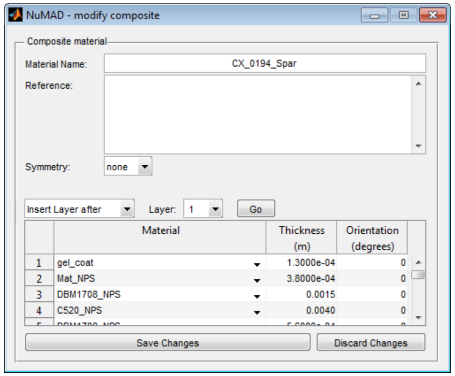
NuMAD was developed to meet the need for an **open-source** and **efficient tool** to create **high fidelity blade models**

NuMAD v2.0 Interface





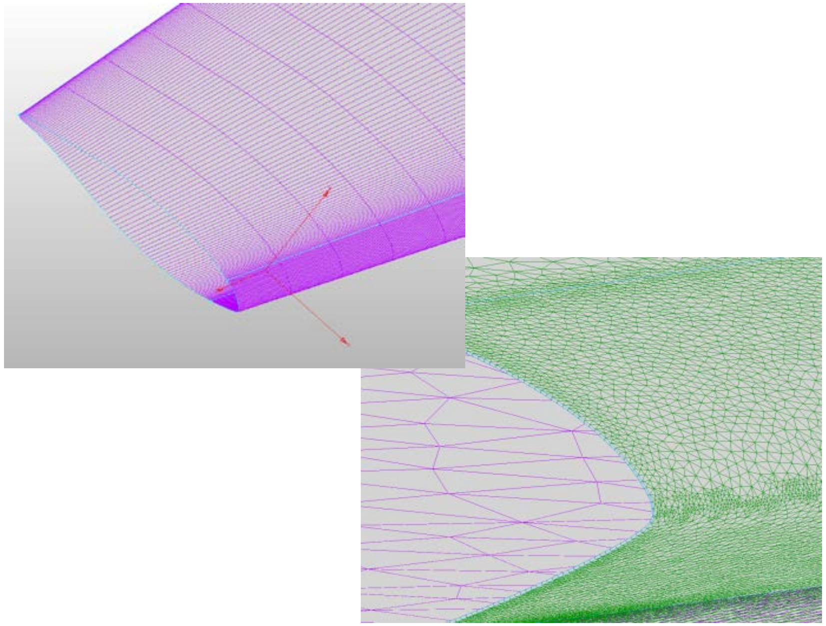


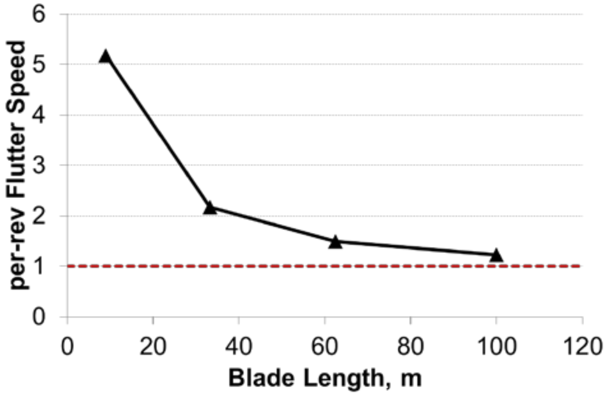


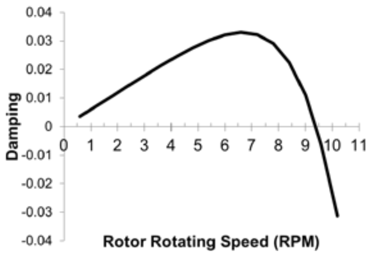
NuMAD interface is clean, modern, and user-friendly. The ability to examine the blade from different angles **saves time** and **reduces errors**.

Accomplishments (FY12)

- Output from NuMAD for CFD mesh generation
  - Suggested by user feedback
  - Enables CFD and structural analyses to originate from the same blade definition
- Implement an improved classical flutter analysis tool
  - Capability is directly integrated within NuMAD
  - Enables “quick check” of wind blade flutter margins
  - Applicable to very large blades

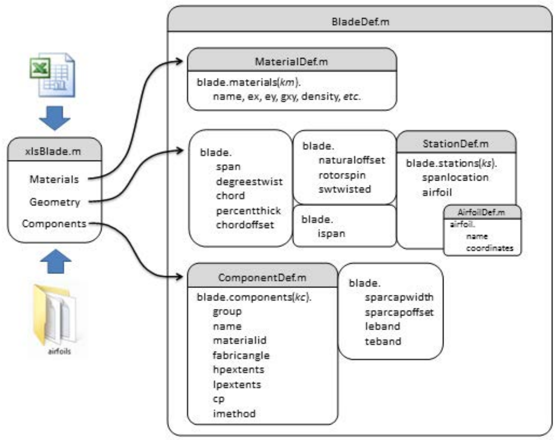


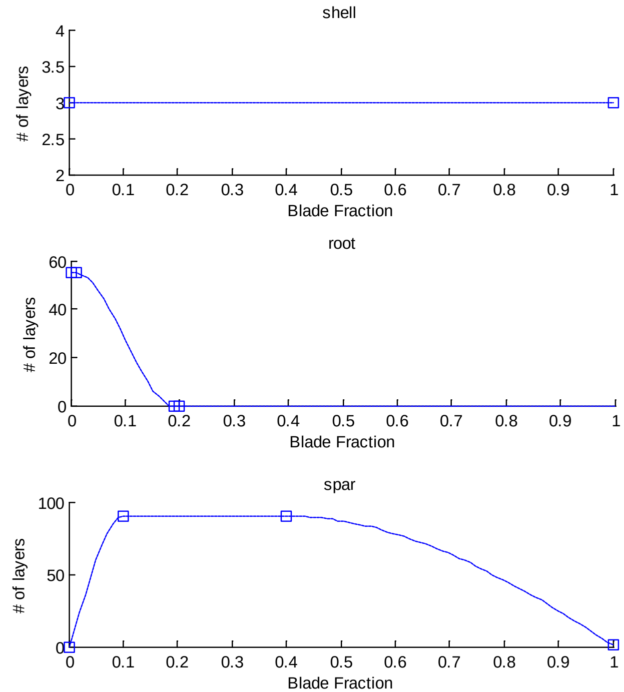


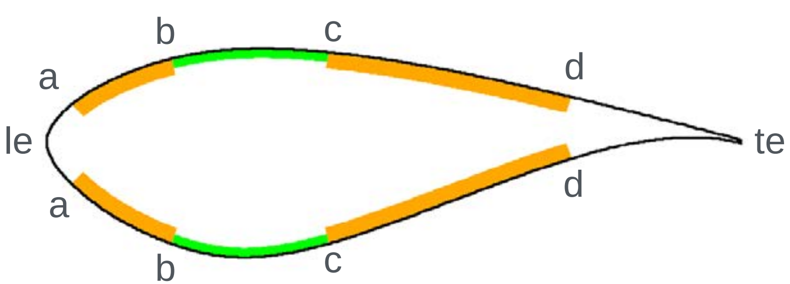


Accomplishments (FY13)

- FY13 activities funded by individual projects (rather than making Design Tools development a separate project)
- Needs of the National Rotor Testbed drove the following accomplishments
  - Developed new object-oriented approach to represent blade information
  - Developed a combined aero-structural optimization framework

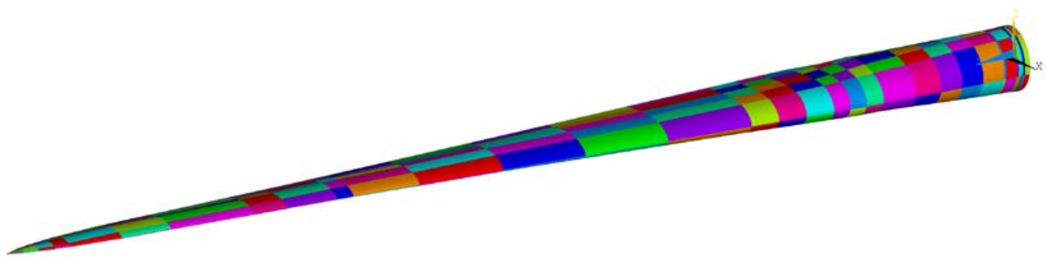






Summary of Accomplishments/Results

- Significant NuMAD development
- Enabled internal projects
  - Large Offshore Rotor (100m blade)
  - Offshore Structural Health studies
  - Blade Reliability Collaborative
  - National Rotor Testbed
  - System Benefits of Increasing Tip Speed
- Released reference model for 5MW / 61.5m wind turbine blade
  - Calculated detailed layup properties for “NREL offshore 5-MW baseline wind turbine”
  - Provides a common reference for blade design studies and tool development



Project Plan & Schedule

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

Summary	
WBS Number or Agreement Number	WE 3.4.1
Project Number	21112
Agreement Number	22527

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Blade Design Tools & System Analysis												
Q1 Milestone: Evaluate 9m blade model (BPE module) against static load test.												
Q2 Milestone: Create NuMAD output that facilitates CFD mesh generation.												
Q3 Milestone: Integrate material failure model capabilities in NuMAD.												
Q4 Milestone: Release NuMAD v2.0												
Current work and future research												

Comments

- NuMAD v2.0 files were packaged and ready for release by Q4 milestone date, but copyright assertion process was delayed by circumstances outside our control.

Communications and Technology Transfer:

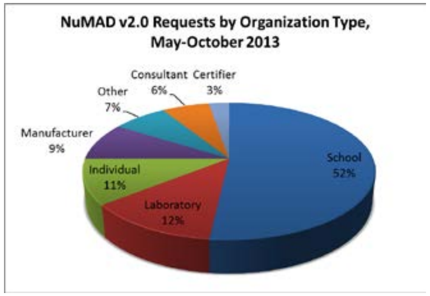
NuMAD v2.0 freely available under open-source license at wind.sandia.gov

Publication, presentation, tutorial/workshop

- Conducted a NuMAD workshop to get user feedback on beta version prior to the SNL Wind Blade Workshop on May 29, 2012
- Resor, B. R. “Definition of a 5MW/61.5m Wind Turbine Blade Reference Model," Sandia National Laboratories: SAND2013-2569, 2013.
- Resor, B. R. Owens, B. C. & Griffith, D. T. “Aeroelastic Instability of Very Large Wind Turbine Blades.” (Scientific Poster) Proceedings of the European Wind Energy Association Annual Conference, 2012.

Partners, Subcontractors, and Collaborators:

- Supports multiple Sandia projects
- Growing external user community



Next Steps and Future Research

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

FY14/Current research:

Continued development of multi-objective optimization framework for innovative blade design, with emphasis on verified algorithms and using High Performance Computing resources.

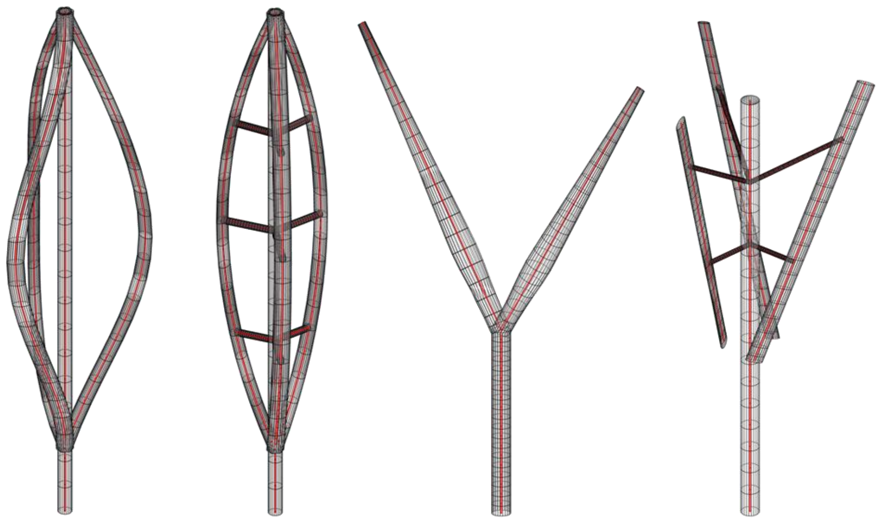
Collaboration with NREL on current work related to Systems Engineering framework, blade cost models, and blade design optimization.

NRT, Large Offshore Rotor, Tip Speed Study, Low-cost Carbon Fiber

Proposed future research:

Future developments will be driven by individual projects with common themes:

- Higher fidelity
- Multi-disciplinary (including cost modeling)
- More confidence to guide decisions for lowering COE



WE 5.1.2 Offshore Wind RD&T: Innovative Concepts

D. Todd Griffith, PhD
Sandia National Laboratories
dgriffi@sandiia.gov (505) 845-2056
March 25, 2014

Purpose & Objectives

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

Problem Statement: The objective of this project was to develop design tools for investigation of deep-water offshore VAWTs.

Impact of Project: These tools enable and augment existing research efforts -- at Sandia and in the broader research community -- that are investigating the feasibility of offshore VAWTs.

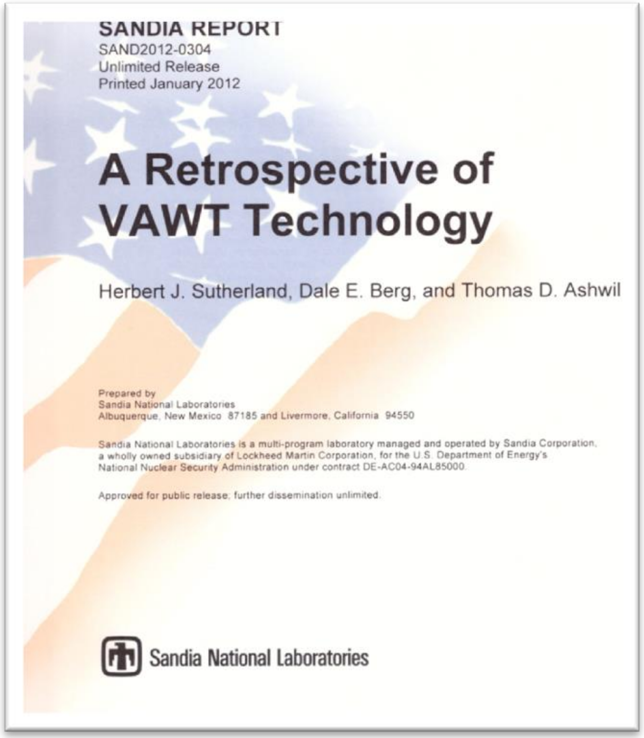
This project aligns with the following DOE Program objectives and priorities:

- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

This work addresses high-risk innovation for deep-water turbine technology. It is well-aligned with the program's strategies to dramatically reduce cost-of-energy of offshore wind in the U.S. and assume a leadership role in development of deep-water offshore wind technologies.

Technical Approach (1/2)

- In early FY12, a report documenting a Sandia retrospective of VAWT technology was published, capturing important lessons learned from earlier VAWT research.
- Legacy and existing VAWT design tools were surveyed and documented, and a plan for future VAWT design tool development was created.



SANDIA REPORT
SAND2012-0304
Unlimited Release
Printed January 2012

A Retrospective of VAWT Technology

Herbert J. Sutherland, Dale E. Berg, and Thomas D. Ashwill

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Approved for public release; further dissemination unlimited.

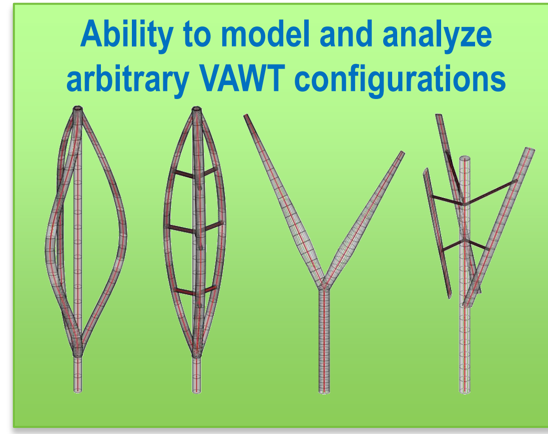
Sandia National Laboratories

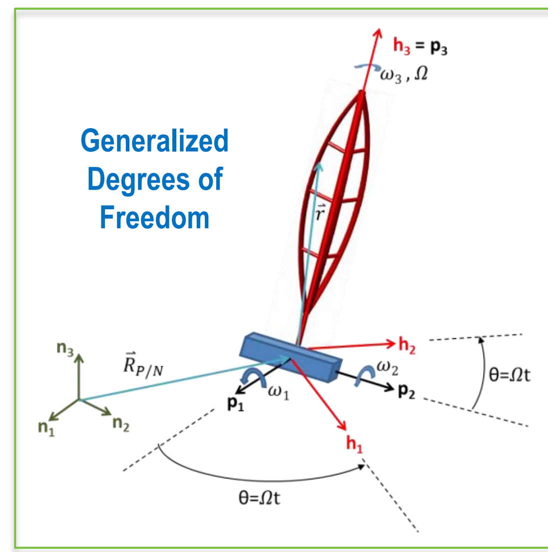
Technical Approach (2/2)

- Approach taken:
  - Identify the most pressing needs for design and analysis tools for offshore VAWTs that are not currently available
  - Then, address those needs through a targeted code development effort
  - During FY12, we identified the need for
    1) A VAWT structural dynamics model, and
    2) The ability to couple this model with a model for a floating platform leveraging existing floating platform and wave kinematics models to develop a coupled hydro-aero-elastic model for a floating VAWT.
  - Completion of these two code activities in FY13

Accomplishments and Progress (1/4)

1) Sandia VAWT Retrospective Report
   - Sandia VAWT testbeds (e.g. 34-meter) and commercialization
   - VAWT design and analysis codes
2) VAWT Design Codes
   - OWENS: Structural Dynamics Code
   - VAWTGen: Pre-processor; Model Geometry
   - Structural Dynamics + Platform Code Coupling
3) Code Verification and Validation Completed
4) Structural Dynamics Design Impact Studies
   - Support Structure Type
     - land-based, monopile, floating (semi-sub, spar)
   - Number of Blades

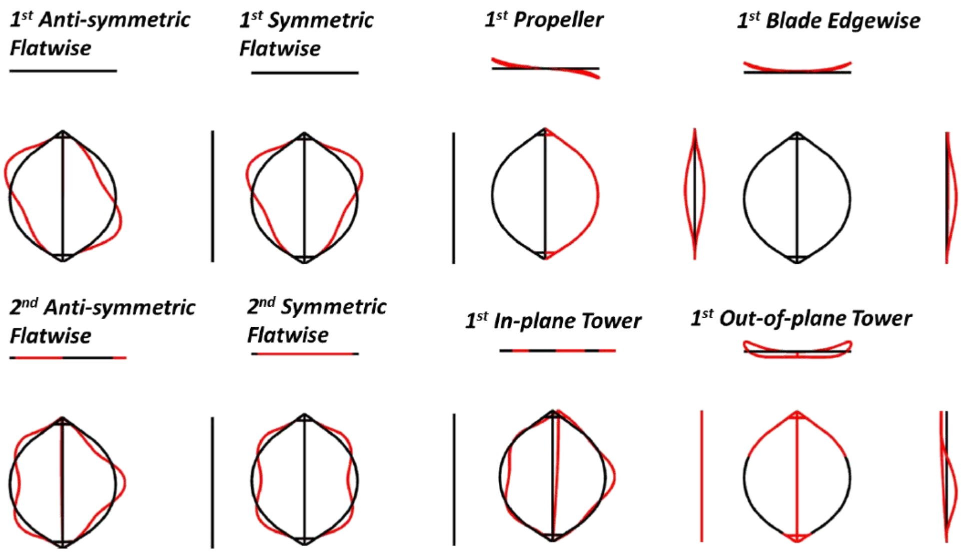


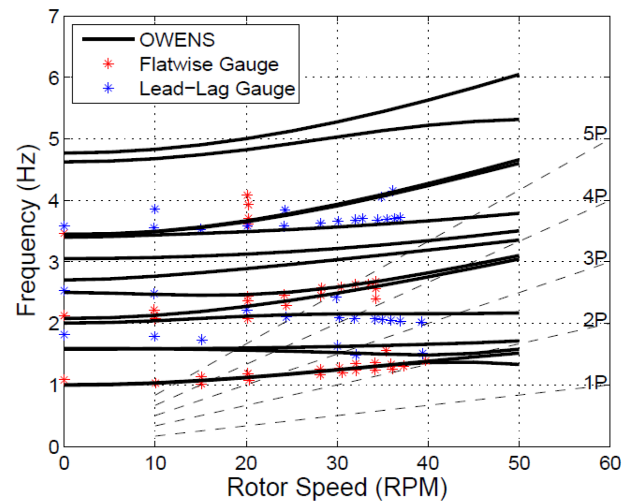


OWENS Verification and Validation

1. Whirling Shaft
2. OWENS-ANSYS (Code to Code)
3. Validation with Sandia 34-meter

Sandia 34-meter VAWT Testbed

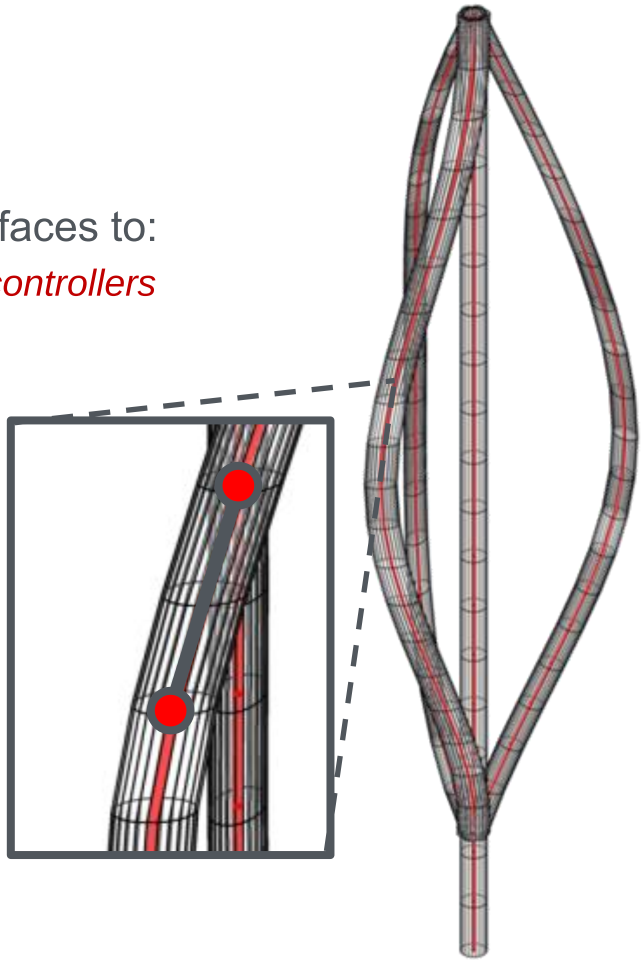




OWENS structural dynamics code successfully verified and validated

OWENS Features

- Enables modal and transient analysis capabilities.
- Modular analysis framework enables couplings/interfaces to:
  - *Aerodynamics, Hydrodynamics, Drivetrain/generator, controllers*
- Finite element method
  - *Flexibility and robustness in implementation*
  - *3D Timoshenko beam*
  - *Rotational effects and geometric nonlinearities*
  - *Structural couplings (bend-twist, sweep-twist, etc.)*
  - *Offset mass axes, concentrated mass, etc.*
- Mesh generator
  - Considers VAWTs of arbitrary geometry
  - Interfaces with existing design tools
  - Visualization
- Open-source, batch capability

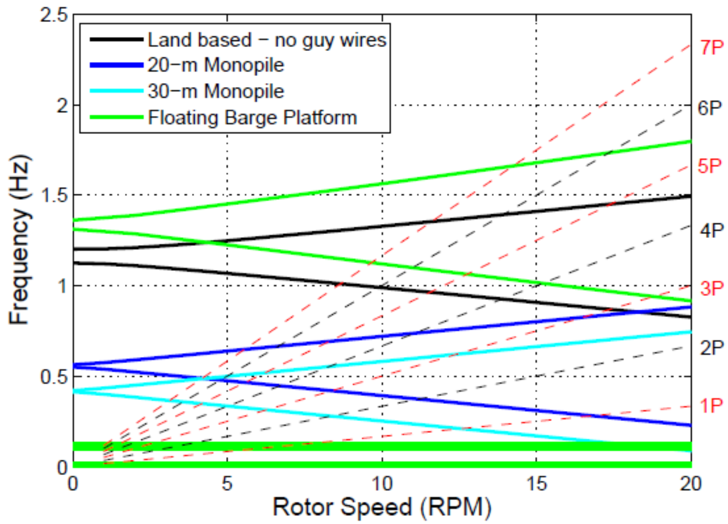


OWENS filled a key need for modal and transient analysis of VAWTs.

Structural Dynamics Design Impact Studies

(1) Support Structure Type

- Land-based
- Monopile
- Floating (semi-sub, spar)



Campbell diagram of SNL 34-meter VAWT tower modes for various support conditions

Table 2. Critical per-rev tower resonance design sensitivities (hub-frame)

# of Blades	Per-Rev Sensitivity	Example Configuration
1	1,2,3,4	
2	1,3,5,7	SNL 17-m,[1] SNL 34-m,[1] DeepWind[2,3]
3	2,4,5,7	VAWTPower VP60[4]
4	3,5,7,9	
5	4,6,9,11	
6	5,7,11,13	Lux[12]
7	6,8,13,15	
8	7,9,15,17	
9	8,10,17,19	
10	9,11,19,21	

(2) Number of Blades

Definitive Guidelines for VAWT Designers

Opportunities for Design to Avoid Resonance Identified

Reference: Owens, B.C., Griffith, D.T., and Hurtado, J.E., "Modal Dynamics and Stability of Large Multi-megawatt Deepwater Offshore Vertical-axis Wind Turbines: Initial Support Structure and Rotor Design Impact Studies," Proceedings of 32nd ASME Wind Energy Symposium, National Harbor, MD, USA, January 2014.

Project Plan & Schedule

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

Summary	
WBS Number or Agreement Number	WE 2.5.1.2
Project Number	
Agreement Number	22622

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
◆	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: WE 5.1.2 Innovative Concepts												
Q1 Milestone: Publish VAWT 'practical lessons learned' report	◆											
Q2 Milestone: Publish memo evaluating legacy VAWT design codes and methods.		◆										
Q3 Milestone: Develop a plan for creation of a VAWT design code base			◆									
Q4 Milestone: Document initial updates and improvements to the most critical design codes				◆								
Q1 Milestone: (1) Identify floating turbine platform hydrodynamics model					◆							
Q2 Milestone: Complete initial implementation of coupled VAWT rotor/platform model						◆						
Q3 Milestone: Complete verification study of coupled VAWT rotor/platform dynamicsmodel							◆					
Q4 Milestone: Demonstrate coupled dynamics model by calculating mode shapes with and without floating base								◆				

Comments

- Project start in FY11, completed in FY13
- All milestones met on schedule

Project Budget

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

Budget History					
FY2012		FY2013		FY2014	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$75K	--	$75K	--	$0K	--

- ~$20K carryover into FY14/Q1 to cover university contract through December 2013.

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

Subcontract: Texas A&M University (PI: Prof. John E. Hurtado; PhD Student: Brian Owens)

Communications and Technology Transfer:

This project is providing design codes for a DOE FOA project led by Sandia on the topic of deep-water Offshore VAWT rotors.

Tech Transfer: Sandia Copyright Assertion for OWENS and VAWTGEN has been requested to permit dissemination.

Publications: See Next Slide

Communications and Technology Transfer (cont'd):

Publications:

1. Sutherland, H.J., Berg, D.E., and Ashwill, T.D., "A Retrospective of VAWT Technology," Sandia National Laboratories Technical Report, SAND2012-0304, January 2012.
2. Owens, B., Hurtado, J., Barone, M., and Paquette, J. "An Energy Preserving Time Integration Method for Gyric Systems: Development of the Offshore Wind Energy Simulation Toolkit," Proceedings of the European Wind Energy Association Conference & Exhibition, Vienna, Austria, 2013.
3. Owens, B.C., Hurtado, J.E., Paquette, J., Griffith, D.T. and Barone, M., "Aeroelastic Modeling of Large Offshore Vertical-axis Wind Turbines: Development of the Offshore Wind Energy Simulation Toolkit," 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April 8-11, 2013, Boston, MA, USA, AIAA-2013-1552.
4. Owens, B.C., "Theoretical Developments and Practical Aspects of Dynamic Systems in Wind Energy Applications". Ph.D. Dissertation (Texas A&M University), 2013.
5. Owens, B.C., Griffith, D.T., and Hurtado, J.E., "Modal Dynamics and Stability of Large Multi-megawatt Deepwater Offshore Vertical-axis Wind Turbines: Initial Support Structure and Rotor Design Impact Studies," Proceedings of 32nd ASME Wind Energy Symposium, National Harbor, MD, USA, January 2014.

Next Steps and Future Research

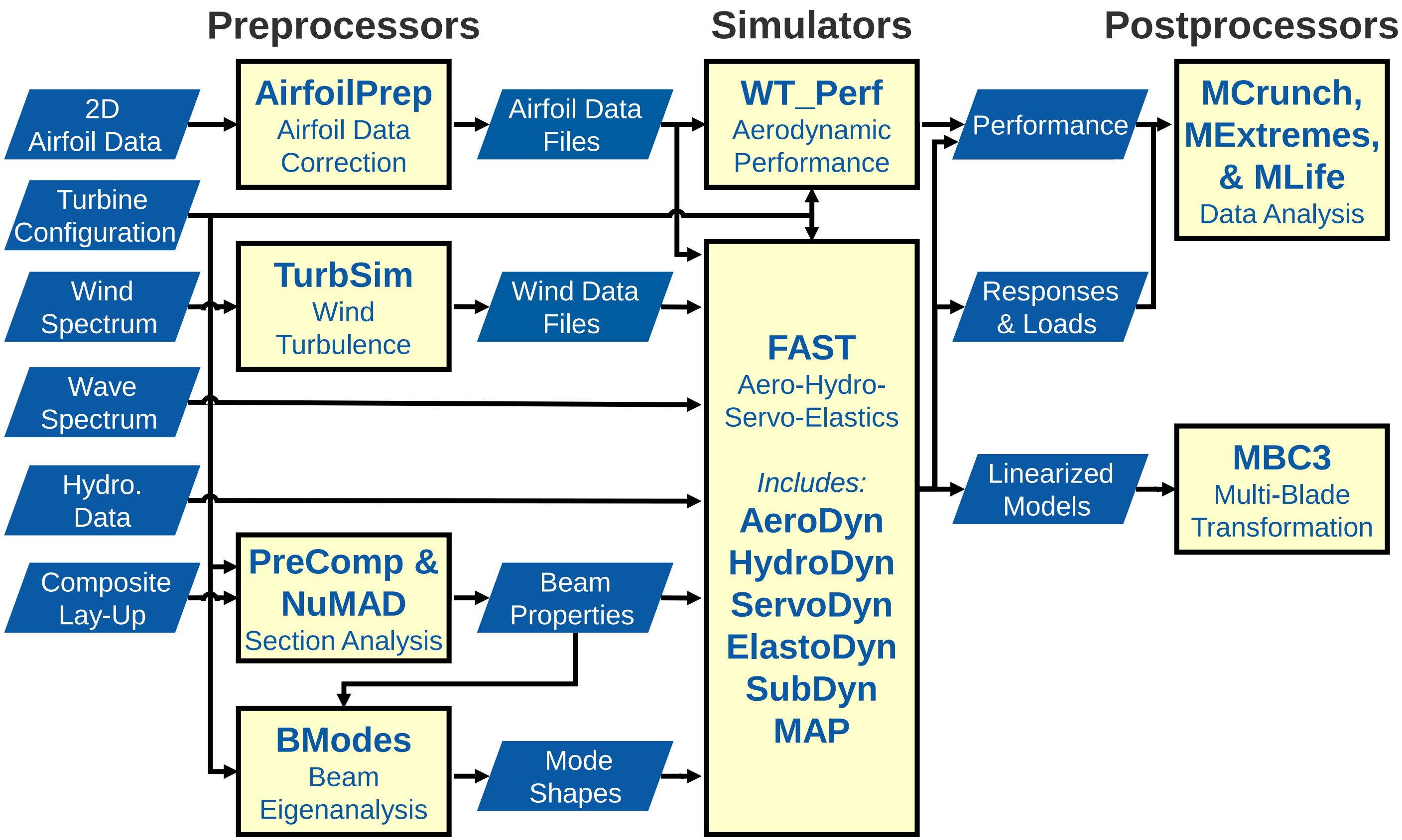
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY14/Current research:

This project was closed out in FY14/Q1. In the years to come, these codes will continue to be used for VAWT design studies by Sandia and the broader research community.

Proposed future research:

1. Code comparison effort requested by several European groups (DTU Wind, Cranfield, NTNU)
2. Public release of OWENS and VAWTGen codes
3. IEA based working group on VAWT Codes



Principle Investigator:

Jason Jonkman

Key Staff:

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Rick Damiani
Greg Hayman (Contractor)
Bonnie Jonkman
John Michalakes
Ed Muljadi
Khanh Nguyen
Andy Platt
Mohit Singh (Post Doc)
Mike Sprague
Qi Wang

Computer-Aided Engineering (CAE) Tools

Jason Jonkman

National Renewable Energy Laboratory
jason.jonkman@nrel.gov, (303) 384–7026

March 25, 2014

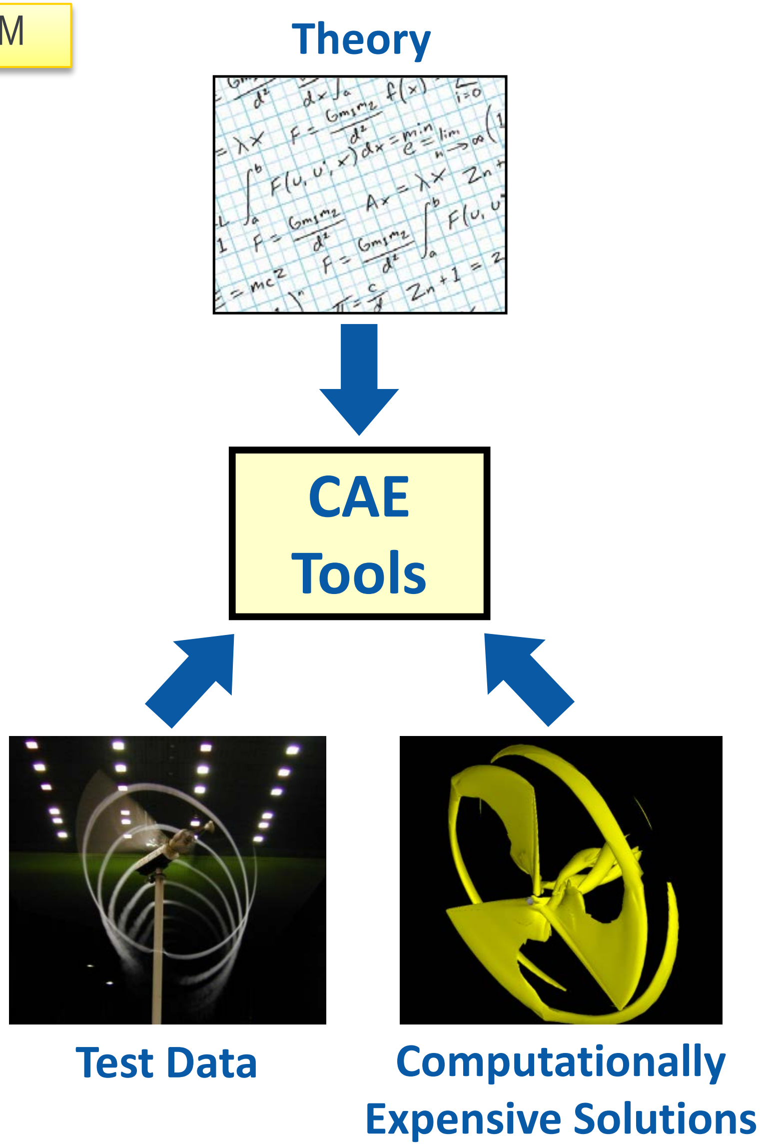
Budget, Purpose & Objectives

Total DOE Budget[1]: $2.290M

Total Cost-Share[1]:$0.000M

Problem Statement

- The wind community relies extensively on CAE tools for performance, loads, and stability analyses
- Limitations—and consequent inaccuracies—in the CAE tools slow the advancement of wind power
- Accurate tools are required for the wind community to develop more innovative, optimized, reliable, and cost-effective wind technology
- Overcoming current modeling limitations increases in importance as wind turbines upscale to larger sizes, incorporate novel designs, include load-control technologies, are installed on offshore support platforms, and are designed for the wind plant level



[1]*Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Budget, Purpose & Objectives

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

Impact of Project

- This project implements improvements to advanced CAE tools, based on the latest research in support of the wind community, that are required for developing innovative, lower-risk, and higher-performing turbine technology needed to achieve the COE, reliability, and deployment objectives of the WWPTO.

This project aligns with the following DOE Program objectives and priorities

- **Optimize Wind Plant Performance:** Reduce wind plant levelized cost of energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new, high-tech U.S. industries
- **Advanced Grid Integration:** Provide access to high-wind resource areas and provide cost-effective dispatch of wind energy onto the grid
- **Testing Infrastructure:** Enhance and sustain the world-class wind-testing facilities at universities and national laboratories to support mission-critical activities
- **Modeling and Analysis:** Conduct wind techno-economic and lifecycle assessments to help the Program focus its technology-development priorities and identify key drivers and hurdles for wind-energy technology commercialization

Technical Approach

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

Driven by the WWPTO strategic initiatives and industry needs, the CAE tools project:

- Improves the CAE tool predictions of aero, electrical, and structural dynamics
- Modularizes the tools to support enhanced functionality, improved numerical performance and robustness, and shared code development
- Enables the efficient design and analysis of innovative, lower-risk, and higher-performing land- and offshore-based wind turbines and wind plant systems
- Provides technical support to the many organizations in the wind industry that rely on the CAE tools in their design-and-analysis activities

Knowledge Areas

Winds & Waves
Aerodynamics
Aeroacoustics
Hydrodynamics
Structural Dynamics
Control Systems
Electrical Drives
Design Standards
Experimentation & HPC

Wind energy knowledge is transferred to the wind industry through CAE tools

CAE Tools

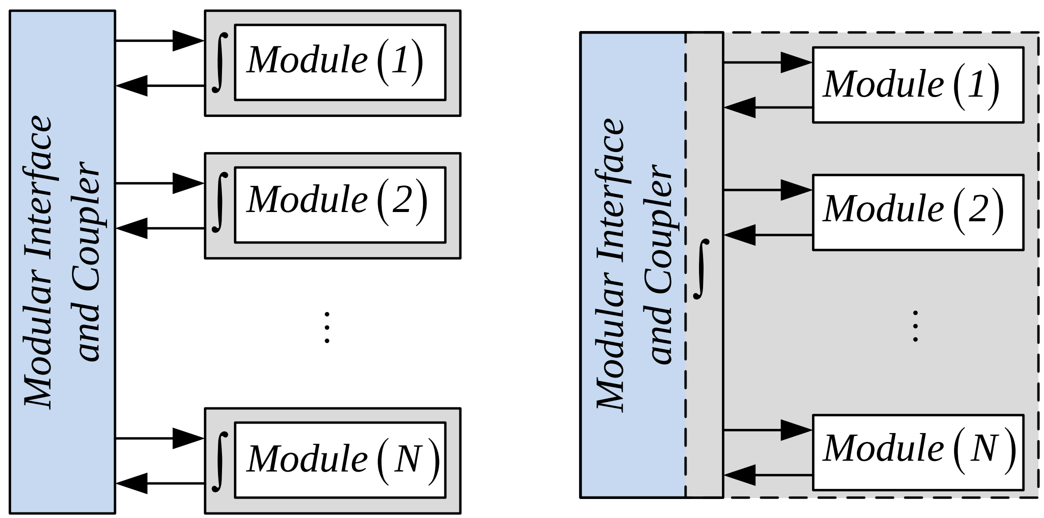
Application Areas

Conceptual Design
Rotor Performance
Control System Design
Loads Analysis
Stability Analysis
Design for Certification
Design for Reliability
Analyst Training
Testing Support

The advancement of wind technology is limited by CAE tool capability

Modularization Framework

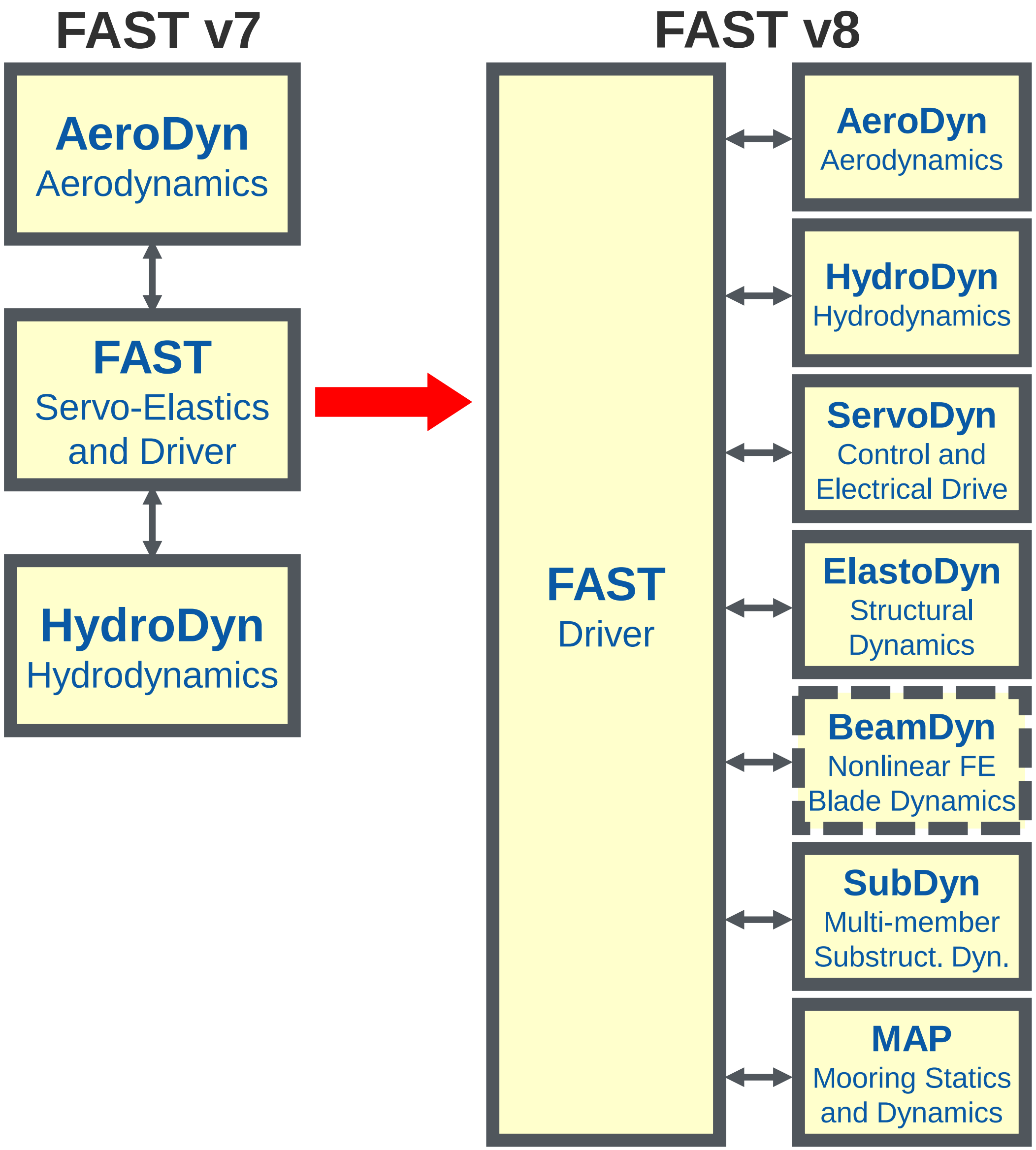
- A new modularization framework for the **FAST** wind turbine CAE tool was developed that is envisioned to transform **FAST** into a powerful, robust, and flexible tool with a large number of developers across the wind community and a range of modeling fidelities across the aero, hydro, servo, and structural-dynamic components
- A programmer's handbook was published explaining the **FAST** modularization framework, code-development requirements, and best practices
- A paper explaining the features of the **FAST** modularization framework was published and presented at AIAA ASM 2013
- A workshop on the topic was hosted at AWEA OFFSHORE WINDPOWER 2012



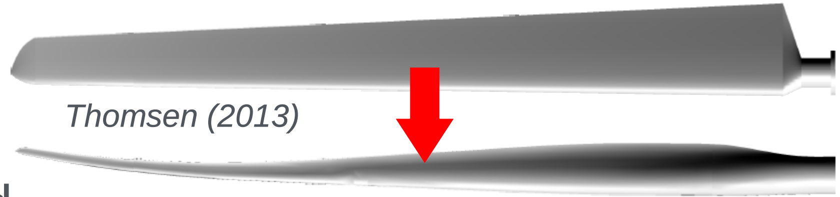
Loose- (left) and Tight- (right) Coupling Schemes

Modularization Framework

- The first version of **FAST** under the new framework (**v8**) was released, including:
  - Conversion of **FAST** and its various modules into the framework (including **AeroDyn** and **HydroDyn**)
  - Splitting out **ServoDyn** and **ElastoDyn** into new modules
  - Implementation of a new driver program supporting loose coupling of modules with independent time and spatial discretizations
  - Interfacing of the recently developed **SubDyn** and **MAP** modules



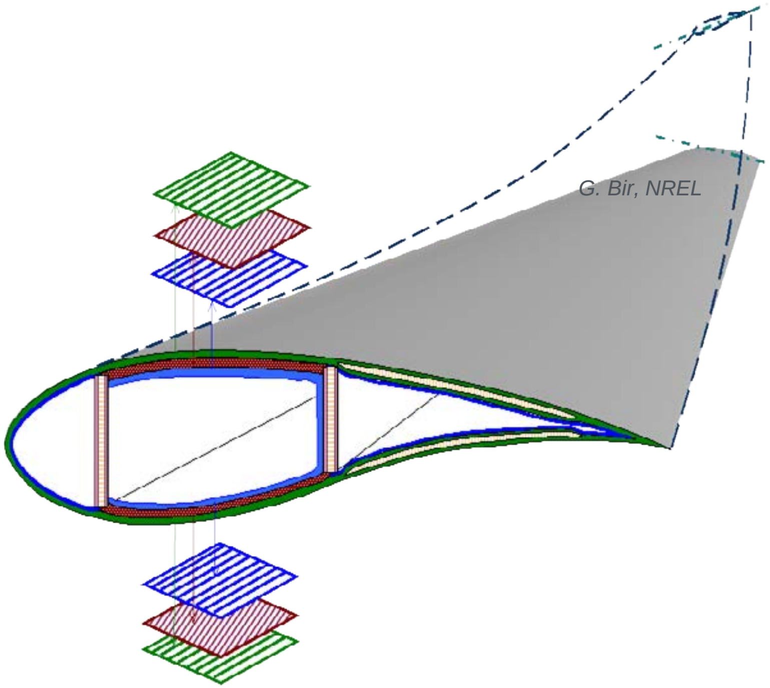
Structural Dynamics



Advancement in Blade Design

For modeling of highly flexible composite blades, the theoretical basis was developed and implementation was initiated for a new **BeamDyn** nonlinear beam finite-element (FE) module

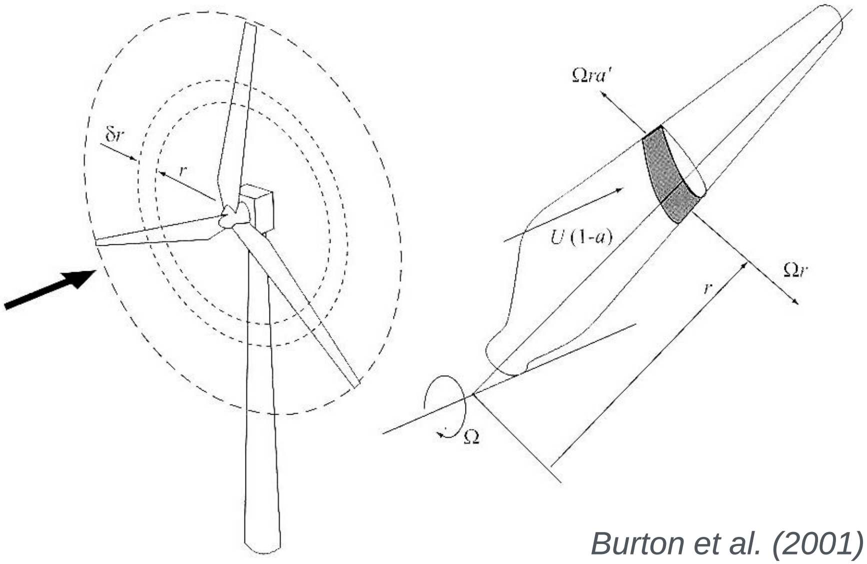
- Derived from a displacement-based implementation of geometrically exact beam theory (GEBT) using spectral FEs, including:
  - Full geometric nonlinearity
  - Bending, torsion, shear, and extensional DOFs
  - Anisotropic material couplings
  - Sectional offsets
  - Initially curved/swept blades



Blade Twist-Induced By Anisotropic Layup

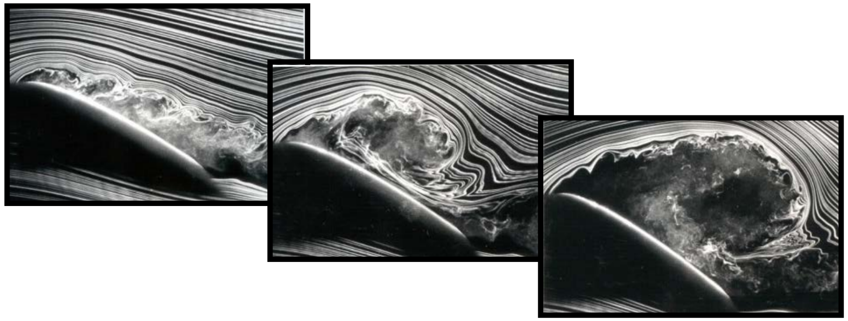
Aerodynamics

- For more accurate aero predictions and improved modularization, the **AeroDyn** overhaul continued with updates to the theoretical basis for skewed-flow, dynamic-inflow, unsteady aero, and tower-drag modeling
- Developed a library for **AeroDyn** to support the use of new, multi-dimensional airfoil data files



Burton et al. (2001)

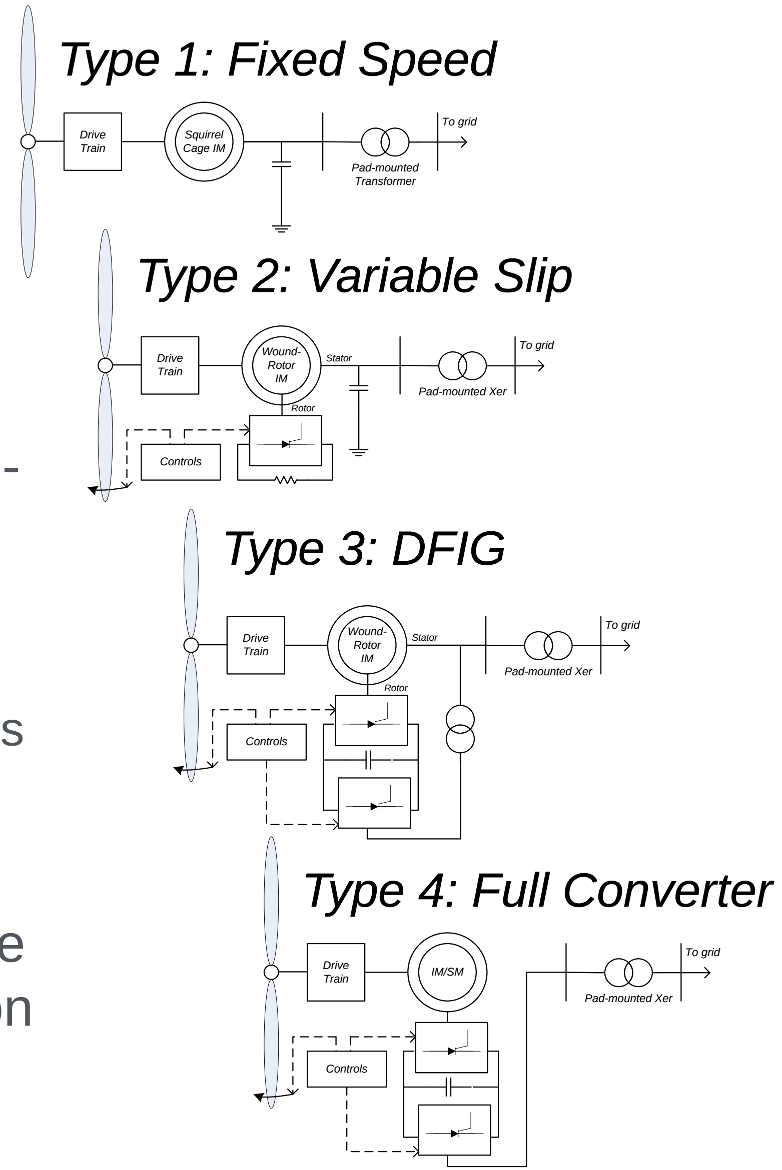
Blade-Element Discretization



Unsteady Airfoil Aerodynamics

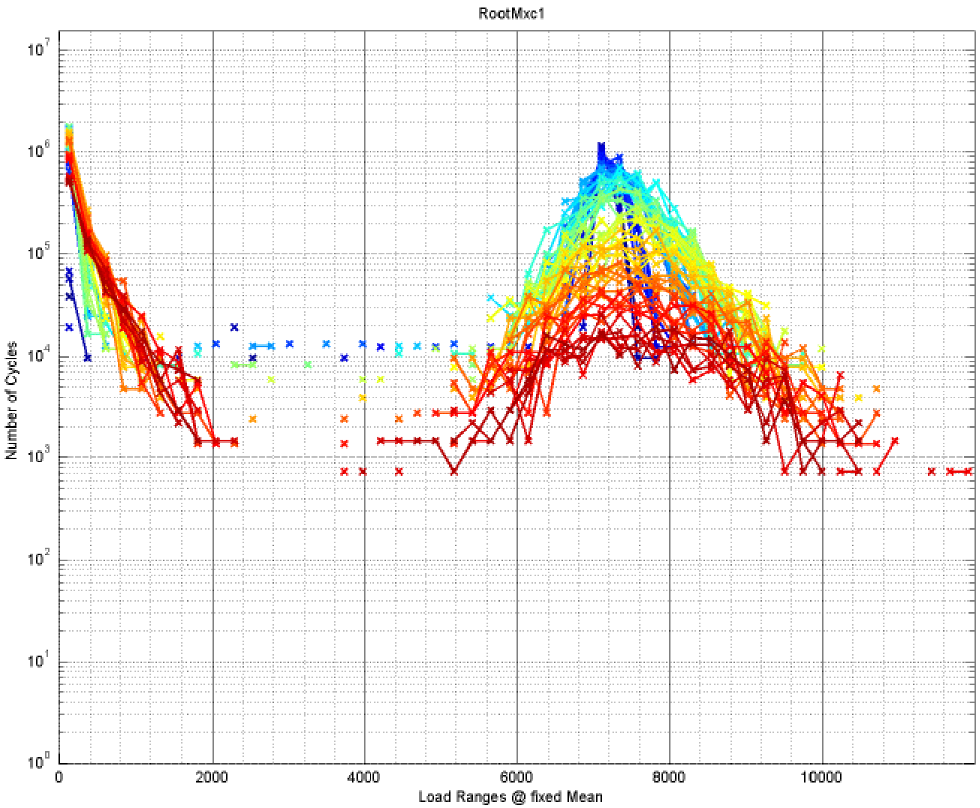
Control and Electrical Systems

- Developed detailed models of the electrical drive within **FAST,** based on **MATLAB** / **Simulink's SimPowerSystems** toolbox
- Applied to problems involving mechanical-electrical interaction:
  - Impact of grid faults on wind turbine components
  - Influence of wind ramps on power systems
- Presented through a series of conference papers
- Released a new **FAST**-**LabVIEW** interface supporting hardware-in-the-loop simulation



Postprocessors and Utilities

- Developed and disseminated **MLife**—a postprocessor that follows the fatigue-analysis requirements of the IEC design standards
  - Includes calculations for lifetime damage and damage-equivalent loads from any number of time-domain simulations
- Drafted a handbook describing how to perform an IEC-style loads analysis using **FAST**



*Example **MLife** Output*

Lifetime Cycles of In-Plane Blade-Root Bending Moment Per Simulation (different colors represent simulations at different wind speeds)

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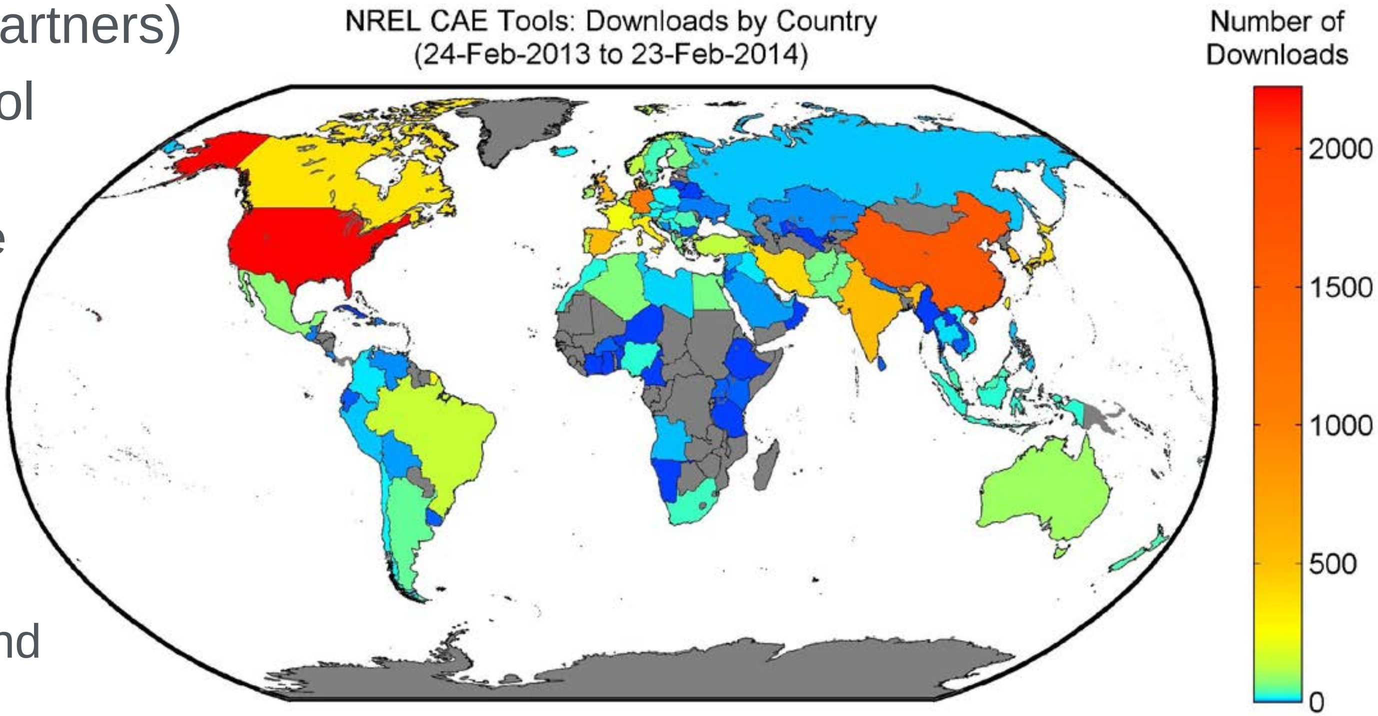
CAE Tool Technical Support

- Hosted 4 wind turbine modeling workshops attended by ~50 people each
- Provided ongoing technical support to the many organizations in the wind industry that use the tools
- Implemented a server and policy for source-code control and tracking (both internal to NREL and with FOA partners)
- Tracked CAE tool usage:
  - 12,605 unique downloads in the past 12 months by 4,273 users from 1,839 organizations in 47 states and 113 countries



Project Plan & Schedule

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

Summary	
WBS Number or Agreement Number	3.1.10
Project Number	
Agreement Number	22503

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Computer-Aided Engineering (CAE) Tools												
Q1 Milestone: Develop and disemminate MLife												
Q2 Milestone: Host a wind turbine modeling workshop												
Q3 Milestone: Draft a programmer's handbook												
Q4 Milestone: Prototype automatic code generation within the FAST framework												
Q1 Milestone: Convert existing FAST modules into the modularization framework												
Q2 Milestone: Host a wind turbine modeling workshop												
Q3 Milestone: Draft report on the electrical drive modeling												
Q4 Milestone: Release an upgraded version of AeroDyn												
Current work and future research												
Q1 Milestone: Host a wind turbine modeling workshop												
Q2 Milestone: Present a paper on the implementation of BeamDyn												
Q3 Milestone: Release an upgraded version of FAST												
Q4 Milestone: Draft a report on an updated skewed wake model of AeroDyn												

Comments

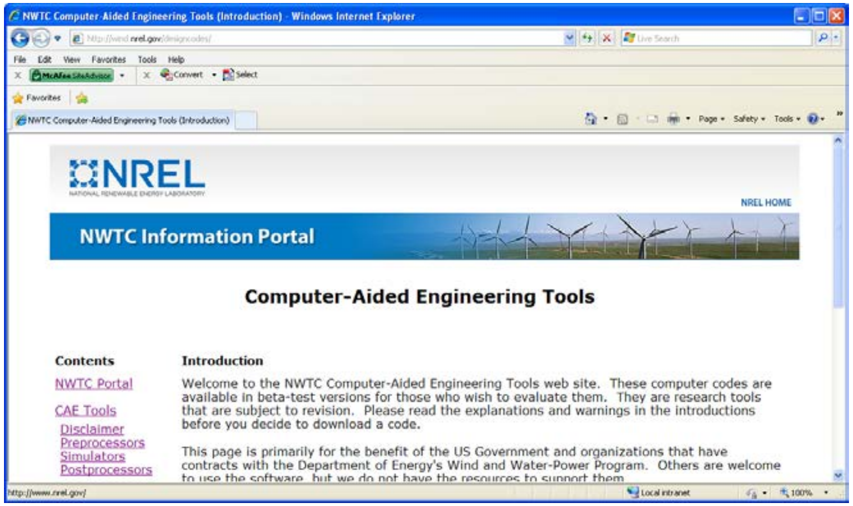
- The conversion of **FAST** to the new modularization framework took a bit longer than planned

Partners, Subcontractors, and Collaborators

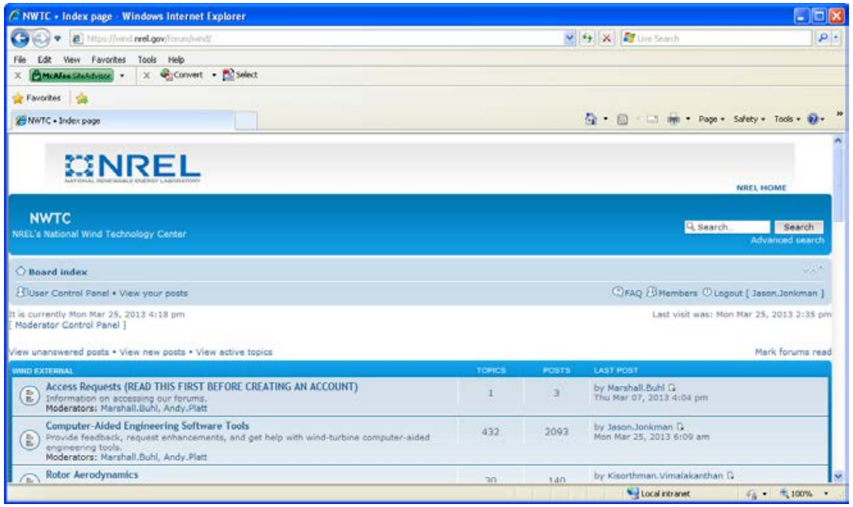
- The project involved regular engagement with many CAE tool users across the wind community
- In FY 2014, Siemens is collaborating to support **FAST** validation against data from the 2.3-MW wind turbine sited at NREL

Communications and Technology Transfer

- Publications and presentations included:
  - 5 workshops
  - 6 conference papers/presentations
  - 1 journal article



NREL Wind Turbine CAE Tools Website



NREL Wind Forum

Next Steps and Future Research

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FY14/Current research:

Further development of the FAST modularization framework

Completion, verification, & validation of **BeamDyn** & the **AeroDyn** overhaul

Inclusion of more built-in control options within **ServoDyn**

Further development & application of electrical-drive models

Development of IEC-style loads-analysis scripts for users

Continued CAE tool technical support

Validation of **FAST** against data from the Siemens 2.3-MW WT sited at NREL

Proposed future research:

New developments (e.g., animation capability, simpler student versions)

Enhanced modularization (e.g., linearization, parallel processing)

Higher-fidelity modeling (e.g., drivetrain dynamics, free wake, flow control)

Further verification & validation

Further integration with systems engineering (e.g. for cost & optimization)

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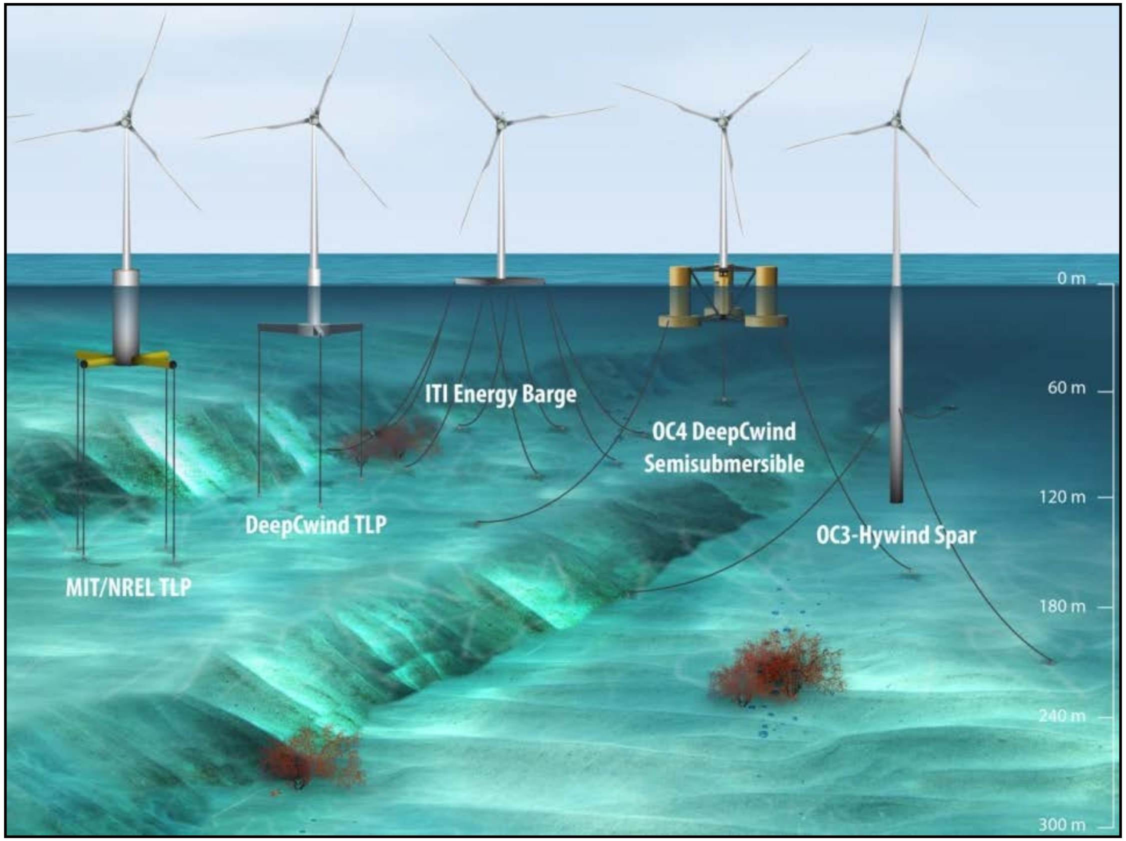

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Floating Platform Dynamic Models

Jason Jonkman

National Renewable Energy Laboratory

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March 25, 2014

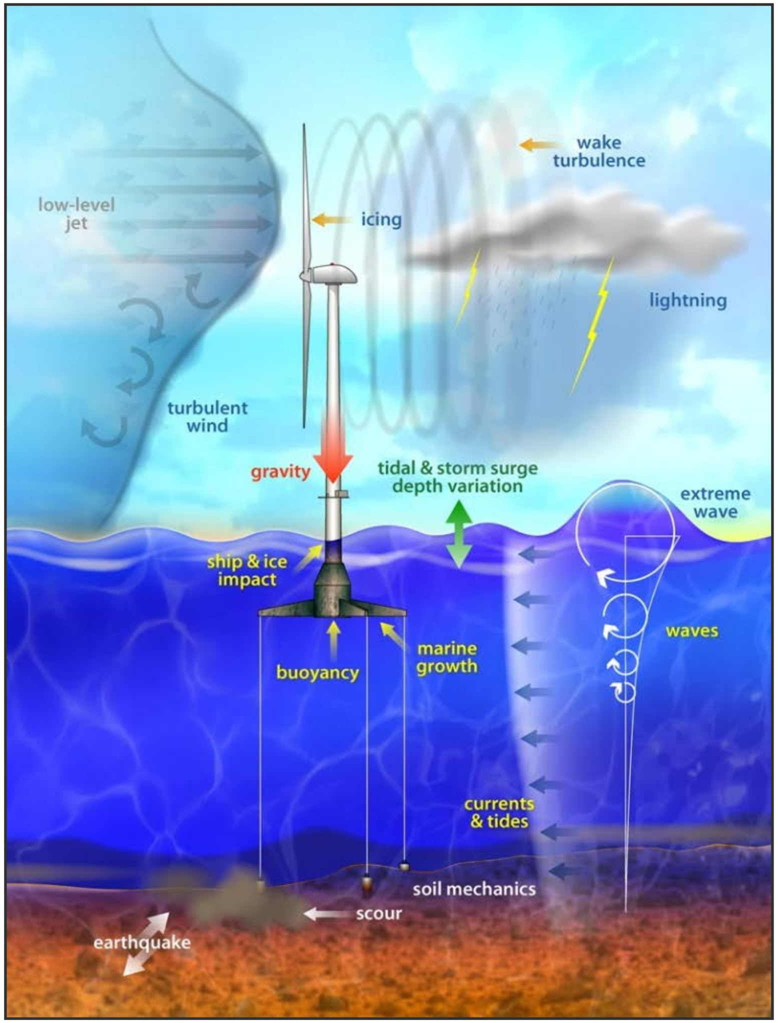
Budget, Purpose, & Objectives

Total DOE Budget [1,2]: $0.000M

Total Cost-Share[1]: $.186M

Problem Statement

- The U.S. Offshore Wind: DE-FOA-0000415 was issued to develop tools and innovative technologies that lower the COE of offshore wind plant systems
- An NREL-led team was selected for funding under topic area 1.1 of DE-FOA-0000415 to improve the dynamics modeling of wind turbines on offshore floating platforms
- According to DOE's *20% Wind by 2030* report, the U.S. could feasibly build 54 GW of offshore wind power by 2030
- Offshore floating wind turbines hold great potential if the technical challenges can be solved in an economically feasible way



Modeling Requirements

[1]*Budget/Cost-Share for Period of Performance FY2012 – FY2013*
[2] *Project remained active using DOE funds received prior to FY2012*

Budget, Purpose, & Objectives

Impact of Project

- Computer-aided engineering (CAE) tools that model the coupled aero, hydro, control system, and structural response of floating wind systems are needed to support the development of innovative technologies that are reliable and cost effective

This project aligns with the following DOE Program objectives and priorities

- **Optimize Wind Plant Performance:** Reduce wind plant levelized cost of energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new, high-tech U.S. industries
- **Testing Infrastructure:** Enhance and sustain the world-class wind-testing facilities at universities and national laboratories to support mission-critical activities
- **Modeling & Analysis:** Conduct wind techno-economic and lifecycle assessments to help the Program focus its technology-development priorities and identify key drivers and hurdles for wind-energy technology commercialization

Technical Approach

The 3-yr project will address all requirements of topic 1.1 of DE-FOA-0000415 through development and validation of **FAST**, as highlighted in the work breakdown structure below:

1 Project Management
- 1.1 Award subcon-tracts to MIT & UMASS
- 1.2 Hold progress update meetings
- 1.3 Participate in DOE project review meetings

2 Improve Hydrodynamics Modeling
- 2.1 Incorporate 2nd-order hydrodynamics
- 2.2 Develop nonlin-ear fluid-impulse module
- 2.3 Establish state-space-based hydrodynamics

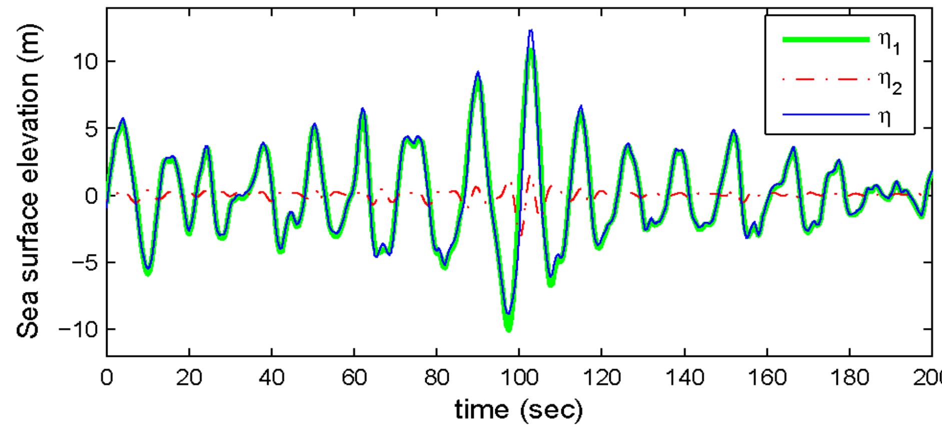
3 Enhance Modularization & Coupled Simulation
- 3.1 Assess loose versus tight coupling schemes
- 3.2 Implement independent discretations in FAST

4 Validate the Improved Modules
- 4.1 Process data from floating wind-system tests
- 4.2 Develop CFD models to assess extreme loads
- 4.3 Validate the floating system functionality of FAST

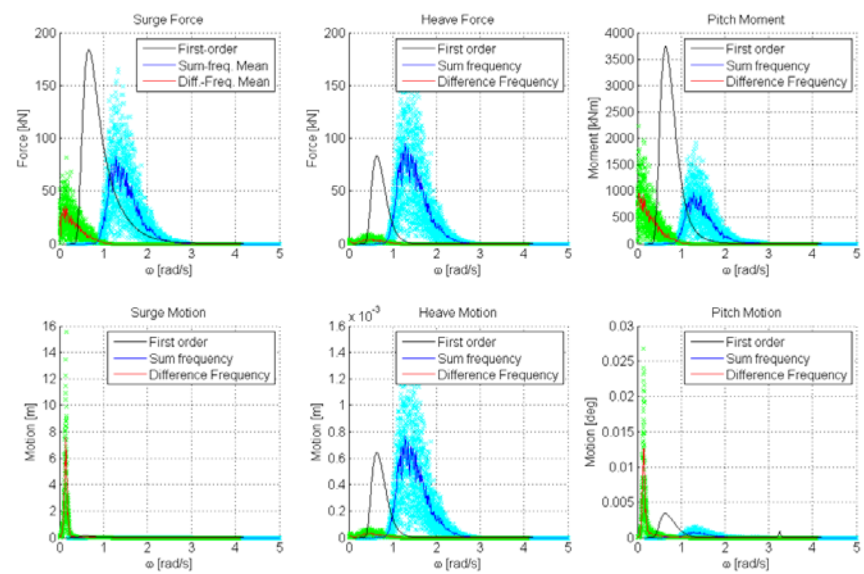
All new or enhanced modules will link with **FAST**, include user and theory documentation, and will be publicly available, on open source, for free.

2nd-Order Hydrodynamics

- Developed a detailed plan for modeling 2nd-order hydro and initiated implementation in **HydroDyn**
  - To address improved accuracy of hydro load modeling at the natural periods of floaters
  - Includes wave directional spreading
- Assessed the influence of 2nd-order terms on a spar- and TLP-based 5 MW floating wind turbine
  - To help establish guidelines on when 2nd-order hydro effects are important
  - Published results at DeepWind 2013
- Initiated a similar assessment for a semi-submersible



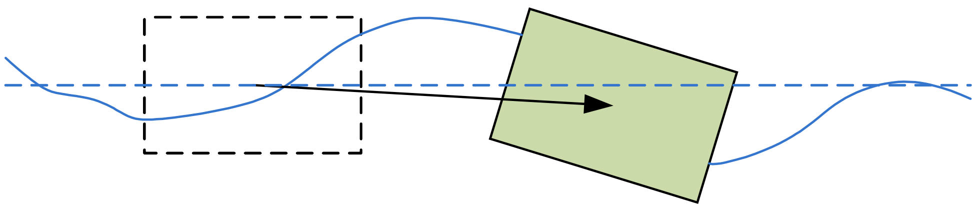
Sea-Surface Elevation from the Summing of 1st- and 2nd-Order Waves



TLP Response with H_s = 3.7 m & T_p = 9.7 s

Fluid-Impulse Hydrodynamics

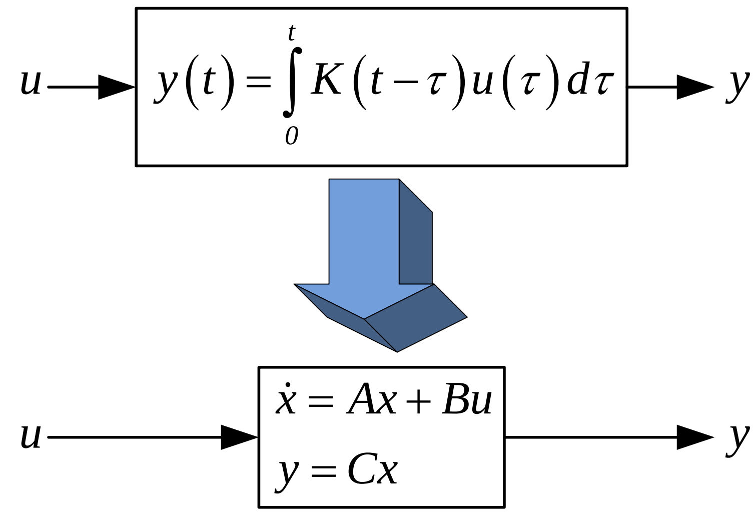
- Subcontractor Paul Sclavounos of MIT developed computational algorithms for a new hydrodynamics module for **FAST,** incorporating nonlinear fluid-impulse theory (FIT)
- FIT bypasses limitations of traditional hydrodynamics theory:
  - No assumption of small body motion
  - No perturbation expansion of higher-order terms
- Important for:
  - Potentially large platform motion
  - Extreme wave loads in severe sea states
- Approach:
  - Implement theory in new module exchangeable with **HydroDyn**
  - 3D time-domain potential-flow solver
  - Panel mesh on the instantaneous body wetted surface



Sea-Surface Interaction With a Platform Experiencing Large Displacement

State-Space Hydrodynamics

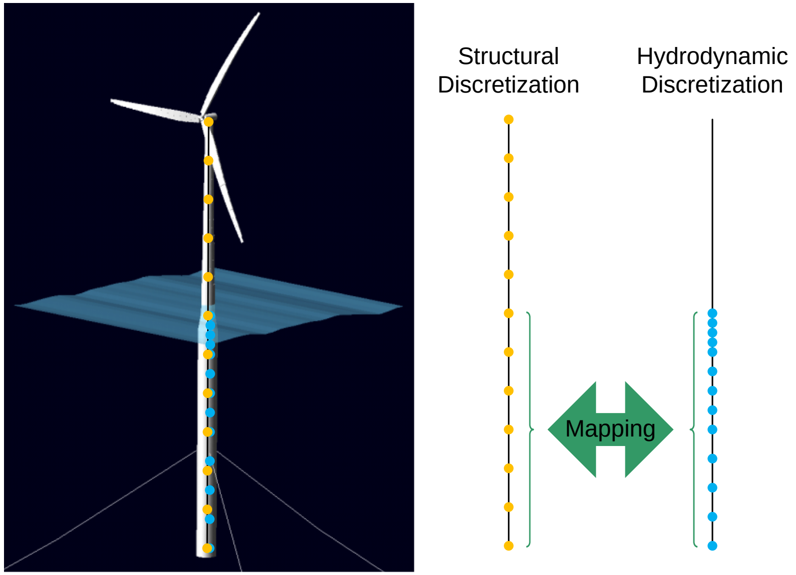
- Introduced a new state-space (SS) hydro implementation of the wave-radiation loads within **HydroDyn**
- **HydroDyn** previously captured wave radiation through convolution which, while accurate, is computationally expensive and prevented model linearization
- The new SS approach will:
  - Enable computationally efficient time-domain solutions
  - Permit model linearization, which is important for:
    - Modal analysis
    - Linear system-based controls design
    - Linearized stability analysis
- Published and presented an OMAE 2013 paper on the approach



Reformulation of Radiation Convolution to Linear SS Form

Modularization and Coupled Simulation

- Algorithms were introduced in the **FAST** modularization framework for coupling modules:
  - With nonmatching spatial discretizations of point- and line-element meshes at interfaces
  - Where module solutions are time advanced with different time steps and different time integrators using a predictor-corrector (PC) procedure



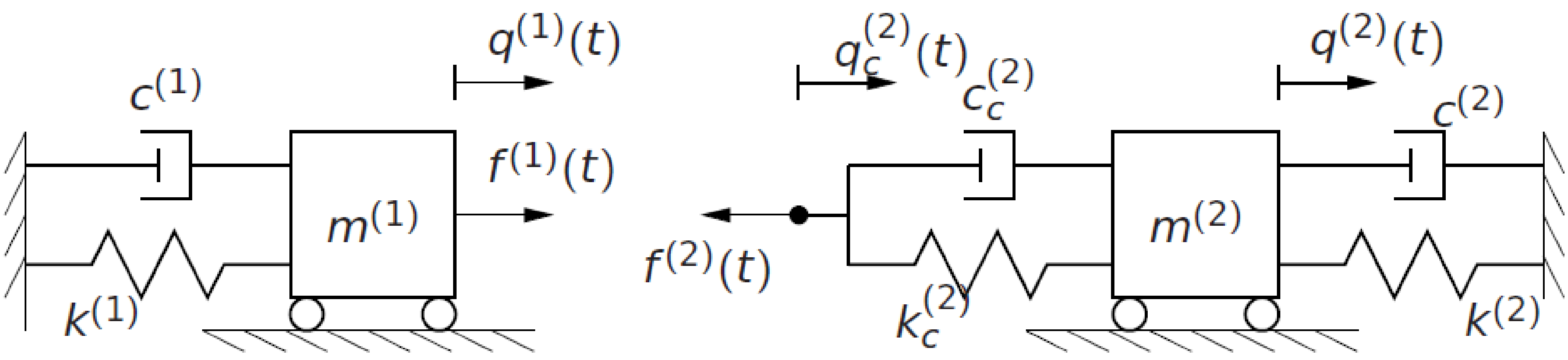
Mapping Independent Structural and Hydrodynamic Discretizations

For Each Time Step (From t_n):
1) Extrapolate Inputs to t_{n+1}
2) Advance States to t_{n+1}
3) Solve for Outputs & Inputs @ t_{n+1}
4) Correct (Go Back to 2) or Save

PC-Based Loose-Coupling Algorithm

Modularization and Coupled Simulation

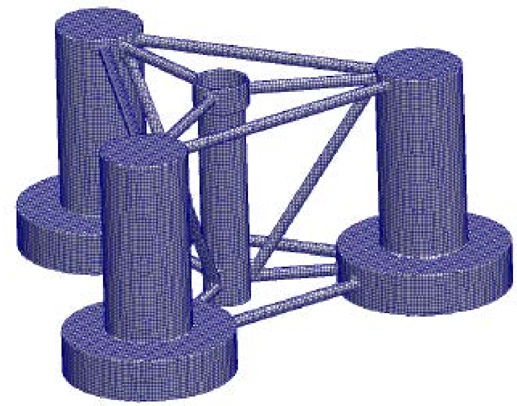
- Examined numerical examples to demonstrate the new coupling capability and explore the stability, accuracy, and efficiency of the algorithms
- Published and presented an AIAA ASM 2013 paper summarizing the coupling approach and solutions

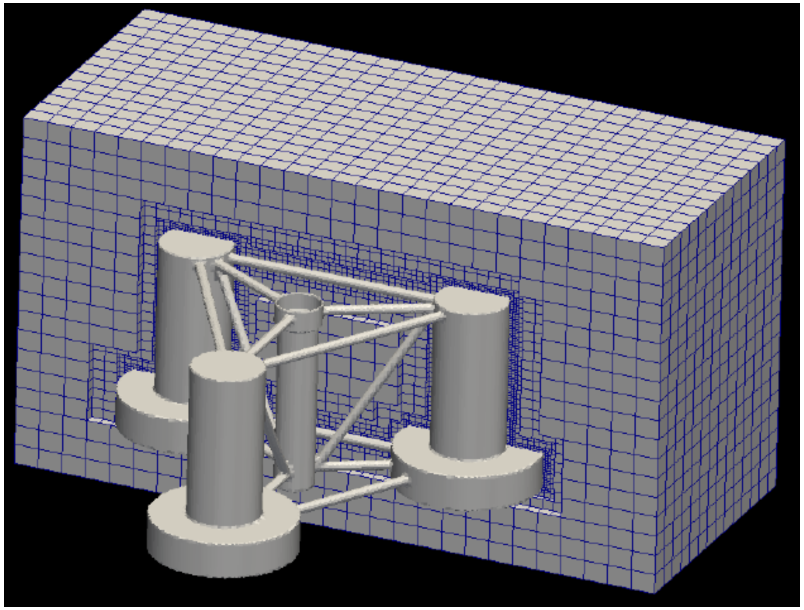


A 2-Mass-Spring-Damper System Split Into 2 Modules for Examination of the Coupling Approach

CFD Modeling

- Subcontractors Matthew Lackner and David Schmidt of UMASS developed, verified, and validated a CFD modeling framework, important for:
  - Analyzing flow details that are not measured in tests
  - Applying to cases where measured data is not available
- Approach:
  - Apply **OpenFOAM**
  - Handle two-phase flow with volume-of-fluid approach
  - Apply body motion from measured data using adaptive meshing
  - Validate model with measured data
  - Apply model to loading scenarios





CFD Meshing of the OC4-DeepCwind Semi-Submersible

Validation of FAST

- Established NDAs with Siemens and Statoil
- Siemens supplied system properties of the Hywind-Norway demonstrator and a **FAST** model was assembled
- Measured wind, wave, and system-response data from the Hywind-Norway demonstrator supplied by Statoil, then processed for quality
- Test data and CFD solutions will be compared with **FAST's** predictions to:
  - Assess the accuracy of the **FAST** simulations and verify its proper implementation
  - Determine which hydrodynamic model is most suitable under various conditions
  - Identify conditions where possible model improvements will be needed

Hywind-Norway Demonstrator

Project Plan & Schedule

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Summary	
WBS Number or Agreement Number	5.1.5
Project Number	
Agreement Number	22505

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

Task / Event	FY2012 Q1 (Octt-Dec)	FY2012 Q2 (Jan-Mar)	FY2012 Q3 (Apr-Jun)	FY2012 Q4 (Jul-Sep)	FY2013 Q1 (Octt-Dec)	FY2013 Q2 (Jan-Mar)	FY2013 Q3 (Apr-Jun)	FY2013 Q4 (Jul-Sep)	FY2014 Q1 (Octt-Dec)	FY2014 Q2 (Jan-Mar)	FY2014 Q3 (Apr-Jun)	FY2014 Q4 (Jul-Sep)
Project Name: Floating Platform Dynamic Models (NREL Prime)												
Q1 Milestone: Award subcontracts to MIT and UMASS												
Q4 Milestone: Draft a report assessing the importance of 2nd-order hydrodynamics												
Q1 Milestone: Implement mapping between nonmatching spatial discretizations												
Q2 Milestone: Publish a paper assessing loose versus tight coupling schemes												
Q3 Milestone: Obtain properties and response data from the Hywind-Norway demo												
Q4 Milestone: Implement a state-space hydrodynamics option in HydroDyn												
Current work and future research												
Q1 Milestone: Draft a paper on the implementation of 2nd-order hydro in HydroDyn												
Q2 Milestone: Present a paper on nonmatching spatial and temporal discretizations												
Q3 Milestone: Release an upgraded version of HydroDyn with 2nd-order hydro												
Q4 Milestone: Draft a paper on validation of FAST against the Hywind-Norway demo												

Comments

- The development of mapping schemes between nonmatching spatial discretizations was harder than anticipated
- It took a while to formalize the NDAs with Siemens and Statoil

Research Integration & Collaboration

Partners, Subcontractors, and Collaborators

- Subcontractor CU and in-kind collaborator ETH Zürich helped assess the importance of 2nd-order hydro
- Subcontractor MIT is developing a module for FIT
- Subcontractor UMASS is developing CFD models
- In-kind collaborator IST–Lisbon helped develop SS hydro models
- In-kind collaborators Siemens and Statoil supplied properties and response data from the Hywind-Norway demonstrator
- The project involved regular engagement with many CAE tool users across the wind industry

Communications and Technology Transfer

- Publications and presentations included 3 conference papers/presentations and 1 journal article—several more are in development

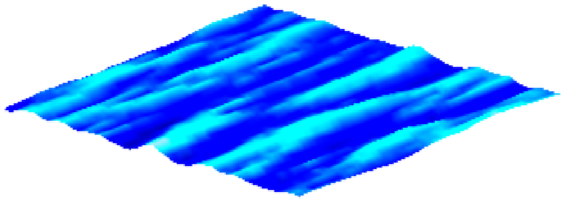
Next Steps and Future Research

FY14/Current research

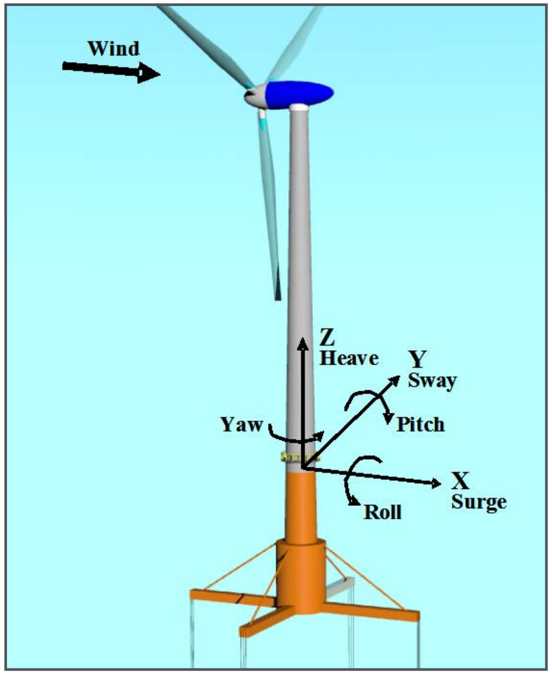
- Assessment of 2nd-order hydro on a semi-submersible
- Implementation of 2nd-order hydro and multi-directional sea-states within **HydroDyn**
- Continued development of a module for nonlinear FIT
- Further development and testing of algorithms supporting mixed time steps between modules
- Continued development and application of CFD models
- Validation of **FAST** against CFD and Hywind data
- Expect to complete the project in 2015

Proposed future research

- Higher-fidelity modeling (e.g., floating platform hydro-elastics, pressure mapping, some 3rd-order terms)
- Further verification and validation
- Further integration with systems engineering

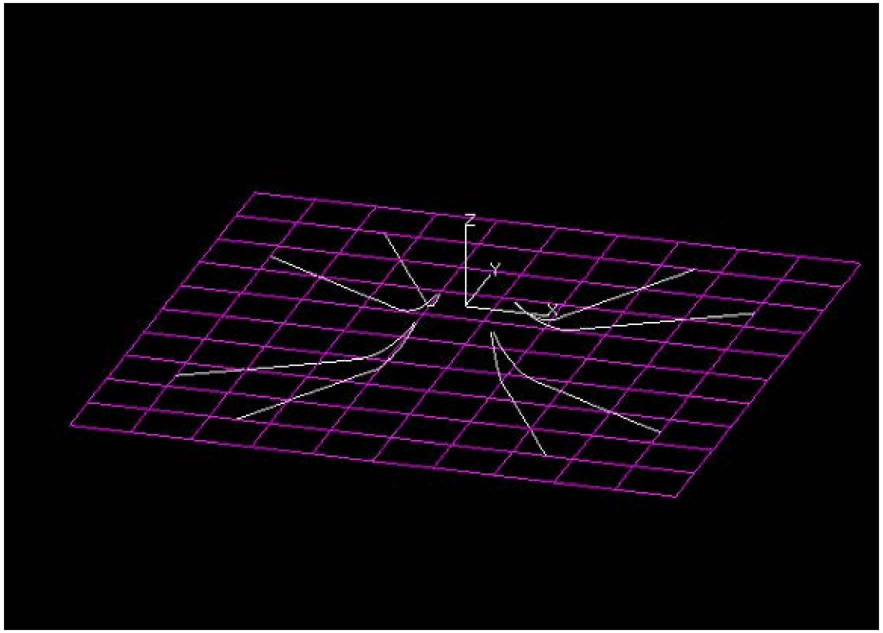


Multi-Directional Sea State



Platform DOFs

DOE Peer Review Meeting: March 2014. Prof. Joseph M.H. Kim



Development of mooring-anchor program in public domain for coupling with FAST

Prof. Joseph M.H. Kim

Texas A&M University

m-kim3@tamu.edu 979 847 8710

3/25/2014

Budget, Purpose, & Objectives

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Total DOE Budget [1,2]: $0.000M

Total Cost-Share[1]:$0.000M

Problem Statement: Current FAST program does not have full mooring dynamics program/anchor-selection program needed for FOWT design

Impact of Project: Full coupled dynamic analysis program for FOWT including mooring dynamics is developed. Anchor-selection data base/program are also established. They will be placed in public domain so that wind-energy industry can use for their design.

[1] *Budget/Cost-Share for Period of Performance FY2012 – FY2013*

[2] *Project remained active using DOE funds received prior to FY2012*

Budget, Purpose, & Objectives

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This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

Technical Approach

Approach: High-order FE (finite element) rod elements mooring dynamics program (FEAM) was developed along with the scheme to connection to FAST newest version. Anchor-selection program was also developed from newly established anchor data base.

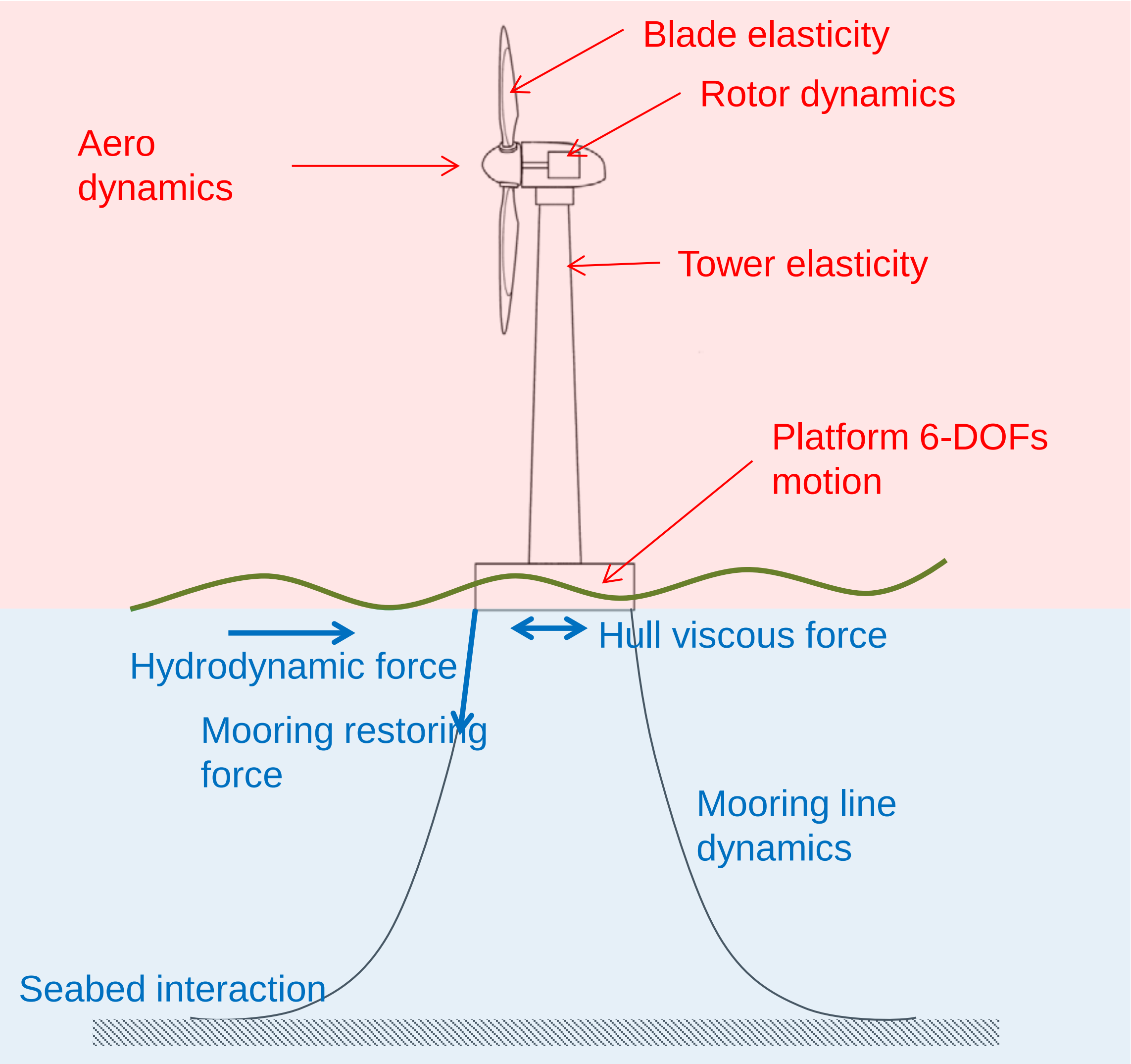
Key issues currently being addressed and their significance: The developed program was verified so that it can be used for real design.

Unique aspects of approach: The program was developed to be consistent with the new NREL-FAST frame and structure (open to public domain).

Coupling between FAST & FEAM

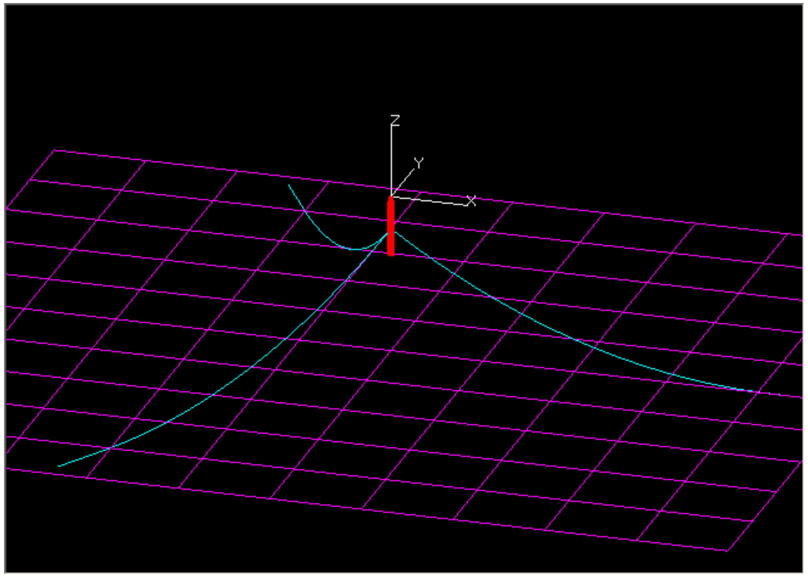
FAST **solves equations of motion** for the entire system except mooring

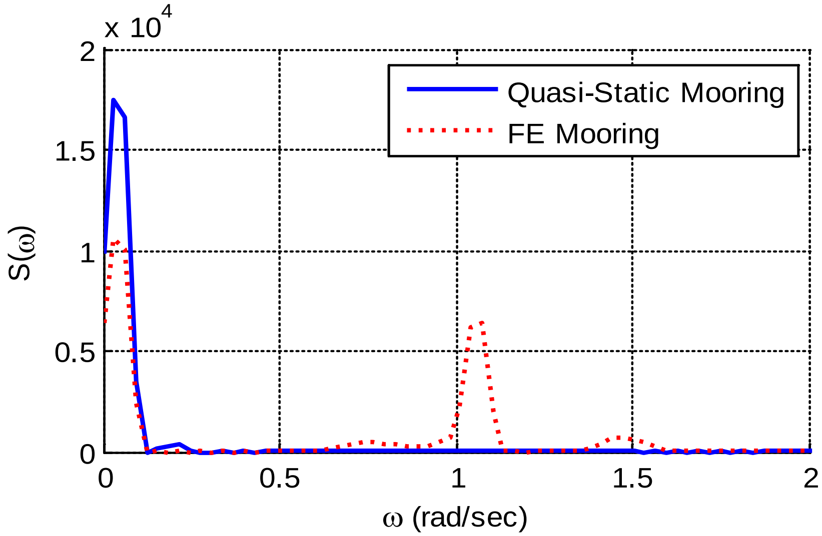
FEAM calculates mooring **external forces** on the platform



Hywind Spar Mooring Tension

Comparison: existing FAST Quasi-static vs new full-dynamic mooring analysis





Verification: DeepCWind Experiment

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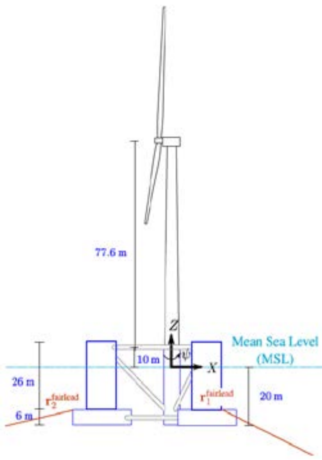
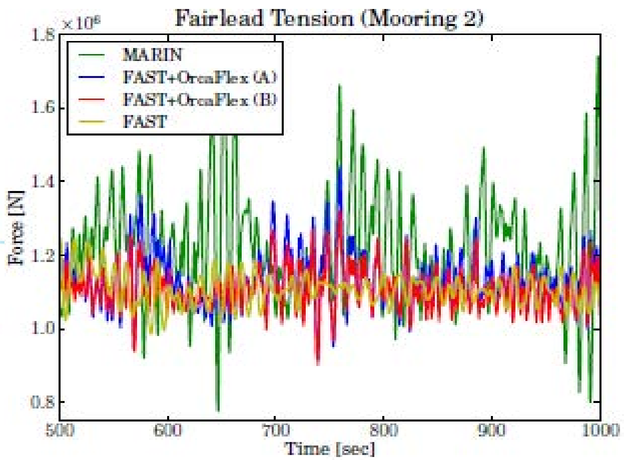
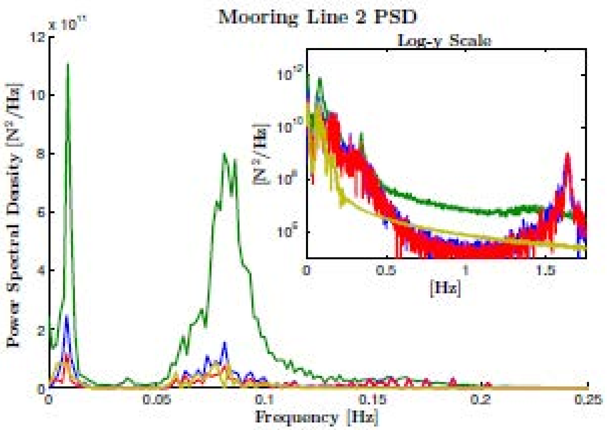
Hs=7.04m , Tp = 12.18s, No Wind

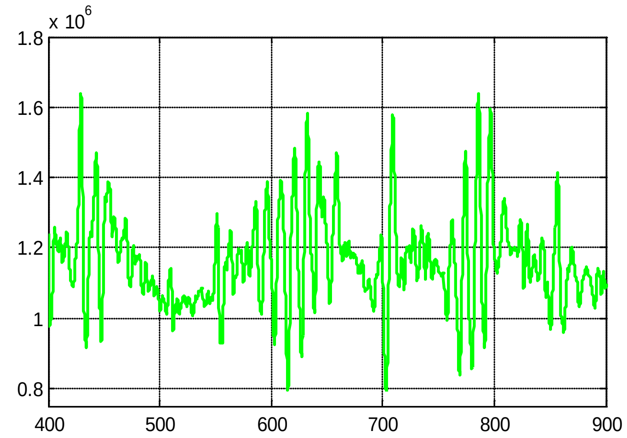


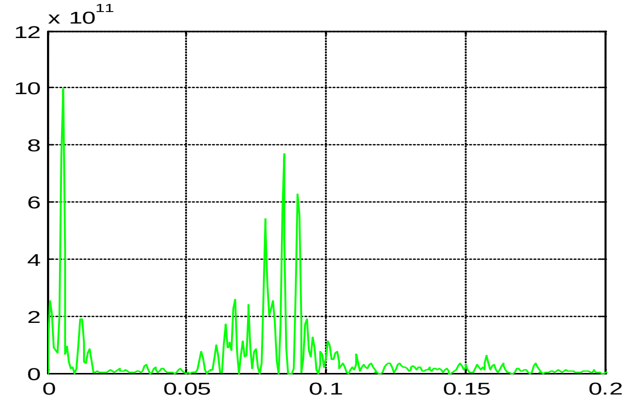
MARIN Experiment (Green line)





TAMU mooring Top Tension(N)





Anchor-selection postprocessor

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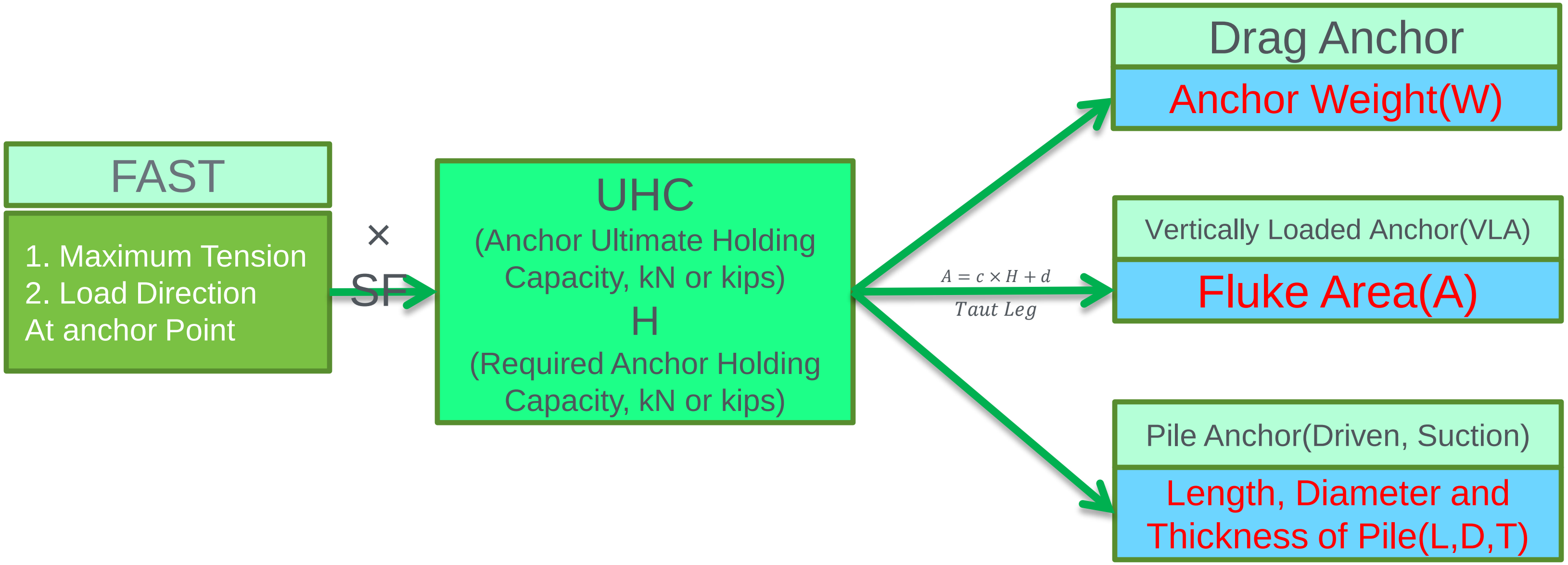
Typical Application of Anchor Types

Mooring Type	*Drag Anchor*	*VLA*	*Driven Pile*	*Suction Pile*
Catenary	√		√	√
Taut Leg		√	√	√
Tendon			√	√



TEXAS A&M UNIVERSITY

Publications (Journal)

- Bae, Y.H. and Kim, M.H., "Influence of control strategy to FOWT global performance by aero-elastic-control-floater-mooring coupled dynamic analysis" *Journal of Ocean and Wind Energy*, Vol 1, No 1, February 2014.
- Bae, Y.H. and Kim, M.H., "Rotor-floater-tether coupled dynamics including 2nd-order sum-frequency wave loads for a mono-column-TLP-type FOWT (floating offshore wind turbine)", *Ocean Engineering*, Vol. 61, 109-122, 201
- Bae, Y.H. and Kim, M.H., "Influence of Failed Blade-Pitch-Control System to FOWT by Aero-Elastic-Control-Floater-Mooring Coupled Dynamic Analysis" *Ocean Systems Engineering, International Journal* Vol. 4, No. 4, 2013

- **Project Technical Report** (anchor selection data base): "Offshore anchor data for preliminary design of anchors of floating offshore wind turbines" (by ABS, Oct. 2013, this deliverable will be in public domain)
- **ABS' design guideline** "Design guideline for station-keeping systems of floating offshore wind turbine (June, 2013 by ABS)"

Project Plan & Schedule

Project Plan & Schedule		
FY2012	FY2013	FY2014
Initial version of FE mooring dynamics program (FEAM) & anchor data base were successfully developed as planned	The developed program was fully tested. FEAM was further refined and modified to be consistent with the NREL's new FAST frame. All the proposed work was successfully completed	Final remaining work for combining FEAM into the latest version of FAST program

Comments

- Original Schedule: 1/1/2012 – 12/31/2013
- No-cost extension to 6/30/2014 due to the delay of NREL's posting of FAST latest version on collaboration site (Oct. 2013)
- No go/no-go decision for FY12 and FY13

Partners, Subcontractors, and Collaborators:

Subcontractor 1: ABS (America Bureau of Shipping) for building a generic anchor-selection data base

Subcontractor 2: NREL (National Renewable Energy Lab) get help for implementing mooring dynamics module into the newest version of FAST program & DeepCWind experimental results.

Communications and Technology Transfer:

Presentations (also published in Proceedings)

•Bae, Y.H., Kim, M.H. and Yu, Q., "Coupled dynamic analysis of FOWT with partially broken blades" *Proceedings of the 23rd International Offshore and Polar Engineering Conference*, Anchorage, 2013

•Bae, Y.H., Kim, M.H, "Turbine-floater-tether coupled dynamic analysis including 2nd-order sum-frequency wave loads for a TLP-type FOWT" *Proc. 31th Int. Offshore Mechanics and Arctic Eng. Conference*, Nantes, 2013

•Bae, Y.H., Kim, M.H., and Im, S.W., "Effects of tower elasticity and aero loading in aero-elastic-control-floater-mooring coupled dynamic analysis for a TLP-type FOWT" *Proceedings of The 22th Int. Offshore and Polar Engineering Conf.*, ISOPE, Rhodes, 2012

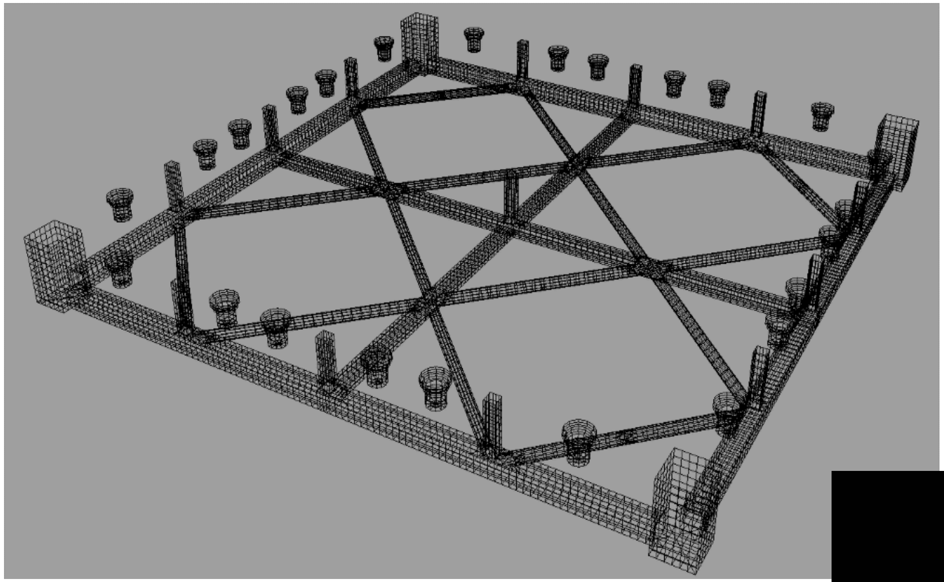
Next Steps and Future Research

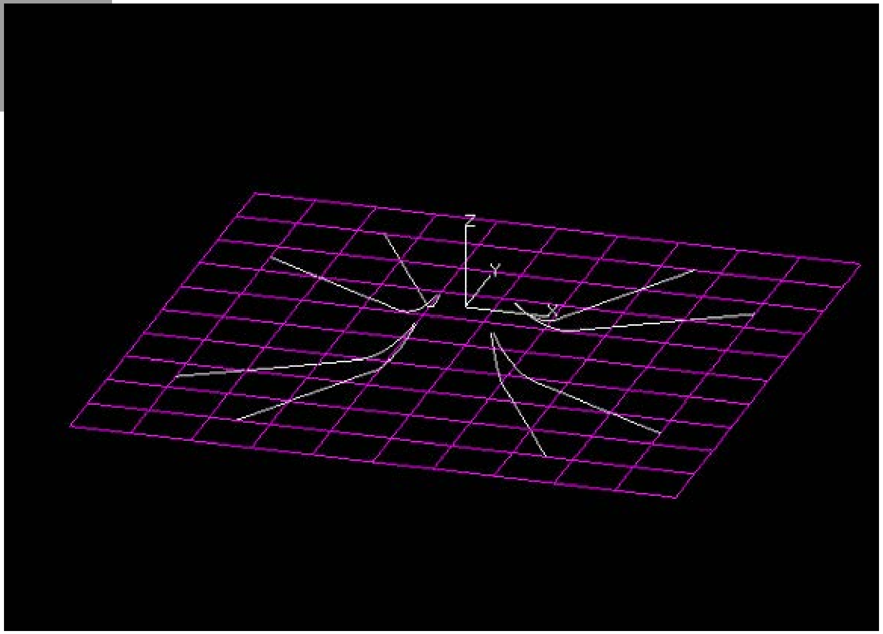
FY14/Current research: Finalizing the remaining work for combining FEAM into the latest version of FAST program

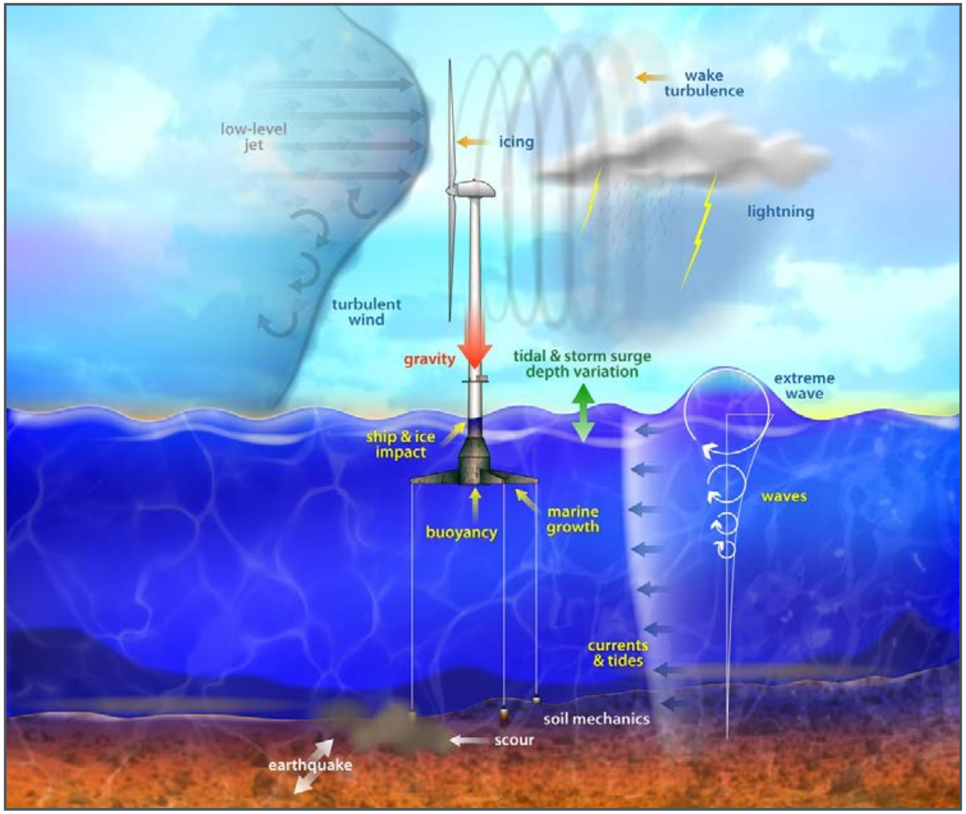
Proposed future research (at $70,000 additional budget):

1. Add the simulation capability with submarine earthquakes.
2. Add the simulation capability with the potential failure of lines/connection.

Major Byproduct of the Project: Analysis program for multi-turbines on a single floater







Principal Investigator

- Amy Robertson

Key Personnel

- Walt Musial
- Jason Jonkman
- Marco Masciola
- Rick Damiani
- Huimin Song

Offshore Wind Structural Modeling and Analysis

Jason Jonkman

National Renewable Energy Laboratory

Jason.Jonkman@nrel.gov, (303) 384-7026

March 29, 2014

Budget, Purpose, & Objectives

Total DOE Budget[1]: $1.771M

Total Cost-Share[1]:$0.000M

Problem Statement: To support the design and analysis of advanced offshore wind systems through the improvement of modeling tools to accurately represent all offshore wind system configurations.

Impact of Project: Instill confidence in the accuracy of FAST, and provide the capabilities needed, for the analysis and innovation of offshore wind system designs. Advanced CAE tools are required for developing the innovative, lower-risk, and higher-performing turbine technology needed to achieve the COE, reliability, and deployment objectives that are part of the Program's mission.

This project aligns with the following DOE Program objectives and priorities

- **Optimize Wind Plant Performance:** Reduce wind plant levelized cost of energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Testing Infrastructure:** Enhance and sustain the world-class wind testing facilities at universities and national laboratories to support mission-critical activities
- **Modeling & Analysis:** Conduct wind techno-economic and lifecycle assessments to help the Program focus its technology-development priorities and identify key drivers and hurdles for wind energy technology commercialization

[1]***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach

Work under this task is focused on three main areas

- Modeling Tool Improvement
- Verification and Validation
- International Engagement

Technical Approach
Modeling Tool Improvement

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- **Identify and address critical gaps that are needed to mature NREL's offshore wind modeling tools**
  - Multi-member support structures (coordination with CAE tool dev.)
  - 2nd-order hydrodynamics (coordination with FOA 415, TA 1.1)
  - Multi-segmented and dynamic mooring lines (coordination with FOA 415, TA 1.2)
  - Member-level Morison loads
  - Evaluate new designs to understand if NREL's modeling tools support the offshore design space
- **Bring together work being done under different efforts to make an integrated, workable package**
  - FOAs
  - Partnerships
  - CAE Tool development

Technical Approach
Verification and Validation

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Ensure that the modeling tools accurately represent the current technology and identify gaps

- ***Verification*** – compare simulated responses to mathematical models
  - Offshore Codes Comparison Collaborative, Continued (OC4) – a wind research task under IEA focused on code-to-code verification
  - FAST-OrcaFlex coupling (OrcaFlex is a commercial offshore structure modeling tool)
  - Computational Fluid Dynamics (CFD)
- ***Validation*** – compare simulated responses to test data (either from tank testing or in the field)
  - DeepCwind—DOE-funded group that performed tank testing of scaled floating offshore structures
  - SWAY—scaled open-ocean demonstration of a tethered spar
  - WindFloat—Principle Power's full-scale demonstration of floating semisubmersible

Collaborate with national and international partners to gain knowledge and expertise from world leaders in offshore wind

- International research projects
- Design standards support
  - Support research on modeling needs for floating systems in support of IEC 61400-3-2
- Conferences, review papers, sit on thesis committees

Accomplishments and Progress: *Modeling of Jackets and Tripods*

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Accomplishment: NREL completed a 3-year effort to expand the capabilities of FAST to enable modeling of multimember, fixed-bottom, offshore systems (e.g., tripods and jackets)

- These types of offshore wind structures are being built in what is called the “transition” region of water depth (30-60 m)
- The new capabilities include:
  - **SubDyn module:** uses a linear, finite element approach with a Craig-Bampton reduction for modeling the substructure flexibility
  - **HydroDyn module:** hydrodynamic loading from linear waves (including distributed inertia, added mass, and viscous drag loads from Morison’s equation, and distributed buoyancy and dynamic pressure loads)

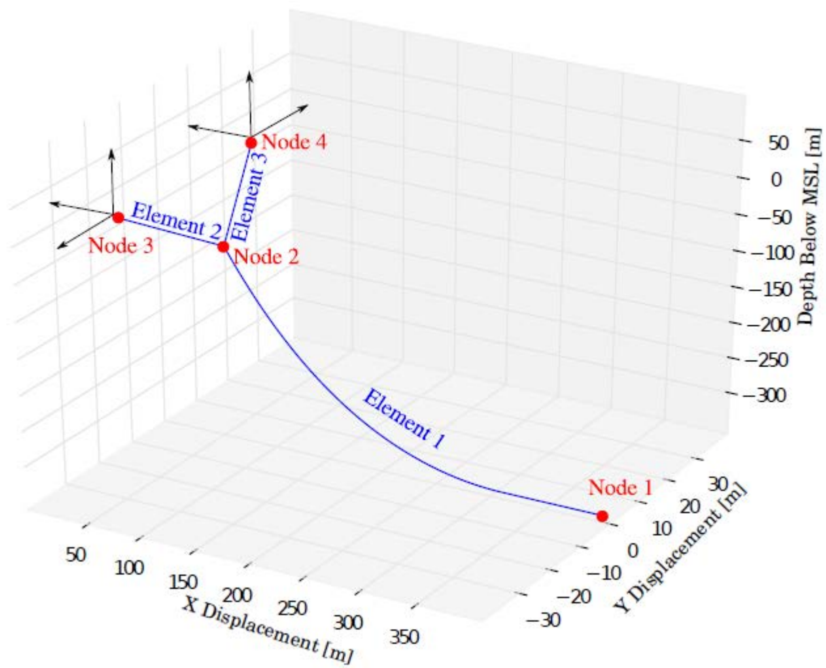
OC4 Jacket

Project Impact: FAST is now able to model the full range of offshore wind system designs being proposed in the industry.

Accomplishments and Progress: *Mooring Analysis Program (MAP)*

Accomplishment: NREL completed the development of a new mooring module called the Mooring Analysis Program (MAP)

- Developed within the FAST modularization framework
- Provides capability to model multi-segmented mooring lines of floating offshore wind systems



Example of a multi-segmented mooring line model in MAP

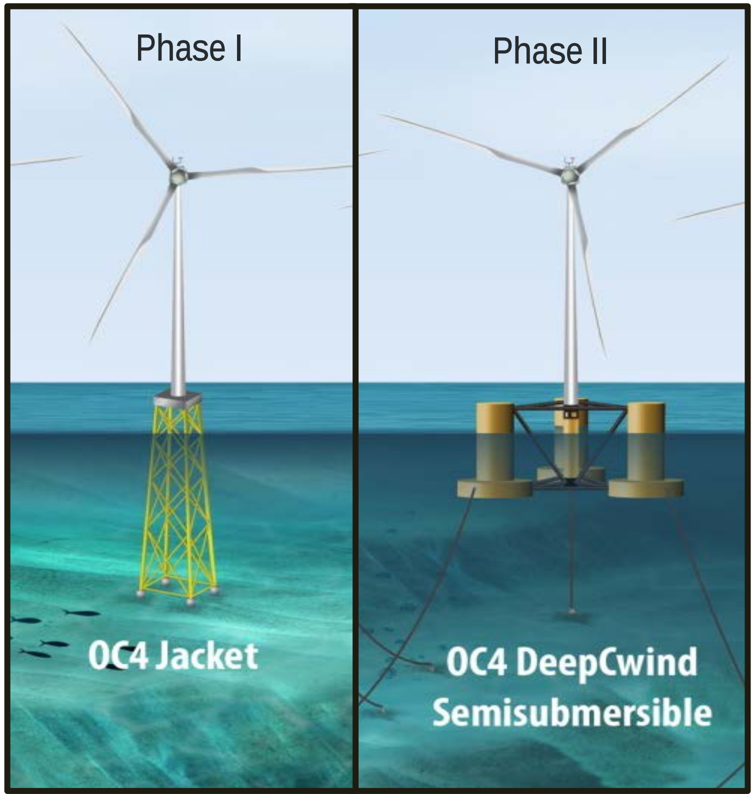
Project Impact:

- Allows FAST to model more mooring designs, such as bridle system used by the Hywind floating spar.
- Provides the platform on which a dynamic mooring line module will be developed.

Accomplishments and Progress: *IEA Task30 - OC4 Verification Project*

Accomplishments:

- Phase I, focused on a jacket-type substructure, was completed in FY12
  - 84 participants from 36 organizations in 15 countries.
  - Published findings at ISOPE 2012 conference, journal article being reviewed
- Phase II focused on a floating semi, finished its modeling work during FY13
  - Led by NREL, responsible for leading all the meetings, developing a model description document, defining a set of load cases to be run, and summarizing the findings
  - 139 participants from 55 organizations in 19 countries



Systems analyzed in the OC4 Project

Project Impact:

- Verified computer codes being used by the industry worldwide
- Identified model deficiencies and needed code improvements
- The advancement of the offshore wind industry is closely tied to the development and accuracy of system-dynamics models

Accomplishments and Progress: *OC4 Validation Workshop*

Accomplishment: NREL held a topical-experts meeting under IEA Task 30 to develop a plan for international collaboration on validating offshore wind-modeling tools

- 60 international and domestic attendees from national labs, industry, and academia
- Presentations given by 16 experts in the field

Project Impact:

- Based on feedback, NREL agreed to develop a proposal for a new IEA Wind Task devoted to validating offshore wind codes through code-to-data comparisons
- Proposal was presented to the IEA and approved at the beginning of FY14

Alpha Ventus Jacket Turbine

Accomplishments and Progress: *DeepCwind—Code Validation*

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Accomplishment: NREL, in conjunction with the Univ. of Maine, completed its first validation of FAST's offshore modeling capabilities through the DeepCwind project

- DeepCwind tested 3 floating systems at MARIN to obtain data for code validation
- Built FAST models of each system and compared simulations to tank-test data

DeepCwind 1/50 Scale Models (semisubmersible, spar, TLP)

Project Impact:

- Identified deficiencies in FAST for accurately modeling offshore wind systems (2nd-order hydrodynamics, member-level viscous drag, and mooring dynamics)
- Initiated a set of standard practices for offshore validation
- Provided insight into which physics phenomena offshore codes are modeling well and which are lacking
- DeepCwind data will be made available to the public for other validation work

Accomplishments and Progress: *SWAY—Tethered Spar*

Accomplishment:

- NREL employees installed sensors and a data-acquisition system on the SWAY scaled floating wind turbine to ensure the collection of field test data needed to perform model validation
- NREL has built a model of the system in FAST—validation work is on-going

Project Impact:

- Provided NREL and DOE with practical experience in the testing of offshore wind systems
- Test data is proprietary, but findings from the validation work will be published

NREL employees travel to SWAY turbine to install measurement equipment (Garth Johnson, Espen Mork-Knudsen (SWAY), Rob Wallen, and Eric Nelson)

Accomplishments and Progress: *Floating Wind Standards Support*

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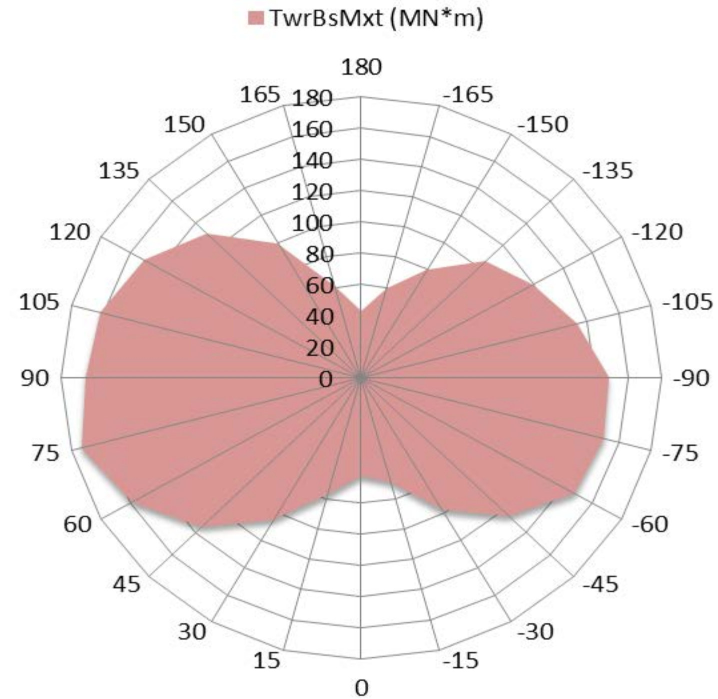
Accomplishment: NREL, in conjunction with partners, completed a set of analyses assessing simulation requirements for the design of floating offshore wind systems

- Appropriate simulation time
- Number of wind/wave misalignment cases needed
- Work performed for a spar system, future work will examine other systems

Project Impact:

- Work supports the IEC 61400 working group 3-2
- Seeks to identify how existing design standards for offshore wind systems need to be modified to address the added dynamic characteristics of floating systems.



Loads rose for tower fore/aft bending, representing the extreme loads as a function of wind/wave misalignment

Accomplishments and Progress: *International Engagement*

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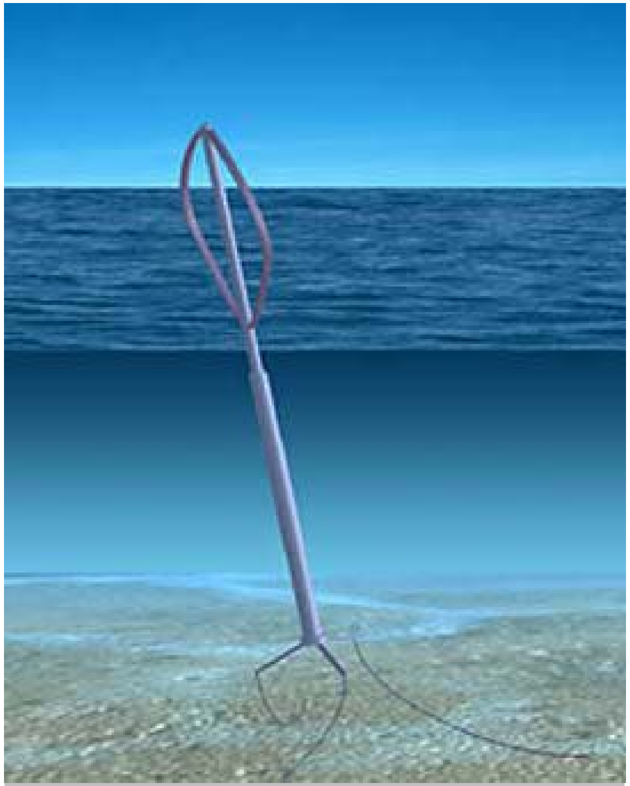
Accomplishment: NREL participated in the following international projects:

- ORECCA—developed a roadmap for research activities in offshore renewables
- NOWITECH—research on making wind farms in deep water cost effective
- DeepWind—developing a new Darrieus floating wind turbine
- UpWind—supported the design of very large wind turbines
- INNWIND—offshore wind tool validation

Project Impact: These international collaborative efforts helped NREL stay abreast of the latest RD&D developments and innovations in offshore wind.



DeepWind Floating VAWT

Project Plan & Schedule

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Summary	
WBS Number or Agreement Number	5.1.1
Project Number	
Agreement Number	26864

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Wind Energy Forecasting Methods and Validation for Tall Turbine Resource Assessment												
Q1 Milestone: Modify HydroDyn for multi-member structures												
Q2 Milestone: Complete OC4 Phase II specification document												
Q3 Milestone: Hold workshop on offshore code validation under IEA Task 30												
Q4 Milestone: Release FAST with new HydroDyn version for multi-member structures												
Q1 Milestone: Complete comparison of SWAY test data to FAST simulation results												
Q2 Milestone: Complete initial modifications to FAST for multi-member substructures												
Q3 Milestone: Couple new mooring analysis program (MAP) to FAST												
Q4 Milestone: Complete simulations for Phase II of OC4												
Current work and future research												
Q1 Milestone: Hold a kick-off meeting for the extension of the IEA Wind Task 30												
Q2 Milestone: Complete NREL report summarizing findings of validation work for SWAY												
Q3 Milestone: Simulate all load cases for IEA Wind OC3 tripod and OC4 jacket in FAST8												
Q4 Milestone: Comlpete system-level verification of viscous drag model in FAST8												

Comments

- FY13 Q3 milestone for MAP was delayed due to unforeseen issues in coupling a code based in C++ to Fortran

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators:

Risø DTU	CRADA	DeepWind project; IEA Wind Task 30 (OC4) collaboration
ECN	CRADA	Cost analysis; IEA Wind Task 30 (OC4) collaboration
CENER	CRADA	DeepCwind; provide insight from Acciona testing; source code improvements to FAST modules
NOWITECH	MOU	NREL is a member of the NOWITECH scientific advisement committee
Fraunhofer IWES	Agreement under IEA	Co-operating agent on OC4 - increase collaboration to gain access to other EU projects
ORECCA/EU	MOU	Support finalization of work package summaries
University of Delaware	CRADA	Testing collaboration and cost modeling; CFD assessment of hydrodynamic load models
University of Stuttgart	MOU	Collaborated on research for floating wind standards
Leibnitz Univ. Hannover	MOU	Advised student on inverse load calculation method using offshore wind turbine response
University of Maine	DeepCwind	Collaborated on DeepCwind project, and validation of floating models for the project
University of Massachusetts	MOU	Collaborated on research for floating wind standards
SWAY	CRADA	Collaboration on their offshore wind demonstration project
Principle Power	CRADA	Collaboration on their offshore wind demonstration project in Portugal
MMI Engineering	MOU	Collaboration on DeepCwind validation and earthquake analysis
NTU Singapore	MOU	Collaboration on SWAY validation work
Texas Tech University	DeepCwind	Collaboration on DeepCwind validation work
NTNU (Norway)	MOU	Advised student on floating semi analysis
Penn State University	MOU	Collaborated on research for floating wind standards
University of Colorado	DeepCwind	Student worked on analysis of DeepCwind spar

Communications and Technology Transfer

1. Coulling, A.; Goupee, A.; Robertson, A.; Jonkman, J.; Dagher, H., "Validation of a FAST Semi-submersible Floating Wind Turbine Numerical Model with DeepCwind Test Data," Journal of Renewable and Sustainable Energy, Vol. 5, Issue 2, March 2013.
2. Ramachandran, G.; Robertson, A.; and Jonkman, J. (2013) "Investigation of RAOs computed using WAMIT and FAST for various floating offshore wind turbines subjected to different wind and wave conditions," presented at The International Society of Offshore and Polar Engineers Conference, July 2013.
3. Song, H.; Damiani, R.; Robertson, A.; Jonkman, J. (2013). "A New Structural-Dynamics Module for Offshore Multimember Substructures within the Wind Turbine CAE tool FAST," presented at The International Society of Offshore and Polar Engineers Conference, July 2013.
4. Masciola, M.; Jonkman, J.; Robertson, A; (2013). "Implementation of a Multi-Segmented, Quasi-Static Cable Model in the Mooring Analysis Program," presented at The International Society of Offshore and Polar Engineers Conference, July 2013.
5. Masciola, M.; Robertson, A.; Jonkman, J.; Coulling, A.; Goupee, A. (2013). "Assessment of the Importance of Mooring Dynamics on the Global Response of the DeepCWind Floating Semisubmersible Offshore Wind Turbine," presented at The International Society of Offshore and Polar Engineers Conference, July 2013.
6. Robertson, A. N.; Jonkman, J. M.; Masciola, M. D.; Molta, P.; Goupee, A. J.; Coulling, A. J.; Prowell, I.; Browning, J. (2013). "Summary of Conclusions and Recommendations Drawn from the DeepCWind Scaled Floating Offshore Wind System Test Campaign," presented at the Ocean, Offshore and Arctic Engineering Conference, June 2013. NREL Report No. CP-5000-58076.
7. Haid, L.; Stewart, G.; Jonkman, J.; Robertson, A.; Lackner, M.; Matha, D. (2013). "Simulation-Length Requirements in the Loads Analysis of Offshore Floating Wind Turbines," presented at the Ocean, Offshore and Arctic Engineering Conference, June 2013. NREL Report No. CP-5000-58153.
8. Couling, A. J.; Goupee, A. J.; Robertson, A. N.; Jonkman, J. M. (2013). "Importance of Second-Order Difference-Frequency Wave-Diffraction Forces in the Validation of a Fast Semi-Submersible Floating Wind Turbine Model," presented at the Ocean, Offshore and Arctic Engineering Conference, June 2013. NREL Report No. CP-5000-57697.
9. Damiani, R.; Jonkman, J.; Robertson, A.; Song, H. (2013). "Assessing the Importance of Nonlinearities in the Development of a Substructure Model for the Wind Turbine CAE Tool FAST," Ocean, Offshore and Arctic Engineering Conference, June 2013. NREL Report No. CP-5000-57850.

Communications and Technology Transfer

10. Stewart, G.; Lackner, M.; Haid, L.; Matha, D.; Jonkman, J.; Robertson, A. (2013). “Assessing Fatigue and Ultimate Load Uncertainty in Floating Offshore Wind Turbines Due to Varying Simulation Length,” presented at ICOSSAR. NREL Report No. CP-5000-58518.
11. Prowell, I.; Robertson, A.; Jonkman, J.; Stewart, G.. (2013). “Numerical Prediction of Experimentally Observed Scale-Model Behavior of an Offshore Wind Turbine Supported by a Tension-Leg Platform”, presented at the Offshore Technology Conference, May 6-9. NREL Report No. CP-5000-57615.
12. Browning, J. R.; Jonkman, J.; Robertson, A.; Goupee, A. J. (2012). “Calibration and Validation of a Spar-Type Floating Offshore Wind Turbine Model using the FAST Dynamic Simulation Tool,” The Science of Making Torque from Wind Conference, October 2012. NREL Report No. CP-5000-56138.
13. Stewart, G. M.; Lackner, M.A.; Robertson, A.; Jonkman, J; Goupee, A.J. (2012). “Calibration and Validation of a FAST Floating Wind Turbine Model of the DeepCwind Scaled Tension-Leg Platform,” The International Society of Offshore and Polar Engineers Conference, June 17-22.
14. Jain, A.; Robertson, A. N.; Jonkman, J. M.; Goupee, A. J.; Kimball, R. W.; Swift, A. H. P. (2012). “FAST Code Verification of Scaling Laws for DeepCwind Floating Wind System Tests,” 13 pp.; NREL Report No. CP-5000-54221.
15. Popko, W.; Vorpahl, F.; Zuga, A.; Kohlmeier, M.; Jonkman, J.; Robertson, A.; Larsen, T. J.; Yde, A.; Saetertro, K.; Okstad, K. M.; Nichols, J.; Nygaard, T. A.; Gao, Z.; Manolas, D.; Kim, K.; Yu, Q.; Shi, W.; Park, H.; Vasquez-Rojas, A. (2012). “Offshore Code Comparison Collaboration Continuation (OC4), Phase I - Results of Coupled Simulations of an Offshore Wind Turbine with Jacket Support Structure,” 12 pp.; NREL Report No. CP-5000-54124.
16. Song, H.; Robertson, A.; Jonkman, J.; Seawell, D. (2012). “Incorporation of Multi-Member Substructure Capabilities in FAST for Analysis of Offshore Wind Turbines,” Offshore Technology Conference, April 30-May 3.
17. Pahn, T.; Jonkman, J.; Rolfes, R.; Robertson, A. (2012). “Inverse Load Calculation of Wind Turbine Support Structures - A Numerical Verification Using the Comprehensive Simulation Code FAST,” 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 23 - 26 April 2012, Honolulu, AIAA 2012-1735.

Next Steps and Future Research

FY14/Current research:

- Finish OC4 Phase II, and initiate new OC5 project focused on offshore modeling tool validation
- Verify new FAST8 capabilities, including multi-member structures and member-level Morison loads
- Validate FAST models of SWAY and WindFloat systems
- Assess simulation requirements for a floating semi to support development of design standards

Proposed future research:

- Further offshore-specific model development, verification, and validation
- Research to support the development of standard practices for the deployment of offshore wind in the US (hurricanes, ice, floating systems)
- Conceptual design and analysis of new offshore wind structures
- Involvement with new offshore projects in the US, and across the globe
    - Would like to be involved in new work in Asia

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Photo courtesy Seppo Keränen

Creation of a Model for Interaction of Bottom-Fixed Wind Turbines with Surface Ice for Use with Common Simulation Codes

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March 25, 2014

Budget, Purpose, & Objectives

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

Total DOE Budget [1,2]: $0.000M

Total Cost-Share[1]:$0.000M

Problem Statement: The wind industry needs tools to estimate the dynamic structural loading from surface ice on fixed-bottom wind turbines installed offshore.

Impact of Project: The project will provide a flexible suite of subroutines for use with aeroelastic models to predict the loading on support structures and resulting turbine response due to dynamic surface ice forces.

This project aligns with the following DOE Program objectives and priorities:

- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

[1] *Budget/Cost-Share for Period of Performance FY2012 – FY2013*

[2] *Project remained active using DOE funds received prior to FY2012*

Scope

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- Provide analysis tools to calculate dynamic surface ice loading on support structures of offshore, bottom-fixed wind turbines considering:
  - Current standards and state of the art ice phenomenology
  - A range of sea and lake environments
  - A range of support structure designs
    - Monopile, tripod, 4-legged jacket structure

- Tools must be flexible and modular:
  - Interface with common wind turbine simulation codes
    - FAST, ADAMS, Bladed, FLEX, HAWC2
  - Be publicly available and open source
  - Be thoroughly documented in theory and users manuals with substantial user guidance

Significance

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- Considerable interest in deploying wind turbines in the Great Lakes
- Moving ice floes apply dynamic loads
- Thus wind turbine designers need codes for ice loads that interact with existing aero-servo-hydro elastic simulations
- Ice loading may be a design driver in some locations
- Ice loading codes used in other industries are:
  - Proprietary
  - Expensive
  - Generally not readily available

Technical Approach

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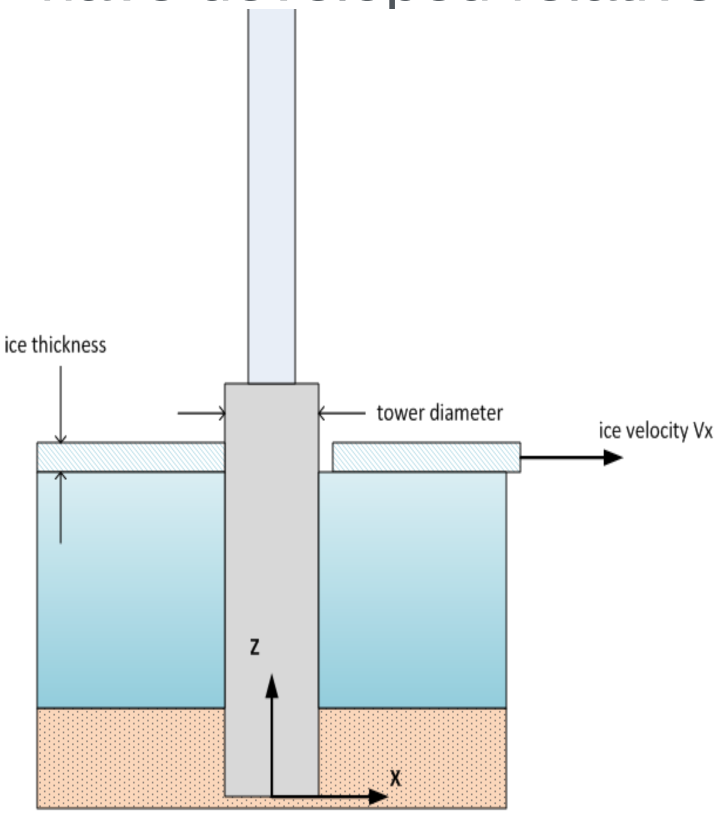
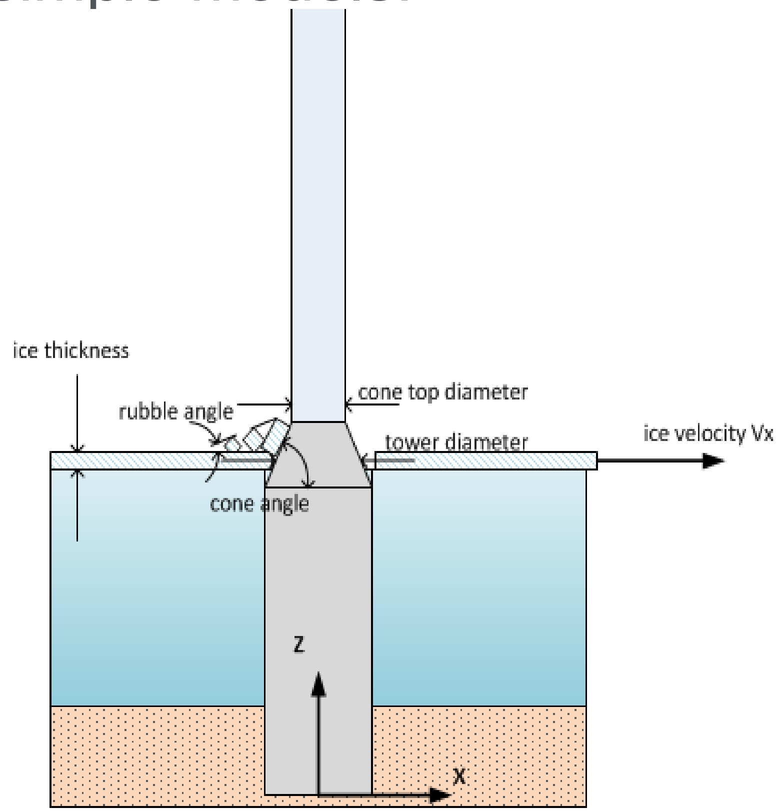
1. Identify ice loading models (7 total)
   - IEC 61400-3, Ed. 1: *Design Requirements for Offshore Wind Turbines* (Informative appendix)
   - ISO 19906, Ed. 1: *Petroleum and Natural Gas Industries – Artic offshore structures*
   - Expert advice: Tom Brown, PhD, IFN Engineering
2. Code ice models in Fortran
   - Link with FAST, ADAMS, Bladed, FLEX, HAWC2
3. Validate implementation of ice models
   - Test all 7 models and validate output against Dr. Brown's model
   - Execute all 7 models for a wide variety of input conditions
4. Document in theory and users manuals

- Ice loading is extremely complex; however, ice experts have developed relatively simple models:



Crushing



Flexural Failure

Ice Load Models

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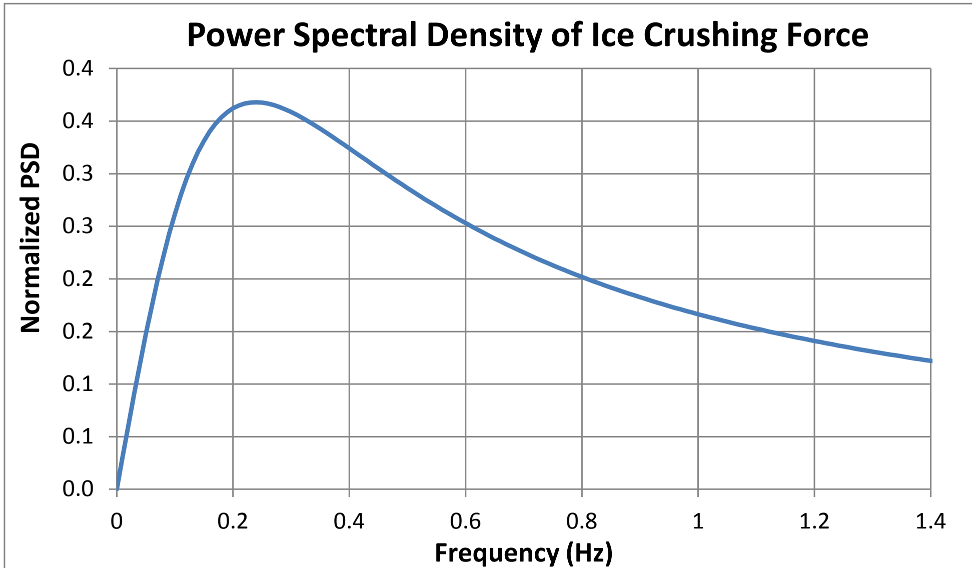
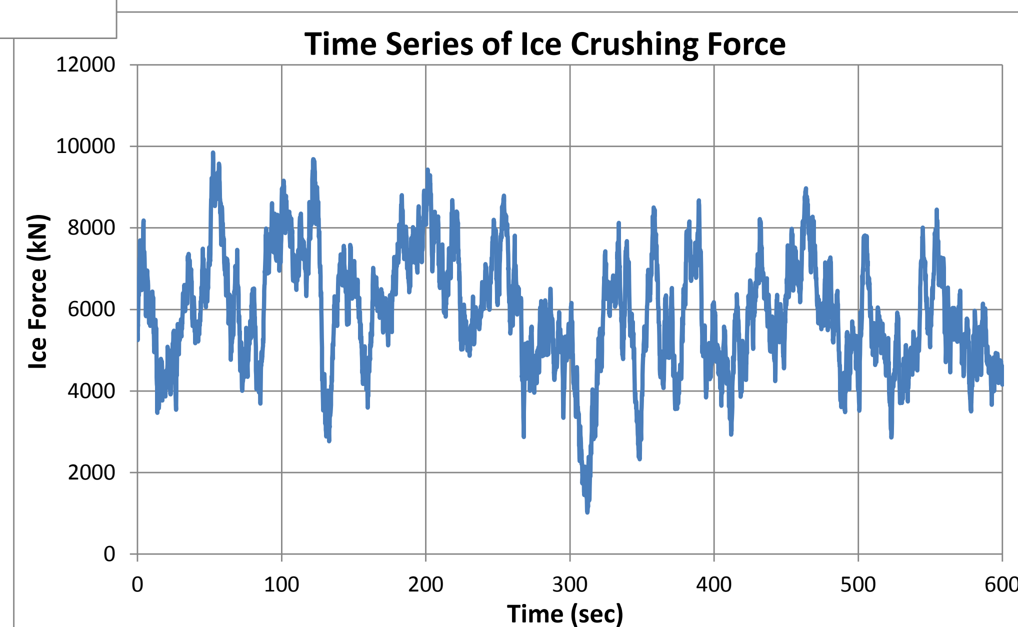
- CRUSHING
  - Ice loads are dependent on ice compressive strength, thickness, velocity
  - Vertical sided structures
  - Loading is generally intermittent
  - However loading frequency can “lock-in” to structure resonance
  - At high velocities loading can be continuous and random

- FLEXURAL FAILURE
  - Ice loads are dependent on ice bending strength, thickness, velocity
  - Added loading from rubble pile up
  - Loading is generally intermittent
  - Peak levels and periods are random

Seven Ice Loading Models

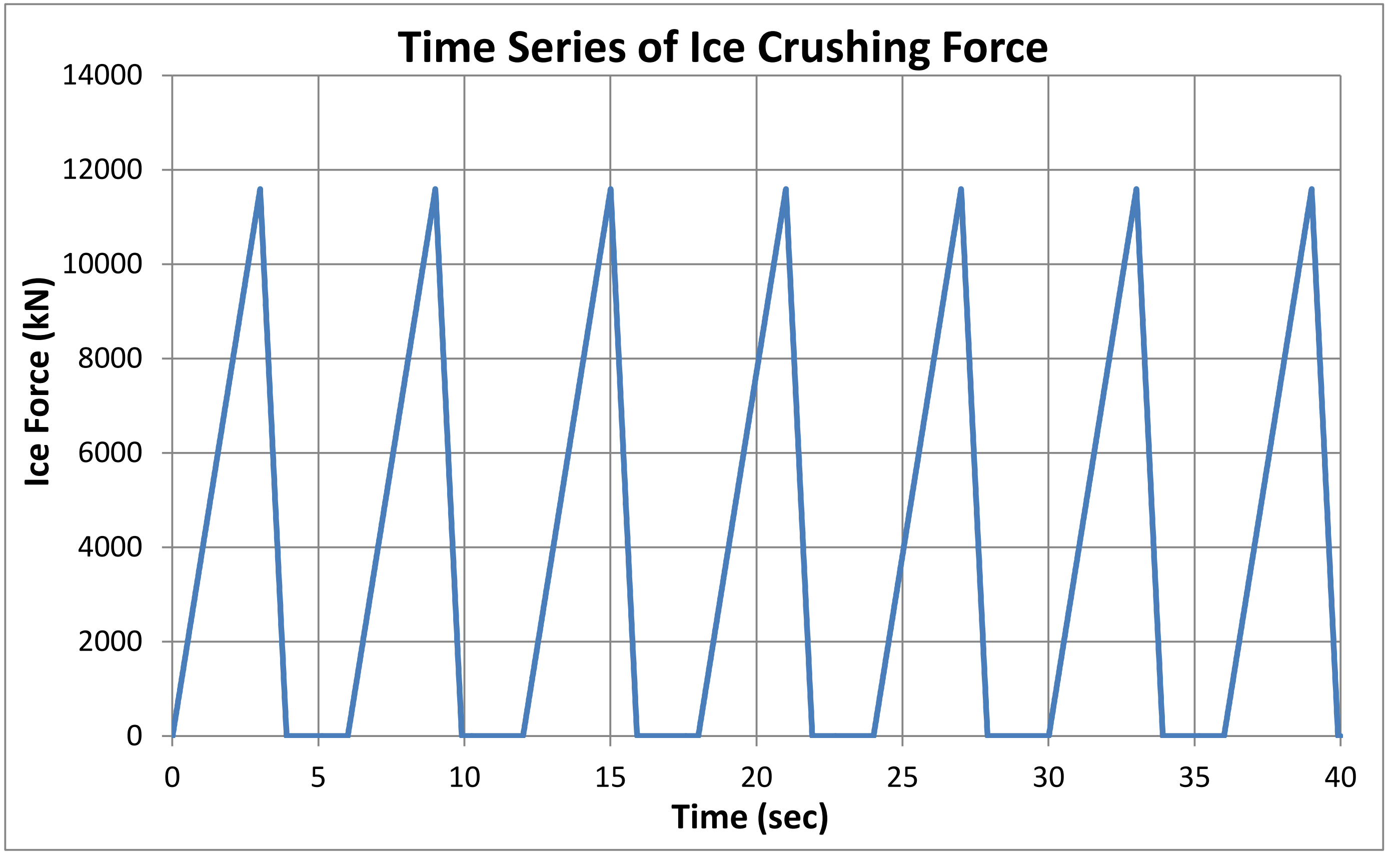
Ice Load Model	Source	Comments
Continuous Random Crushing	Karna 2006	Random waveform based on ice parameters and spectral distribution
Intermittent Crushing	ISO	Intermittent sawtooth waveform at specified frequency
Lock-in Crushing (ISO)	ISO	Sawtooth (ISO) or sinusoidal (IEC) waveform at natural frequency of support structure
Lock-in Crushing (IEC)	IEC	
Coupled Crushing	Maattanen 1998	Lock-in crushing with feedback from structure velocity
Flexural Failure (ISO)	ISO	Bending and snapping against coned surfaces including effects of rubble pile
Flexural Failure (IEC)	IEC	


Power Spectral Density of Ice Crushing Force
Normalized PSD
0.4
0.4
0.3
0.3
0.2
0.2
0.1
0.1
0.0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Frequency (Hz)


Time Series of Ice Crushing Force
Ice Force (kN)
12000
10000
8000
6000
4000
2000
0
0
100
200
300
400
500
600
Time (sec)

Intermittent Crushing Example

- The sawtooth waveform is based on field observations
- Period of waveform >> turbine fundamental period



Lock-in Crushing Example

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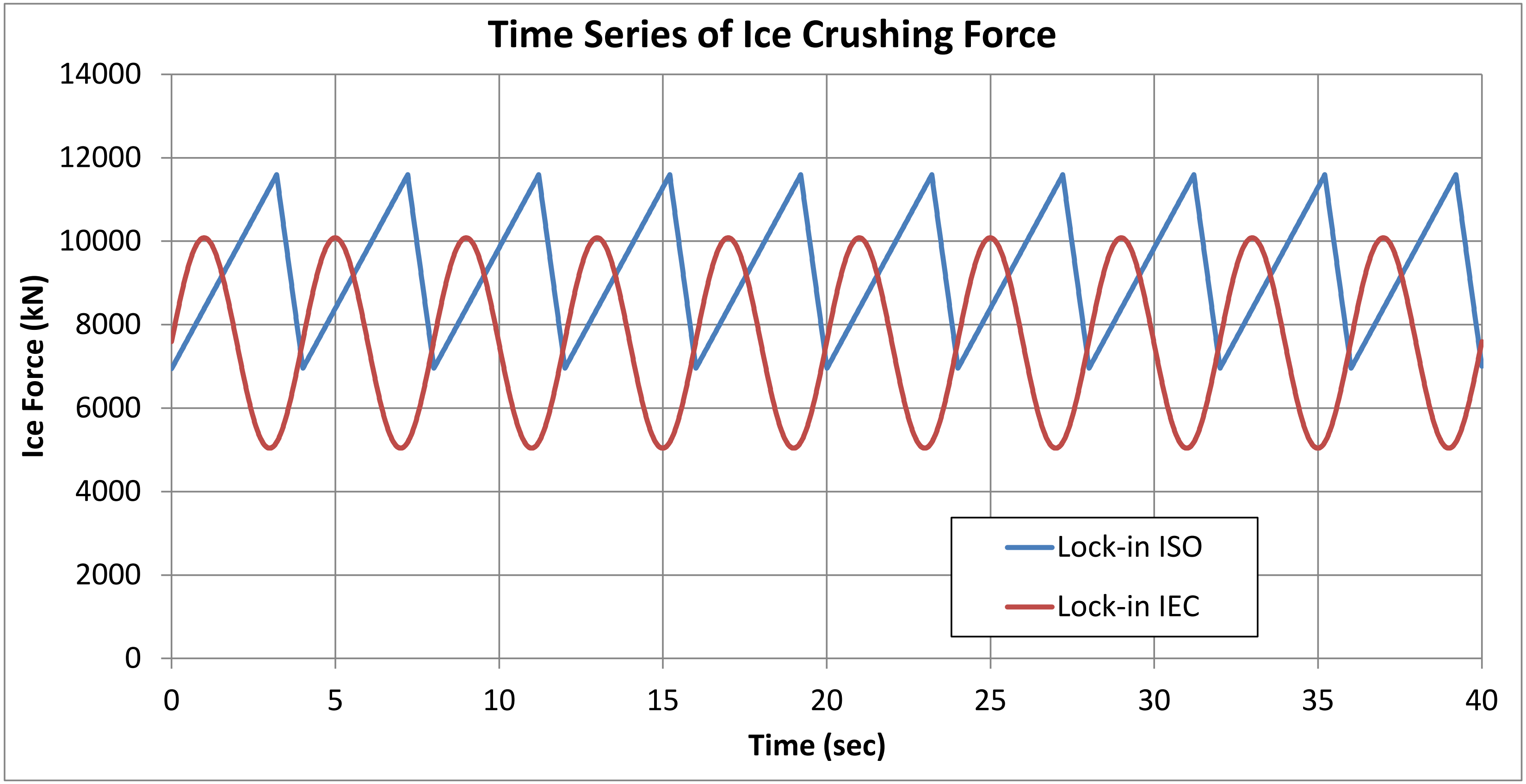
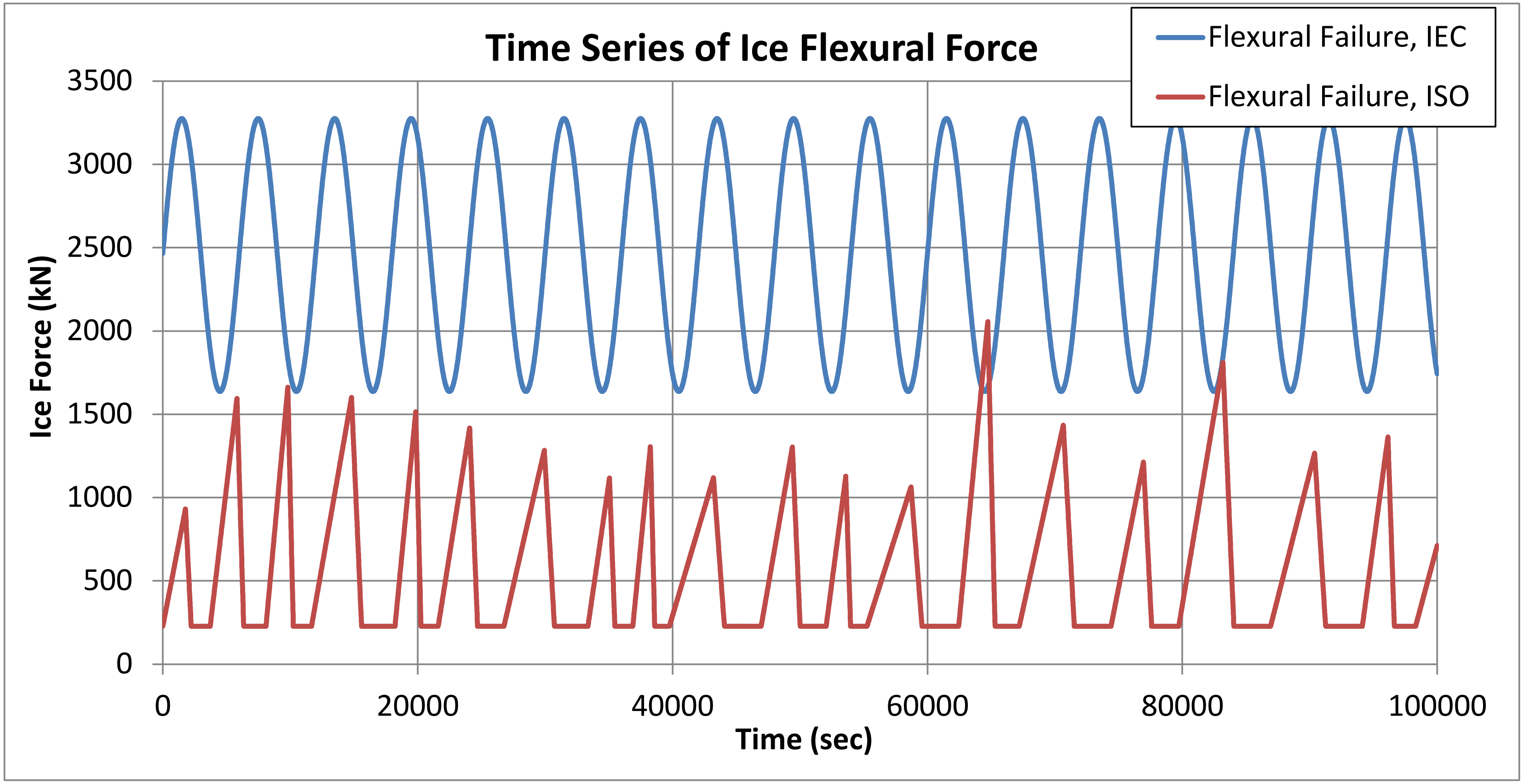
- Frequency of waveform = turbine fundamental frequency
- ISO: sawtooth; IEC: sinusoidal



Flexural Failure Example

- ISO: Period is random, function of ice thickness and velocity
  Peak heights are random, sawtooth waveform
- IEC: Period and amplitude fixed, sinusoidal waveform
- Forces are much lower than for crushing failure mode



Implementation

- All seven modes of ice loading are implemented in Fortran
  - Currently being coupled with FAST by NREL
  - Tested with an external link (DLL, time series files) with ADAMS, Bladed, HAWC2
  - All models provide pre-computed waveforms except coupled crushing, which requires tower velocity as feedback
- All modes implemented and tested except Coupled Crushing

User Settings

- General
  - Random seed
  - Time step
  - Duration
- Ice properties
  - Thickness
  - Velocity
  - Direction
  - Reference strength
  - Flexural strength
  - Modulus of elasticity
  - Density (ice)
  - Density (water)
- Tower configuration
  - Number of legs
  - Diameter
  - Natural frequency
  - Shelter factor (multi-leg)
- Model-specific inputs
  - Too many to list, but generally define the characteristics of ice failure

Validation Approach

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- Scope of verification:
  - Verify implementation with other calculations
  - Run model at a wide range of input parameters to verify behavior
  - Validating ice loading models outside scope of project
  - No ice loading data available for offshore wind turbines
  - Some data available for bridges and other offshore structures used to check order of magnitude of results
- Validation approach:
  - Run test cases across parameter space
    - Verify implementation
    - Verify trends/sensitivities
    - Check for anomalous behavior
    - Tune as necessary
  - Run test cases at extremes and document code limitations

Accomplishments and Progress

- Seven ice load models implemented
- Six ice load models tested
  - Implementation tested with ADAMS, Bladed, HAWC2
- Number of models included and codes tested exceed project expectations

Project Plan & Schedule

Summary	
WBS Number or Agreement Number	DE-EE0005477
Project Number	
Agreement Number	

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Title: Creation of a Model for Interaction of Bottom-Fixed Wind Turbines with Surface Ice for Use with Common Simulation Codes												
Task 1: Generation of computer code and project management												
Task 2: Definition of ice load algorithms and code logic												
Task 4: Testing of code with HAWC2 code												
Current work and future research												
Task 3: Testing of code with FAST simulations												
Task 5: Reporting including theory and users manuals												

Comments

- Initiation date: October 2012; completion date: July 2014
- No schedule slips noted

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators:

- DNV KEMA is subcontracting with Tom Brown, a recognized international expert in ice loading from the University of Calgary.
- Support is provided by NREL for integration of the code into the FAST Framework

Communications and Technology Transfer:

- Source code will be distributed as a standalone package and as part of the FAST Framework
- Papers to be presented at conferences e.g. AWEA, EWEA, AIAA/ASME Wind Symposium

Next Steps and Future Research

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FY14/Current research:

- Project completion is scheduled for July 2014.
- Remaining tasks include:
  - Continue to tune coupled model
  - Integration with FAST
  - Theory and users' manuals
- No barriers to completion are seen

Proposed future research:

- Instrumentation of a turbine undergoing ice loading for validation
- Inclusion of other ice load models to the suite of options

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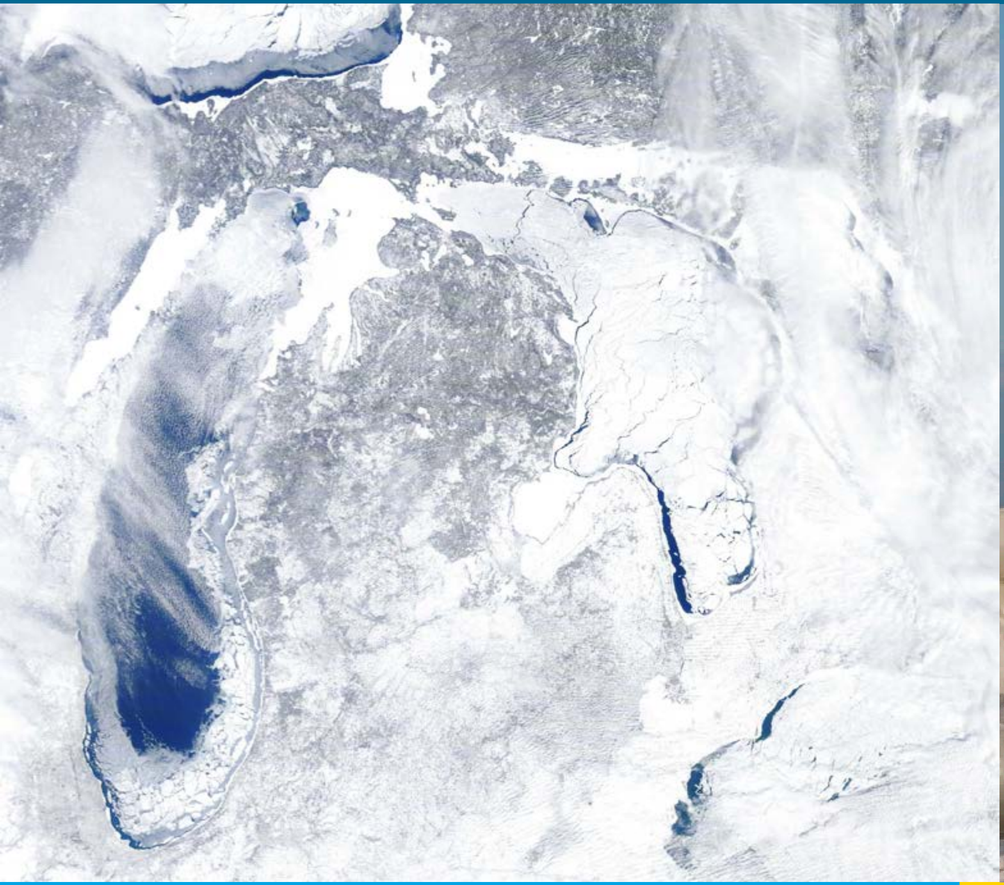


Bottom Fixed Platform Dynamics Models Assessing Surface Ice Interactions for Transitional Depth Structures in the Great Lakes

Dale G. Karr

[University of Michigan]

dgkarr@umich.edu 734 764 3217

March 25, 2014

Budget, Purpose, & Objectives

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

Total DOE Budget [1,2]: $0.000M

Total Cost-Share[1]:$0.000M

Problem Statement:

Offshore wind turbine structures in the Great Lakes will be subjected to ice forces which are often difficult to predict.

Consideration of ice forces is necessary for the design of offshore wind turbines and assessment of safety and performance.

Computer-aided engineering (CAE) tools currently lack the capability to model design-driving ice load effects on offshore turbines.

The project's objective is to develop mathematical modeling capability for the prediction of structural response of offshore wind turbines caused by contact with floating ice features.

[1]*Budget/Cost-Share for Period of Performance FY2012 – FY2013*
[2] *Project remained active using DOE funds received prior to FY2012*

Budget, Purpose, & Objectives

Impact of Project:

The project will enable offshore wind power deployment in cold regions by expanding CAE design tool capabilities and thus enhance reliability and safety, and reduce design timelines.

This project develops an ice-loading module that is coupled to FAST, the CAE tool maintained by the National Renewable Energy Laboratory (NREL) for simulating onshore and offshore wind turbine dynamics.

New capabilities also include expanding the range of turbine designs beyond monopole systems and establishing design ice environments for deeper waters in the Great Lakes.

This project aligns with the following DOE Program objectives and priorities:

- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources
- **Advanced Grid Integration:** Provide access to high wind resource areas, and provide cost effective dispatch of wind energy onto the grid
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

Technical Approach

Current ice model developments include six models for ice crushing, floe impact, ice/lock-in, random vibration and two newly developed models for ice bending and non-simultaneous ice failure.

FAST Version 8 has a new modulation framework to allow coupling of externally developed codes to integrate with the offshore wind turbine simulation. SubDyn and HydroDyn modules within allow for modeling of multi-member structures such as jackets and tripods.

Both the structural response of the turbine and the deformations of the ice features are captured in the time simulations and thus the coupled response of the two systems can be accounted for in the design of intermediate depth turbine systems.

Accomplishments and Progress

A key design requirement is for providing structural resistance necessary to cause ice failure. Non-simultaneous ice failure is a very important aspect of establishing design forces. Our new model offers a technique to accurately predict total ice forces on large structures.

The new modularization framework allows for coupling FAST 8 with the new ice forcing module to investigate governing load cases for multi-pile jacketed structures in cold regions.

A Users' Manual has been developed and a preliminary version has been distributed to interested parties.

Three technical papers have been completed.

Project Plan & Schedule

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

Summary	
WBS Number or Agreement Number	
Project Number	
Agreement Number	

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Bottom Fixed Platform Dynamics Models Assessing Surface Ice Interactions for Transitional Depth Structures in the Great Lakes												
Task 1.0 Develop Ice Load Models												
Task 2.0 Assess Environmental Conditions in Lake Michigan and Lake Huron												
Task 3.0 Implement Load Models and Environmental Conditions into Ice Module												
Task 4.0 Couple Module to FAST												
Task 5.0 Asess Design Drivers for Wind Turbines in Ice												
Task 6.0 Project Management and Reporting												
Current work and future research												
Complete task 4.0												
Complete task 5.0												
Submit journal articles for publication												
Update Users' Manual and submit Final Report												

Comments

- Project original period of 10/1/11-9/30/2013.
- Notice of award received: 3/12/12; project completion revised to 12/31/13.
- No cost extension granted to 6/30/2014 to include the new FAST Version 8.

Partners, Subcontractors, and Collaborators:

National Renewable Energy Laboratory; Senu Sernivas
American Bureau of Shipping; Qing Yu
Keystone Engineering Inc. ; Zachary Finucane

Communications and Technology Transfer:

Industry Presentations and Workshops :

AWEA NREL DOE Workshop.

AWEA OFFSHORE WINDPOWER 2012 Virginia Beach, VA "Offshore Wind Turbine Interacting with Surface Ice"

Michigan Alternative and Renewable Energy Center: Offshore Wind Turbines Vs. Winter on the Great Lakes

American Bureau of Shipping: "An Ice Loading Module for NERL's Offshore Wind Turbine Simulation Package FAST"

Communications and Technology Transfer

Presentations to Academia:

- Michigan Technological University: "Ice/Structure Interaction: Offshore Structural Design"
- University of Toledo: "Ice/Structure Interaction Modelling for Offshore Wind Turbines in the Great Lakes"
- University of California Berkeley: "Ice/Structure Interaction Modeling for Offshore Structures"

Conference Papers, Presentations and Proceedings:

- Offshore Mechanics and Arctic Engineering Conference 2013 "A Surface Ice Module For Wind Turbine Dynamic Response Simulation Using FAST", also submitted to the *Journal of Offshore Mechanics and Arctic Engineering*
- Arctic Technology Conference 2014 "An Ice-Structure Interaction Model for Non-Simultaneous Ice Failure"
- Offshore Mechanics and Arctic Engineering Conference 2014 "Ice Non-simultaneous Failure, Bending and Floe Impact Modeling For Simulating Wind Turbine Dynamics Using FAST" , also submittal to the *Journal of Offshore Mechanics and Arctic Engineering*

Next Steps and Future Research

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

FY14/Current research:

1. The ice module written in the new FAST 8 framework is being integrated with FAST and software is being verified.

2. Modelling a newly designed twisted jacket for running the IEC ice load cases to identify governing loads is a current focus.

Proposed future research:

1. New ice pressure ridge models with non-simultaneous failure zones would offer further improvement in ice force predictions.

2. Presently there is no coupling between ice and wind and waves; such an added capability in FAST would enable us to better asses effects of environmental conditions.

3. The newly developed ice models eventually should be validated with actual field measurements or scaled ice model tests.

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

Shallow Water Offshore Wind Optimization for the Great Lakes

Freshwater Wind I, LLC

Stanley M. White, P.E.

Ocean and Coastal Consultants, Inc.

Stanley.white.pe@gmail.com 860-574-3904

March 25, 2014

Budget, Purpose, & Objectives

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

Total DOE Budget [1,2]: $0.000M

Total Cost-Share[1]:$0.142M

Problem Statement: The Great Lakes hold a large potential for offshore wind energy development. However, there are significant challenges due to vessel restrictions and ice not found in existing offshore wind projects. How can offshore wind be developed in Lake Erie and lower LCOE for a utility scale project?

Impact of Project: The Project demonstrated that offshore wind development in Lake Erie using a GBF is viable and able to reduce LCOE by 22.3%

This project aligns with the following DOE Program objectives and priorities

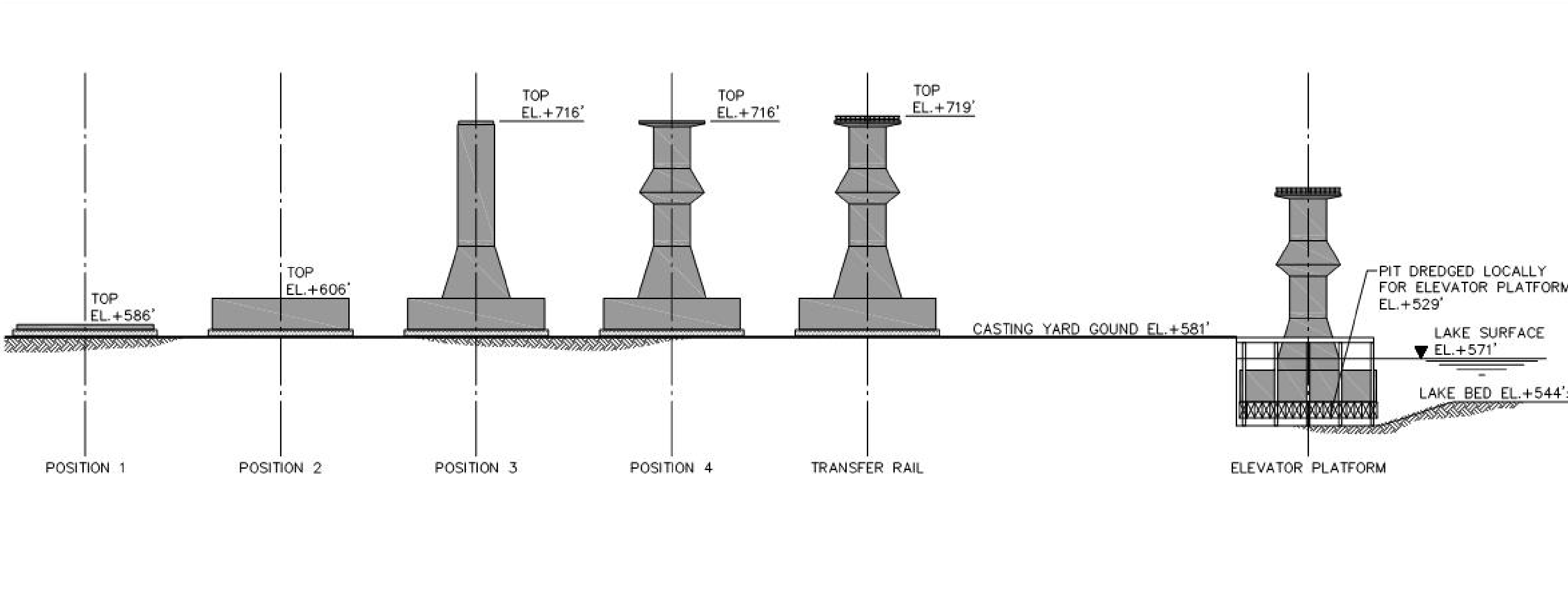
- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries

[1] *Budget/Cost-Share for Period of Performance FY2012 – FY2013*
[2] *Project remained active using DOE funds received prior to FY2012*

Technical Approach

- Project used historic geotechnical data coupled with recently performed geotechnical investigation
- Project developed “assembly line” process for fabrication
- Project developed innovative concept designs for three different semi-floating Gravity Base Foundations
- Project developed innovative concept designs for supplemental floatation pontoons that eliminate heavy lift barges
- Project addressed lake ice issue
- Project results applicable to a wind range of freshwater and ocean sites

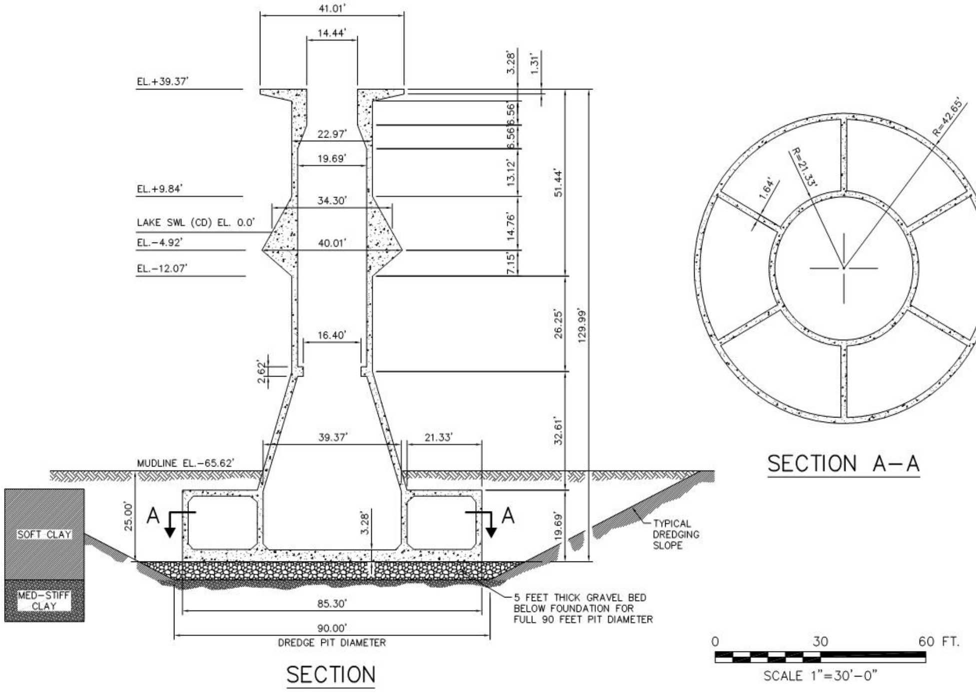
Technical Approach – Fabrication Yard



- 50 Foundations per year
- 24 GBF fabricated simultaneously, 6 parallel Assembly Lines

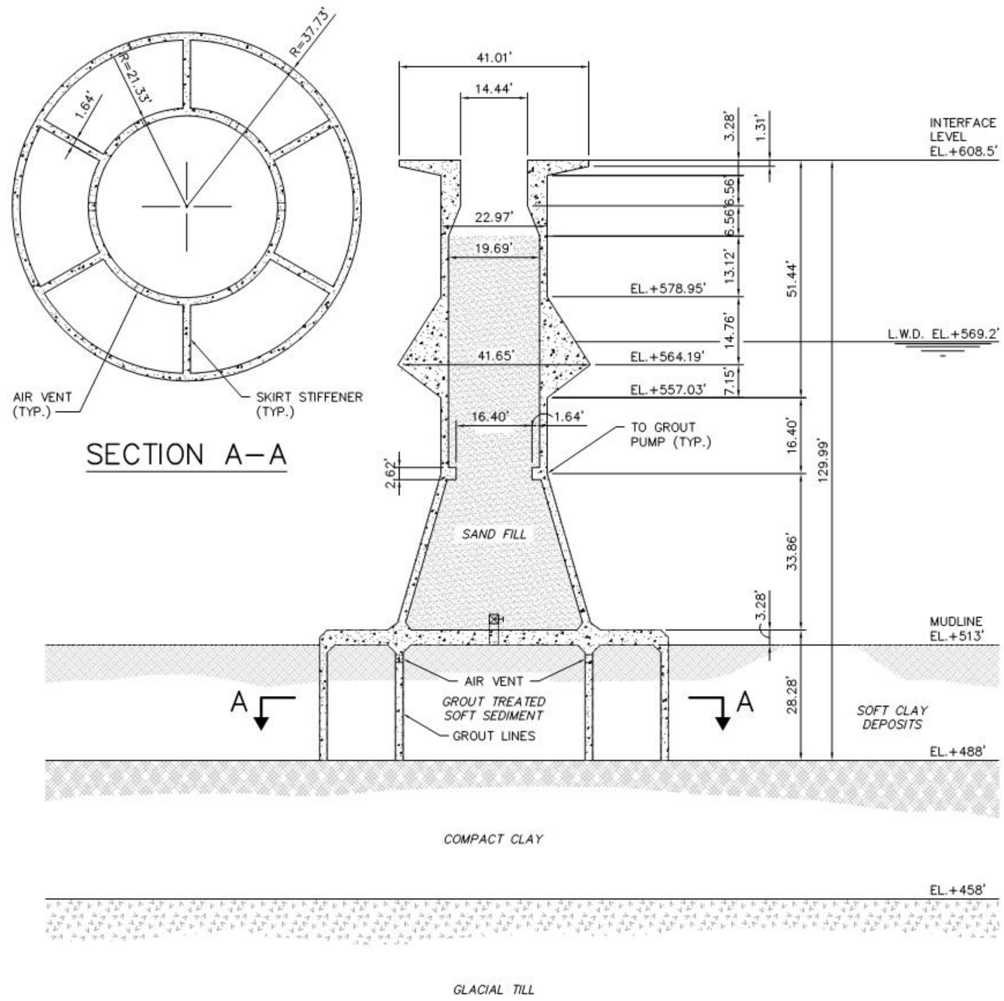
Technical Approach – Semi Floating GBF

- Semi-floating GBF eliminates need for heavy lift vessel for foundation installation
- Lake bottom requires preparation
- Utilizes production line fabrication
- Local supply chain



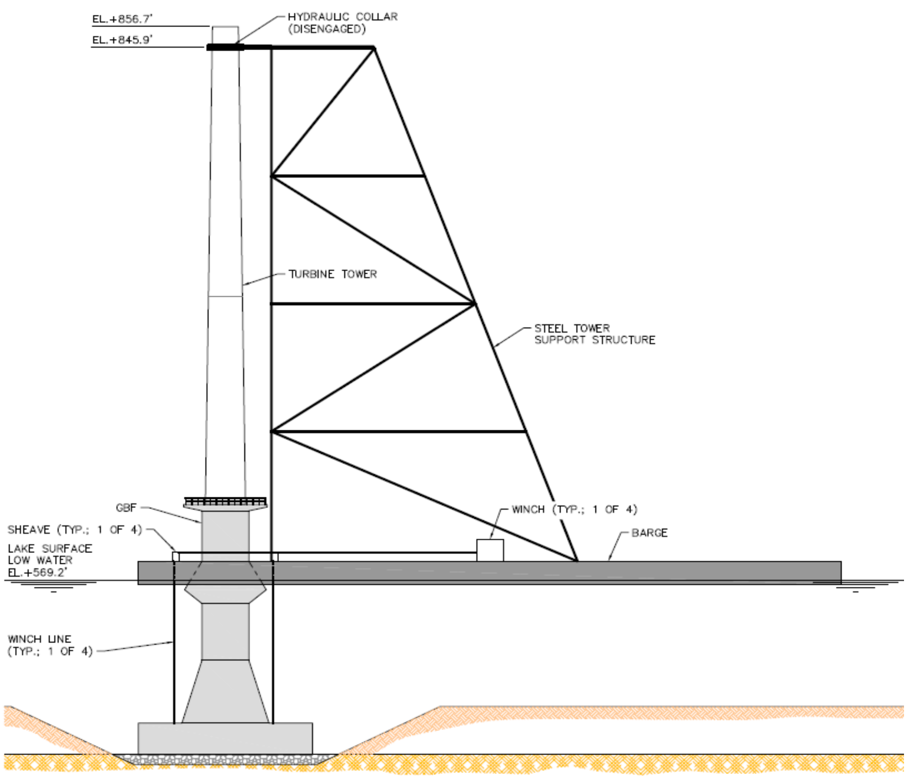
Technical Approach – Penetration Skirt GBF

- Semi-floating GBF eliminates need for heavy lift vessel for foundation installation
- Penetration skirt eliminates the need for lake bottom preparation
- Interior grout ports utilized for soil improvements
- Utilizes production line fabrication
- Local supply chain



Technical Approach – Integrated GBF and Tower

- Semi-floating GBF eliminates need for heavy lift vessel for foundation installation
- Lake bottom preparation required
- Utilizes production line fabrication
- Requires specialty barge to stabilize integrated GBF and tower
- Integrated approach reduces installation steps and vessel costs
- Might be able to install nacelle and rotor at port



The project was substantially complete by 31 December 2013, approximately nine months ahead of schedule.

The project was performed to the satisfaction of DOE within the original budget.

The project demonstrated that Gravity Base Foundations are a cost effective support structure for large turbines (5.0MW or larger).

The project demonstrated that LCOE could be lowered by 22.3% using assembly line fabrication techniques and no heavy lift crane barges for the support structure. Additional reductions possible.

SOPO Task Status:

Task 1 Develop Cost Model and Baseline COE	Complete (green)
Task 2 Document Site Conditions	
2.1 Updated Wind Data Receipt and Incorporation	Complete (green)
2.2 Geotechnical Data Receipt and Incorporation	Complete (green)
Task 3 Conceptual Analysis Design Overview	Complete (green)
Task 4 Conceptual Analysis Report	Complete (green)
Task 5 Develop and Study Innovations	

5.1 BOS Engineering To Produce Component Dimension and Material	Complete (green)
5.2 Constructability Evaluation Tasks	Complete (green)
5.3 Turbine Innovations	Complete (green)
5.4 Wind Plant Layout	Complete (green)
5.5 O&M Strategy	Complete (green)
Task 6 Evaluate COE Impact of Innovations	Complete (green)
Task 7 Project Management and Reporting	Complete (green)

Complete	green
Not Applicable	yellow
In Progress	red

Project Plan & Schedule

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

Summary	
DE-FOA-0000415	
EE0005488	
Shallow Water Offshore Wind Optimization for the Great Lakes	

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Shallow Water Offshore Wind Optimization for the Great Lakes												
Develop Costs Model and Baseline LCOE												
Document Site Conditions												
Develop and Study Innovations												
BOS Engineering to Produce Component Dimensions and Quanities												
Constructability Evaluation Tasks												
O&M Strategy and COE Impact of Innovations												
Current work and future research												
DOE Webinar												
Present at Office Wind Conference												

Comments

- Project Start: 09/30/2011 Project Scheduled Completion: 09/30/2014
- Project has been completed
- There are no outstanding issues

Partners, Subcontractors, and Collaborators:

Freshwater Wind I, LLC – Principal Investigator

The project partners that participated in the cost share:

OCC|COWI – Designer of record

Weeks Marine, Inc. – Project Contractor

URS Corporation – Geotechnical Desktop Study

LEEDCo – Geotechnical Program (2013) (FOA DE-EE0005989)

The project partner that did not participate in cost share:

NREL – Cost Model and LCOE

Communications and Technology Transfer:

30 May 2013 DOE Presentation Conceptual Design Report (Interim Report)

27 February 2014 DOE Webinar Concept Design Report (Final Report)

TBD Presentation at Offshore Wind Conference

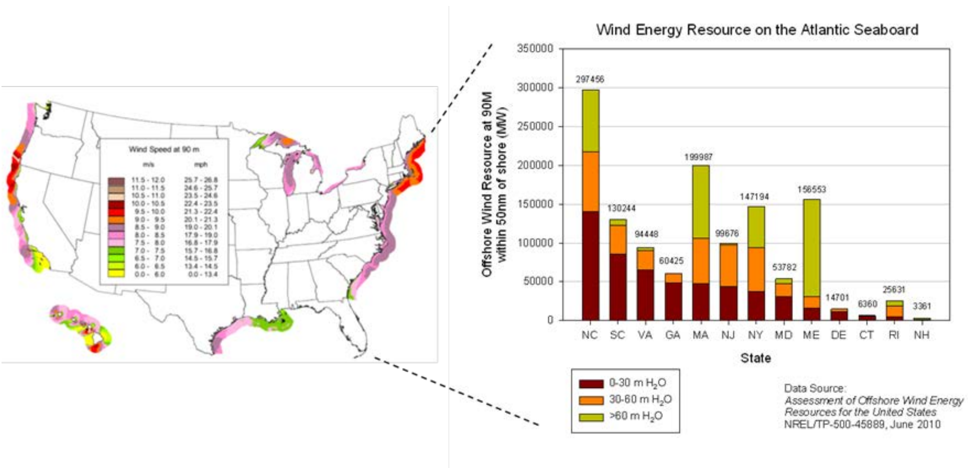
Next Steps and Future Research

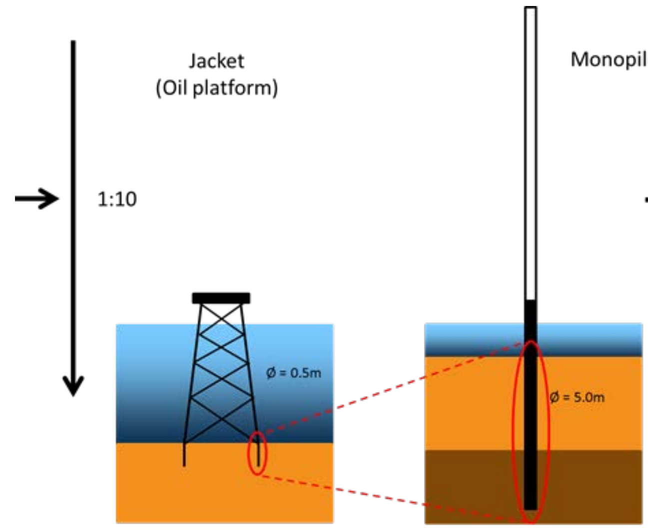
FY14/Current research: The project is complete.

Proposed future research: At this time there are no plans for future research related to this project.

Suggest further development of:

1. GBF with Penetration Skirt to advance the Body of Knowledge of industry.
2. Work with turbine manufacturers to allow nacelle and rotor to be installed at the staging area and floated out.





SRNL SAVANNAH RIVER NATIONAL LABORATORY · Burroughs & Chapin Center for Marine & Wetland Studies, Coastal Carolina University · MMI engineers • scientists • innovators · NREL NATIONAL RENEWABLE ENERGY LABORATORY

Advanced Technology for Improving the Design Basis of Offshore Wind Energy Systems

Ralph L. Nichols

Savannah River National Laboratory

Ralph.nichols@srnl.doe.gov, 803.725.5228

March 2x, 2014

Budget, Purpose, & Objectives

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

Total DOE Budget[1]: $.590M

Total Cost-Share[1]:$0.000M

Problem Statement: Forty percent of the offshore wind energy off the Atlantic Coast is located in shallow water on the outer continental shelf (OCS) susceptible to hurricanes. Current design codes address hydrodynamic loads on structural members that have a small diameter relative to wave length, and do not rigorously address hydrodynamic loads from steep and breaking waves on large diameter bodies. The slap and slam loads from plunging breakers lead to large overturning moment (OTM) loads and are the largest contributor to OTM loads in big storms at wind speeds above the operating range of 25m/s.

Impact of Project: Advance the state-of-the-art for determining the design basis due to breaking waves reducing the uncertainty in design basis for offshore wind power generation systems and resulting in more robust designs. Inform standards making bodies with new data regarding loads from breaking waves.

This project aligns with the following DOE Program objectives and priorities

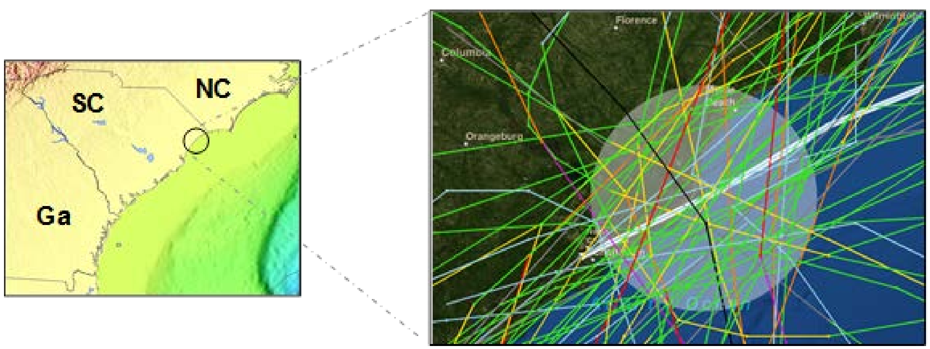
Mitigate Market Barriers: Reduce market barriers to preserve or expand access to quality wind resources.

Optimize Wind Plant Performance: Reduce Wind Plant Levelized Cost of Energy (LCOE)

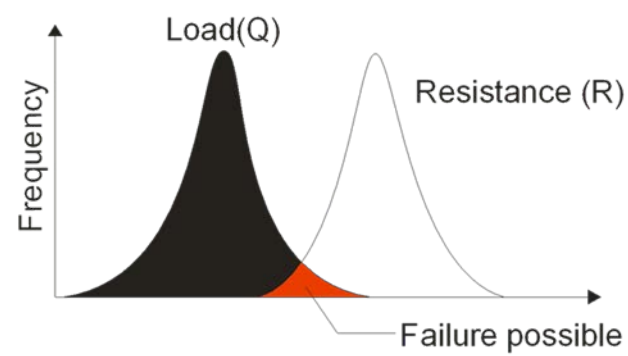
[1]***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach

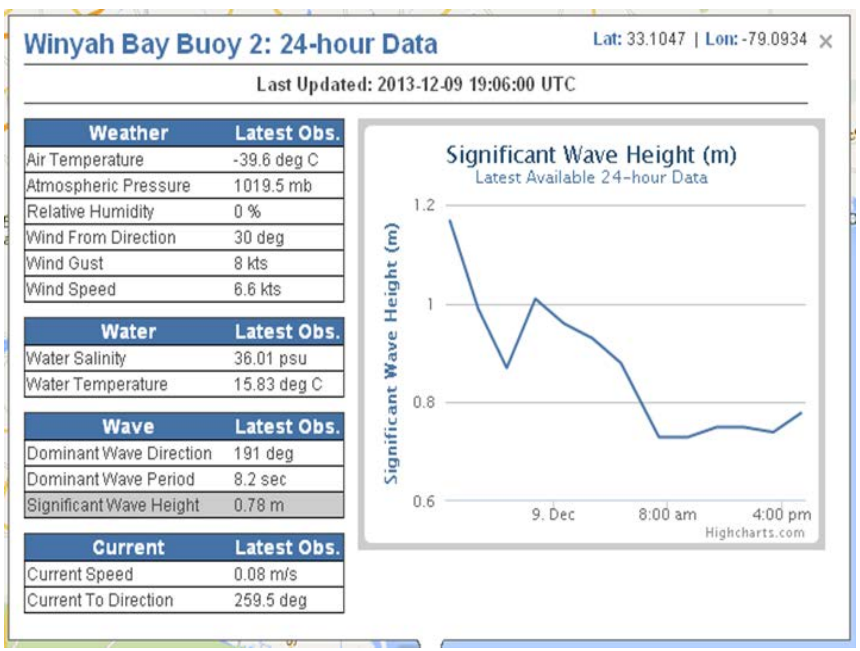
- This study focuses on the portion of the South Atlantic Bight that extends from North Carolina to Georgia. This area is characterized by extensive shallow water (<30m) on the OCS, frequent tropical cyclones, and a large portion of the shallow water wind energy resource in the Atlantic Ocean.
- Spatial and temporal variability of met-ocean conditions will be analyzed using a dynamically coupled met-ocean model assembled from software in the public domain. Specifically, WRF, SWAN, and ROMS will be coupled using the Earth Science Modeling Framework from NCAR. Publically available data and data from the project will be used to validate simulation of storms.
- Buoys equipped with an ADCP, AWAC, water quality sensors, and weather station will be deployed to characterize met-ocean conditions. The AWAC signal will be analyzed using new methods to identify trends in air bubble density in an effort to distinguish breaking waves from non-breaking waves.
- Use CFD model to simulate steep and breaking waves and hydrodynamic loads on monopile foundations. Compare results to forces predicted by existing design codes.
- Develop team with members from industry, academia, and national laboratories to assemble assets necessary to conduct project.

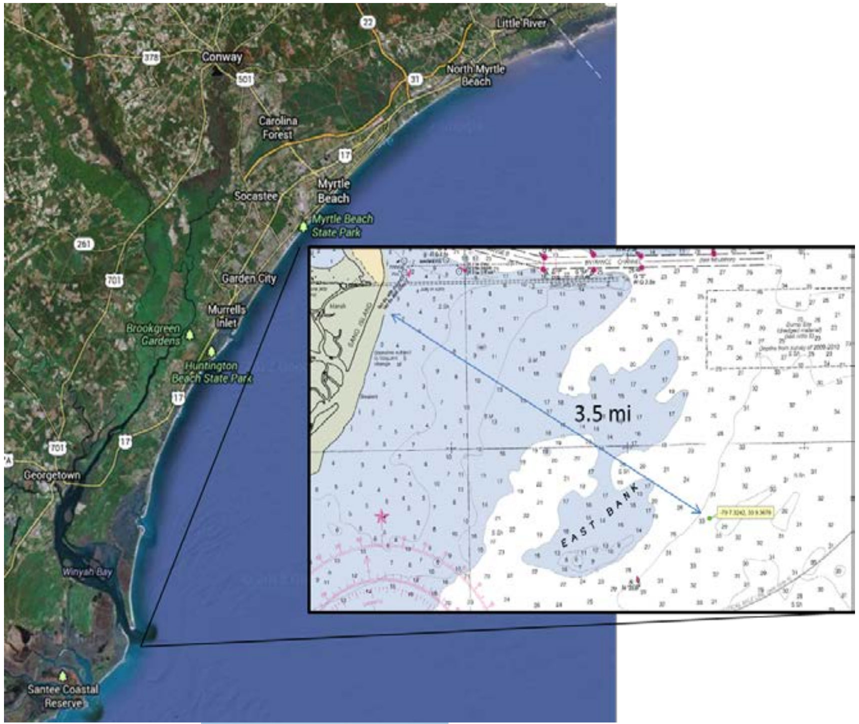


Tracks for all tropical cyclones that passed within 50 miles of the study location between 1851 and 2005.



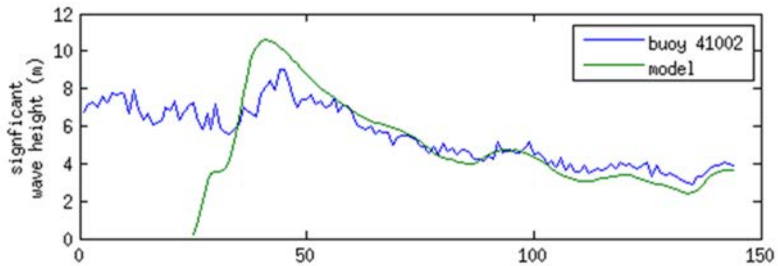
- Research Site Selected
- Buoys and AWAC deployed in in hurricane area.

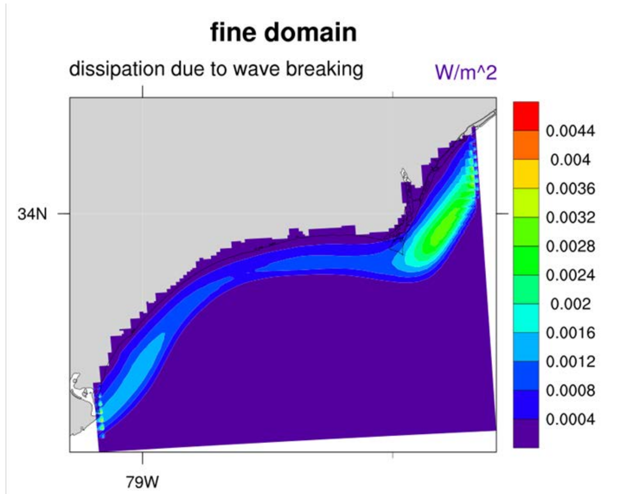


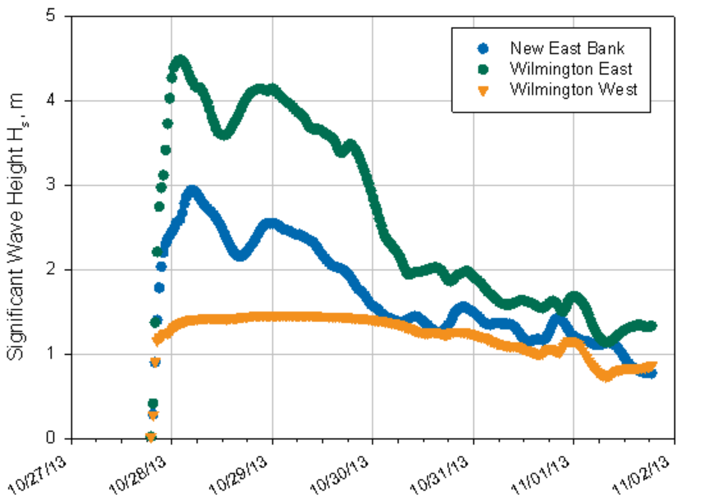


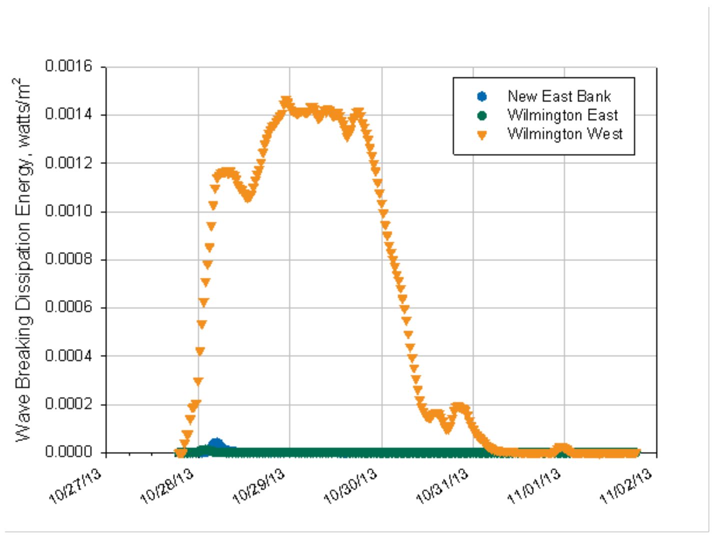
Accomplishments and Progress

- Dynamically coupled met-ocean model operational and validated. Built using open source met-ocean models and computational framework.
- One storm analyzed, Hurricane Irene

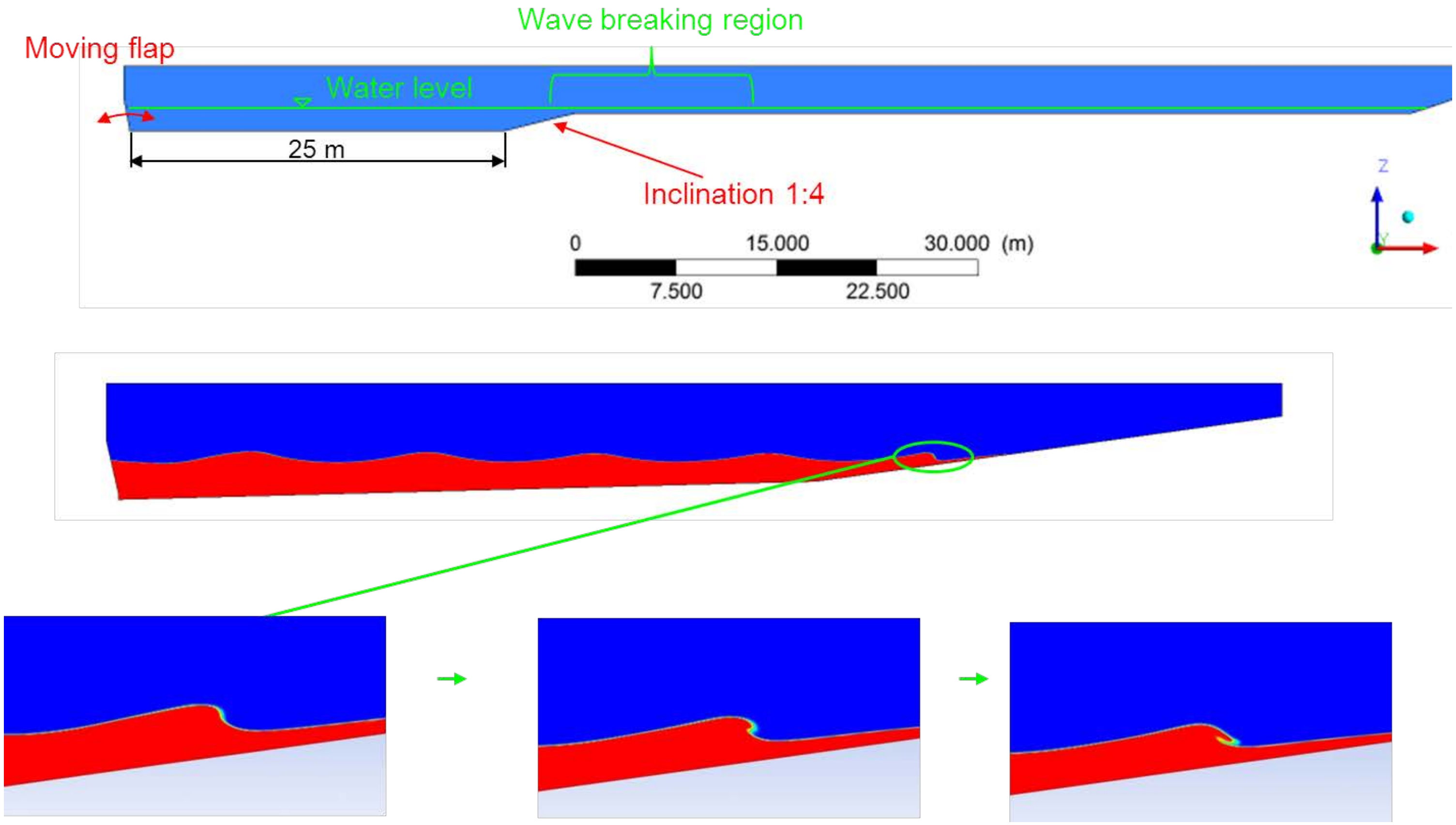








2d CFD simulation of breaking waves completed



Project Plan & Schedule

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

Summary	
WBS Number or Agreement Number	
Project Number	24628
Agreement Number	

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Wind Energy Forecasting Methods and Validation for Tall Turbine Resource Assessment												
Review existing data and model results												
Prepare maps of wave parameters												
Identify field site												
Prepare buoy and AWAC for deployment												
Deploy buoy and AWAC												
Current work and future research												
Analyze additional storms with met-ocean model												
CFD modeling of waves at test site												

Comments

- Initiation date July 1, 2012, Completion date June 30, 2015
- Project was delayed to clarify subcontracting responsibilities

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

- Coastal Carolina University
- MMI Engineering
- National Renewable Energy Laboratory

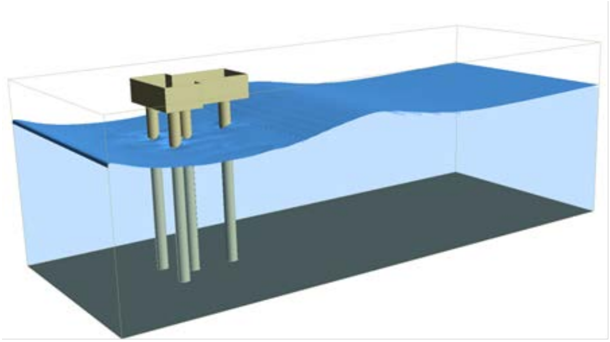
Communications and Technology Transfer

- Presented at EWEA Offshore 2011 and 2013
- Presented at AWEA Offshore 2012, and 2013
- Presented at 2011 Offshore Technology Conference
- Presented at AGU Ocean Sciences 2014
- Presented at AMS Annual Meeting 2014
- Participated in 2 meetings on US involvement in standards development

Next Steps and Future Research

FY14/Current research:

- Analyze 2 additional storms
- Prepare maps of wave statistics from storms
- Continue operating buoy and AWAC
- Initiate 3d CFD modeling of waves and interaction with monopile
    - Numerically intensive, leveraging teams computing resources



Proposed future research:

- Validate CFD modeling using larger scale measurements
    - Parametric studies
- Investigate effect of cyclic lateral loads on soil strength

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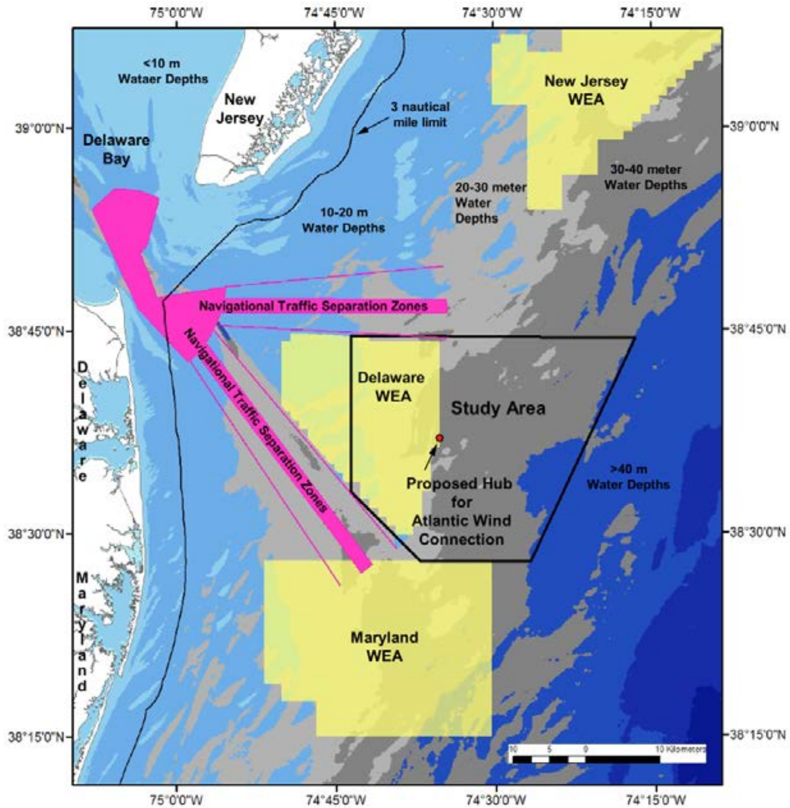


System Design Optimized for a Large-Turbine Wind Farm near Wilmington Canyon

Dr. Willett Kempton

University of Delaware

willett@udel.edu 302-831-0049

3/25/2014

Budget, Purpose, & Objectives

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

Total DOE Budget [1,2]: $0.000M

Total Cost-Share[1]:$0.018M

Problem Statement: A principal barrier to deployment of offshore wind energy is cost, in part driven by component specifications that may contribute to cost of capital investment.

Impact of Project: The project is developing a cost-optimized, integrated system design of an offshore wind farm in order primarily to reduce the cost of energy and secondarily to shorten deployment timeline of offshore wind energy.

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources
- **Advanced Grid Integration:** Provide access to high wind resource areas, and provide cost effective dispatch of wind energy onto the grid

[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

[2] ***Project remained active using DOE funds received prior to FY2012***

Technical Approach

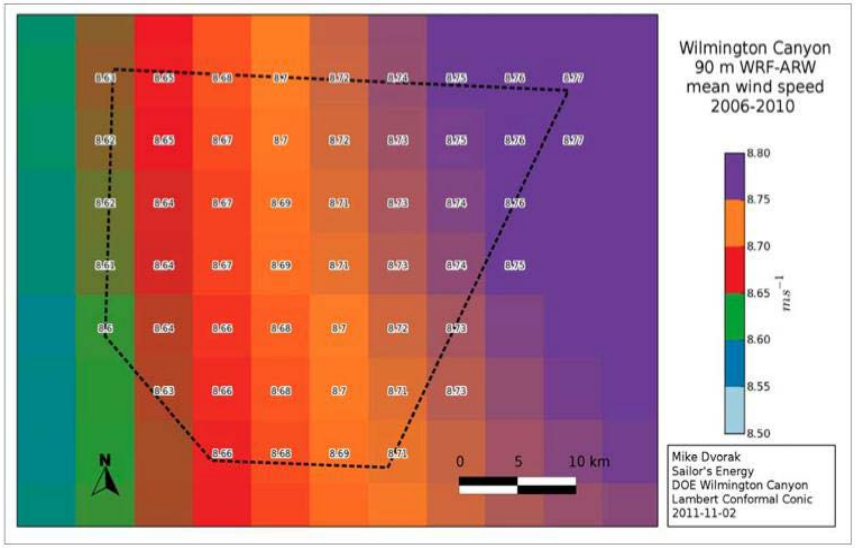
Integrated design: involve all firms involved in the design, installation, construction of wind turbines and interconnection infrastructure, plus metocean

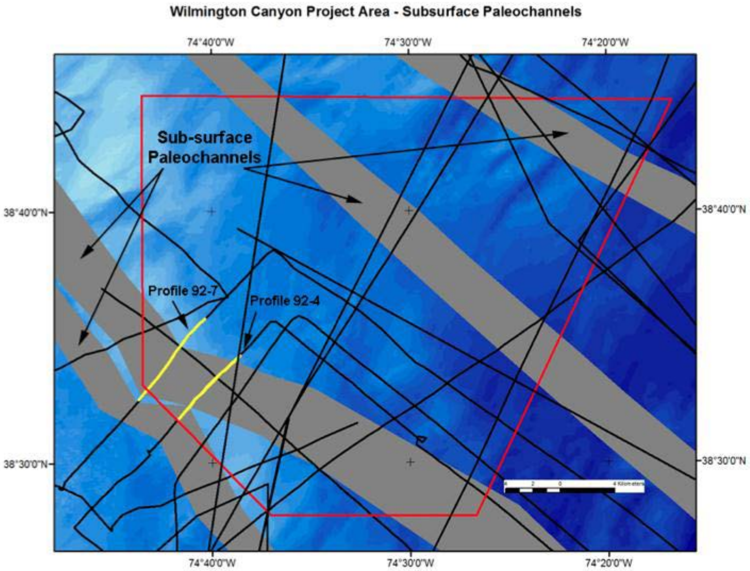
- Case study location near Wilmington Canyon
- Joint design meetings with partners for first-cut designs combining integrated turbine, foundation, vessel, and installation

Currently analyzing costs and benefits of suction bucket versus jacket foundations, with matching vessel and process to minimize capital cost

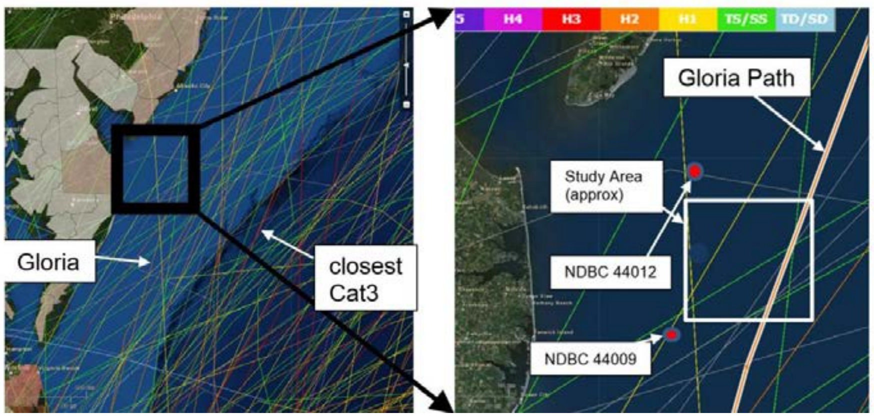
This design project is unique because integrates all players to achieve collective cost and time reductions.

- Characterized the site wind resource and geology to identify suitable areas for development

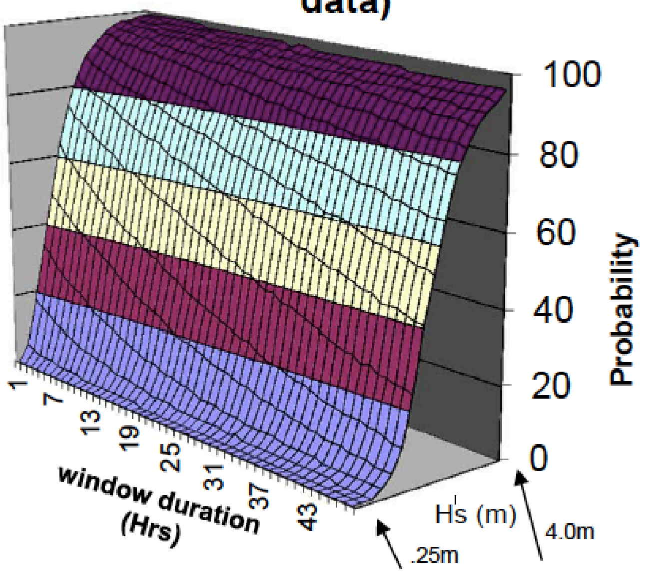




- Characterized site wave dynamics, hurricane occurrences, significant wave heights, sea states

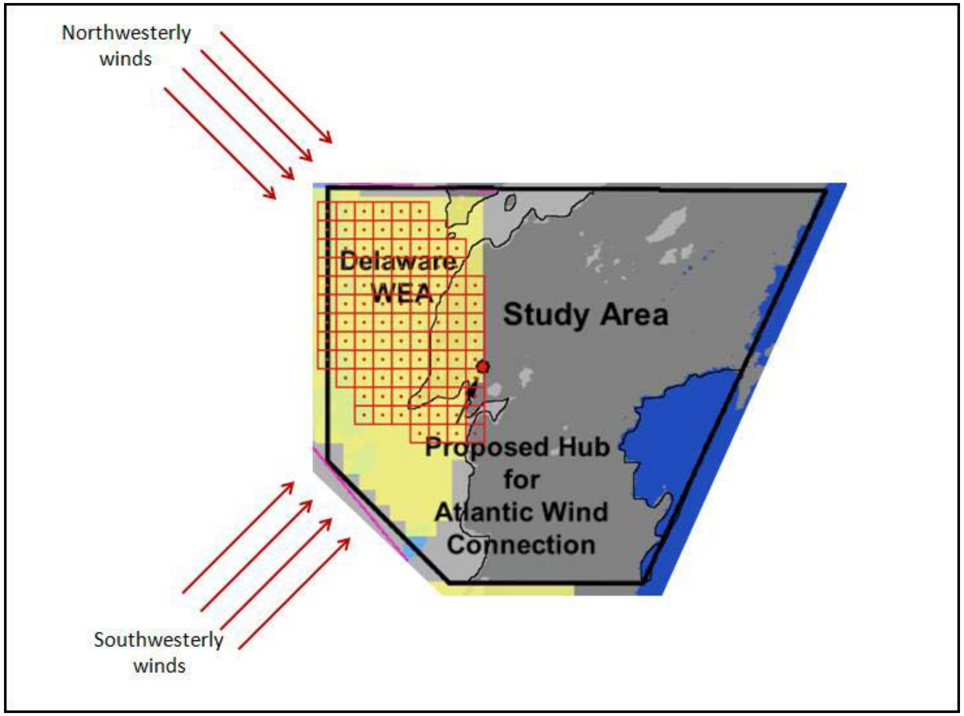


Probability of qualifying sea state (January data)

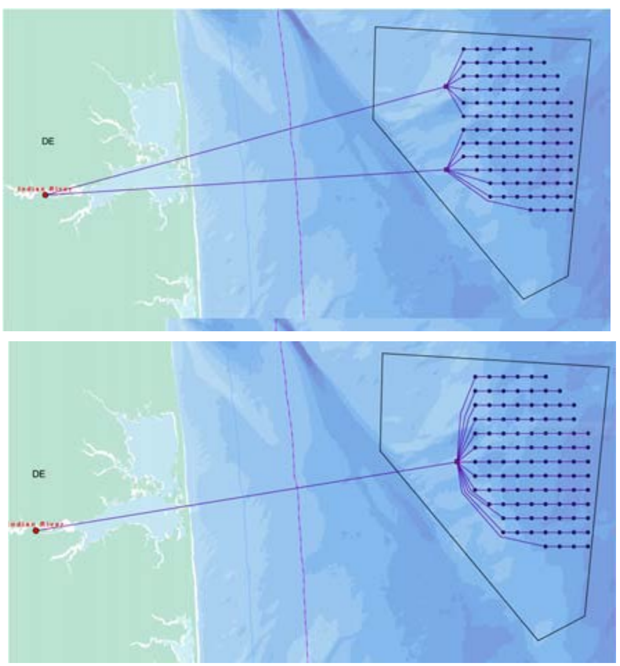


Accomplishments and Progress

- Identified appropriate spacing due to wake losses: 10D
- Location of wind turbines is in intermediate depth waters (~30 m), per proposal

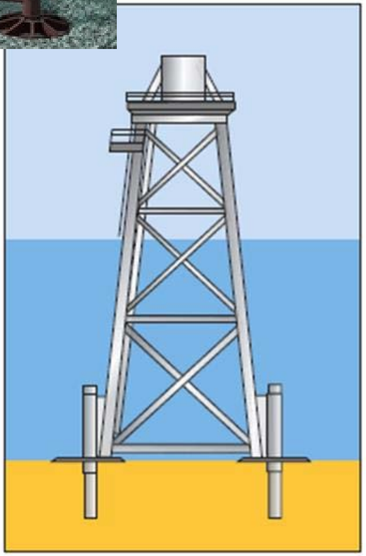


- Electrical system layouts: AC radial ties vs. DC interconnection
- Remaining work includes cost calculations and transmission losses



http://atlanticwindconnection.com

Accomplishments and Progress



- **Design option 1**
  - All turbines will be assembled in quay on jacket structure that will be floating on suction buckets
  - Deployment options are still being considered
    - self-buoyant tow
    - auxiliary buoyancy tow
    - semi-submersible installation vessel
    - winch barge
    - crane barge
- **Design option 2**
  - Jacket structure with piles
  - Conventional deployment

Accomplishments and Progress

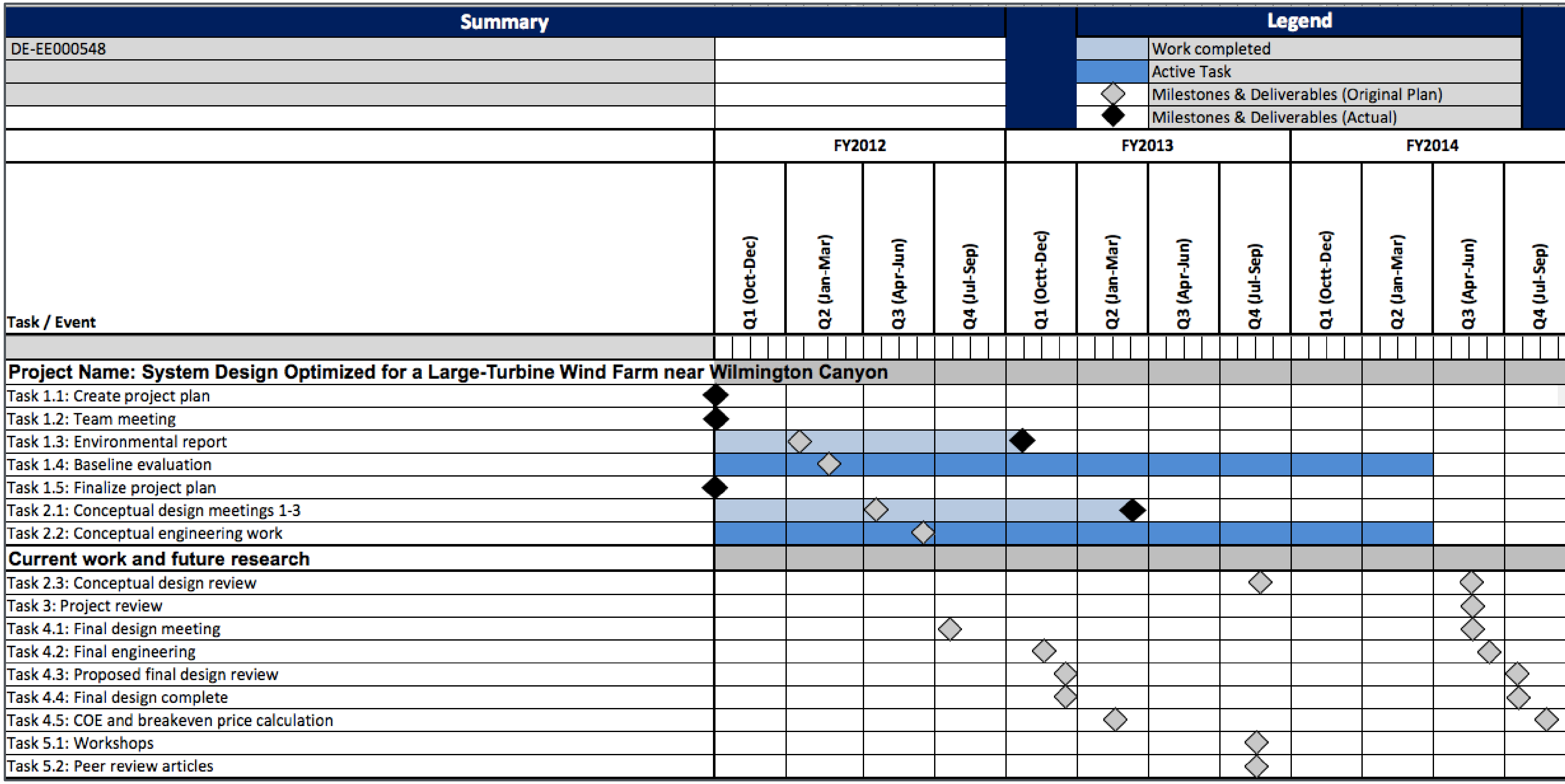
- Behind original schedule due to partners dropping and delays on some tasks:
  - Acquiring geotechnical data
  - Partners withdrawing (Clipper Windpower, Saipam)
  - Creating new partnerships (SPT Offshore, Steel Fabricators Erectors)
  - Timing of release of funding

- Still able to realize goals, within the revised timeline

- Anticipate reduced capital and faster deployment, to reduce cost barriers for offshore wind

Project Plan & Schedule

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



Comments

- Original initiation date: October 2011, Completion date: August 2015
- Task 1.4: Plan change requested to allow simultaneous baseline and proposed design evaluation
- Task 2.2: 95% complete, vessel concepts for suction underway

Project Budget

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

Budget History When Work Was Done					
FY2012		FY2013		FY2014	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$59,512	$0	$156,078	$18,219	$12,393	--

Budget History When DOE Funded UD					
FY2012		FY2013		FY2014	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$0	$0	--	$18,219	--	--

- Total DOE contribution: $227,983
- Total cost-share: $18,219

Research Integration & Collaboration

Partners, Subcontractors, and Collaborators:

- Clipper Windpower (specifications for a 10 MW offshore machine; fully designed but not planned for production)
- CG Global
- Atlantic Grid Developers
- Moffatt and Nichol: Gerry Houlahan
- Weeks Marine (vessel design and cost)
- Independent: Alberto Tono (vessel design and turbine deployment)
- SPT Offshore (offshore wind foundations)
- University of Aalborg (suction bucket design)
- Steel Suppliers Erectors (Dan Bloom, estimate cost of subsea structure build)

Communications and Technology Transfer: None to date.

Next Steps and Future Research

FY14/Current research: .

- Conceptual Design Review: decide on single final design
- Project Design Review: review design results with DOE
- Final Design Meeting: final design refinements
- Cost Calculations: cost-of-energy and break-even price, gross annual energy production, HVDC variant price
- Dissemination

Proposed future research: Further work on whether float-out would be with rotor attached or separate. If detailed cost calculations confirm lower cost of our design, then: 1. more detailed vessel design; 2. secure partners and funding for a 2-4 turbine install and operate, 3. document and measure demonstration, 4. seek commercial user.

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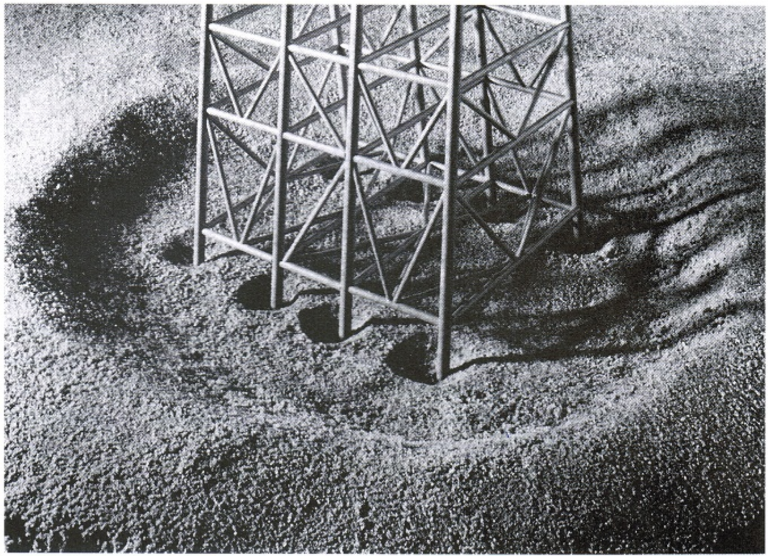
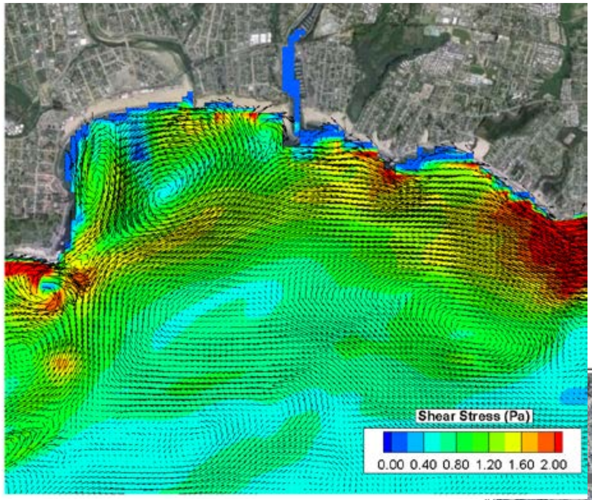
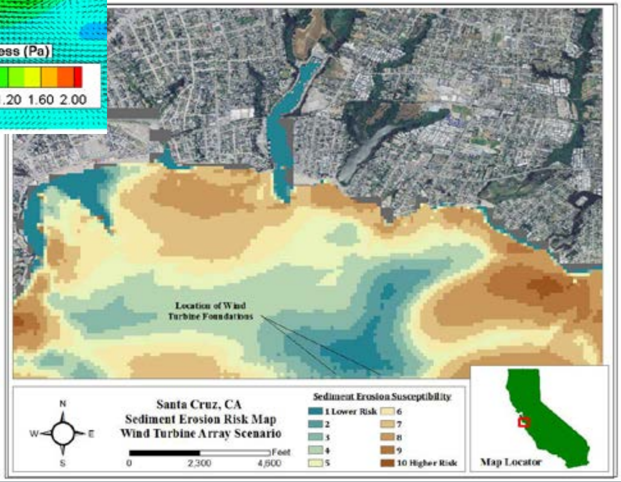






Offshore Wind RD&T: Sediment Transport

Daniel Laird

Sandia National Laboratories

dllaird@sandia.gov; 505-844-6188

March, 25, 2014

Budget, Purpose, & Objectives

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

Total DOE Budget[1]: $.550M

Total Cost-Share[1]:$0.000M

Problem Statement: Sub-aqueous Offshore Wind (OW) structures must perform with *minimal* maintenance. A primary risk driver for OW projects is often the potentially harmful interaction between OW sub-structures/cables and the seafloor.

Impact of Project:

1) **Reduce installation and lifecycle maintenance costs** through intelligent siting and design of OW array.
2) **Reduce permitting time and costs** by enabling prediction of site-specific environmental responses to OW farm designs

Aligns with these DOE Program objectives and priorities:

- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy commercialization

Allow developers to **assess and minimize wind farm and ecosystem risk** from seafloor-structure interactions to reduce LCOE and accelerate deployment

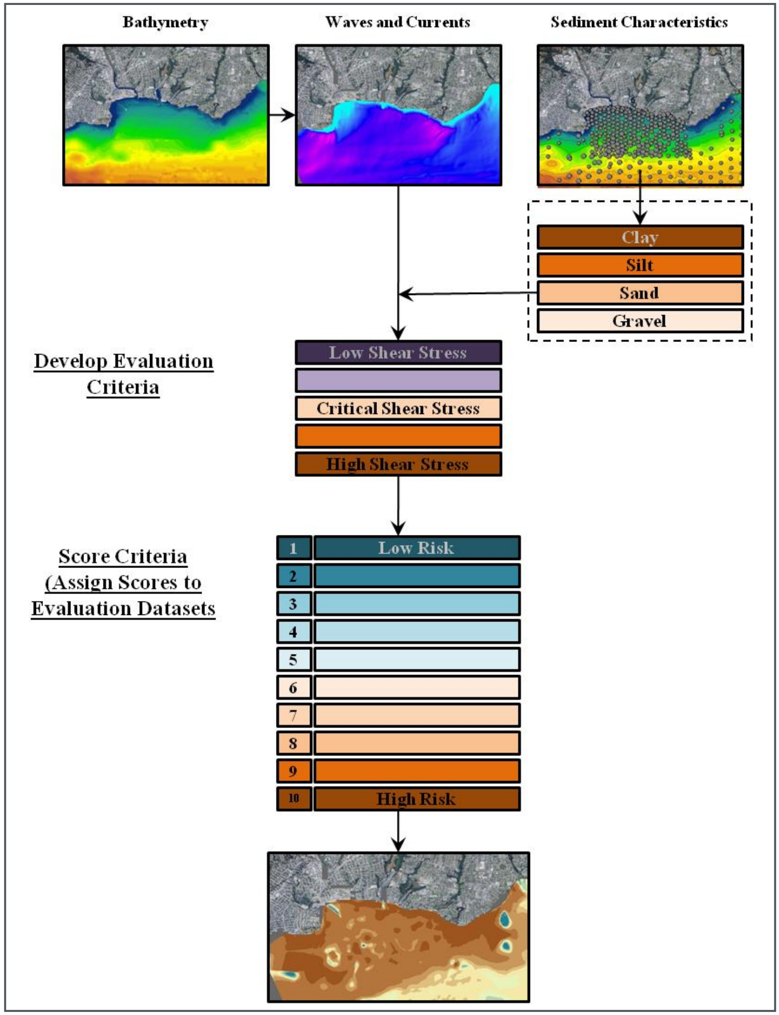
[1] *Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Technical Approach

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

- Sediment Stability Risk to OW Infrastructure
  - **Develop and validate tools/methods** to create sediment stability risk maps at OW sites
    - Use coupled hydrodynamic and sediment transport models to assess spatial patterns of likely sediment erosion, transport, and deposition
  - Develop mobile laboratory device to **quantify sediment mobility** in coastal environments
    - Eliminate reliance on uncertain industry standard analysis techniques likely not representative of site
    - SEAWOLF: erosion from time and directionally varying flow to mimic ocean conditions
    - Characterize time varying flow and shear (PIV)
  - **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 & SNL-EFDC

Sediment Stability Risk Framework



Develop, apply, and facilitate industry use of open-source OW-specific sediment mobility assessment tools/techniques

Leverage MHK tool development

Accomplishments and Progress

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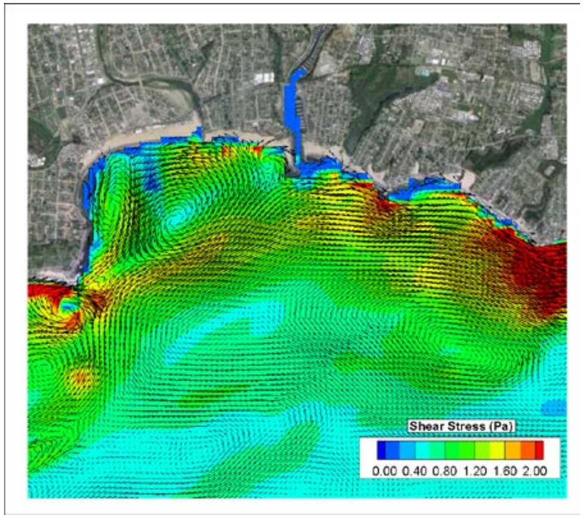
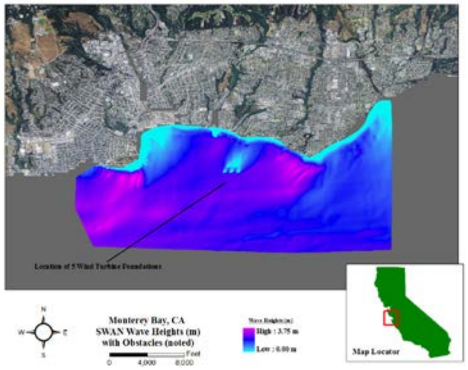
- Sediment Stability Risk Mapping Tool
  - Evaluated proof-of-concept methodology for spatial evaluation of regional sediment stability
    - Considered overall circulation from wind, waves, and tides
    - In the presence and absence of OW arrays (various sizes)
  - Validation of baseline tool
    - Predicted sediment transport patterns in Monterey Bay were compared with site data (leveraged available data)
    - Sediment transport trends were well represented

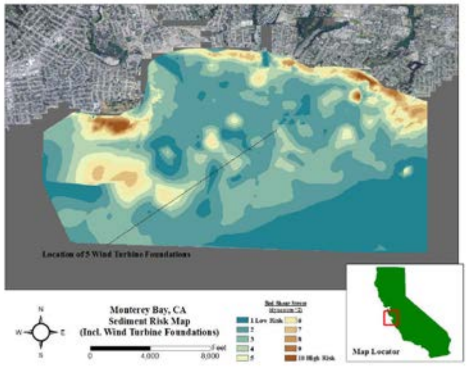
Bed Shear Stress and Velocity Vectors



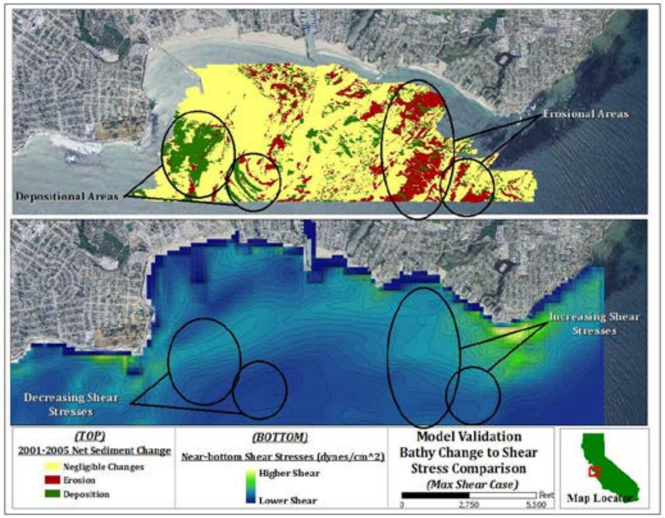
Wave Propagation



Sediment Stability Risk



Site Data (top) vs. Model Prediction (bottom)



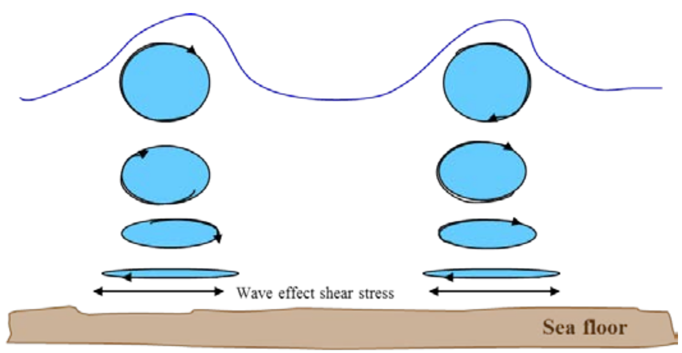
Completed beta-version of sediment stability mapping tool

Accomplishments and Progress

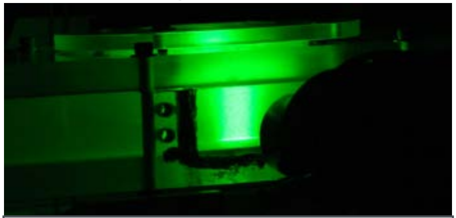
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

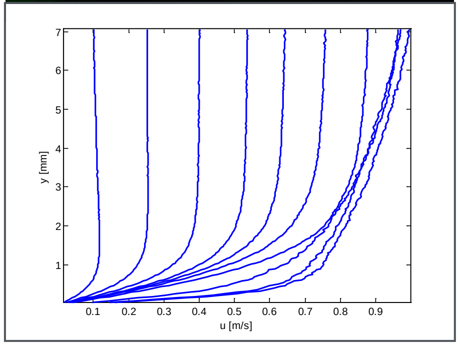
- SEAWOLF flume Characterization
  - Oscillating flow required interrogation with PIV to determine wall shear (erosion driver)
  - Built/installed PIV test channel
  - Characterized 'smooth wall' SEAWOLF flume
    - Shear time history for 15 flow cases (mimic wave environ.)
    - Tested pressure differential method
  - Developed plan for 'rough wall' SEAWOLF tests
    - Expected to better represent ocean conditions
    - Prevent/minimize laminar-turbulent transitions

Wave Transformation to Seabed



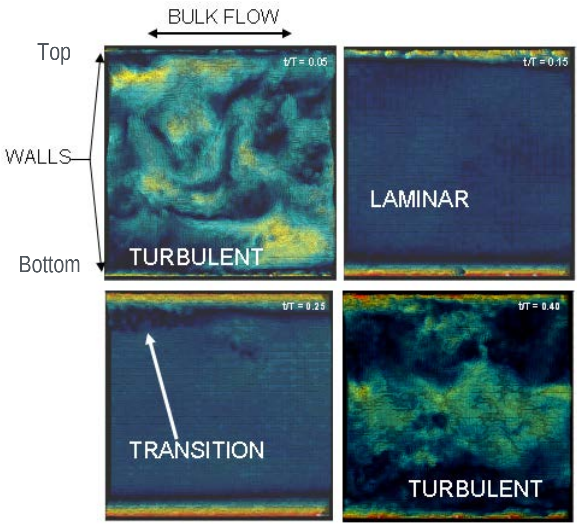
PIV Interrogation of flow field



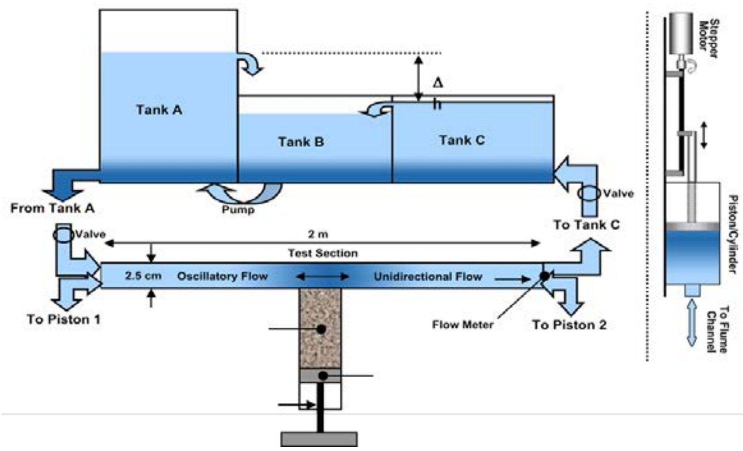


Velocity Profiles Over a Wave Period

Flow Structure in SEAWOLF



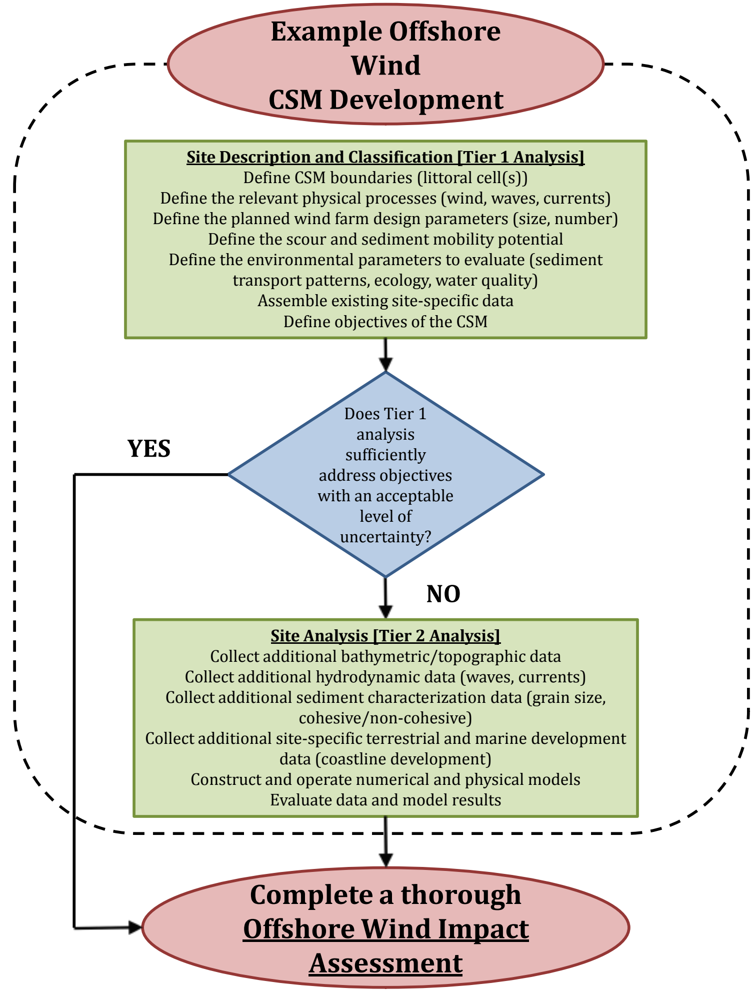
SEAWOLF Flume Schematic

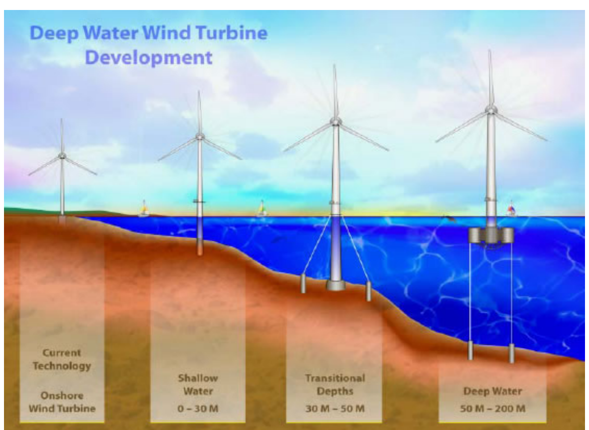


SEAWOLF will directly measure sediment erosion under realistic ocean conditions

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

- Offshore Wind Guidance Document
  - Conceptual site model (CSM) framework used to guide assessment of sub-aqueous OW infrastructure risk.
  - Considers OW infrastructure siting to minimize installation and maintenance risk and costs
  - Environmental evaluation techniques to minimize ecological risk and accelerate permitting
- Industry Advisory Group
  - Voluntary: 9 members
  - Review effort and provide feedback
  - Help SNL/DOE better serve industry's needs





Actively working to support industry's needs

Project Plan & Schedule

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

Summary	
WBS Number or Agreement Number	
Project Number	
Agreement Number	

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Project Name: Wind Energy Forecasting Methods and Validation for Tall Turbine Resource Assessment												
Q1 Milestone: Report on wave modeling with and without OW devices												
Q2 Milestone: Draft Oceanographic and Sediment Stability Guidance Document												
Q3 Milestone: Fine-scale erosion and scour modeling report												
Q4 MS: Sediment stability risk mapping tool report and guidance document update												
Q1 Milestone: Sediment stability model validation test plan and SEAWOLF OP												
Q2 Milestone: Preliminary sediment stability tool validation and SEAWOLF test matrix												
Q3 Milestone: Report on IAG review/assessment and SEAWOLF flow testing												
Q4 Milestone: Yearend report on sediment stability tool validation												
Q4 Milestone: Finalize version 1 of the Offshore Wind guidance document												
Q4 Milestone: SEAWOLF characterization and applicablity of erosion testing reports												
Current work and future research												
Q1 Milestone: Report on standardized scour test cases for model development												
Q2 Milestone: Report comparing scour predictions with test cases												
Q3 Milestone: Report on scour tool enhancements to improve scour predictions												
Q4 Milestone: yearend report on OW applicable scour methodology and tool develop.												

Comments

- Project initiated May, 2011 – Ongoing
- All milestones completed on time

Work is progressing according to plan

Research Integration & Collaboration

Subcontractors:

- Sea Engineering: Supports numerical model and guidance development
- Fugro Atlantic: Supports field data assimilation

Industry Advisory Group:

- Alpine Ocean Seismic, Fisherman's Energy, Mott McDonald, Global Marine, Fugro Atlantic, Atlantic Wind Connection, Prysmian, MMI Engineering, Coastal Vision

Communications and Technology Transfer:

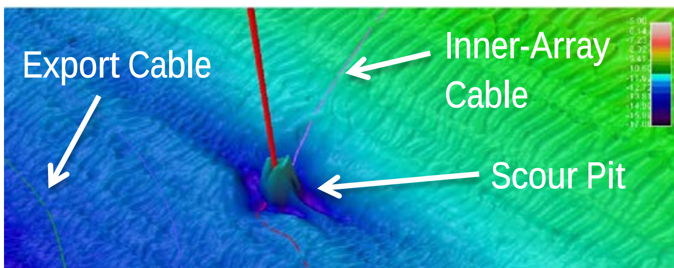
- Technical Reports:
  - 6 DOE/SNL technical reports
- Offshore Wind Guidance Document:
  - Oceanographic and Sediment Stability (Version 1)
- Conference Proceedings/Presentations:
  - AWEA Offshore Wind Conference 2012 presentation in Virginia Beach, VA
  - APS Fluid Dynamics Conference 2013 presentation in Pittsburgh, PA
- SNL website houses publications

Actively seeking industry support and feedback

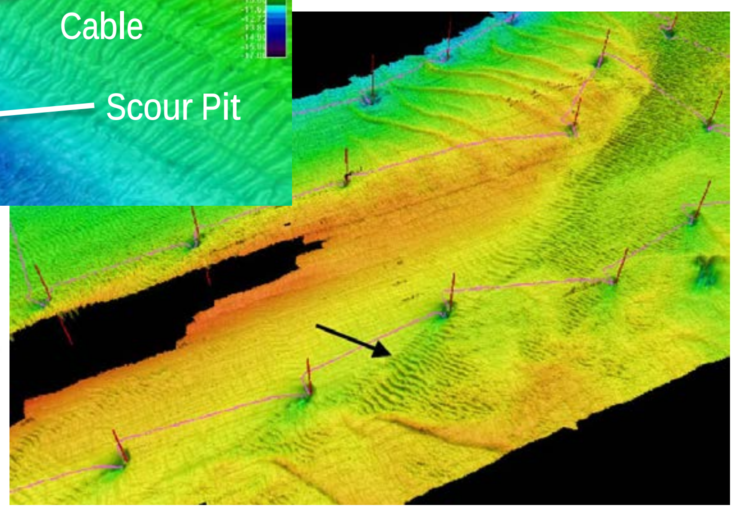
Next Steps and Future Research

FY14/Current research:

- Develop and integrate local scale scour tool with regional sediment stability
- Integration with FAST
    - High resolution wave and current loads (and load ranges)
    - Seabed variations for expected ranges of foundation exposure
- Identify and support development of offshore wind standards
- Feedback from Industry Advisory Group

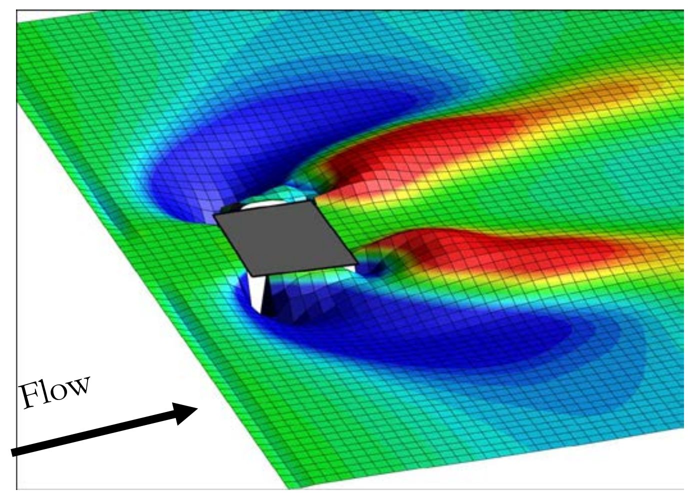


Scroby Sands Wind Farm



Images Modified from CEFAS 2006

Local-Scale Scour Tool Development



Increase functionality and confidence in sediment stability assessment tools
Ensure usefulness to industry

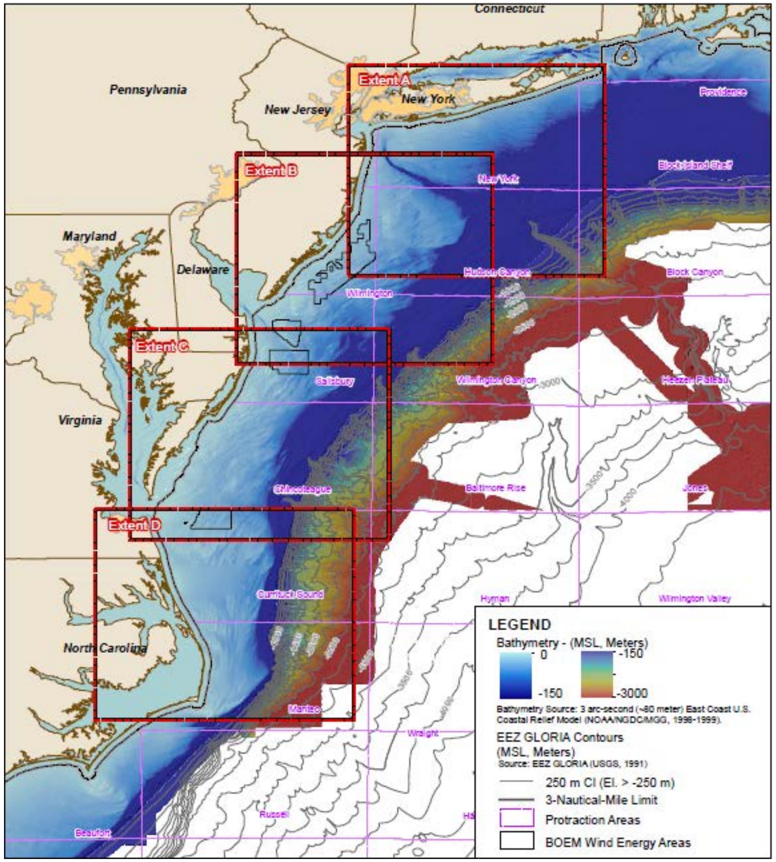
Next Steps and Future Research

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

Proposed future research:

- Develop large-scale coastal circulation models of US coast
  - **Benefits– Cost effective site screening studies**
- Demonstrate the tool at a US based offshore wind site (TBD)
  - **Benefits– Industry outreach, tool refinement, and quantify cost/risk reductions.**
- Finalize characterization of the SEAWOLF flume and begin erosion studies
  - **Benefits– Increase confidence in sediment mobility assessments**
- Continue to work with Industry to **quantify potential direct and indirect cost savings and risk reduction**.

Example: Mid-Atlantic Bight



Graphic courtesy of Fugro Atlantic

Demonstrate potential cost savings to meet industry needs

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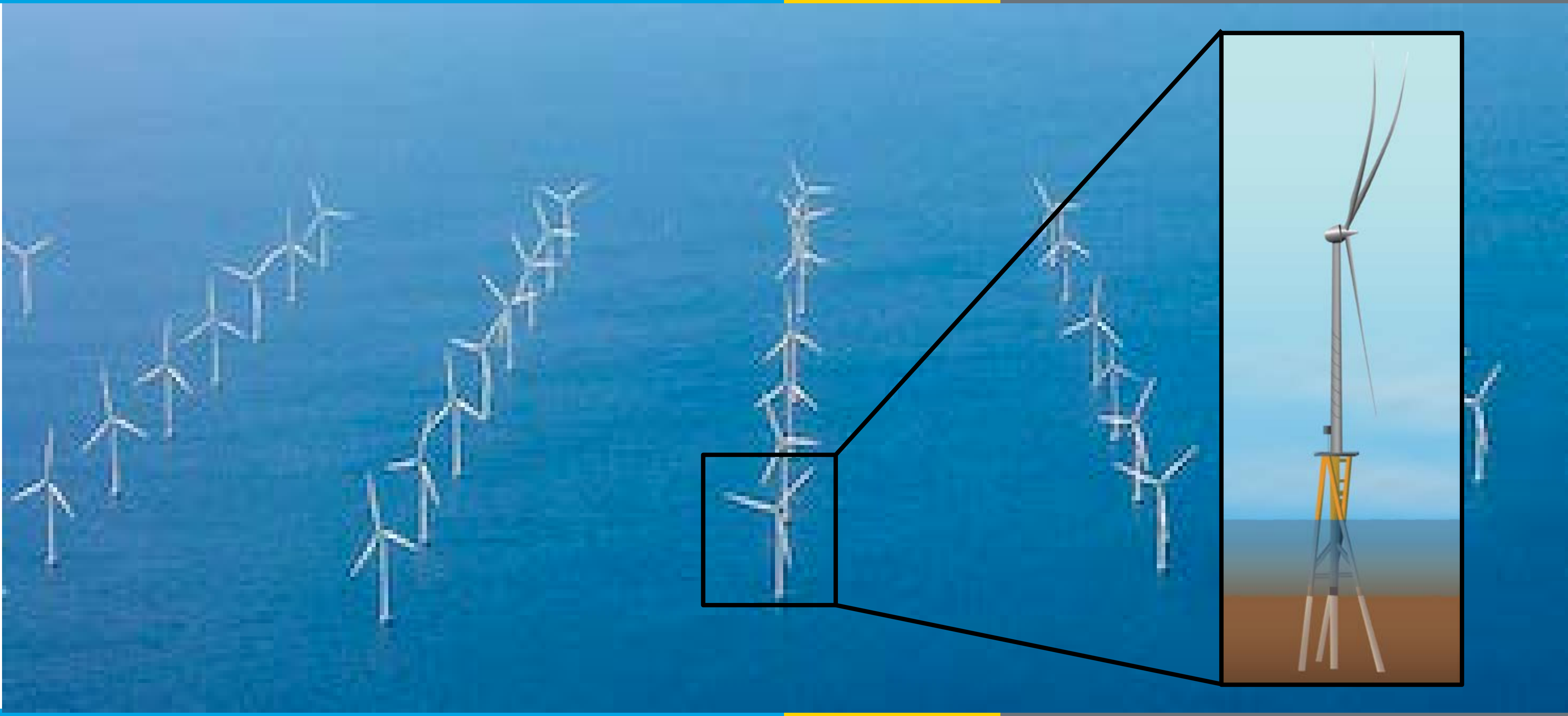


Hurricane Resilient Wind Plant Concept Study (FOA)

Scott Schreck
NREL's National Wind Technology Center
scott.schreck@nrel.gov +1 (303) 384 - 7102

March 2014

Budget, Purpose, & Objectives

Total DOE Budget [1,2]: $0.000M

Total Cost-Share[1]:$0.125M

Problem Statement:

- Holistic concept study
  - Wind plant system for hurricane prone areas
  - Technical feasibility and cost effectiveness
- Wind/ocean inputs appropriate for hurricane prone areas
- Conceptual designs for 10 MW class components
  - Advanced, lightweight blades
  - Permanent magnet direct drive generator
  - Upscaled wind turbine tower
  - Innovative fixed substructure
- Integrated system concept design for 10 MW wind turbine
- Integrated system concept design for 500 MW wind plant

[1] *Budget/Cost-Share for Period of Performance FY2012 – FY2013*
[2] *Project remained active using DOE funds received prior to FY2012*

Budget, Purpose, & Objectives

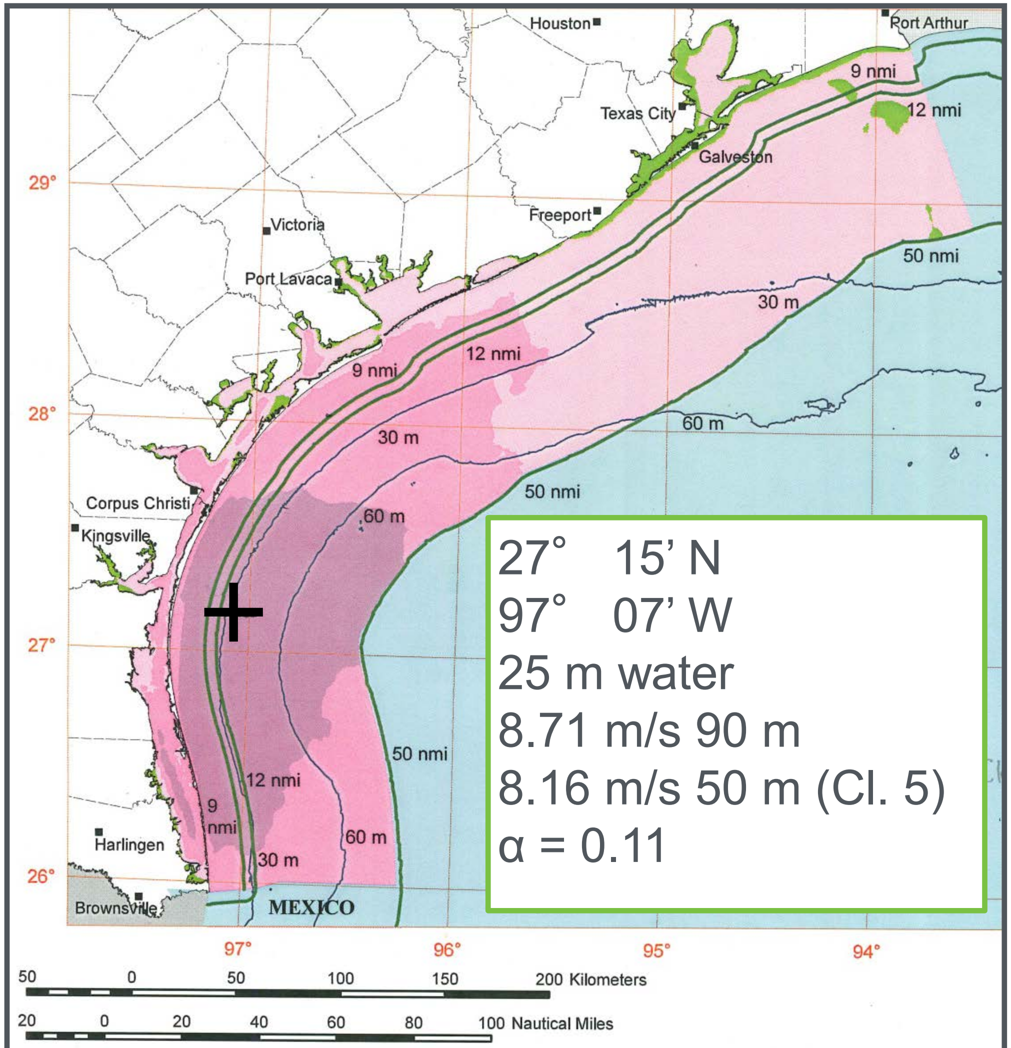
Impact of Project:

- Facilitate responsible wind resource exploitation
  - Hurricane prone regions in US lower latitudes
  - Coastal shallow water sites (depth < 30 m)
  - 475 MW of offshore wind energy

Project aligns with these DOE Program objectives & priorities:

- Optimize Wind Plant Performance: Reduce Wind Plant Levelized Cost of Energy (LCOE)
- Accelerate Technology Transfer: Lead the way for new high-tech U.S. industries

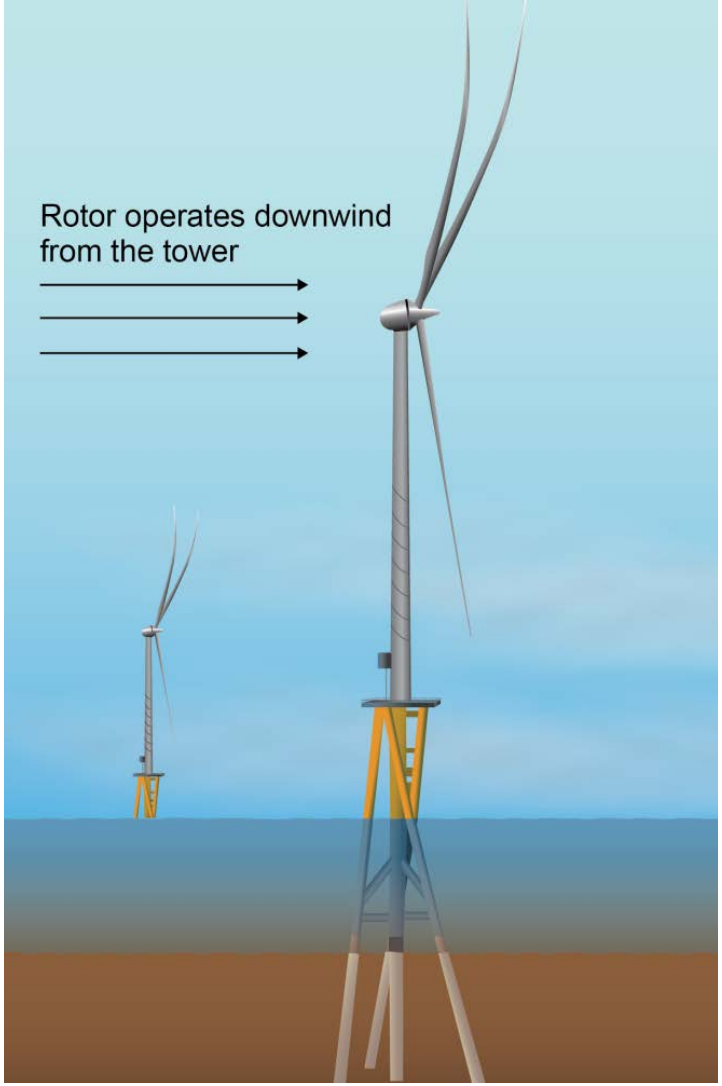
Technical Approach
Concept Study Site



- Concept study site
  - SW Gulf of Mexico
  - Hurricane prone
  - Wind resource
  - Water depth < 30 m
  - Near load center
- Inflow definition
  - Operating: IEC 61400 (routine inflow)
  - Parked: API 2MET (hurricane survival)

Turbine Features
Proposed Concept

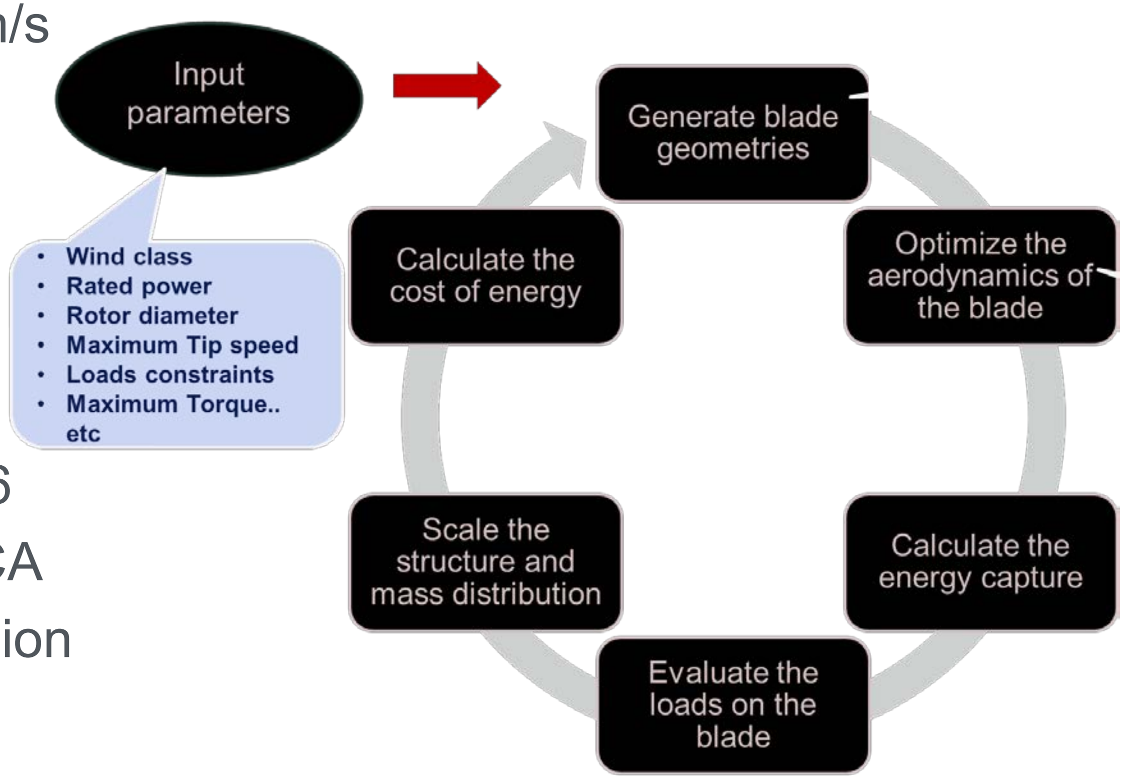
- 10 MW rating, 180 m rotor
- Downwind rotor with rigid hub
- Aggressive downwind coning
- Thick airfoils, advanced structure
- Passive blade load attenuation
- Reduced blade planform area
- PMDD generator
- Twisted jacket substructure
- 500 MW wind plant



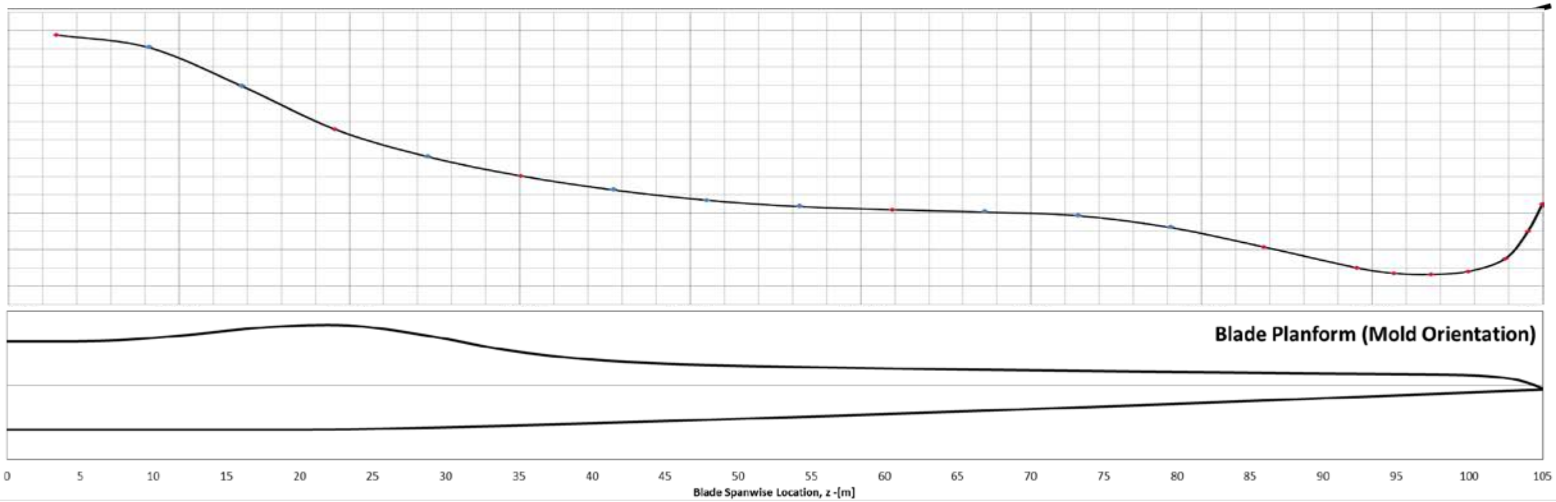
Technical Approach

- Wetzel Engineering Inc.
  - Blade and rotor design
- Siemens Wind Power Inc.
  - PMDD generator and drivetrain
- Keystone Engineering Inc.
  - Twisted jacket substructure
- National Renewable Energy Lab
  - Tower design
  - Turbine system integration
  - Plant layout, O&M, LCOE

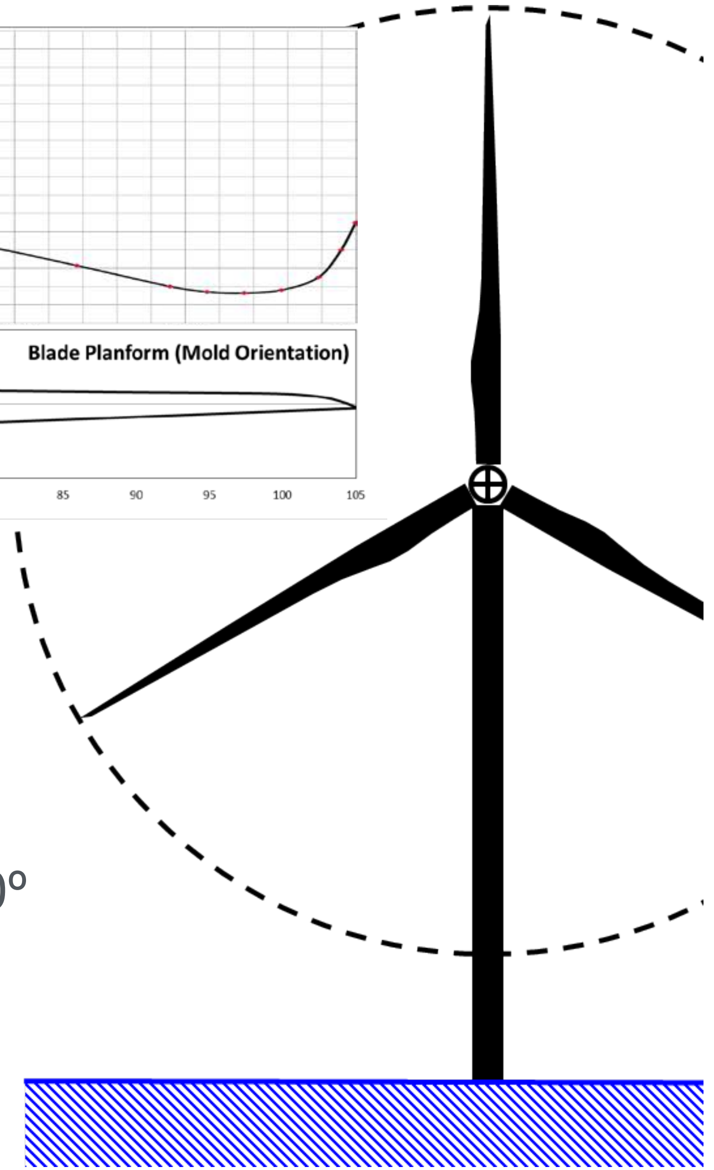
- Rotor optimization parameters
  - Bladelength=90,95,100,105 m
  - Vtip_max=85,95,105m/s
  - Preconeangle=0º,4º
  - Turbulence=14.6%
  - Extendedloadssets
  - Bladetipairgap=26 m
  - Torsion-bendcoupling
  - Radialairfoilsections=6
  - Airfoilfamilies:DU,NACA
  - Bladesanalyzed≈4 million



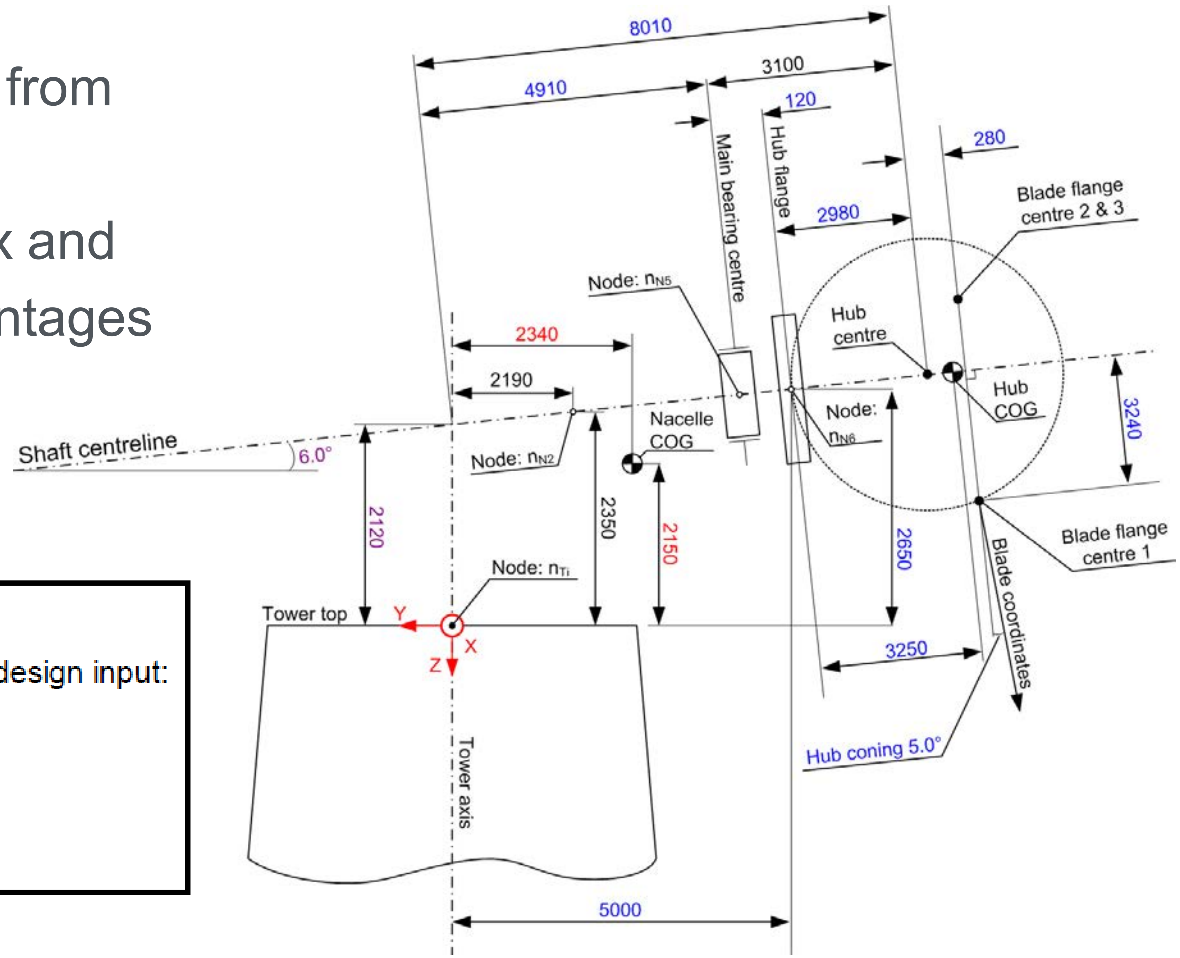
Accomplishments and Progress
Wetzel Engineering Optimization



- Optimized rotor
  - D = 218 m
  - Precone = 0º
  - V_{tip_max} = 85 m/s
  - h_{HUB} = 135 m
  - Airgap = 26 m
- Optimized blade
  - Length = 105 m
  - c_{max} = 7.0 m
  - -3.4º ≤ twist ≤ 10.0º



- Permanent magnet direct drive generator
  - Scaled to 10 MW from 3 – 6 MW regime
  - Eliminate gearbox and reliability disadvantages
  - Reduced weight



2. Design Concept no. 1

Design concept is based on provided rotor design input:

- Blade length: 105 m
- Rated power: 10,000 kW
- Rated rotational speed: 7.45 rpm
- Rated torque: 14570 kNm

Accomplishments and Progress
Siemens Generator Design

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2. Design Concept no. 1

Design concept is based on provided rotor design input:

- Blade length: 105 m
- Rated power: 10,000 kW
- Rated rotational speed: 7.45 rpm
- Rated torque: 14570 kNm

Nacelle / Hub Geometry and Hub Mass		
Design Concept no. 1		
Geometry		
Distance from tower top to hub flange, horizontal/vertical	:	5000 mm (horiz.) 2650 mm (vertical)
Distance from hub centre to hub flange	:	2980 mm
Blade flange position relative to hub centre	:	280 mm upwind at 3240 mm radius
Rotor coning angle	:	5.0 degrees (towards the wind)
Rotor skew angle, flap/edge	:	0.0 degrees (flap) degrees (edge)
Distance from hub flange to centre of main bearing	:	120 mm
Distance from hub centre to tower axis along main shaft	:	8010 mm
Distance from main bearing centre to tower axis along main shaft	:	4910 mm
Mass Properties		
Hub mass	:	251 metric ton
Distance from hub flange to hub centre of gravity	:	3250 mm
Distance from hub centre to hub centre of gravity	:	270 mm
Hub mass moment of inertia about the x-axis (BHawC)	:	1.24E+06 kgm^2
Hub mass moment of inertia about the y-axis (BHawC)	:	2.46E+06 kgm^2
Hub mass moment of inertia about the z-axis (BHawC)	:	1.25E+06 kgm^2

Nacelle Mass and Aerodynamics		
Design Concept no. 1		
Mass Properties		
Nacelle mass	:	429 metric ton
Longl. distance from nacelle COG to tower axis	:	2340 mm upwind
Vert. distance from nacelle COG to tower top	:	2150 mm
Nacelle mass moment of inertia about the transv. x-axis (BHawC)	:	1.04E+07 kgm^2
Nacelle mass moment of inertia about the longl. y-axis (BHawC)	:	4.69E+06 kgm^2
Nacelle mass moment of inertia about the vertical z-axis (BHawC)	:	8.25E+06 kgm^2
Notes: • Mass moments of inertia refer to tower top, see Figure 2-1. • Nacelle mass properties comprise tower top mass excluding hub and blades. I.e.: Nacelle bedframe and rear end, generator rotor/stator, main bearing, yaw bearing and equipment.		
Aerodynamic Properties		
Nacelle front area times drag coefficient	:	51 m^2
Nacelle side area times drag coefficient	:	160 m^2
Distance from aerodynamic centre of nacelle to tower axis	:	0.00 m

Generator Main Data		
Design Concept no. 1		
Nominal power	:	10,000 kW
Nominal rotational speed	:	7.5 rpm
Electrical system efficiency at rated power	:	0.88
Generator tilt angle	:	6.0 degrees
Distance from the tower top to the generator axis (vertical)	:	2120 mm
Mass Properties		
Generator rotor mass moment of inertia about the x-axis (BHawC)	:	4.64E+05 kgm^2
Generator rotor mass moment of inertia about the y-axis (BHawC)	:	7.55E+05 kgm^2
Generator rotor mass moment of inertia about the z-axis (BHawC)	:	4.67E+05 kgm^2

Project Plan & Schedule

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Summary	
WBS Number or Agreement Number	5.1
Project Number	5.1.11
Agreement Number	

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Hurricane Resilient Wind Plant Concept Study												
Q1 Milestone: Finalize subcontracts for all subtier contract awards												
Q2 Milestone: Letter report on hurricane wind/wave inflows from API 2MET												
Q3 Milestone: Wetzel Engineering to complete baseline rotor design												
Q4 Milestone: Siemens Wind Power to complete baseline generator design												
Current work and future research												
Q1 Milestone: NREL to complete initial OpenWind windplant layout study												
Q2 Milestone: NREL to complete baseline wind turbine tower conceptual design												
Q3 Milestone: NREL to transmit data needed for substructure design to Keystone												
Q4 Milestone: Draft report sections to be delivered by Wetzel, Siemens, Keystone												

Comments

- Project kickoff meeting held September 2012

Research Integration & Collaboration

Partners, Subcontractors, and Collaborators:

- National Renewable Energy Lab (prime award)
- Wetzel Engineering Inc. (subtier)
- Siemens Wind Power (subtier)
- Keystone Engineering Inc. (subtier)

Communications and Technology Transfer

- Comprehensive, publicly releasable report will document all aspects of the concept study after project completion

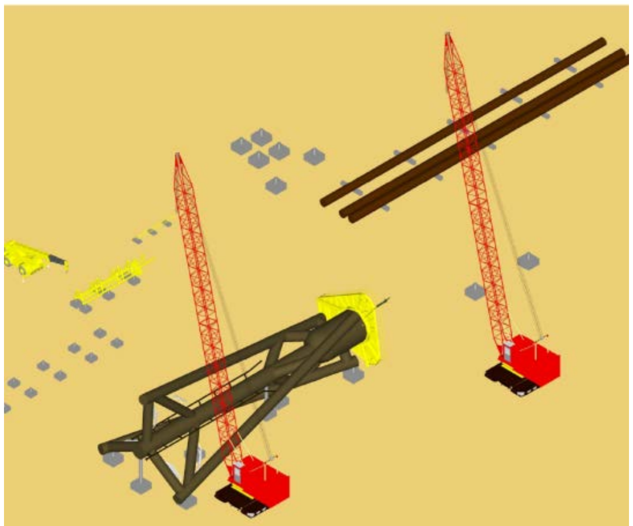
Next Steps and Future Research

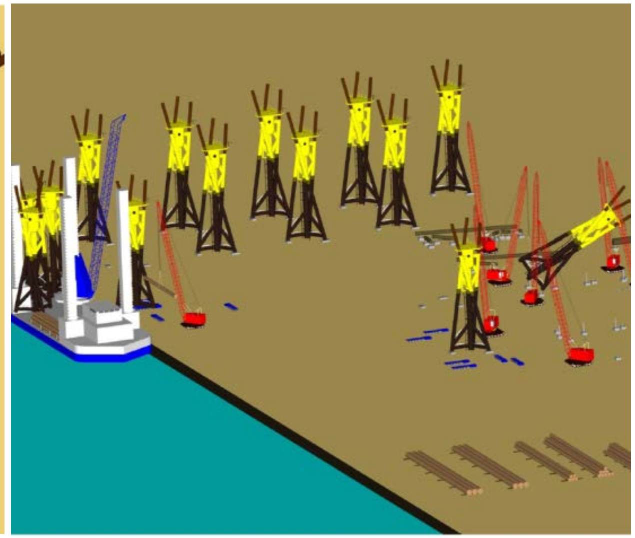
FY14/Current research:

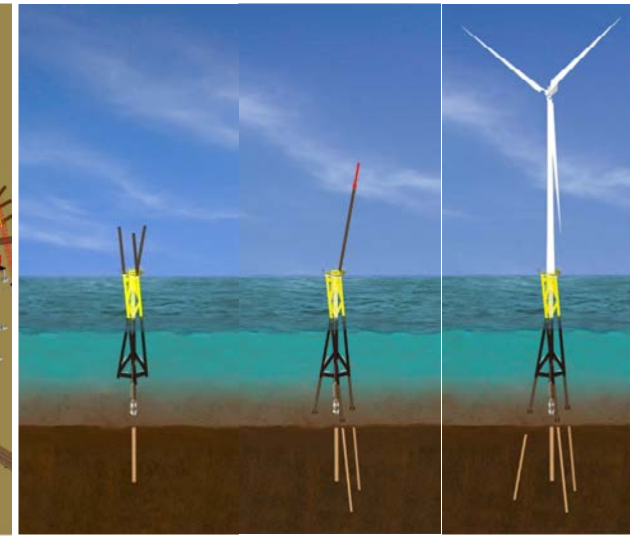
- NREL wind turbine tower design
- Keystone Engineering substructure design
- Turbine and wind plant system integration studies
- Documentation of technical activities

Next Steps and Future Research
Keystone Engineering Substructure

- Keystone Engineering “twisted jacket” concept design study



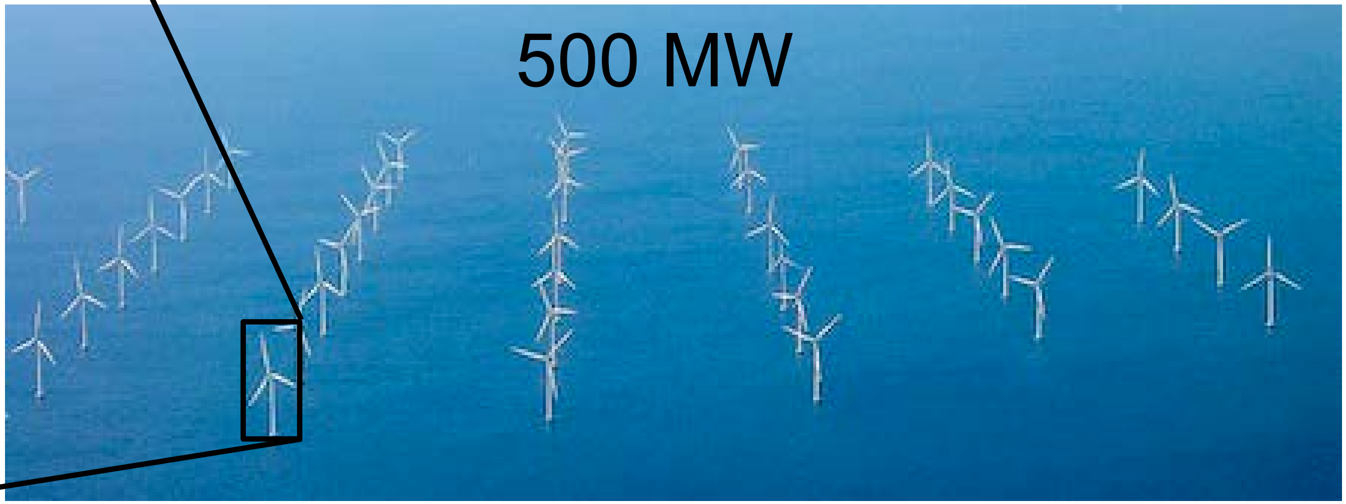




- Fabrication
  - Fewer components
  - Lower work heights
  - Pipe fabrication
  - Needs less area
  - Assembly line
- Transportation
  - Load in vertical position
  - Transporter or vessel crane lift
  - Small footprint
- Installation
  - Piles quickly driven
  - Drive or drill piles
  - Need not reposition
  - No welding needed
  - Work above water

Next Steps and Future Research
NREL Integration Studies

- System level integration studies
  - Turbine system integration – FAST
  - Wind plant system layout – OpenWind
  - Operations and maintenance – ECN Tool
  - Levelized cost of energy – DOE/NREL Model



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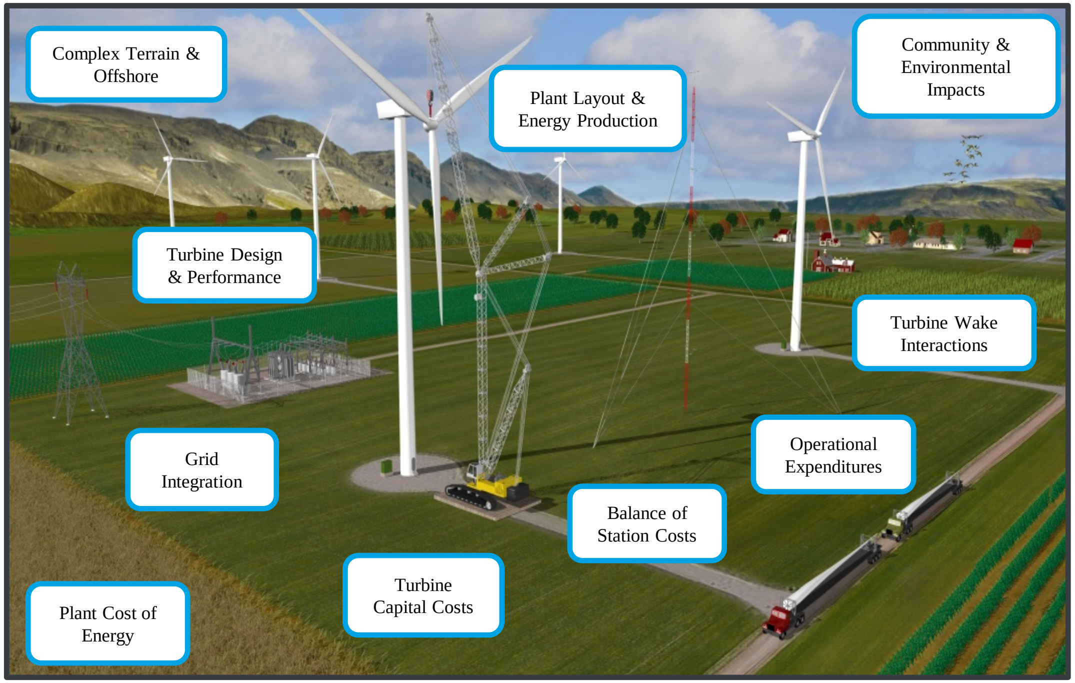

Agreement Lead:
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Project Manager:
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Wind Plant Optimization and Systems Engineering

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National Renewable Energy Laboratory
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March 25, 2014

Alt.: Katherine Dykes, katherine.dykes@nrel.gov

Budget, Purpose, & Objectives

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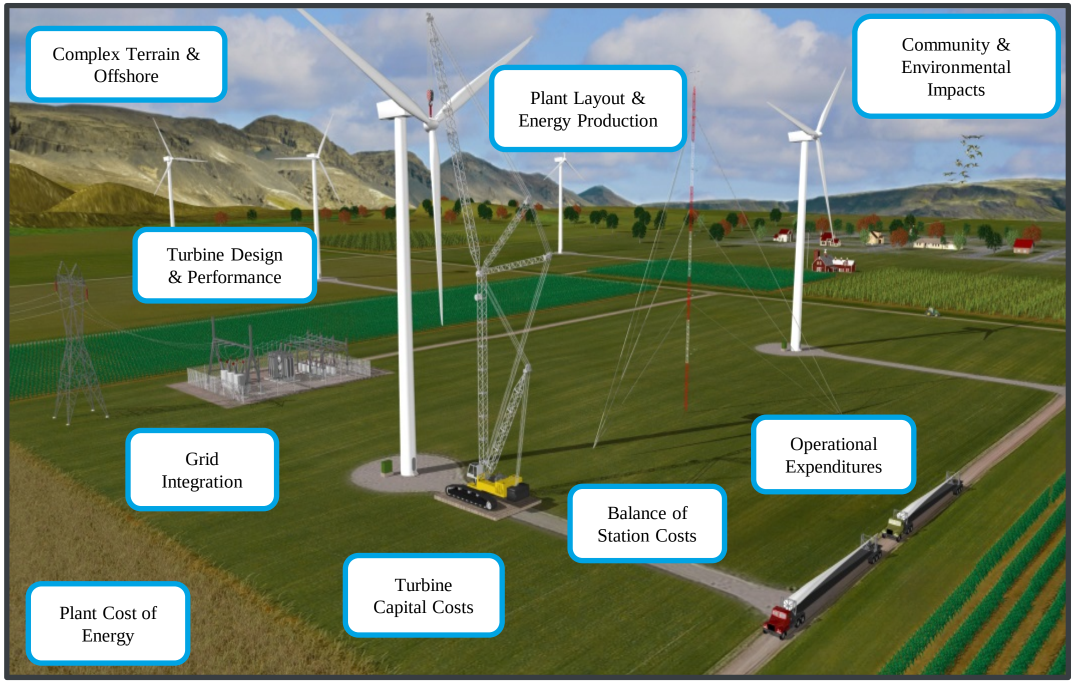
Total DOE Budget[1]: $0.985M

Total Cost-Share[1]:$0.000M

Problem Statement

- A wind plant is a complex, interconnected system with a large number of stakeholders (OEMs, suppliers, developers, contractors, operators, utilities, financiers, and communities).
- Assessment of design improvements and new technology innovation impacts on overall system cost of energy is challenging and may limit adoption.



[1] *Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Purpose & Objectives

Impact of Project

- Wind Plant Optimization & Systems Engineering (WPO&SE) seeks to provide a research capability and open source software platform for integrated system modeling of wind plants.
- The capability can be leveraged by various stakeholders in the wind energy industry and research community to investigate how new technologies, system uncertainties, and design processes impact overall wind plant system performance and cost.

This project aligns with the following DOE Program objectives and priorities

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new, high-tech U.S. industries
- **Modeling & Analysis:** Conduct wind techno-economic and lifecycle assessments to help the Program focus its technology-development priorities and identify key drivers and hurdles for wind energy technology commercialization

Technical Approach

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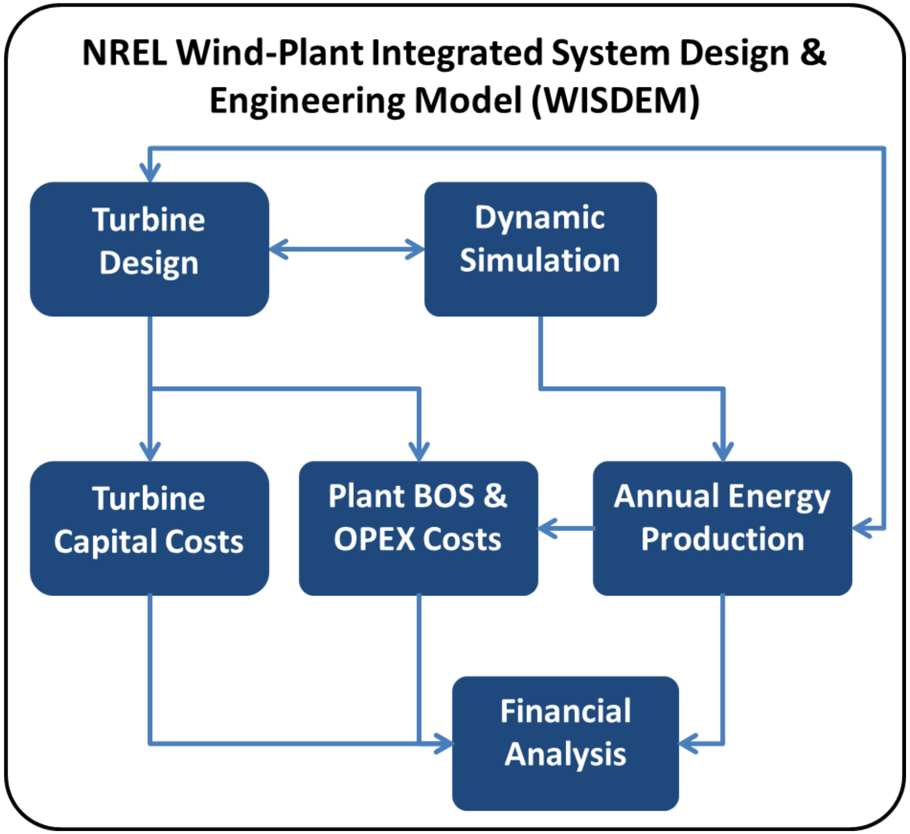
The WPO&SE technical approach involves the development and application of the Wind-Plant Integrated Systems Engineering & Design Model (WISDEM) software that:

- Integrates wind-plant modeling for full system analysis.
- Enables advanced multi-disciplinary analysis and optimization (MDAO), uncertainty quantification (UQ), etc.
- Serves as a flexible platform that accommodates new models via standardized framework.

Version 1.0 (through FY15) focuses on initial capability with emphasis development on turbine design and sizing models and overall initial plant-modeling capability.



A2E Center Function: Tool for assessment of technology advancement within a full-system, wind-plant context

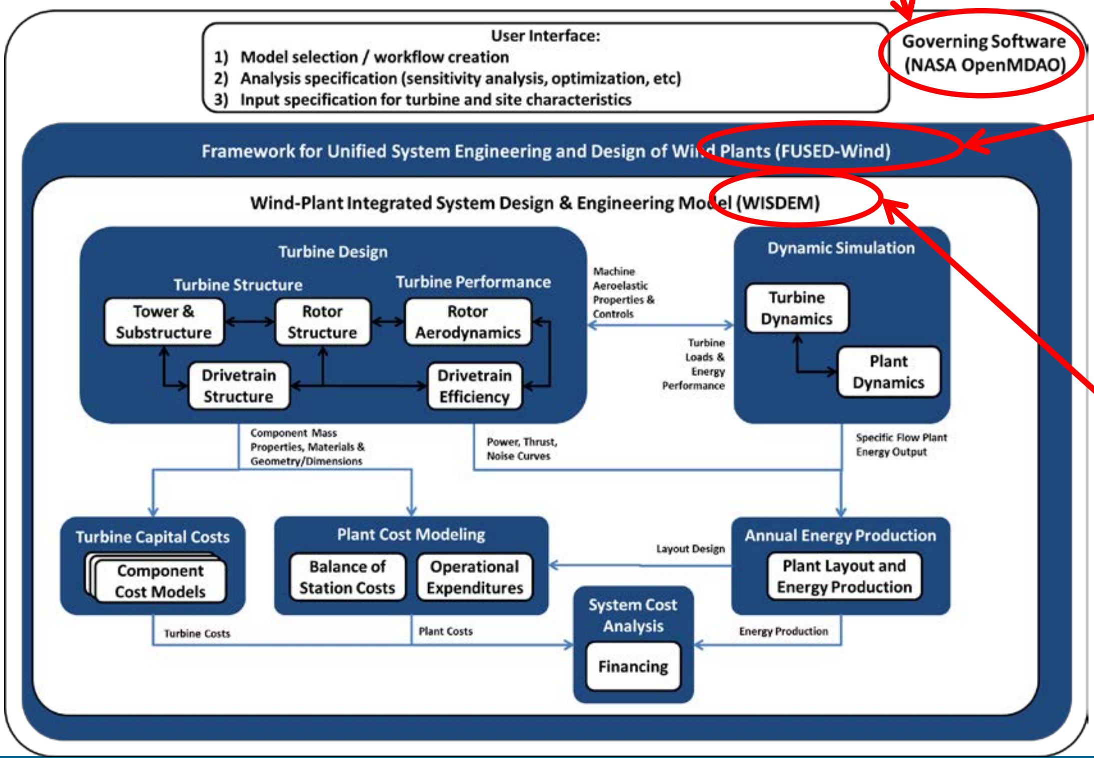
Technical Approach

OpenMDAO:

- Work flows integrate models together in structured ways (use of NASA's OpenMDAO software)
- Easily reconfigured (model selection and analysis structure)

FUSED-Wind:

- Support software for structured interface of wind-turbine and plant-modeling tools into OpenMDAO
- Allows interchange of models, sharing of common turbine- and plant-input descriptions



WISDEM:

- Collection of engineering and cost turbine- and plant-analysis tools integrated into FUSED-Wind and OpenMDAO
- Full wind turbine and plant model set planned for release

General software development of WISDEM Version 1.0

- Created basic architecture and initial implementation of full system cost analysis capability
  - Initial version included Python-based NREL Cost and Scaling Model (NREL CSM)

- Created plan for and executed development and integration of improved model set

Current model options include either the NREL CSM or an improved model option in each category

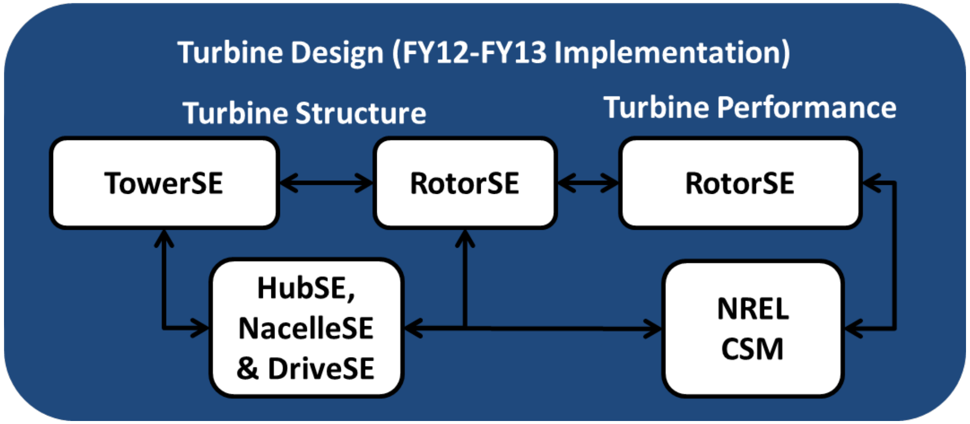
Rotor Aero	Rotor Structure	Nacelle Structure	Tower Structure	Turbine Costs	Plant BOS Costs	Plant OPEX	Plant Energy Production	Plant Finance
NREL CSM	NREL CSM	NREL CSM	NREL CSM	NREL CSM	NREL CSM	NREL CSM	NREL CSM	NREL CSM
RotorSE	RotorSE	NacelleSE (with DriveSE option)	TowerSE	Turbine_CostsSE	NREL Land-Based or Offshore BOS	NREL OPEX or ECN Offshore OPEX	AWS openWind	SAM

Accomplishments and Progress: *Software Development*

Development of turbine systems engineering (TurbineSE) design and sizing tools:

- RotorSE – new optimization-friendly rotor aerodynamic and structural analysis model set
- HubSE and NacelleSE – semi-empirical models based on WindPACT and related work
- DriveSE – new loads-based sizing models for key drivetrain components including hub, low-speed shaft, main bearings, gearbox, and yaw drive
- TowerSE – integrated tower/monopile structural-analysis model set

All turbine models have been approved for release as open source.



Accomplishments and Progress: *Software Development*

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Rotor subsystem analysis example:

- Geometry and materials are pre-defined
- Outputs include blade mass properties and rotor performance

Rotor model can use different fidelity sub-models for aero and structural analysis

<<< INPUTS

ROTOR INPUTS

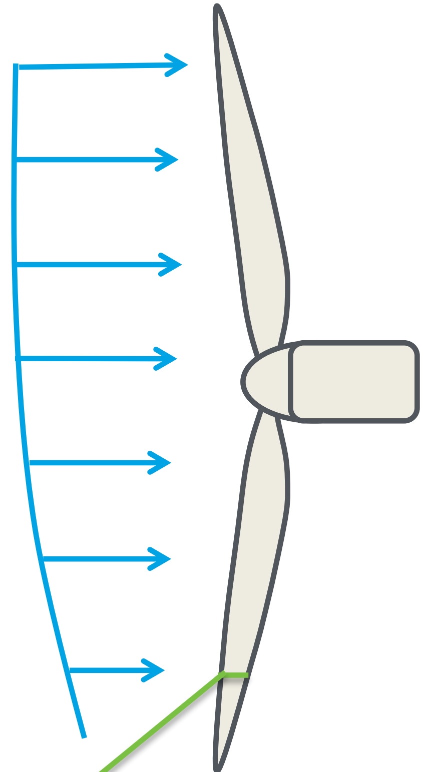
- Number of blades
- Precone, tilt

TURBINE INPUTS

- Hub height
- Cut-in and cut-out speed
- Min/max rotation speed
- Rated power
- Machine type (fixed/variable speed/pitch)
- Drivetrain efficiency

ATMOSPHERE

- Density
- Viscosity
- Shear exponent
- Wind speed distribution



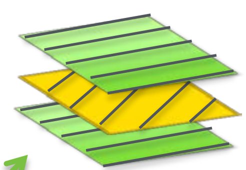
OUTPUTS >>>

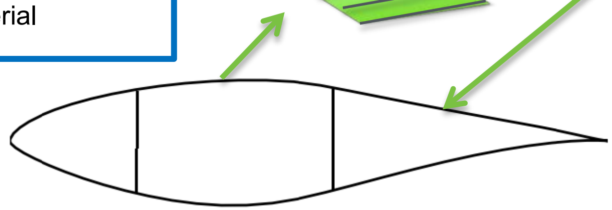
ROTOR STRUCTURE & PERFORMANCE

- Blade mass and moments of inertia
- Cost
- Power curve
- Turbine AEP
- Hub loads
- Sound power level
- Natural frequencies
- Blade displacements
- Panel buckling loads
- Axial and shear stress

LAMINATE STACK

- Sequence of lamina
- Number of plies
- Ply thickness
- Ply orientation
- Ply material





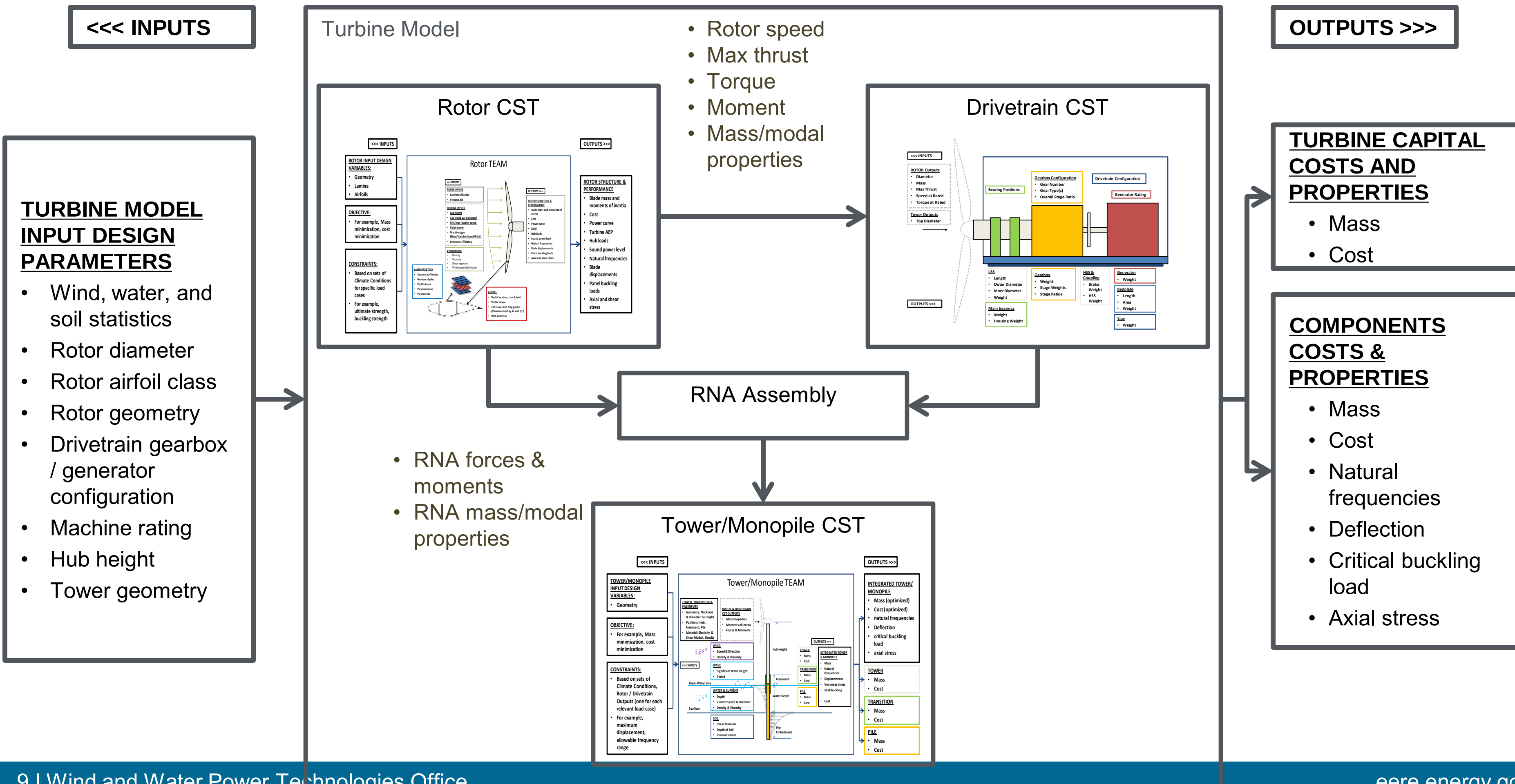
AIRFOIL

- Radial location, chord, twist
- Profile shape
- Lift curves and drag polars (parameterized by Re and t/c)
- Web locations

Accomplishments and Progress: *Software Development*

Turbine structure and cost model example:

- Structure and cost models aggregate together for full turbine structure model preserving interactions between sub-systems

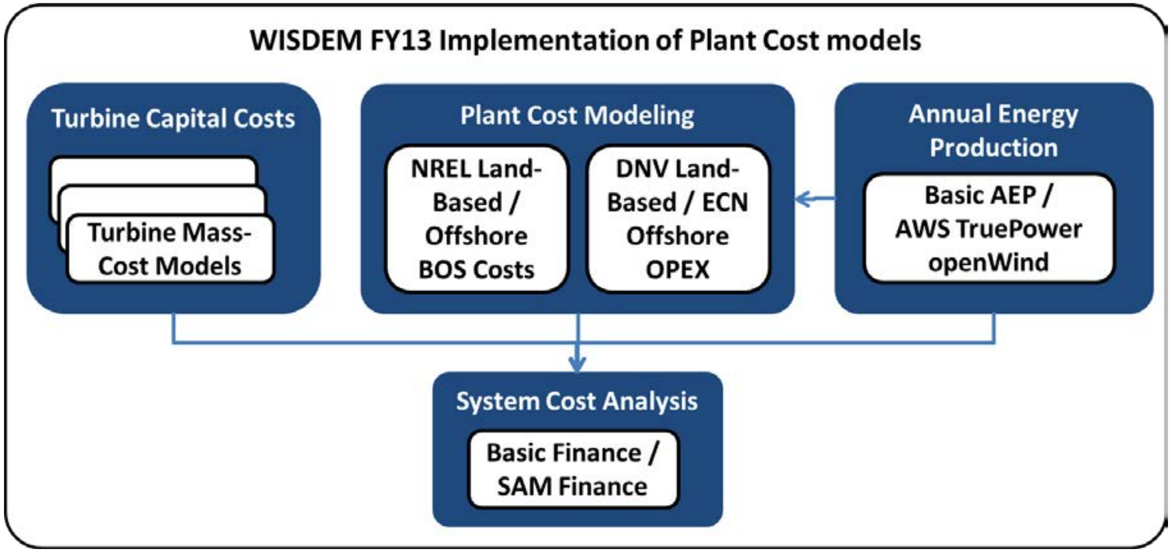


Accomplishments and Progress: Software Development

Existing cost and energy production models were integrated with the software:

- Turbine_CostsSE – a new component mass-based cost model of a turbine based on limited data set
- Plant_CostsSE – Python wrappers for multiple models of plant balance-of-station costs and operational expenditures for both land-based and offshore wind plants
- Plant_AEPSE – Python wrapper for a plant layout and energy production software
- Plant_FinanceSE – python wrapper for NREL System Advisor Model finance module

Integration of full-model set into WISDEM, which has been approved for release as open source. Release of all model beta-versions is planned for FY14 Q4.

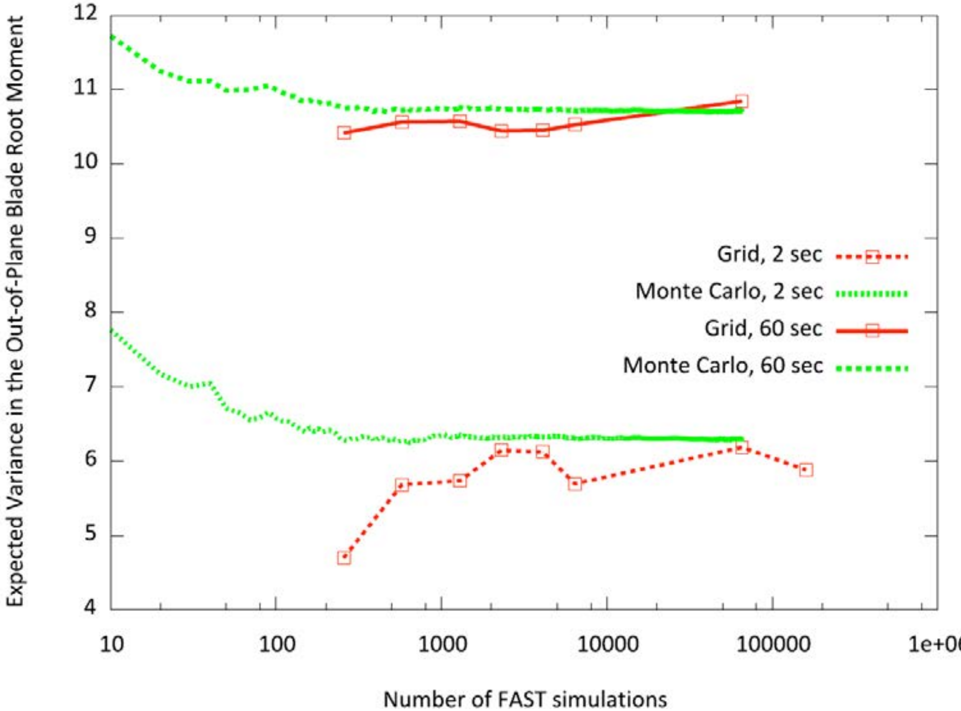


Note: must obtain proprietary models and licenses separately — not included with WISDEM

Additional Software Development

- Integration of Sandia National Laboratories' DAKOTA (Design Analysis Kit for Optimization and Terascale Applications) software as an OpenMDAO driver (released as open source in 2013, adapted by NASA for formal integration as OpenMDAO plugin)
- Integration of FAST version 7.0 via a Python-based wrapper

Coupling of DAKOTA and FAST has been used in demonstration work of sampling methods applied to loads analysis.



Demonstration of sampling via DAKOTA for FAST loads analysis

Example Analysis: Sensitivity Study

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Initial Analysis work includes:

- Global sensitivity analysis of system performance and cost to turbine configuration (rotor diameter, rated power, etc) using different model combinations
  – Example analysis: rotor diameter

Percent Changes in Parameters	WISDEM w/ NREL CSM		WISDEM w/ New Models	
Rotor Diameter [m]	-10.0%	+10.0%	-10.0%	+10.0%
COE	↑	↓	↑	↓
AEP [kWh / turbine-yr]	↓	↑	↓↓	↑↑
TCCs [$ / kW]	↓↓	↑↑	↓	↑
BOS Costs [$ / kW]	--	--	↓	↑
O&M Costs [$ / kWh]	↓	↑	↓	↑

  – Changes in COE was more pronounced using new set of models that capture more *system interactions*:
    - Rotor diameter influences balance-of-station model in latter case; overall BOS impact on costs of energy are higher for new model set.
    - Impacts on energy production are much higher due to power-curve changes
    - Turbine capital costs are lower since costs are now associated with component masses rather than directly to rotor diameter

Initial analysis work and publications include:

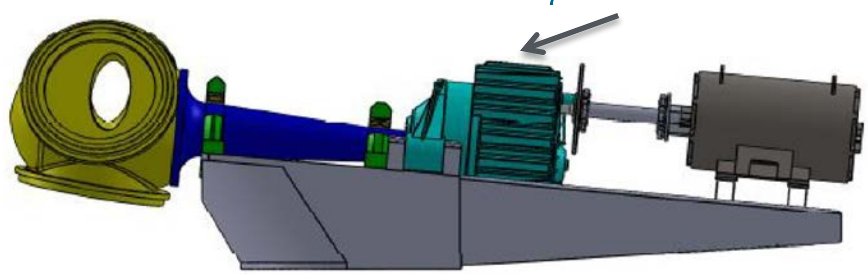
- Multi-disciplinary optimization studies
  - Evaluation of aero-structural optimization results using different system objectives (AEP, AEP/Weight, Overall LCOE)
  - Optimization under plant wind resource uncertainty using simplified model set

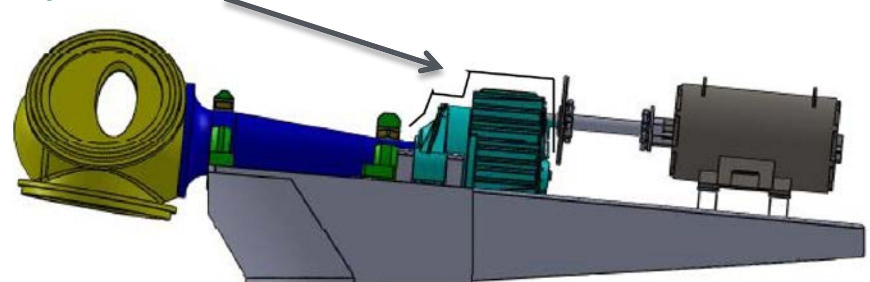
- Investigation of maximum allowable tip speed on overall system costs
  - Collaboration with Sandia National Laboratories involved sequential optimization of rotor, drivetrain and tower followed by system cost analysis

Tip Speed Study Preliminary Results

% COE Reduction	80 m/s Optimized	100 m/s Optimized
From Baseline	4.5%	8.0%
From 80 m/s Optimized Design		4.0%

Torque reduction results in decreased gearbox size





Project Plan & Schedule

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Summary	
WBS Number or Agreement Number	3.1.11
Project Number	
Agreement Number	22503

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Wind Energy Forecasting Methods and Validation for Tall Turbine Resource Assessment												
Q1 Milestone: Initial Systems Engineering Architecture Plan												
Q2 Milestone: Automated load-case analysis with FAST												
Q3 Milestone: Initial sensitivity study of wind turbine designs												
Q4 Milestone: Multi-disciplinary optimization of offshore-wind plant												
Q1 Milestone: Complete documentation of FY12 Models												
Q2 Milestone: Convene the 2nd NREL Wind Energy Systems Engineering Workshop												
Q3 Milestone: Integration of wind plant layout software with system tool												
Q4 Milestone: Complete sensitivity study and report using updated system tool												
Current work and future research												
Q1: Integration of FAST version 7.0												
Q2: Study of effects of tip speed on system cost of energy and complete report												
Q3: Perform joint turbine-plant optimization and complete report												
Q4: Software release of Beta-version of WISDEM Version 1.0												

Research Integration & Collaboration

Partners, Subcontractors, and Collaborators

- DTU Wind Energy – MOU pending for joint contribution to overall software framework
- NASA Glenn Laboratories OpenMDAO team – general software support and DAKOTA driver maintenance
- Sandia National Laboratories DAKOTA team – maintenance of DAKOTA python wrapper
- Sandia National Laboratories wind program team – analysis and software collaboration
- AWS Truepower openWind team – adaptation of software

Communications and Technology Transfer

- Bi-annual workshop brings together wind plant systems engineering researchers and practitioners (130+ attended in 2013)
- Quarterly newsletter highlights new industry and academic research and design activity in WPO&SE
- Publications demonstrate results of integrated system analysis, see:

http://www.nrel.gov/wind/systems_engineering/

Next Steps and Future Research

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FY14/Current research

- Development of underlying wind plant system modeling framework with DTU Wind Energy and Sandia National Laboratories
- Completion of research and publication of initial analysis work:
  - Case study on offshore support structure design
  - Case study on drivetrain configuration impact on system cost of energy
  - Case study on the effects of tip speed limits on system cost of energy
  - Case study on joint turbine configuration and plant layout optimization
  - Case study on joint plant control and layout design
  - Case study on uncertainty techniques applied to loads analysis
- Formal beta-release of individual models and overall WISDEM software

Proposed future research

- Continued development and integration of models and software release
- Applied studies of innovations and design improvements on full system using MDAO, uncertainty analysis, and other methodologies

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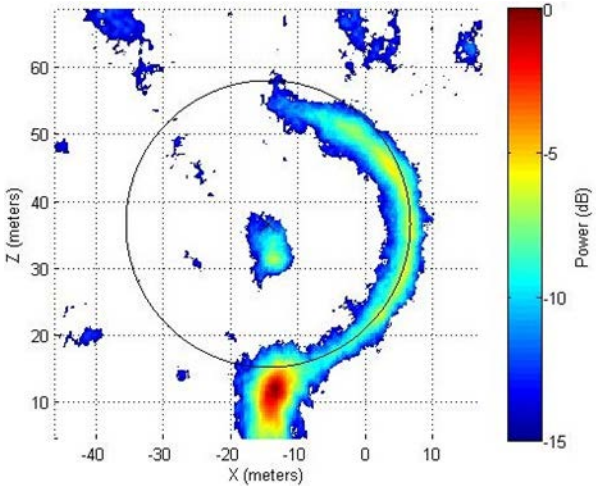


Aeroacoustics

Advanced Rotor Systems

Patrick Moriarty

NREL

patrick.moriarty@nrel.gov

(303) 384-7081

March 26, 2014

Budget, Purpose, & Objectives

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

Total DOE Budget[1]: $0.375M

Total Cost-Share[1]:$0.000M

Problem Statement:

- Acoustic noise is a prominent issue for plant siting
- Noise-reduced operation results in lost energy
- Current field measurement systems are inadequate to gain an improved understanding of noise production and mitigation

Impact of Project:

- Improved understanding of noise generation, propagation, and mitigation will reduce noise barrier for greater wind energy penetration

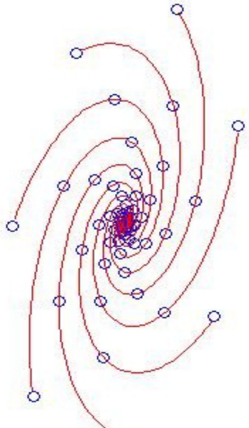
This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce wind plant levelized cost of energy
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources
- **Testing Infrastructure:** Enhance and sustain the world-class wind testing facilities at universities and national laboratories to support mission-critical activities

[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

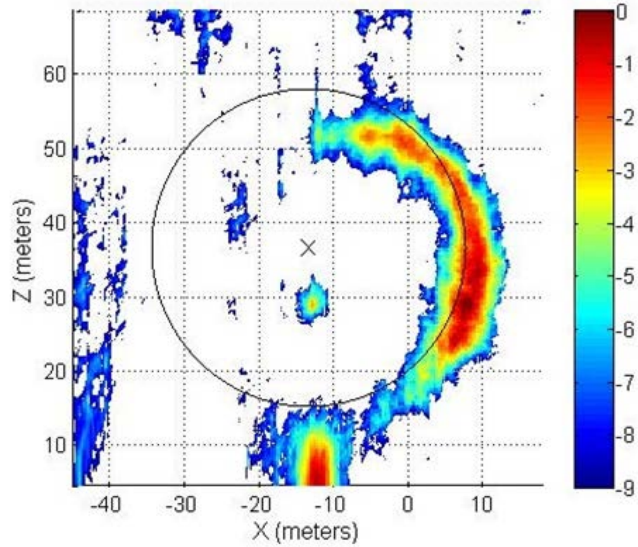
Technical Approach

- Build and deploy 63-microphone acoustic array
- Complete measurements of NWTC turbines, including mitigation devices
- Upgraded array will enable higher fidelity observations of noise source locations and levels
- Weather durability will allow array to be deployed for extended periods

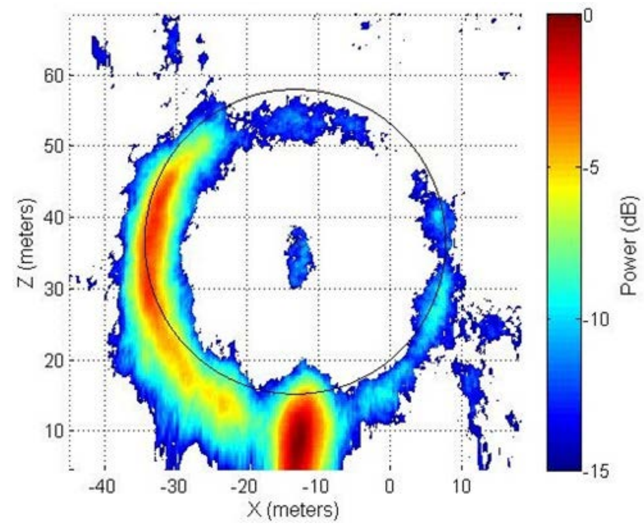


Accomplishments and Progress

- 63-microphone array demonstrated improved performance relative to previous design
- Noise is highly variable depending on turbine operation and atmospheric conditions
- Weather durability – array deployed for more than a year without serious performance degradation



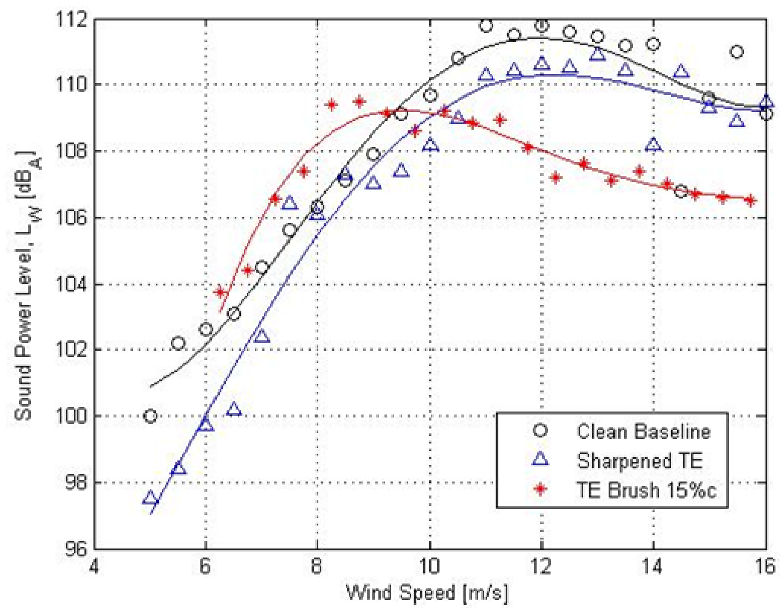
Yaw error = 2°



Yaw error = 31°

Accomplishments and Progress

- Sharpened edges reduced trailing edge noise
- Brushes impact wind speed dependent



Project Plan & Schedule

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

Summary		Legend	
WBS Number or Agreement Number	WE 3.1.5		Work completed
Project Number			Active Task
Agreement Number	2.3	◆	Milestones & Deliverables (Original Plan)
		◆	Milestones & Deliverables (Actual)

Task / Event	FY2012 Q1 (Octt-Dec)	FY2012 Q2 (Jan-Mar)	FY2012 Q3 (Apr-Jun)	FY2012 Q4 (Jul-Sep)	FY2013 Q1 (Octt-Dec)	FY2013 Q2 (Jan-Mar)	FY2013 Q3 (Apr-Jun)	FY2013 Q4 (Jul-Sep)	FY2014 Q1 (Octt-Dec)	FY2014 Q2 (Jan-Mar)	FY2014 Q3 (Apr-Jun)	FY2014 Q4 (Jul-Sep)
Project Name: Advanced Turbine Technology Aeroacoustics												
Q4 Milestone: Deploy and successfully test new 63 microphone acoustic array				◆								
Q1 Milestone: Complete field calibration experiments of acoustic array					◆							
Q2 Milestone: Complete weather proofing data acquisition hardware						◆						
Q4 Milestone: Submit final NREL report summarizing acoustic array performance								◆				
Current work and future research												
Further data analysis												

Comments

- Project original initiation date – October 1, 2011
- Project planned completion date – September 30, 2013
- All milestones completed on schedule

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

University of Colorado (Prof. Scott Palo)
Colorado School of Mines (Prof. Dave Munoz)

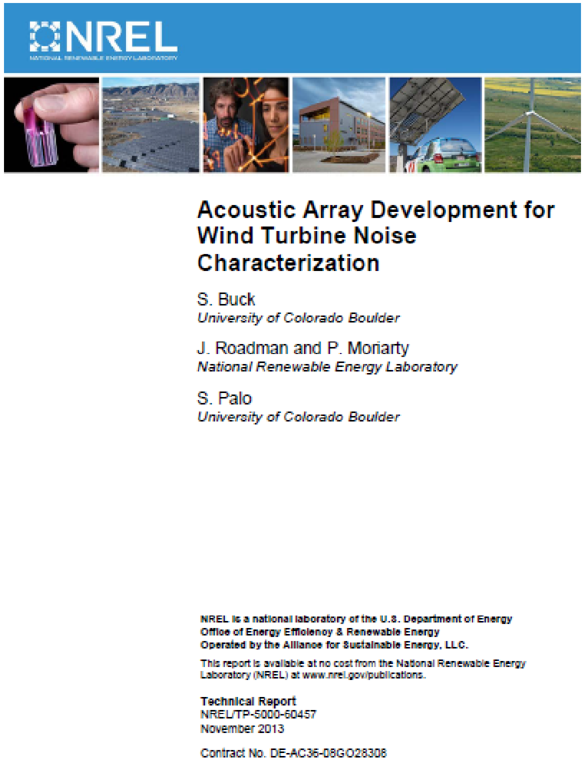
Communications and Technology Transfer:

NREL Technical Report No. TP-5000-60457

- *Acoustic Array Development for Wind Turbine Noise Characterization* by Buck, S., Roadman, J., Moriarty, P., and Palo, S.

Wind Turbine Noise Conference 2013

- Acoustic Array Design for Wind Turbine Noise Measurements
- Aeroacoustic Noise Mitigation Investigation for Wind Turbine Blades
- Application of Phased Array Techniques for Amplitude Modulation
- Authors included Buck, S., Palo, S., Moriarty, P., Roadman, J., Asheim, M., and Munoz, D.



NREL

Acoustic Array Development for Wind Turbine Noise Characterization

S. Buck
University of Colorado Boulder

J. Roadman and P. Moriarty
National Renewable Energy Laboratory

S. Palo
University of Colorado Boulder

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Office of Energy Efficiency & Renewable Energy
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Technical Report
NREL/TP-5000-60457
November 2013

Contract No. DE-AC36-08GO28308

Next Steps and Future Research

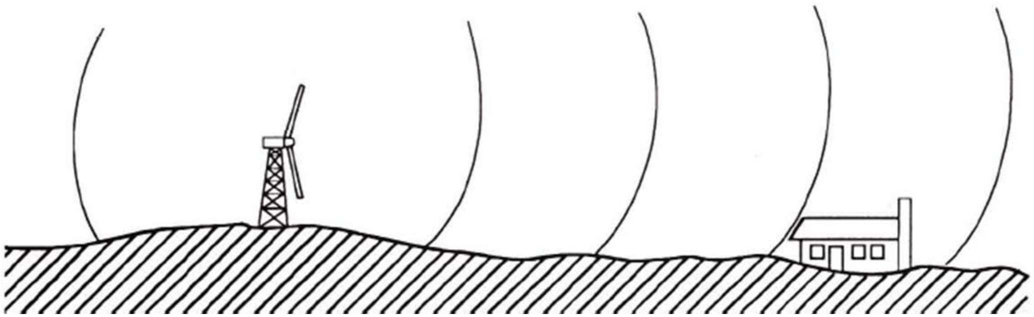
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

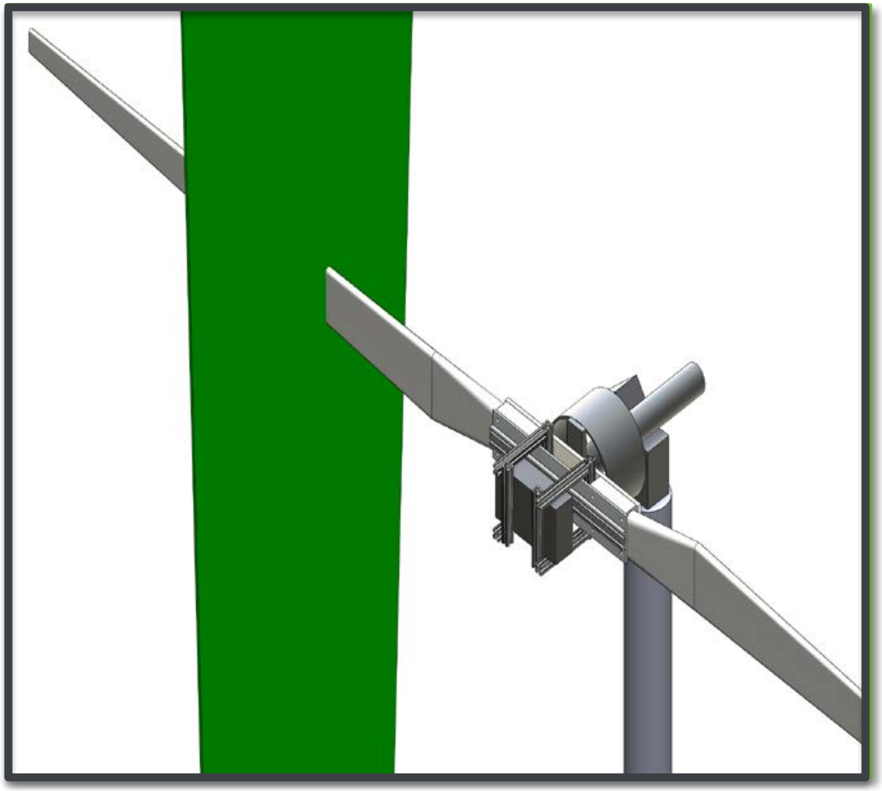
FY14/Current research:

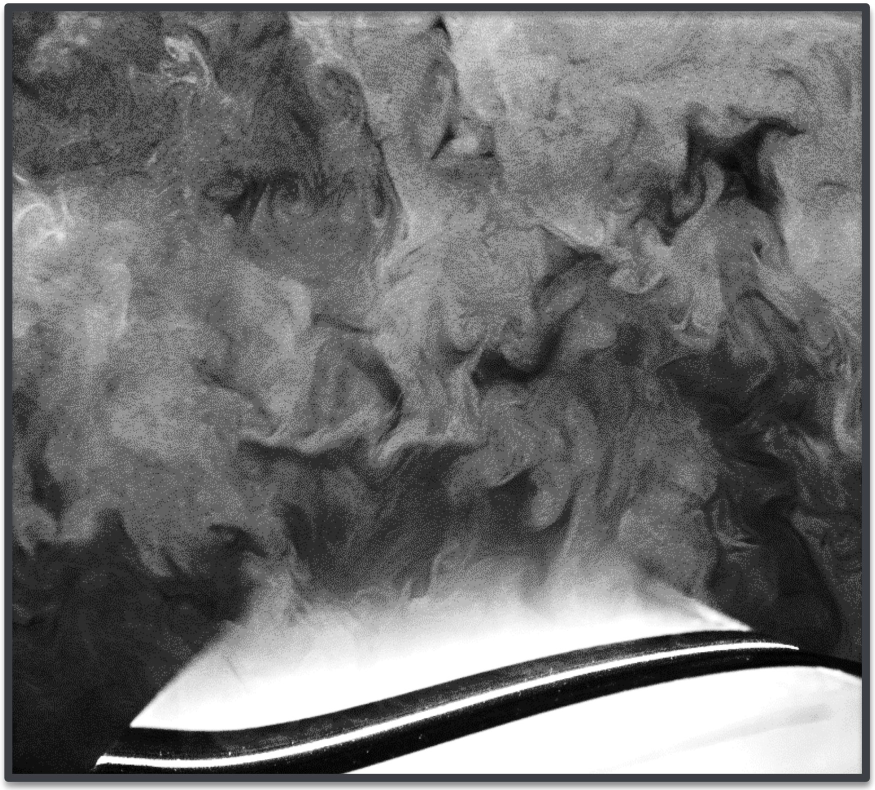
- Funding carryover will support a low-level continuation of analysis of measurements from array on CART2 turbine.

Proposed future research:

- Further array development – atmospheric corrections
- Aeroacoustics is a major thrust area in the A2E initiative
- Proposed activities include turbine technology, plant layout and operation, and community impact. They will begin in FY15.







Wind Turbine In-Situ Particle-Image Velocimetry (PIV)

Rodman Linn
Los Alamos National Laboratory
rrl@lanl.gov, 505-665 6254

March 26, 2014

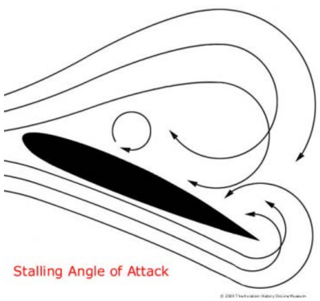
Budget, Purpose, & Objectives

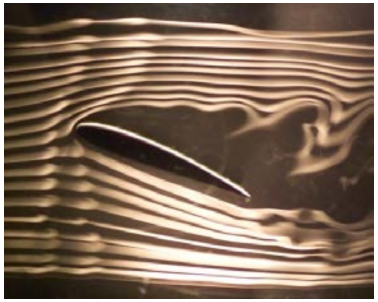
Total DOE Budget[1]: $0.400M

Total Cost-Share[1]:$0.000M

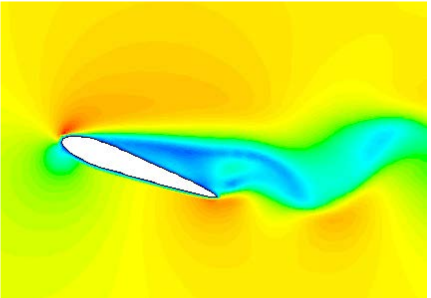
Problem Statement:

High fidelity models can help increase our ability to predict and optimize wind turbine and wind array interactions with the surrounding atmosphere. However, these advances are impaired by a lack of **validation-quality data**. We are working to develop and field test an in-situ particle-image velocimetry (PIV) instrument capable of detailed blade velocity field measurements on full-scale wind turbines.





Flow Visualization



Numerical Prediction

Experimental Data

Impact of Project:

This will be the first application of PIV for turbines operating **in the field**, and will be invaluable for:

- Validating computational models of wind turbine aerodynamic loads
- Designing more aerodynamically efficient blades for realistic operating conditions
- Improving understanding of wind turbine flow fields under typical operating conditions, and how local flow fields produce observed loads

This project aligns with the following DOE Program objectives and priorities:

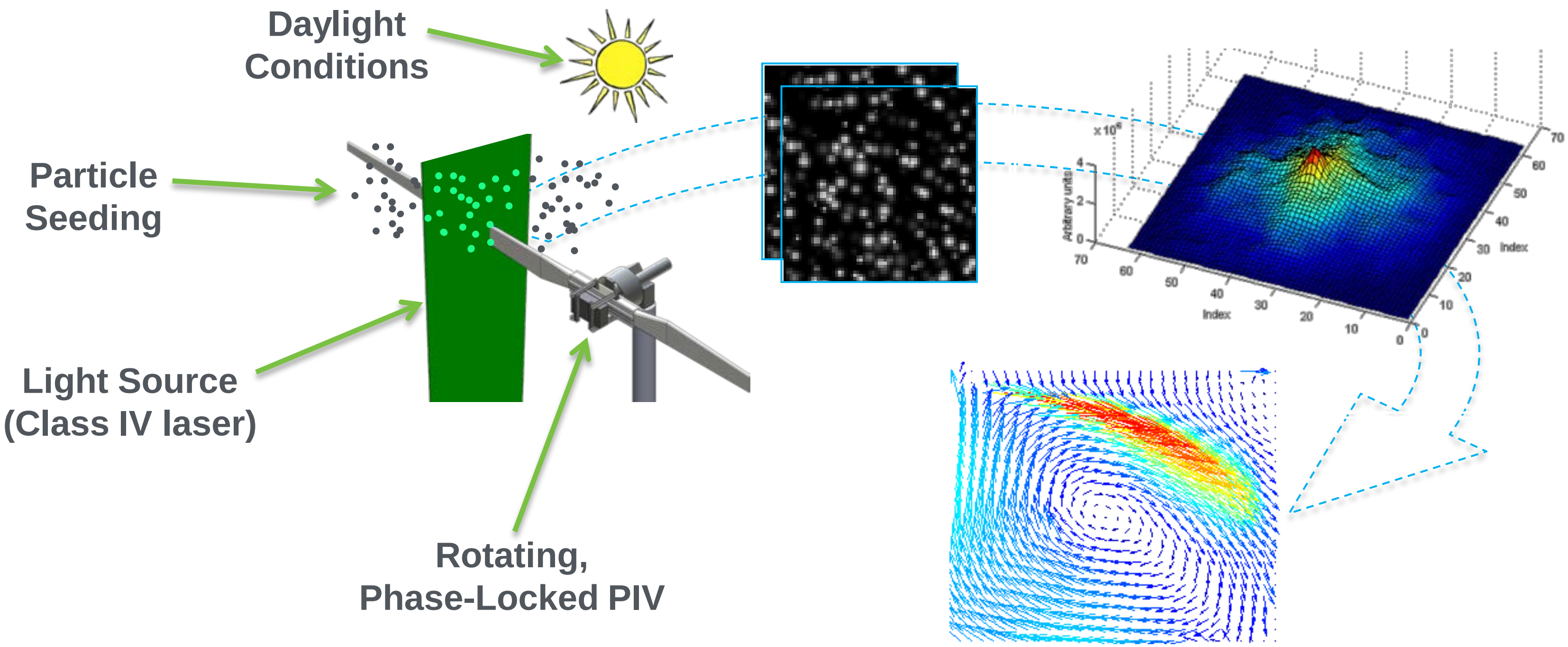
- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Testing Infrastructure:** Enhance and sustain the world-class wind testing facilities at Universities and national laboratories to support mission-critical activities

[1]*Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Technical Approach

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

We are developing a large format rotating PIV diagnostic to obtain high-quality experimental data sets for air velocity fields and turbulence statistics.



Advantages of PIV

- Non-intrusive measurement technique
- Excellent spatial resolution and accuracy
- Velocities obtained in a plane instead of at a single point
- Measure flow near and around blades without interference

Technical Approach

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

Large Format PIV Project Goals and Scope

- System designed to transition LF-PIV to full-scale turbines
- Preliminary tests place diagnostics on smaller, commercially available turbine (4.5 m diameter; 3.2 kW)
- Turbine size is same as those used in the MEXICO experiments
- System designed to transition to field testing at SWIFT and controlled environments such as NASA Ames wind tunnel.

Planned FY-12/13 Technology Development Efforts

TRL 3-4 Convert Small Field-PIV methods to Large-Field PIV system

TRL 4-5 Demonstration LF-PIV under simulated laboratory conditions

TRL 5-6 Transition of Laboratory LF-PIV to a field-deployable system

- Modification of the laboratory LF-PIV to field-testing hardware
- Develop system powering, lighting and triggering methods
- Modify building configuration of LANL Field Station
- Installation of second 3.2 kW wind turbine
- Field Testing Authorization Package (DOE/LANL/FAA)

TRL 6 Demonstration of LF-PIV in single and coupled wind turbine

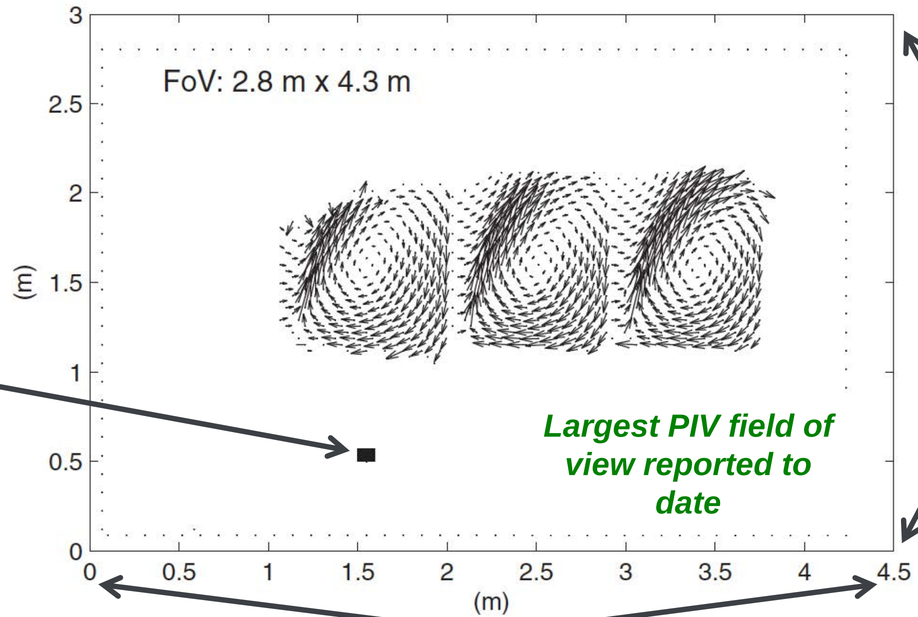
LANL Field Station

- Upstream and downstream met towers with sonic anemometers
- Commercial 3.2 kW wind turbine
- Battery bank and field station
- Turbine power diagnostics

TRL 3-4 Transition Small Field-PIV methods to Large-Field PIV system

TRL 4-5 Demonstration LF-PIV under simulated laboratory conditions

LF-PIV demonstrated in LANL aerosol chamber using 70µm Expancel particles

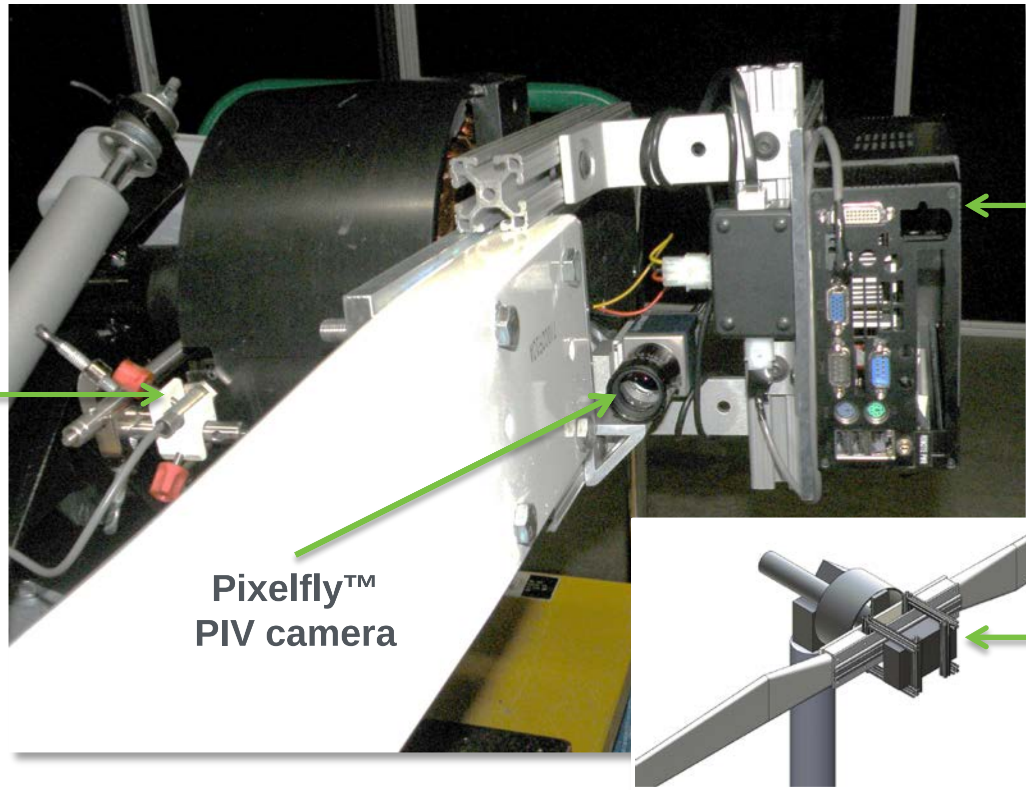


Small Format PIV
(0.07m x 0.095m)

Large Format PIV
(2.8m x 4.3m)

- **Mean velocity vector field obtained for Large Format PIV**
- **The smaller shaded rectangle shows the relative size of Small Field PIV.**
- **40-100 µm Expancel particle enable LF-PIV visualization.**
- **Velocity vectors are obtained about every 22 mm within the measurement plane.**
- **System validated in laboratory for field system up to 12 m^2.**

TRL 5-6 Modification of the laboratory LF-PIV to field-testing hardware



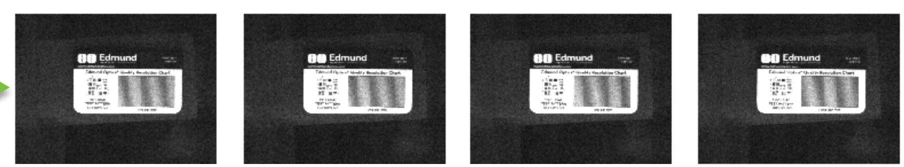
Solid-state Stealth™ computer with wireless telemetry

Hall effect sensor on rotating hub for camera trigger

Pixelfly™ PIV camera

Images acquired with hub-mounted camera rotating at 120 rpm demonstrating phase-locked imaging capability

rev 1 | rev 2 | rev 3 | rev 4…

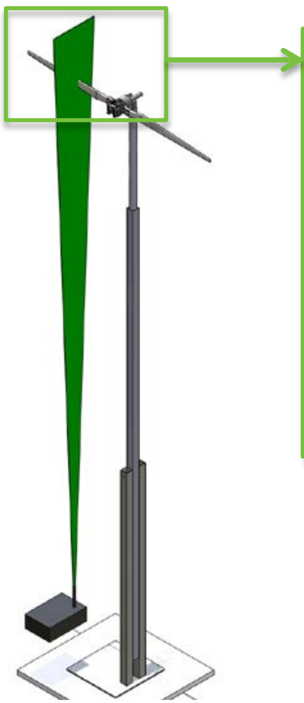


Accomplishments and Progress

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

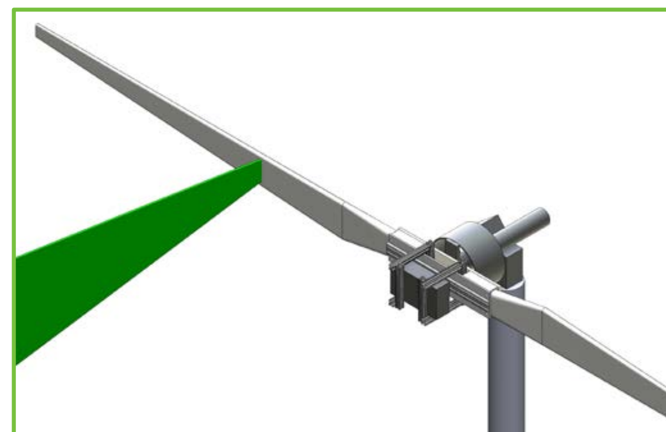
TRL 5-6 Develop system powering, lighting and triggering methods

- Routing the laser light via fiber optic cables to the turbine hub, through a slip ring, and onto the blade
- Encountered light brightness loss due to fiber-optic cable diameter limitations
- Two alternatives pursued in parallel
  - Illuminate the blade from a laser located on the ground (same as LF-PIV set up)
  - Use an over-driven LED or Class III laser mounted on turbine hub
    - Over-driven LED light intensity insufficient for outdoor work during daylight



External Light Source

Enables PIV on both high- and low-pressure blade faces *simultaneously*



On-Blade Light Source

Enables time series development of dynamic stall, separation, etc.

TRL 5-6 Modify building configuration of LANL Field Station
Installation of second 3.2 kW wind turbine
Field Testing Authorization Package (DOE/LANL/FAA)

PIV Instrumentation

- Construction of the on-tower structure to support PIV system
- Installation of laser alignment system beneath the spinning turbine.
- DOE Site Office authorization of field laser operations completed
- FAA Approval for outdoor laser use completed
- LANL work authorization complete

Installation of second turbine tower

- Relocation of field site battery and DAQ system
- Tower Siting
- Archeological and Seismic Evaluation Complete
- Country Permitting Complete
- Concrete pad and tower installed.
- Wiring second turbine tower

Seeding particles

- Procurement of Expancel particles
- Expancel hopper/aerosol generator fabricated
- Trailer mounted boom identified

Coupled Wind Turbines

PIV system 90% ready for field operations (PIV hardware stored off-site)

Technical Targets since FY-12 Program Review

- Transition Laboratory PIV to Field Hardware (Complete)
- Obtain DOE and LANL work authorization (Complete)
- Publish manuscript on aerodynamic scaling (Complete)
- Install second turbine on predominant wind vector (Complete)
- *Measurement of inflow vs. power for single and coupled turbines (Incomplete)* *
- Develop correlation for inflow turbulence and load/power fluctuations (Incomplete) *
- Outline transition of LF-PIV and R-PIV scale-up to larger field (Incomplete)*

*Critical path delay on field work authorization (DOE mandated fire restrictions as a result of 2011 Las Conchas Fire and loss of two Principle Investigators (2012, 2013).

Project Plan & Schedule

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

Summary	
WBS Number or Agreement Number	20292
Project Number	
Agreement Number	

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: High-Fidelity Wake/inflow validation experiments at LANL Field Station												
Q1 Milestone: Aerodynamic scaling of wind turbine publication												
Q2 Milestone: Measurement of inflow vs. power output for coupled turbines												
Q3 Milestone: Develop correlation for inflow turbulance and load/power fluctuations												
Q4 Milestone: Demonstrate LF-PIV and R-PIV scale-up to larger feld												
Current work and future research												
Program paused												

Comments

- Program paused with DOE concurrence in FY-13
- Critical path delay on DOE and LANL field work authorization
- Project PI lost in FY-12 (DOE Voluntary Separation Program)
- Project PI and all key personnel lost in FY-13
- New PIV Project Lead, Ricardo Mejia-Alvarez hired in FY-14

Partners, Subcontractors, and Collaborators:

Texas Tech University, Lubbock, TX
University of Michigan, Ann Arbor, MI
Harvey Mudd College, Claremont, CA

Communications and Technology Transfer:

"Design considerations for large field particle image velocimetery (LF-PIV) " Pol, S. U. and Balakumar, B. J. Meas. Sci. Technol. 24 (2013) 025302 doi:10.1088/0957-0233/24/2/025302

"High-Speed Micron Resolution Particle-Image Velocimeter" LANL IP Disclosure, 2012

"Rotating Particle Image Velocimetry (R-PIV) system for wind turbines" Pol, S.; Vance, M.W.; Ammerman, C. N.; Balasubramaniam, B. J. AIAA Aerospace Sciences, 2013.

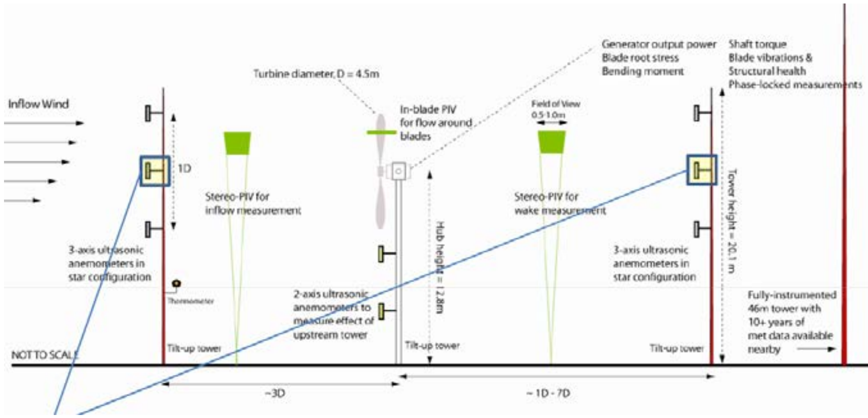
Pol S. Particle Image Velocimetery (PIV) Diagnostics for Wind Energy and Energy Security Research. Invited Presentation at National Renewable Energy Laboratory. CO, June 2012.

Next Steps and Future Research

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

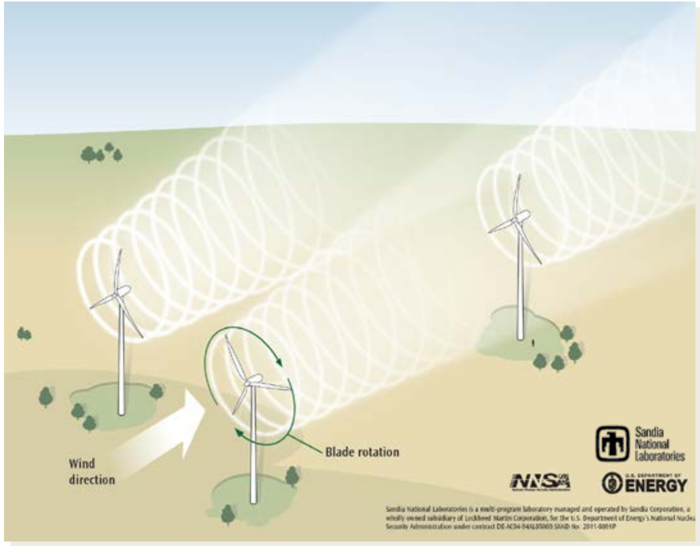
Near Term Research and Development :

- Measurement of inflow vs. power output for coupled turbines
- Develop correlation for in-flow turbulence and load/power fluxuations
- Combined aerodynamic-structural data



Proposed future research:

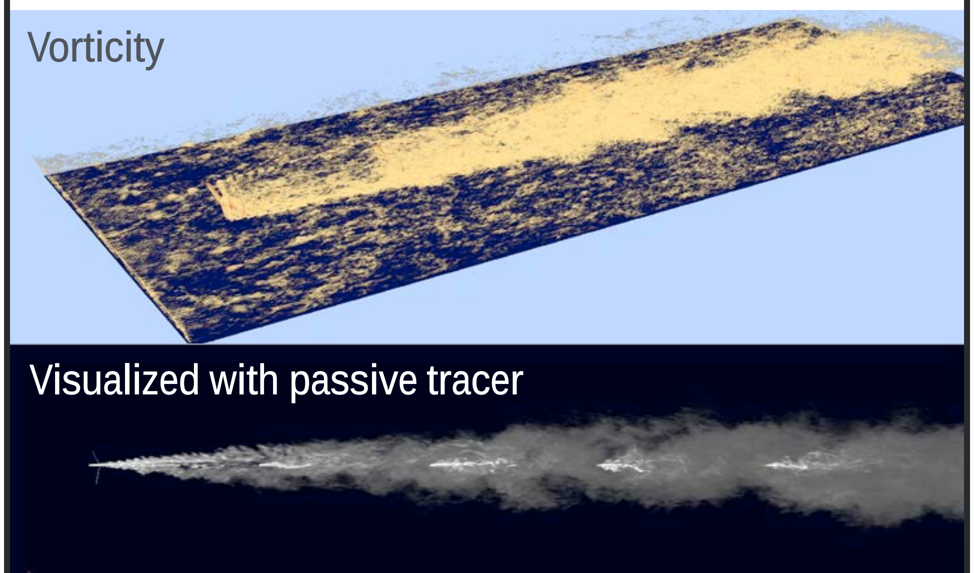
- Begin performing CFD-turbine atmosphere model comparisons
- We propose to extend this PIV diagnostic technique to the DOE/SNL Scaled Wind Farm Technology (SWiFT) Facility, hosted at Texas Tech University
  - Scale-up diagnostic and implement at SWiFT
  - Conduct experimental field campaign
- Integrate new bulk-wind measurement techniques for assessing advective flow properties and entrainment
- Excellent diagnostic to add to the suite at SWiFT
  - Provide in-situ experimental validation data for wind turbine CFD design codes
  - Provide experimental aerodynamics for active aero controls on future smart rotor designs

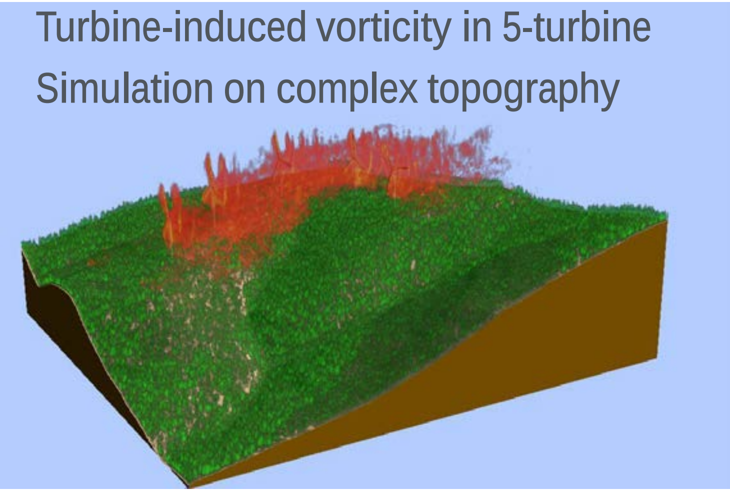


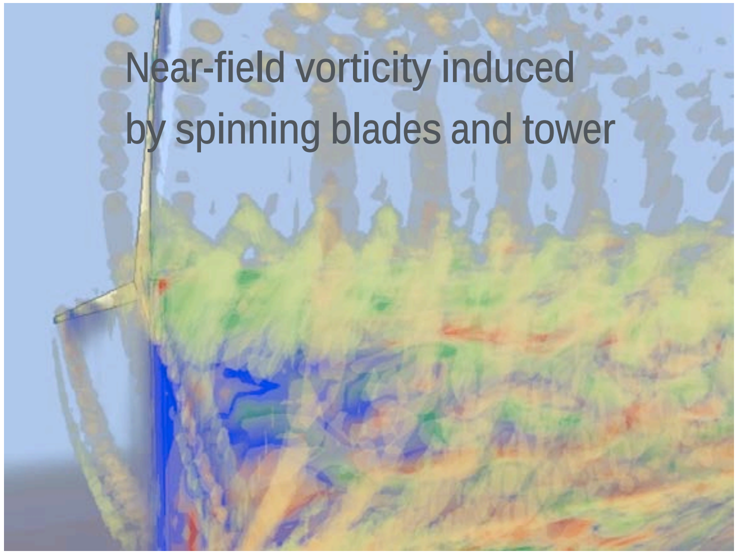
New measurement techniques create new opportunities

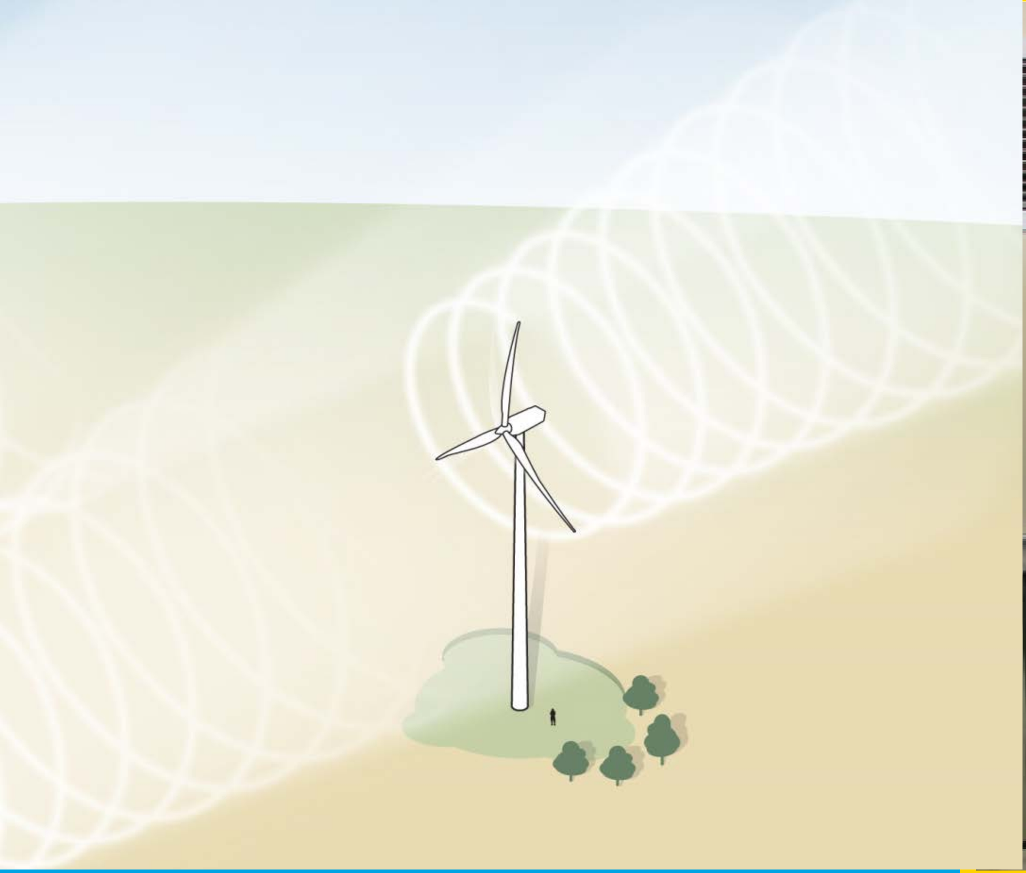
- Model validation
- Phenomenology identification including interaction between atmospheric turbulence and turbine-induced turbulence
- Verification of model-suggested dependencies and phenomenologies

Interaction between 5 inline turbines in turbulent low level jet









Wake Measurement System

Brian Naughton

Sandia National Laboratories

bnaught@sandia.gov 505.844.4033

March 26th, 2014

Budget, Purpose, & Objectives

Total DOE Budget[1]: $2.100M

Total Cost-Share[1]:$0.000M

Problem Statement: Turbine wake formation and evolution is not sufficiently well understood, leading to uncertainty in wind plant performance.

Impact of Project: Innovative instrumentation providing field data will enable validation of research codes and design tools used to optimize wind plant performance.

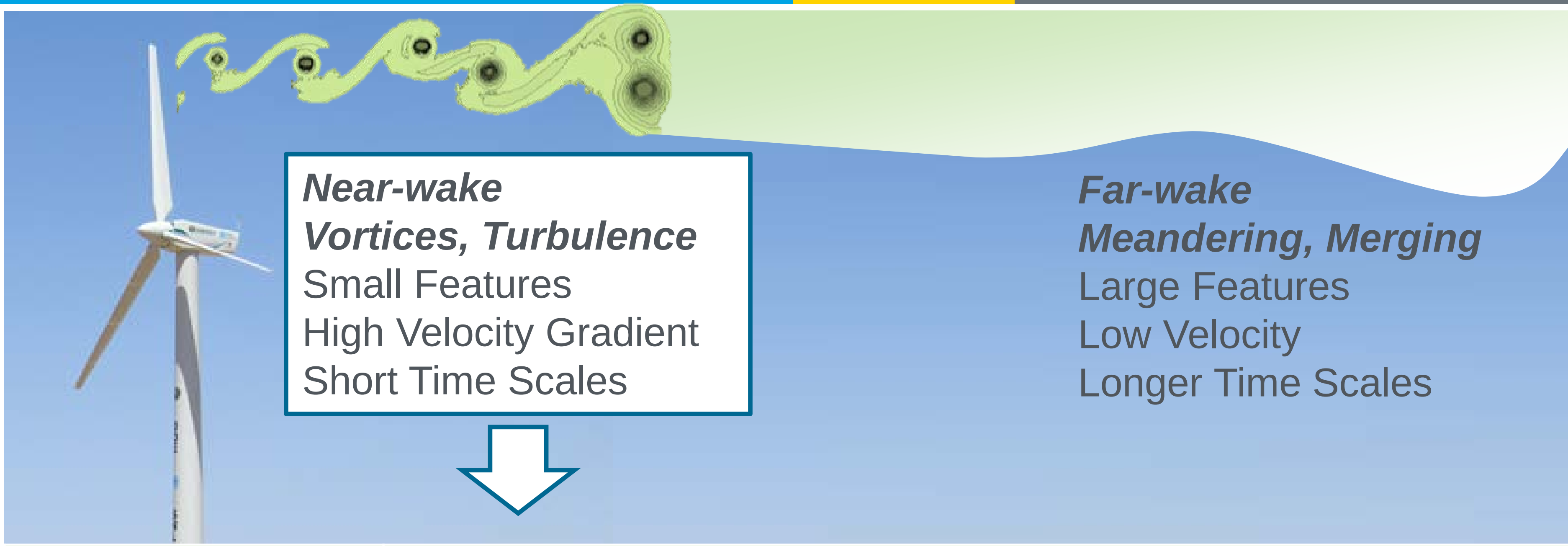
This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Testing Infrastructure:** Enhance and sustain the world-class wind testing facilities at Universities and national laboratories to support mission-critical activities

[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach

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

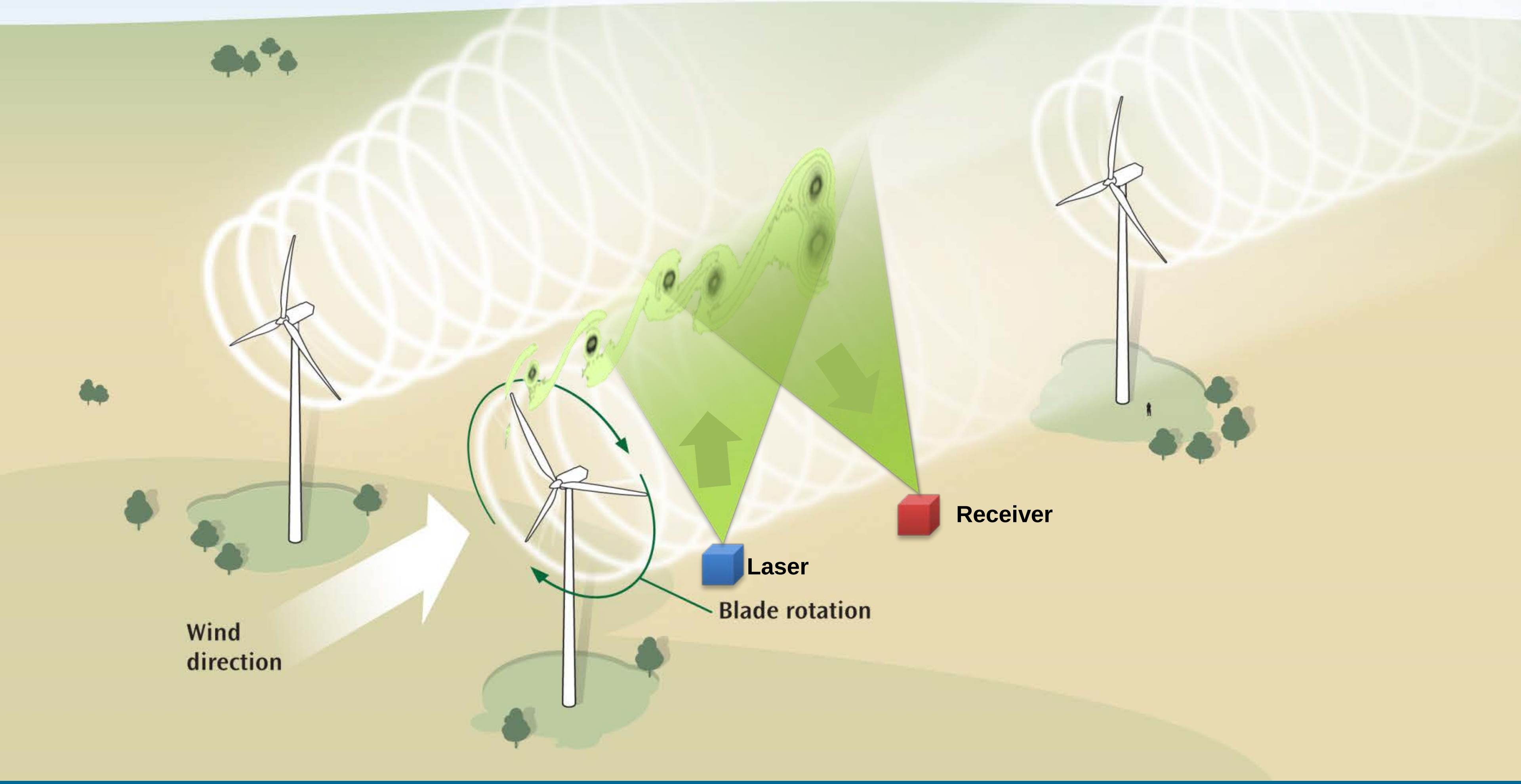


Near-wake
Vortices, Turbulence
Small Features
High Velocity Gradient
Short Time Scales

Far-wake
Meandering, Merging
Large Features
Low Velocity
Longer Time Scales

Existing Systems	Challenges in Near-wake field testing
Particle Image Velocimetry (PIV)	**Small field of view** due to particle size and camera resolution relation. Particle release outdoors an **EH&S challenge**.
Scanning LIDAR	**Time resolution** of scanning point measurements is insufficient to capture coherent flow structures

Measurement Technique: Planar Doppler Velocimetry



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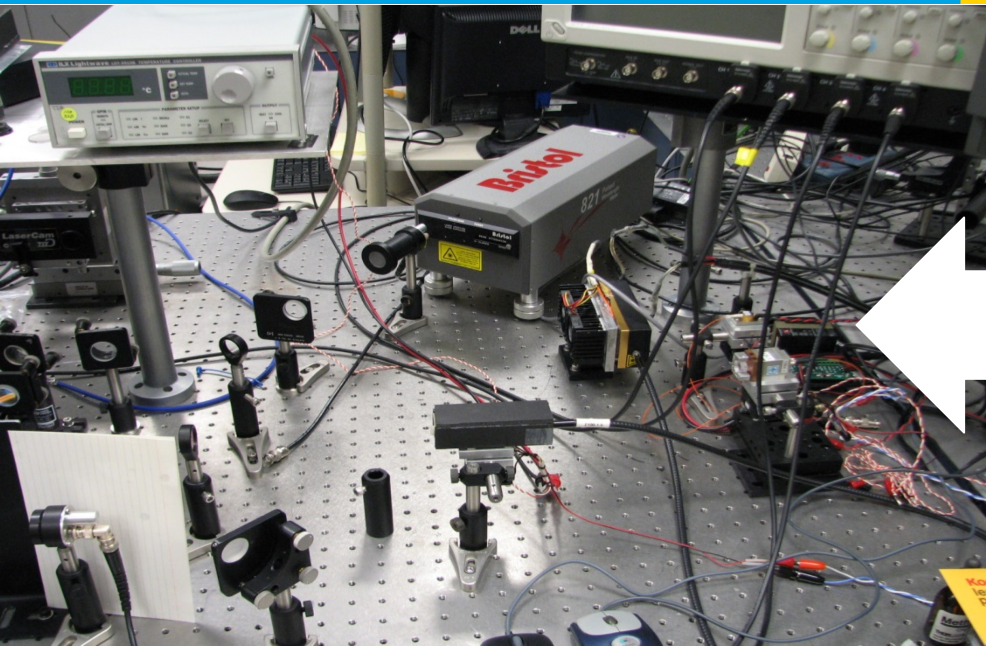
Risk reduction approach:

- Demonstrate simplest possible system
- Address make-or-break components
- Build up from lab to field experiments
- Identify and resolve ES&H issues early
- Leverage deep expertise, equipment, and facilities at Sandia to save time and money

Technical Approach



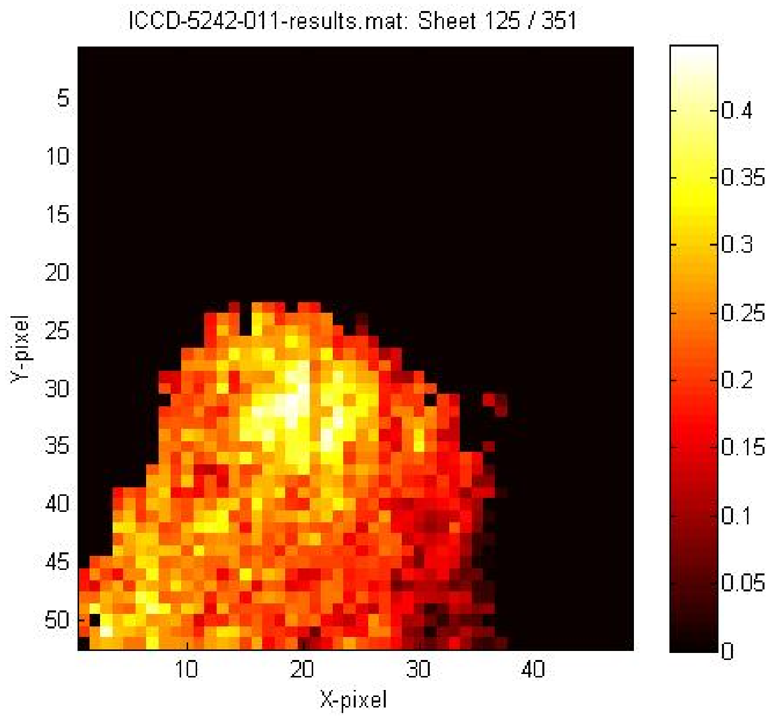
Initial lab experiments:

- characterized hardware
- developed software
- established proof of concept

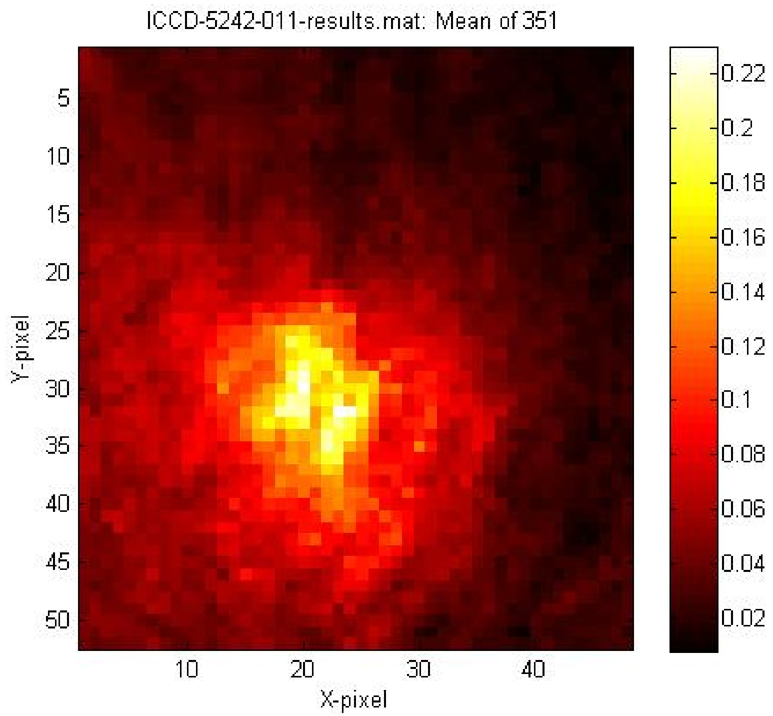
Initial outdoor testing

- Demonstrate scaling
- Identify field-deployment issues

Single Pulse Image



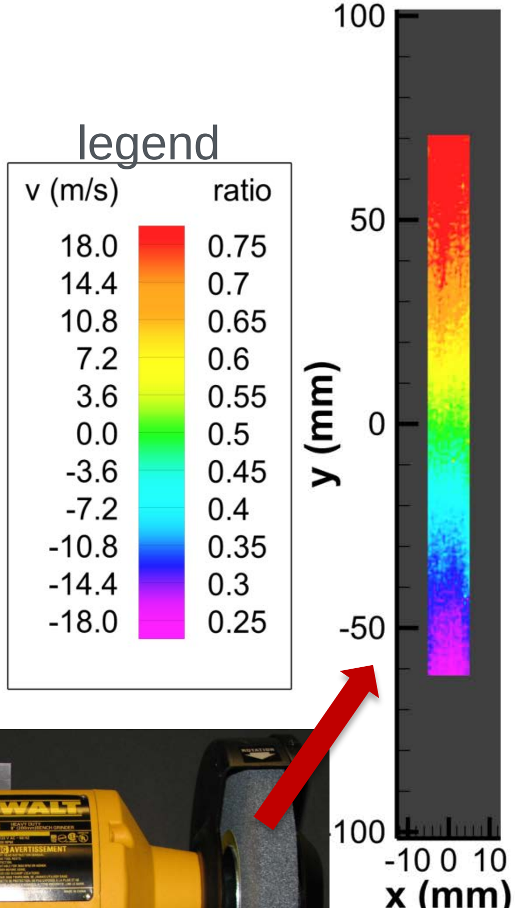
351 Frame Averaged Image

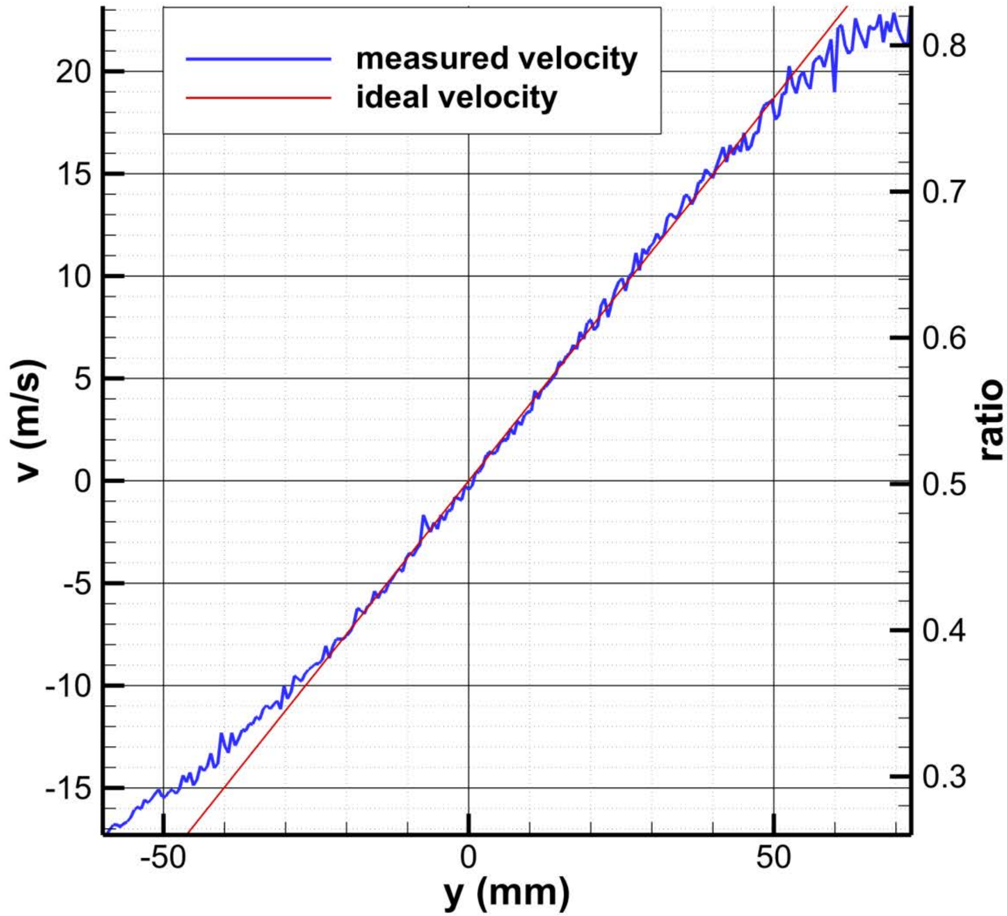


Intensity images of a dust plume were captured. Insufficient laser stability and camera calibration existed to convert intensity to velocity images.

Accomplishments

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





Extensive calibration procedures produced a validated velocity image

Project Plan & Schedule

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

Summary	
WBS Number or Agreement Number **2.1.0.4**	
Project Number	
Agreement Number **23437 (FY13)**	

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Wake Measurement System								
Q1 Milestone: Experimental Design for Laboratory Readiness Experiment								
Q2 Milestone: Draft Report on Laboratory Readiness Experiments								
Q3 Milestone: Project review and risk mitigation meeting with DOE								
Q4 Milestone: Field-deployable system major component specification								
Current work and future research								
Demonstrate system on calibrated target to obtain velocity image								
Draft design specifications for aerosol dispersion system at SNL TA3 test site								
Deliver report to DOE HQ on completed sensitivity test plan at SNL TA3 test site								
Draft SWiFT EH&S site plan for laser safety and aerosol dispersion system								

Comments

- Project start: May 2012. Anticipated completion of instrument: September 2015.
- Significant uncertainty in developing a research instrument has led to unanticipated issues requiring additional time to resolve and in some cases, adjust milestones.

Partners, Subcontractors, and Collaborators:

- 3 Sandia Groups (Wind Technologies, Aerosol Sciences & Laser Sensing)
- Jim Meyers - NASA Langley PDV Developer
- Collaborators include the SWiFT /Texas Tech researchers, and simulation work at University of Minnesota.

Communications and Technology Transfer:

- AIAA SciTech 2015 (anticipated)
- Provisional patent filed 2013
- Field data will be publically available on swift.sandia.gov.

Next Steps and Future Research

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

FY14/Current research:

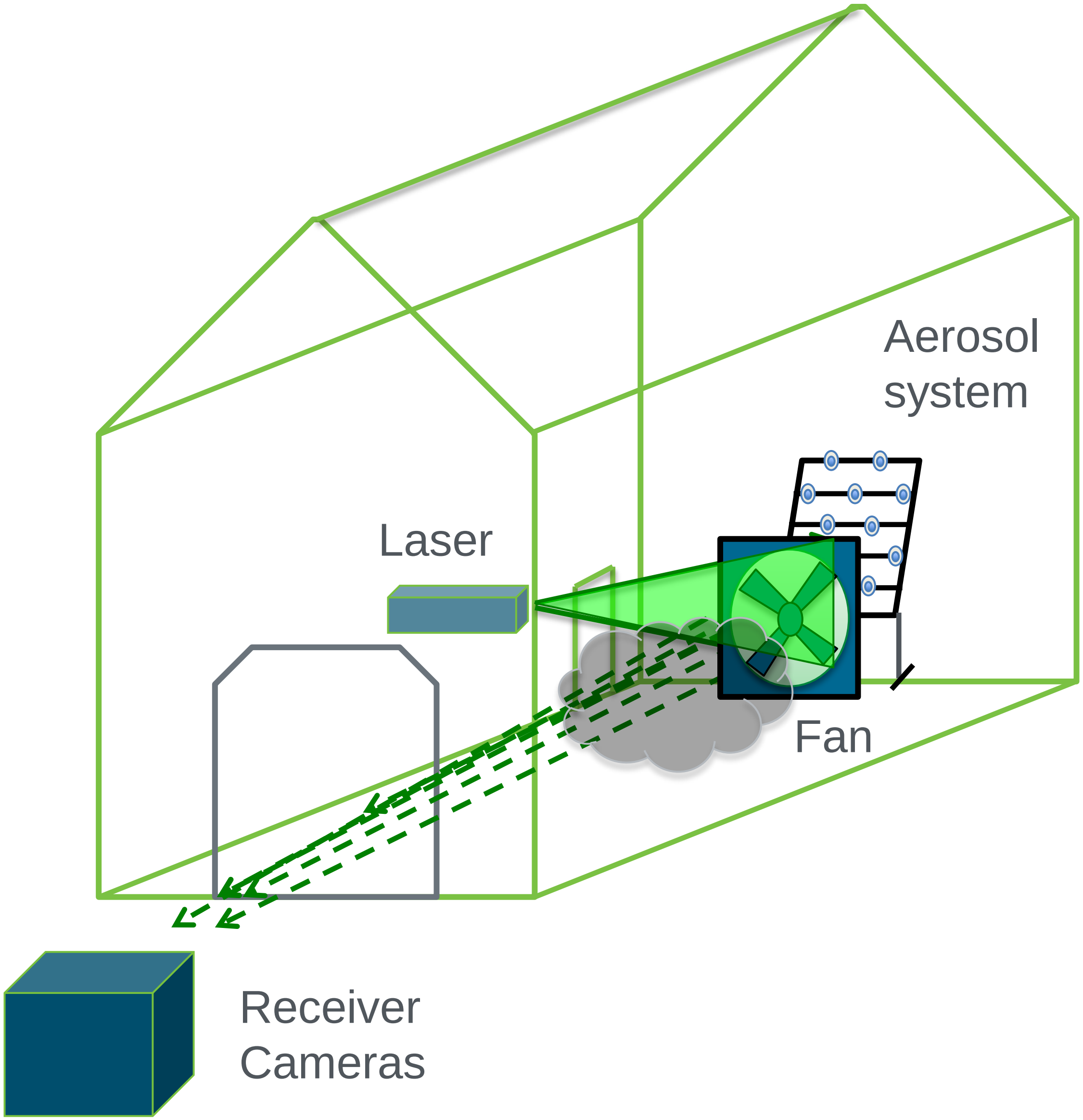
- **Lab tests** to calibrate cameras and obtain velocity image of known target
- **Outdoor testing** to work through seeding methods and determine system capabilities
- **Environmental, Safety & Health** plans to ensure personnel safety, environmental protection and laser operations outdoors (FAA)
- Determine **budget and timeline** to construct and calibrate a field-deployable system at SWiFT in FY15.

Primary objective of FY14 work has been on identifying, prioritizing and reducing technical and ES&H risks.

Next Steps and Future Research

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

Next Steps and Future Research



Objectives:

- Test system on more representative scale
- Refine aerosol dispersion system
- Determine system sensitivity
- Address any field-deployment issues that might arise

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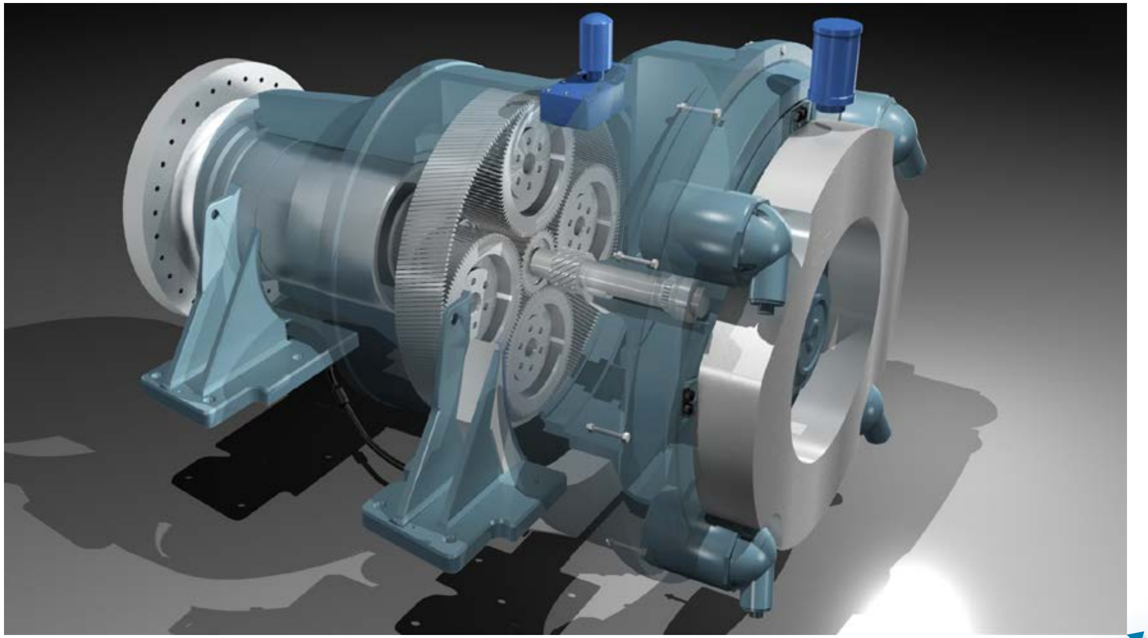
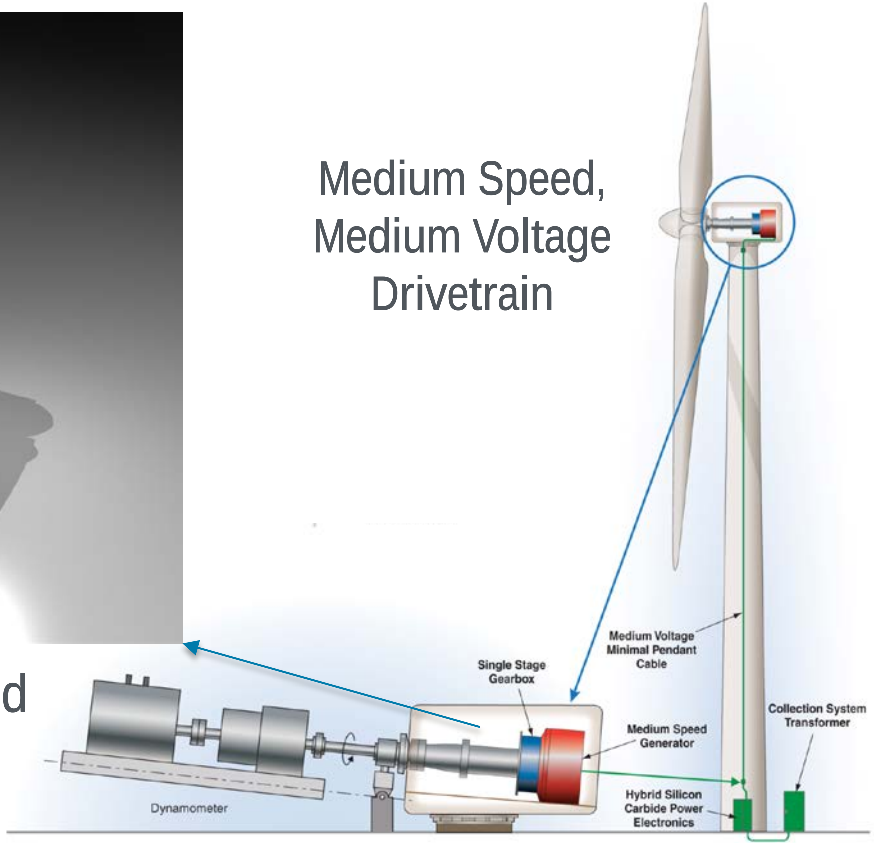


750 kW Drivetrain Technology Test Bed

Medium Speed, Medium Voltage Drivetrain



Innovative Drivetrain Concepts (FOA)

Jonathan Keller

NREL

jonathan.keller@nrel.gov, 303-384-7011

March 26, 2014

Budget, Purpose, & Objectives

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

Total DOE Budget[1]: $1.805M

Total Cost-Share[1]:$1.423M

Problem Statement

- Reduce COE contribution from wind turbine drivetrains due to high capital costs and high weight, efficiency losses, reduced energy production, and low-reliability and high-O&M costs.

Impact of Project

- Measured performance, mitigated technical risks, and advanced Technology Readiness Levels of the key drivetrain innovations, which increase drivetrain capacity, reliability, efficiency, and energy yield—and, subsequently, reduce deployment costs and COE.
- Developed in-depth commercialization plans describing the path to deployment of the key technologies.

This project aligns with the following DOE Program objectives and priorities

- Optimize Wind Plant Performance: Reduce wind plant levelized cost of energy (LCOE)
- Accelerate Technology Transfer: Lead the way for new, high-tech U.S. industries

[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach

Phase I

- Developed conceptual design for a utility-scale drivetrain
- Estimated impacts on COE

Phase II

- Conducted stage-gate review
- Conducting risk-reduction analyses, modeling, fabricating, and bench and dynamometer testing for high-risk technologies
- Conceptual drivetrain design consists of:
  - A high-reliability, low-cost, single-stage gearbox that incorporates premium steels* and additional planets mounted on journal bearings and flex pins to increase reliability and torque density
  - A medium-voltage*, permanent magnet generator with a segmented coil system to improve maintainability
  - A power converter that uses medium voltage, hybrid Silicon-Silicon Carbide (Si-SiC) modules to increase efficiency and incorporates utility interconnect control algorithms to increasing reliability

*Technology assessed but will not be tested

Technical Approach

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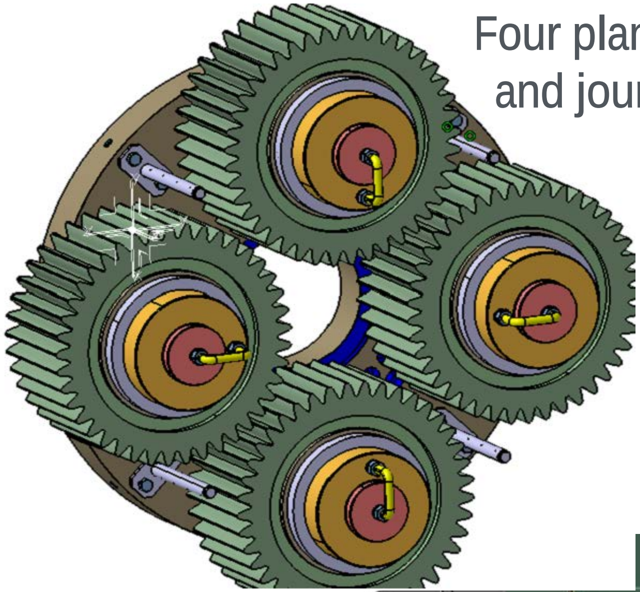
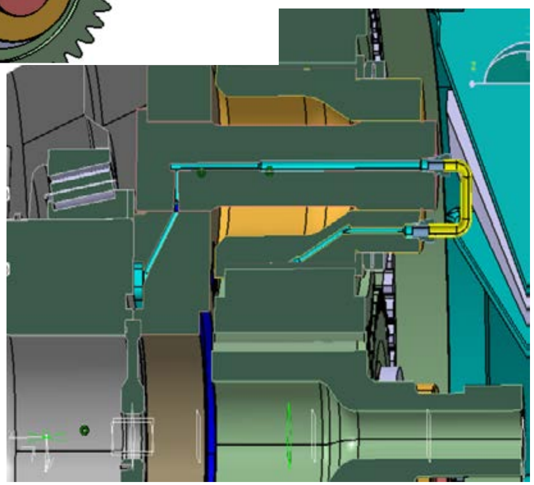
Gearbox Design

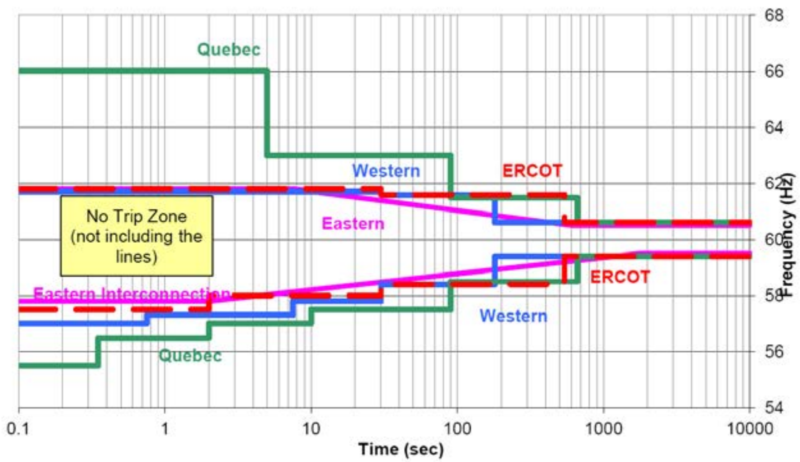


Four planets, flex pins, and journal bearings



Oil feed into rotating frame

Grid Interconnect Software



Medium-Voltage Hybrid Modules

	1	2	3	4	5	6	7	8	9
11				4.6	4.5	4.5			
10			1.6	3.7	4.6	4.5	4.6		
9		4.6	4.5	1.5	4.5	3.2	Low	Low	
8		Low	4.6	4.5	4.3	4.5	4.5	2.6	
7	4.6	4.5	4.5	3.6	4.6	4.6	4.5	4.5	2.0
6	4.5	4.5	4.6	4.5	4.5	4.6	Low	Low	2.6
5	4.6	4.6	4.5	4.6	4.5	4.5	4.6	4.5	4.5
4		3.5	4.5	4.6	4.5	4.6	4.6	3.3	
3		4.6	4.5	Low	Low	4.5	4.5	4.6	
2			1.1	4.6	4.6	4.5	4.6		
1				1.7	Low	3.0			

47 x 4.5 kV SiC JBS Diodes
With ≥ 4.5 kV Blocking

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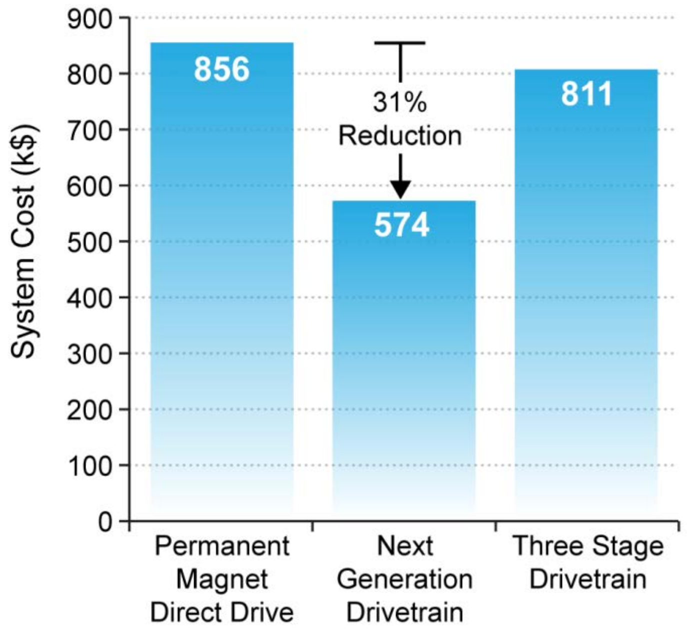
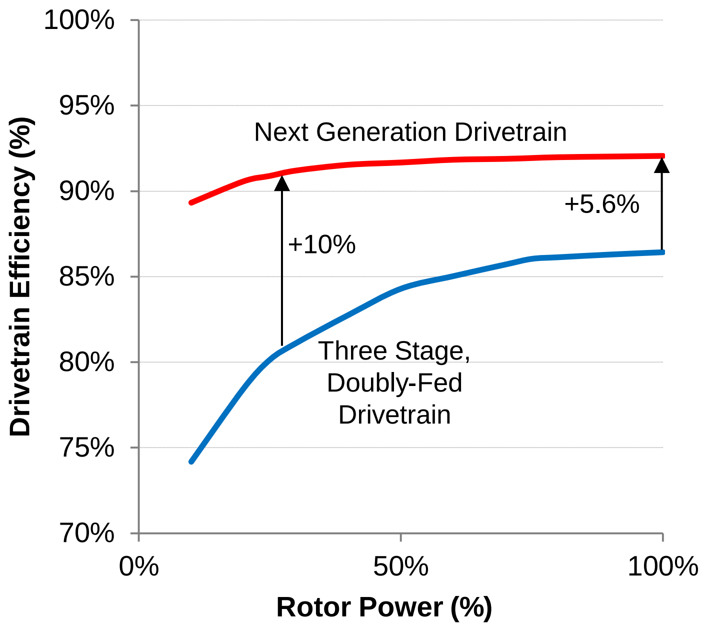
Phase I

- Study indicated proposed drivetrain resulted in:
  - 99% increase in MTBR of the gearbox
  - Up to a 25% increase in torque density
  - Up to a 5% increase in annual energy production
  - Up to a 21% decrease in deployment cost of drivetrain
  - Up to a 13% decrease in the Cost of Energy (COE)



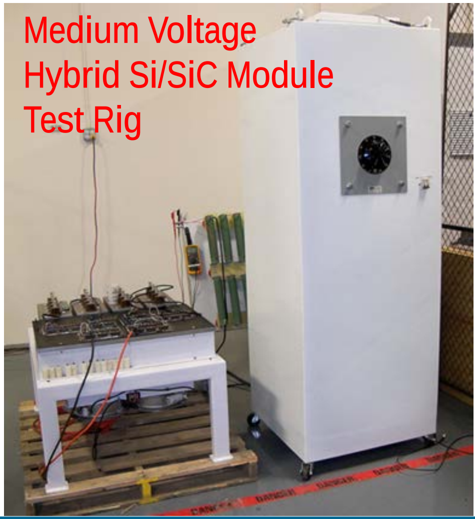


Accomplishments and Progress

Phase II

- July 2012—Stage-gate process occurred
  - Almost immediately, several project partners were forced to drop out
  - Project was refocused
- Feb. 2013—Phase II plans were re-approved
- Feb. to July 2013—Subcontract initiation process and official start of Phase II
- July to Oct. 2013
  - Started single-stage gearbox design
  - Completed construction of the power converter and medium voltage test rig
  - Will complete Phase II hardware in mid 2014 with dynamometer testing planned for late 2014

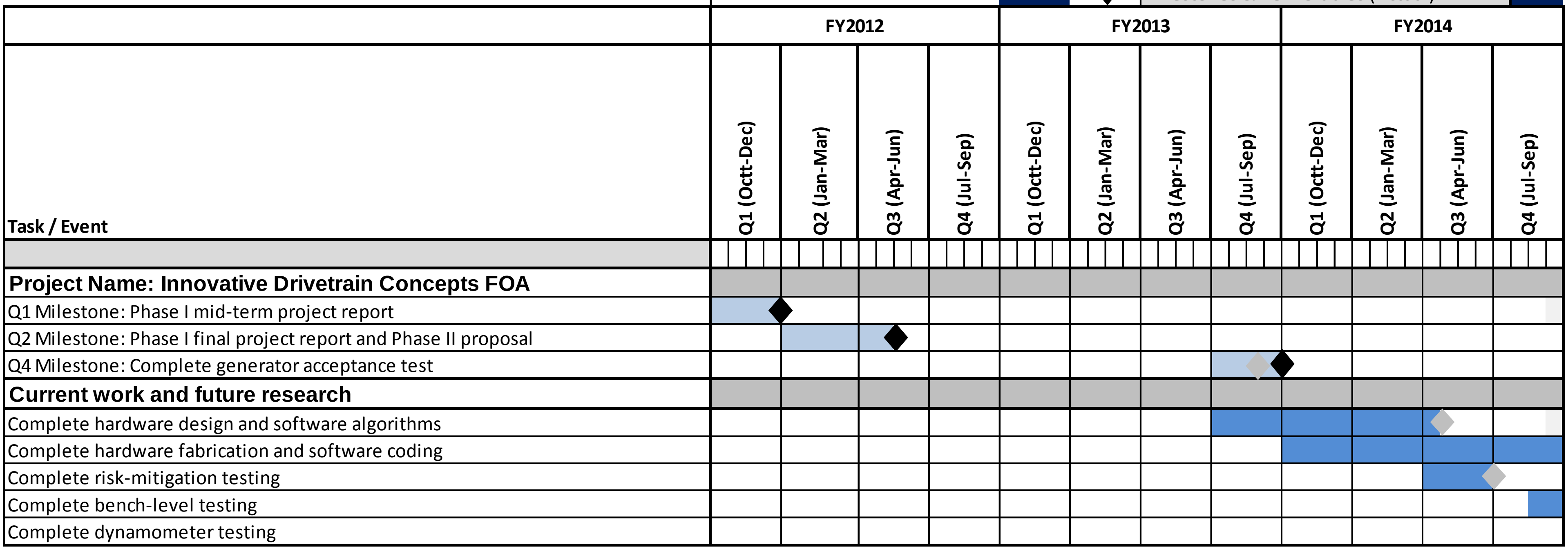
Develop new gearbox and power converter
Reuse existing generator and main bearings



Project Plan & Schedule

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

Summary		Legend
WBS Number or Agreement Number	WE 2.3.0.15	Work completed
Project Number	Next Gen Technology 1	Active Task
Agreement Number		Milestones & Deliverables (Original Plan)
		Milestones & Deliverables (Actual)



Comments

- Phase I—October 2011 to April 2012
- Phase II—July 2013 to March 2015
- Go/no-go decision points—July 2012 and February 2013
- Per DOE direction, milestones are tracked by task instead of by quarter
- Milestones shown here are translated roughly into quarterly format

Partners, Subcontractors, and Collaborators

- CREE ($187.5K funded/$62.5K cost share)
- DNV GL ($525K funded/$410K cost share)
- Romax Technology ($695K funded/$625K cost share)
- GE Wind ($75K in kind)
- Vattenfall ($30K in kind)

Communications and Technology Transfer

- As a FOA, little has been presented publicly to date, including the Phase I Technical Report.
- Exceptions:
  - AWEA Windpower 2012 presentation and planned 2014 poster
  - Press release: http://apps1.eere.energy.gov/wind/newsletter/detail.cfm/articleId=189

Next Steps and Future Research

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

FY14/Current research: Beginning Q4 FY13 in Phase II, the team has designed and will fabricate a low-voltage, 750 kW drivetrain and will test it in the NWTC 2.5 MW dynamometer.

- Single-stage gearbox with four planets, flex pins, and a journal bearing system
- Permanent magnet generator with segmented poles
- Power converter with utility interconnect fault control algorithms

Additionally, the team has designed, fabricated, and will test medium-voltage hybrid Si/SiC power converter modules. The team will assess effects upon the COE and develop commercialization plans.

Proposed future research: Although funding is capped in Phase II, testing of premium steels in the gearbox, testing of hybrid medium voltage modules in the power converter, and development & testing of full SiC, medium voltage modules would be of high value. Field testing of utility interconnect control algorithms would link to A2e initiative.

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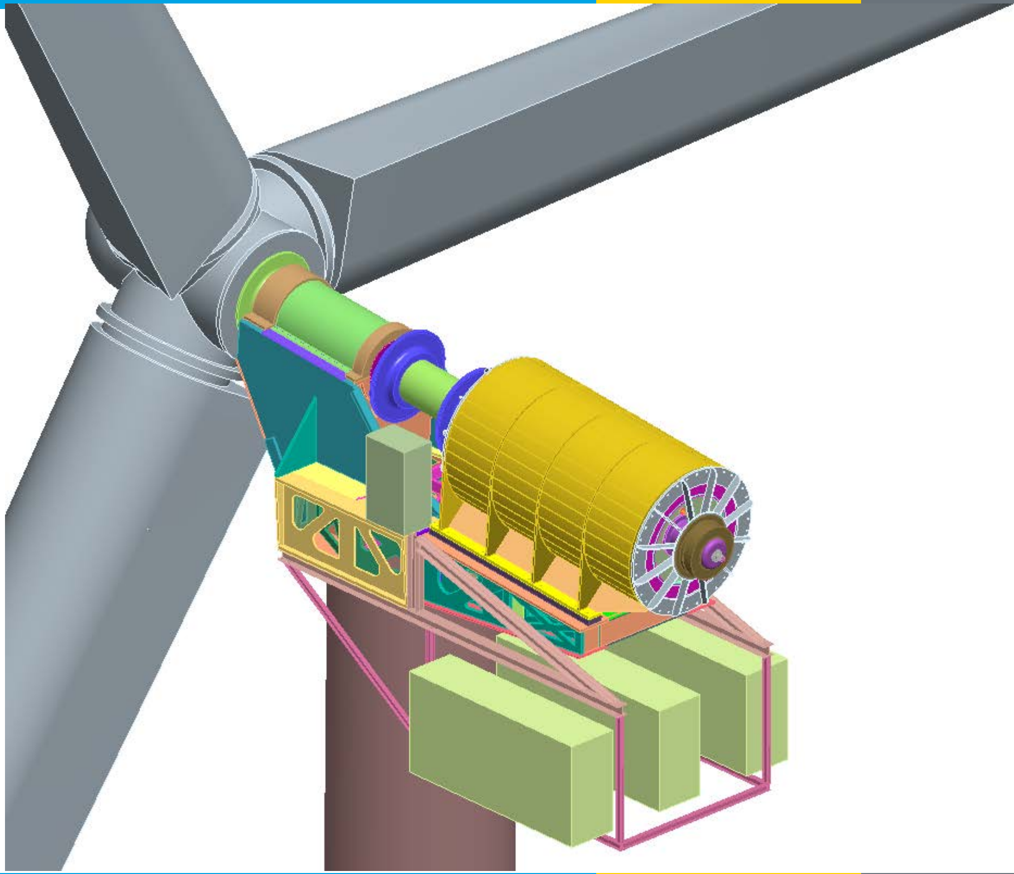


A Lightweight, Direct-Drive, Fully-Superconducting Generator for Large Wind Turbines

Rainer B. Meinke, Ph.D.

Advanced Magnet Lab, Inc.

rbmeinke@magnetlab.com; Tel. 321 728 7543

03/26/2014

DE-EE0005140

Budget, Purpose, & Objectives

Total DOE Budget[1]: $1.486M

Total Cost-Share[1]:$0.574M

Problem Statement: Develop "fully-superconducting direct drive" generator in the 10 MW power range for offshore wind turbines

Impact of Project:

Reducing Cost-of-Energy to 0.07$/kW hr by 2030

This project aligns with the following DOE Program objectives and priorities:

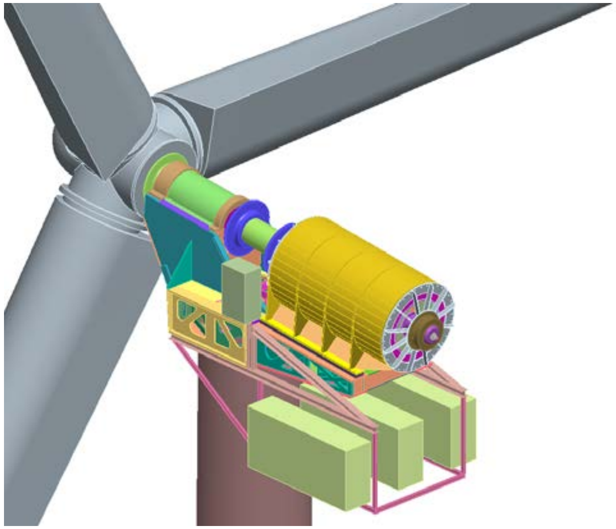
- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries

[1]*Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Technical Approach

Develop 10-MW fully-superconducting generator (FSG) for direct drive wind turbines

- *Reduce generator weight (500 ton → 150 ton)*
- *Increase reliability by eliminating gear box*
- *Intrinsic fault current limitation due to superconducting stator, positively impacting size/cost of balance of turbine components*



Key Generator Parameters

Diameter: 3.5 m
Length: 7.9 m
Mass: 146 tons

Technical Approach

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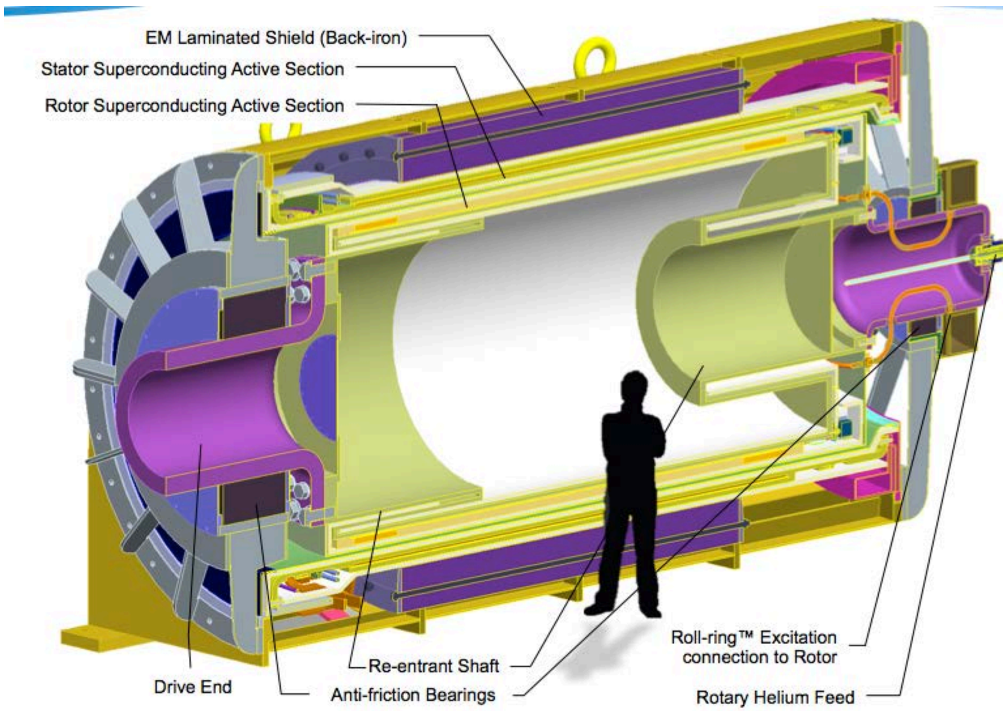

EMERSON.

MgB_2 Superconductor

Low cost materials (boron, magnesium)

- Abundant availability
- Operational temperature 16 K

Re-entrant SS shaft to reduce heat load on rotor winding

Re-entrant composite support for torque transfer of stator winding

Generator Block Diagram

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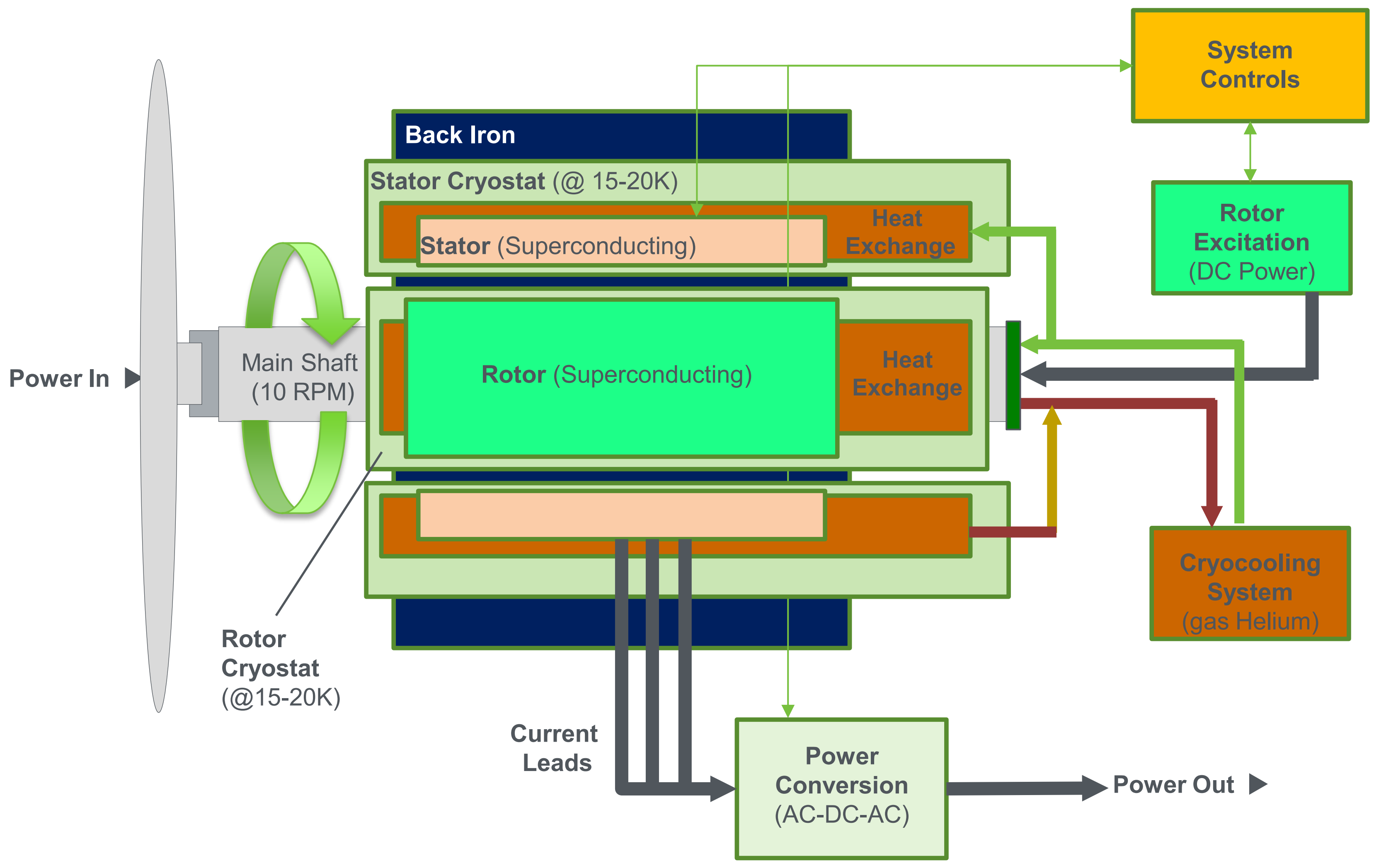
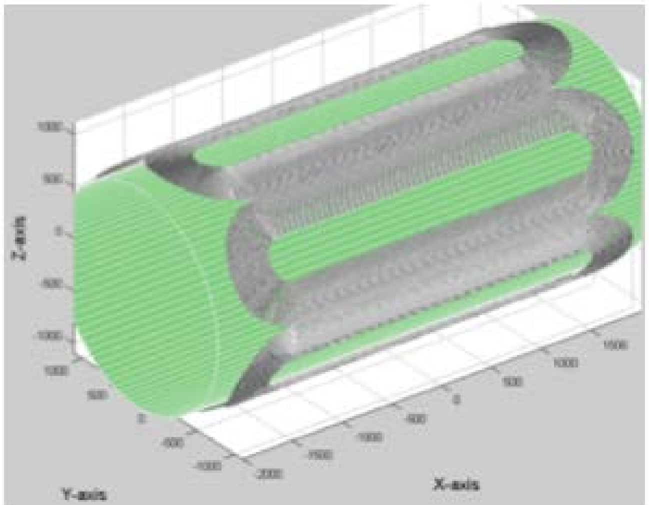


Electromagnetic Coil Design

Enabling AML Coil Technology: "Stacked Saddle Coils"



AML Patented Technology:

- **No quench training required**
- **Insignificant higher-order field errors**

- Sextupole coil configuration (pole number limited by AC losses)
- Superconductor embedded in composite
- Conductor diameter for rotor and stator ~2.5 mm
- Required minimum bending radius of 40 mm

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Required Risk Abatement:

1. **MgB_2 Conductor Development**
   - Required conductor development: J_c, bending radius, filament size
2. **Compliant Composite Development**
   - Differences in CTE between metal and composite at interfaces
3. **Conductor Containment**
   - Fatigue Analysis
4. **Cryogenic Thermal Cycling**
   - Analyze impact of thermal cycling on cooling network efficiency degradation
5. **AC Losses Determination**
   - Determine AC losses under operating conditions in synchronous machine
6. **Fault Current Limitations Test**
   - Test stator current limitations under fault conditions due to SC transition

MgB_2 Conductor Development

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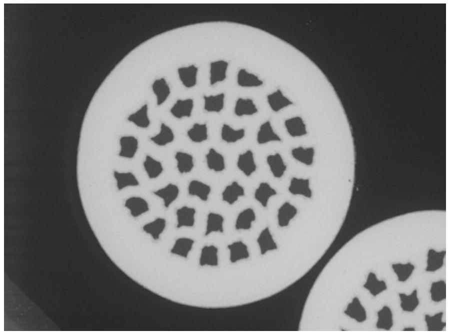
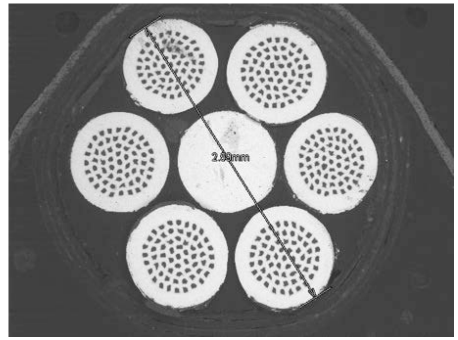
- **Bending Radii in Rotor and Stator Windings Require Mini-Cable**
  - 6-around-1 cable with ≤ 0.8 mm strand diameter
- **Enhancement in J_c; Increase Fill Factor (SC /Non-SC Ratio)**
- **AC Losses in Stator Winding Require Fine Filaments**
  - Development of 10 mm filaments
- **High Resistivity Matrix Material for Stator Conductor**
  - Reduce AC losses
  - Limit fault currents in stator
- **Reacted Conductor**
  - Manufacturing of large multi-layer coils require react-and-wind
- **Conductor Cost**

Rotor and Stator Conductor Development

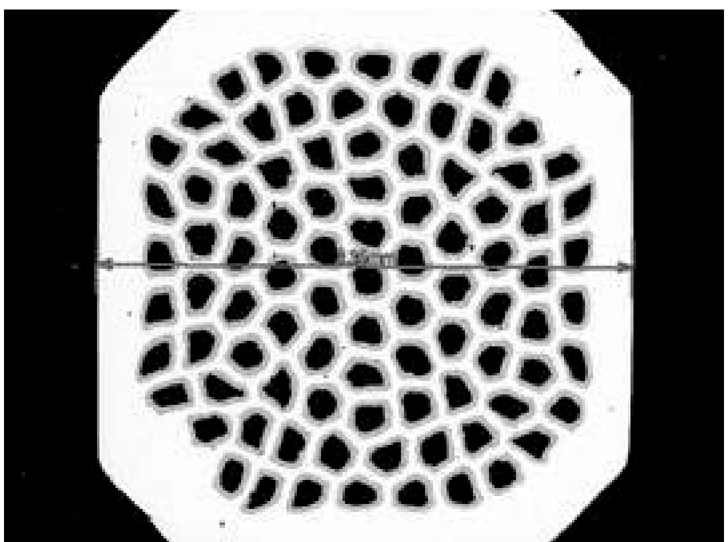
Rotor Strand:



Rotor Mini-cable:



Stator Strand Development



Rotor Conductor:

- Round -MFT298, 37 filaments, diameter 0.78 mm
- No Cable degradation
- Bending radius, no degradation at ρ = 250 mm
- Critical current within 10% of design requirement

Stator Conductor:

- Development of **91-filament** conductor in preparation
- Reduction of reaction layer
- Thinner outer Tube

Compliant Composite Development

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Requirements:

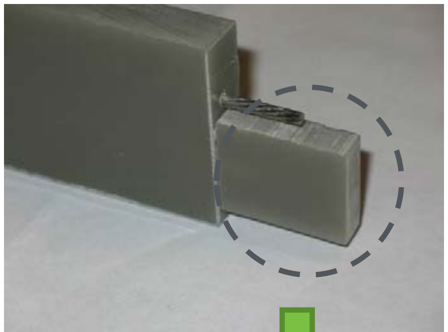
- Match thermal expansion (CTE) of the 304SS rotor shaft material
- Low modulus composite for improved compliance within winding layer and simultaneously high strength to maintain bonds to the shaft, cryogenic cooling tubes and superconductors.
- Material properties at cryogenic temperatures needed for precise FEA analysis
- Determine thermal/mechanical properties of all needed composites in full temperature range from 300 K to operation temperature (~15 K) for actual composition and manufacturing procedure.

EMERSON | WINONA STATE UNIVERSITY | COMTEC

Compliant Composite Development

Developed Composite:

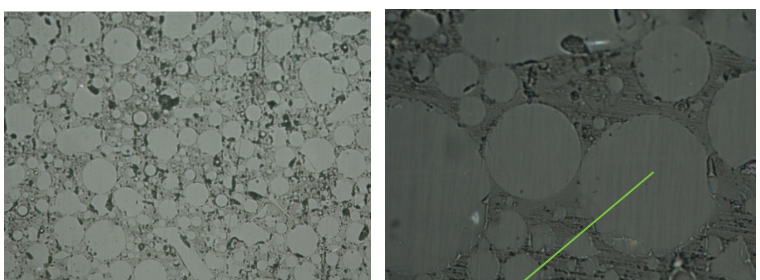
- **Spheriglass Vf 65% with CTD-521 resin**
- Tests based on ASTM standards for testing of filled resin composites
- Tests at 4 K at CTD complete
- Test at Room Temperature and 90 K at COMTEC in progress



Thermal shock and cycling between RT and LN2 (77K)

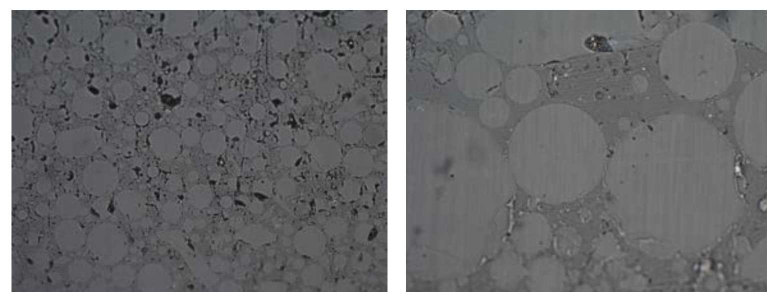
Micro Crack Examination

Pristine Material



Glass beads

Material after 60 thermal cycles



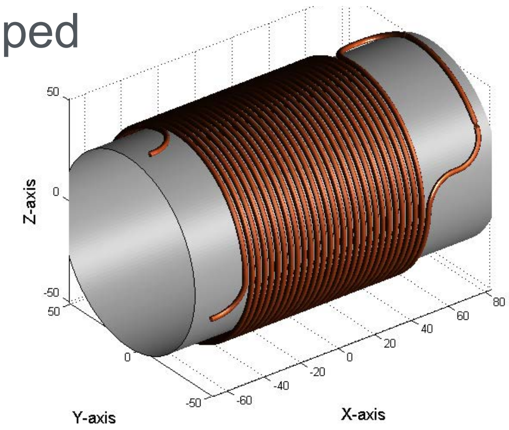
No defects found

WINONA STATE UNIVERSITY

EMERSON.

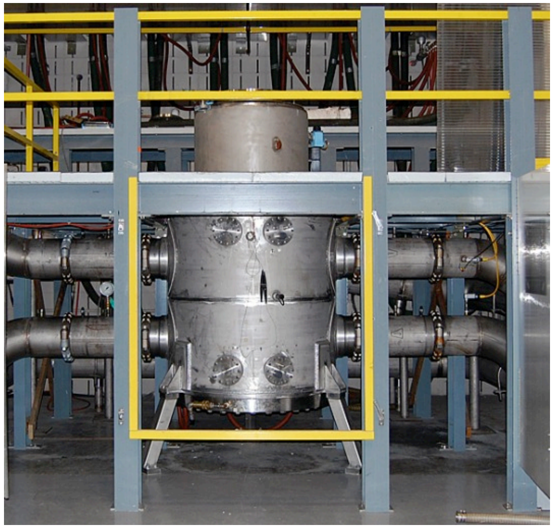
Conductor Containment Analysis

Continuous cycling of bifilar test coil, embedded in developed composite substrate, operating in strong background field



Conductor Loading:
150 N/cm at 3000 A and 5 T (exceed forces in generator winding)

Normal Conducting Solenoid Test Facility at NHMFL



Main Parameters:
Warm bore: 195 mm
Max Field: ~20 T
Cryostat ID: 170 mm

Ramp rate: 200 A/sec
I_{nom} for 5 T 10 kA
T_{ramp} to 5 T: 50 sec

Advanced Magnet Lab

Fatigue (if any) will be manifested by:
- Reduced critical current
- Micro cracks in coil support

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Subscale Torque Tube -- Temperature Cycling Test

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Test Sample Configuration

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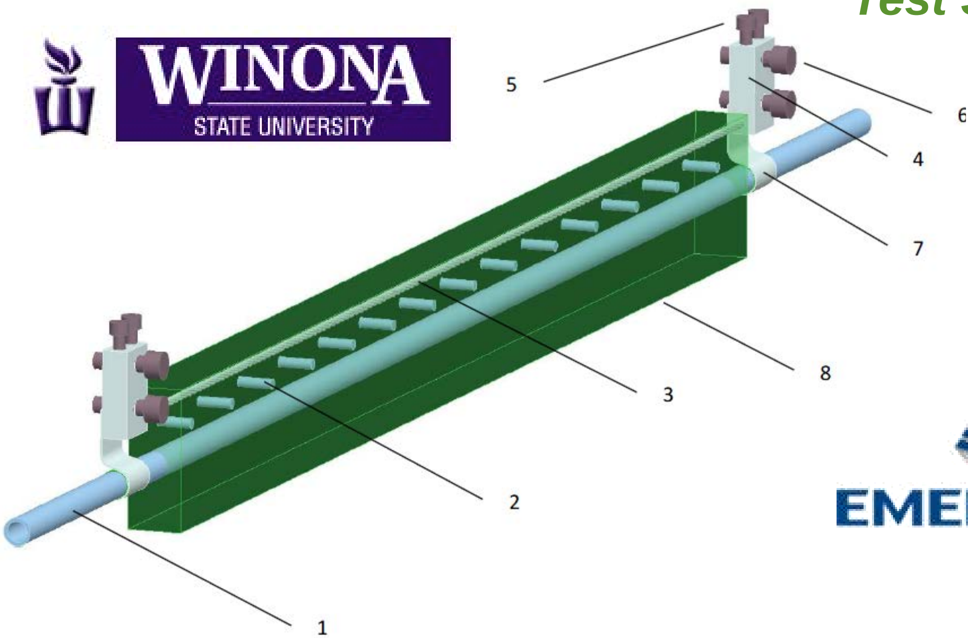

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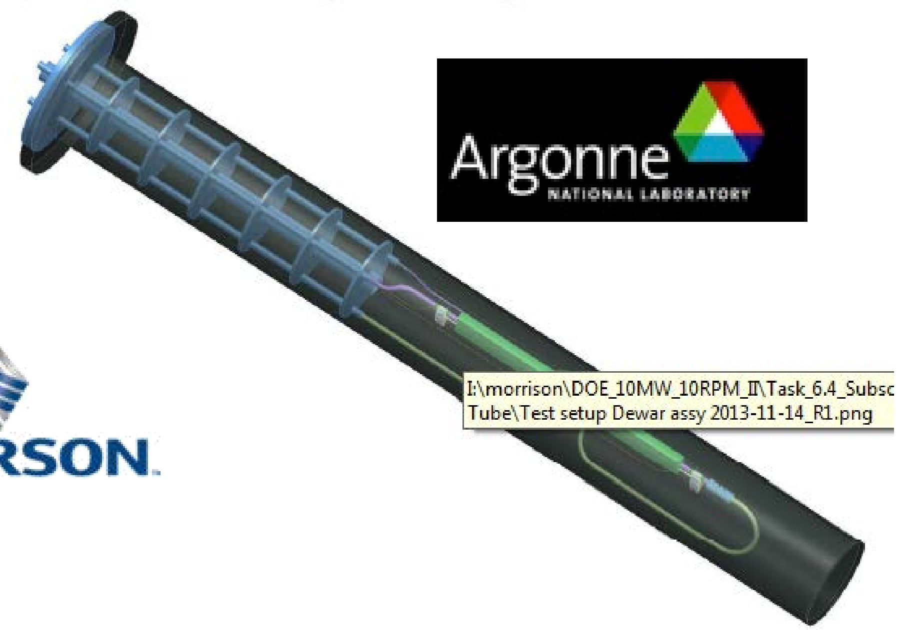
Argonne NATIONAL LABORATORY



1: SS 304 Cooling Tube
2. Cernox Temperature Sensor (15X)
3. Stainless Steel Cable
4. Electro-thermal Attachment Block
5. Cable Clamp Screws
6. Current Lead Connection Screws
7. Thermal Connection to Cooling Tube
8. Cast Compliant Composite

Thermal Cycling Test:

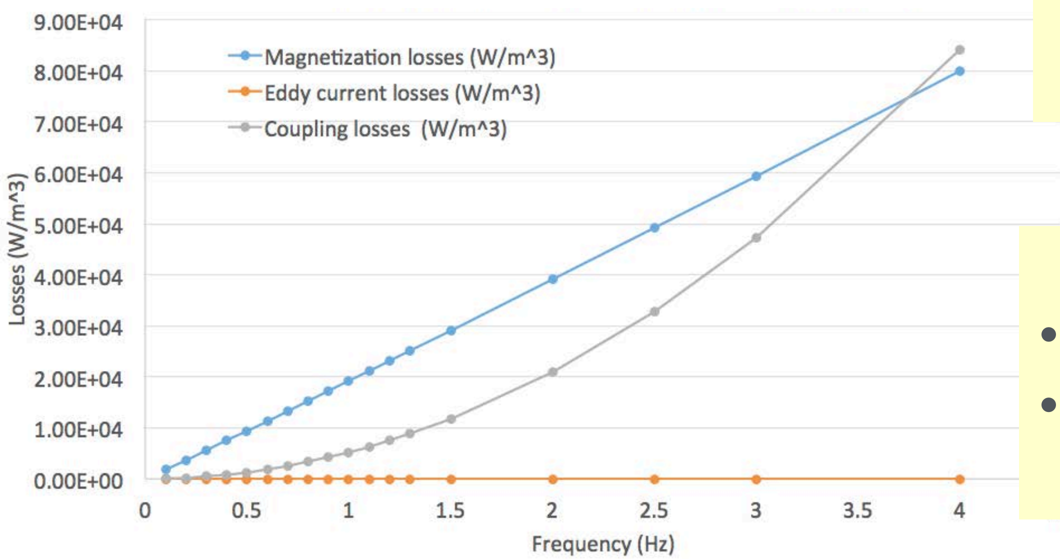
- Perform several thermal cycles (RT to 15K)
- Introduce heat (through a wire embedded in the test sample)
- Monitor thermal profile along wire and look for variations in thermal gradient

AC Loss Determination in MgB_2

- Magnetization losses: (~ ΔB, f, J_c, d_f)
- Coupling losses: (~ ΔB^2, f^2)
- Eddy current losses: (~ ΔB^2, f^2)

ΔB: Flux density sweep
F: Frequency
Jc: Critical current density
d: Filament diameter

AC Losses in MgB2 – High Resistivity Matrix



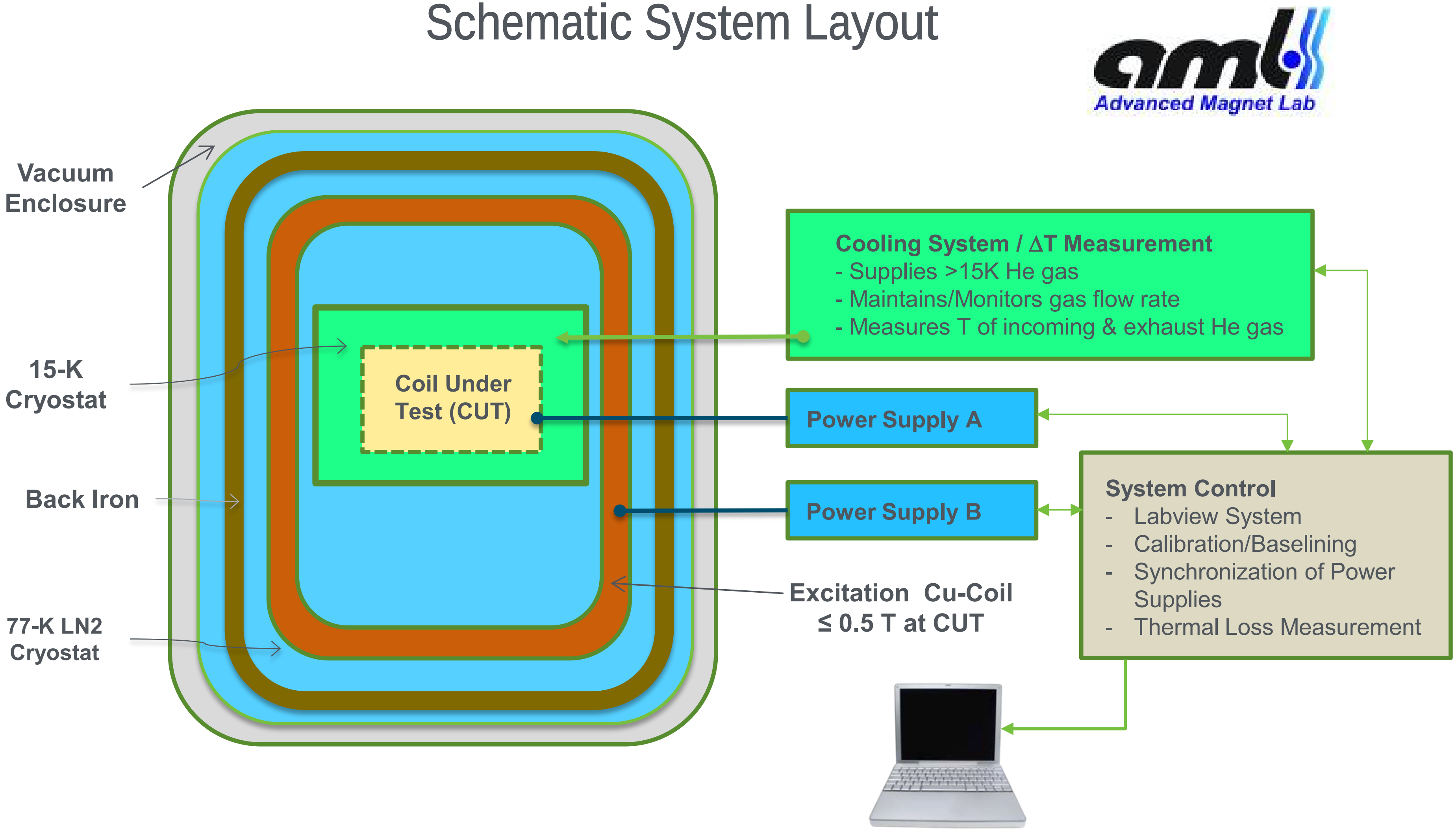
Magnetization losses dominate at low frequency

Synchronous Machine:
- Pulsating and rotating fields
- Plus phase-shifted transport current

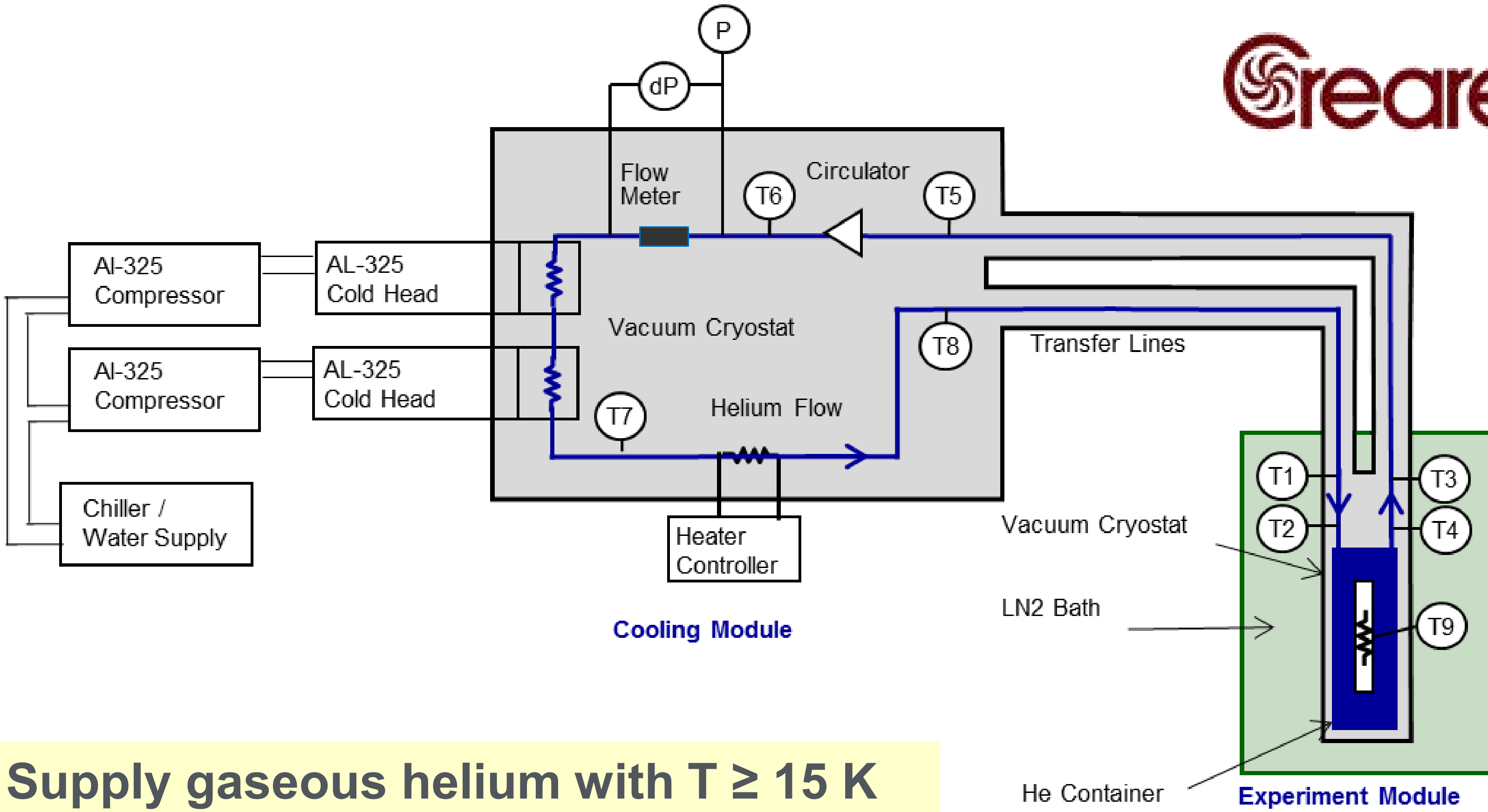
AC Loss Measurement System

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

Schematic System Layout



15K Cooling and Calorimetric Loss Measurement System



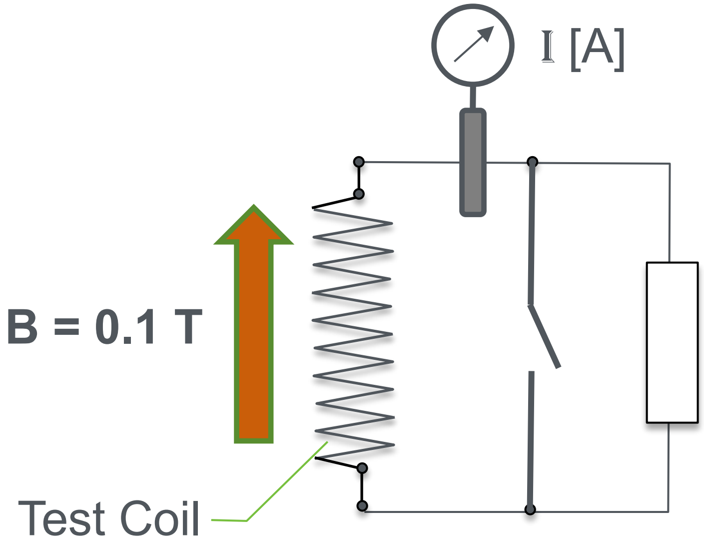
Supply gaseous helium with T ≥ 15 K
Cooling capacity 1-10 W at 15 K

AC Loss Measurement System

Installation and Operation at Center for Advanced Power Systems CAPS

CAPS

Fault Current Limitation Test



Test in AC loss Measurement System

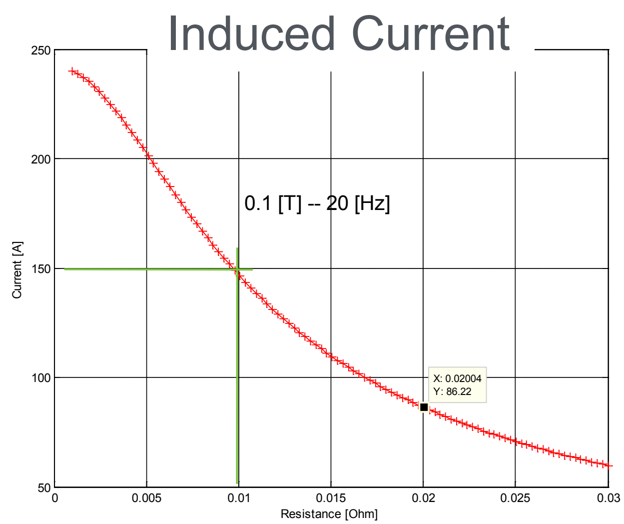
Background field ~0.1 T

Advanced Magnet Lab

CAPS

Exceeding I_c of race track coil → Quench

Fault current limitation key advantage of FSG



Test Coil

Hyper Tech Research Inc.

Accomplishments and Progress

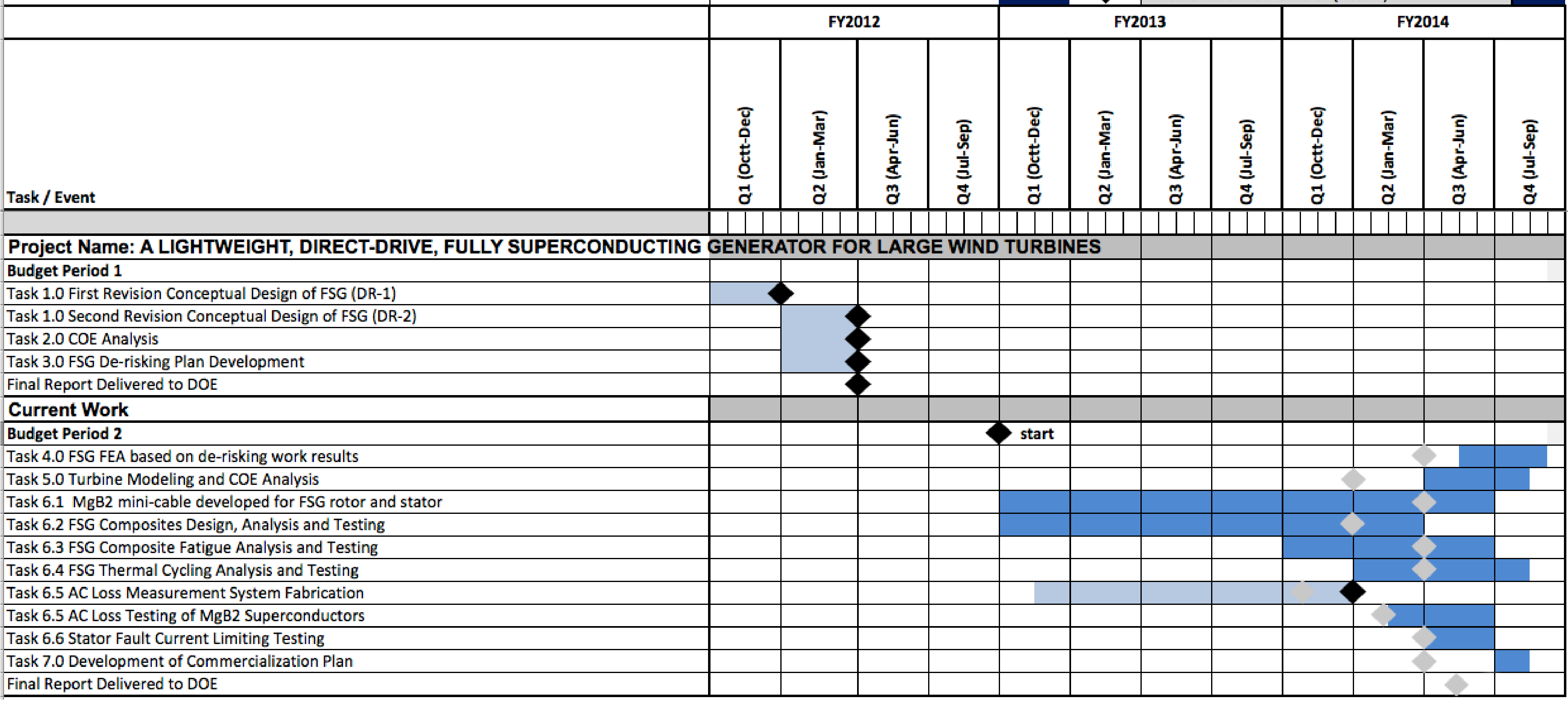
- Concept of fully-SC generator for direct-drive offshore wind generator developed
- Estimated cost-of-energy very close to goal of 0.07 $/kW hr
- Total weight for 10-MW generator less than 150 ton
- System scalable to higher power (→ 15 MW)
- Significant progress in MgB_2 superconductor development (mini-cable, filament ∅)
- Quench training-free coil windings based on patented AML technology
- FSG enables fault current limitation of SC stator winding
- Compliant composite matching CTE of conductor and SS materials developed
- Results on thermal cycling of stator coil mockup show no material deterioration
- Versatile facility for AC loss measurements of superconductors designed, built and set in operation (serve SC community in future)

- Fatigue testing of MgB_2 coils in preparation
- Fault current limiting test of MgB_2 conductor in preparation

Project Plan & Schedule

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

Summary		Legend
WBS Number or Agreement Number	DE-EE0005140	Work completed
Project Number		Active Task
Agreement Number		Milestones & Deliverables (Original Plan)
		Milestones & Deliverables (Actual)



Project Milestones

- Initiation Date: **October 1, 2011** Planned completion date: **September 30, 2014**
- A six (6) month, no cost extension was requested in order to complete testing tasks

Research Collaboration

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

aml Advanced Magnet Lab	**Project Lead, Co-Principal Investigator** Overall System Design, Electro-magnetic, Thermal Design. **Vernon Prince, Dr. Rainer Meinke**
EMERSON	**Co-Principal Investigator** Mechanical, Electrical Design, System Integration, Manufacturing **Darrell Morrison**
Argonne National Laboratory	Thermal Design, Thermal Modeling and Simulations, Cryogenic Test Facility **Dr. Jerry Nolen**
Creare	Cryocooling and Cryogenic Interfaces **Dr. Tony Dietz**
Columbus Superconductors	Superconductor Design, Manufacturing and Test **Dr. Matteo Tropeano**
University of Houston	Superconducting Machine Design and Simulations **Dr. Philippe Masson**
NREL	Modeling of Large Scale Wind Turbines – Cost of Energy **Jason Cottrel, Rick Damiani, Jim Johnson**
Jeff Minnema Consulting, LLC Wind Turbine Specialists	Modeling of Large Scale Wind Turbines – Cost of Energy **Jeff Minnema**
CAPS	Superconducting System Test Facility **Dr. Sastry Pamidi**
WINONA STATE UNIVERSITY	Composite Analysis Design and Test **Dr. Keith Dennehy**
CTD Composite Technology Development	Composite Materials Test - Lafayette, Colorado

Next Steps and Future Research

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FY14/Current research:

- Continuation of MgB_2 conductor development
- AC loss measurements of MgB_2 conductor
- Composite fatigue test
- Fault current limitation test
- Temperature cycling test

Proposed future research:

- Build and test subscale synchronous machine
- Quench detection system for rotor and stator

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

Advanced Rotor Systems Siemens CRADA Aerodynamics

Scott Schreck

National Renewable Energy Laboratory

scott.schreck@nrel.gov, 303-384-7102

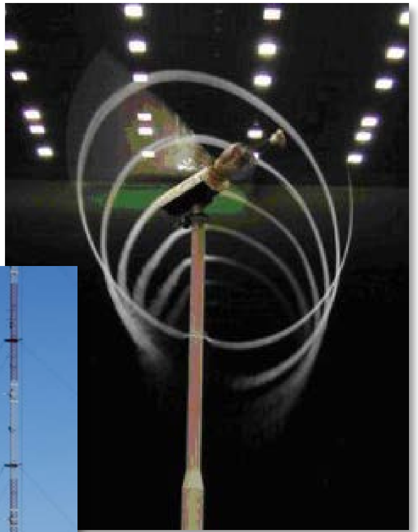
26 March 2014

Budget, Purpose, & Objectives

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

Problem Statement

- Operator and manufacturer issues
  - AEP shortfalls—energy capture
  - O&M failures—fatigue loading
  - Inflow and rotor aerodynamics are key
- Addressing performance issues
  - Enhance and validate design tools
  - Guided by fundamental physics
  - Reliance on accurate measurements
- Diverse measurements are key
  - Scaled experiments for inflow control
  - Multi-MW turbine field experiments
  - Multi-row wind plant field experiments



Budget, Purpose, & Objectives

Total DOE Budget[1]: $1.200M

Total Cost-Share[1]:$8.600M

Impact of Project

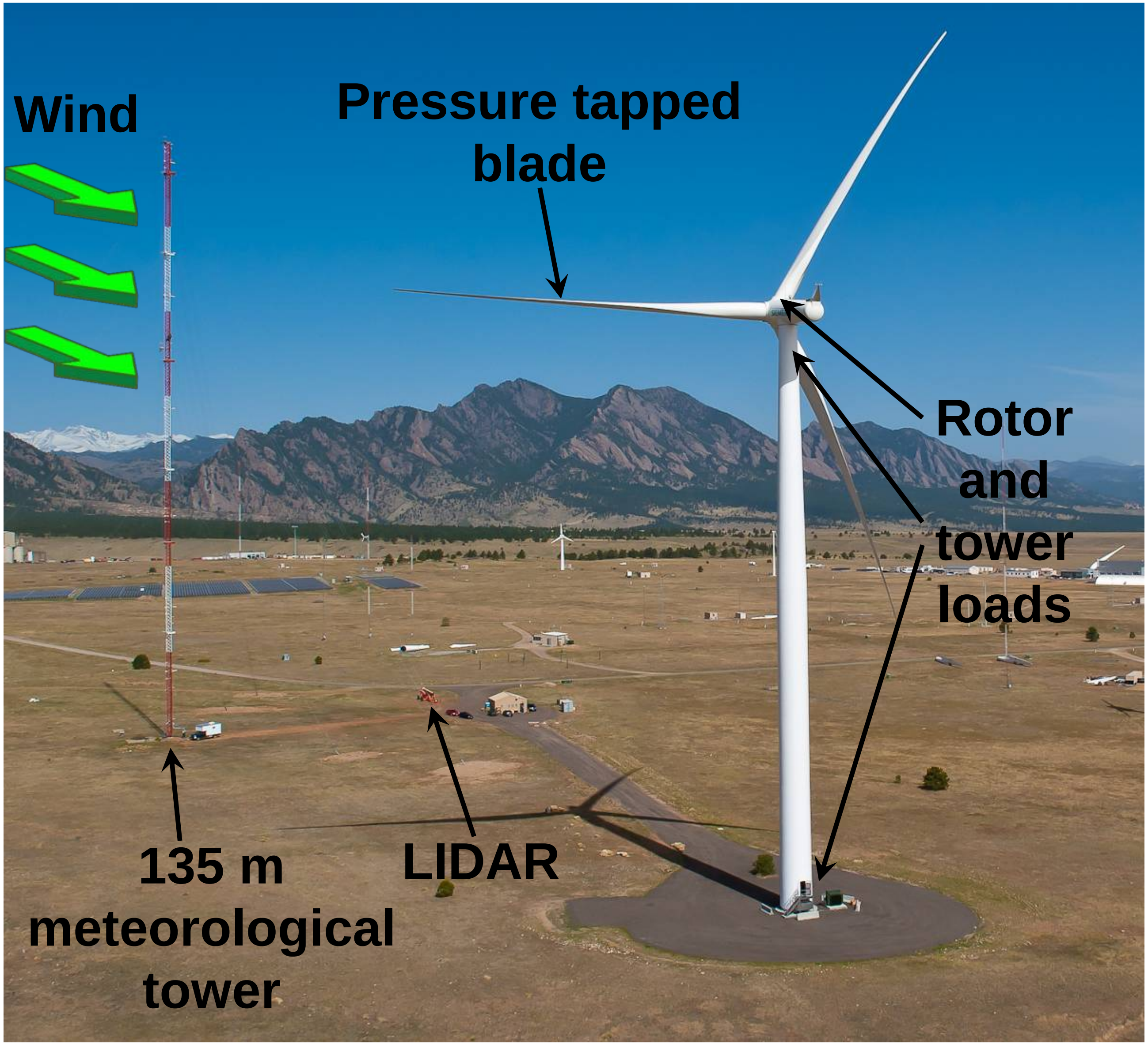
- Leverage and exploit complementary resources
  - Support multiple R&D efforts in parallel
  - Siemens Wind Power 2.3 MW turbine
  - University of Colorado/NOAA LIDAR assets
  - DOE/NREL Site 4.4 and 135 m meteorological tower
- Public-private partnership advantages and considerations
  - Identify and resolve confidentiality and intellectual property issues
  - Move crucial measured data into general wind R&D community

Project aligns with these DOE Program objectives & priorities

- Optimize Wind Plant Performance: Reduce wind plant levelized cost of energy (LCOE)
- Accelerate Technology Transfer: Lead the way for new, high-tech U.S. industries

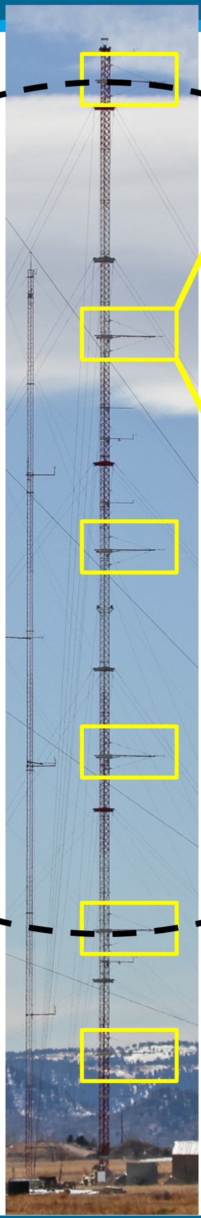
[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

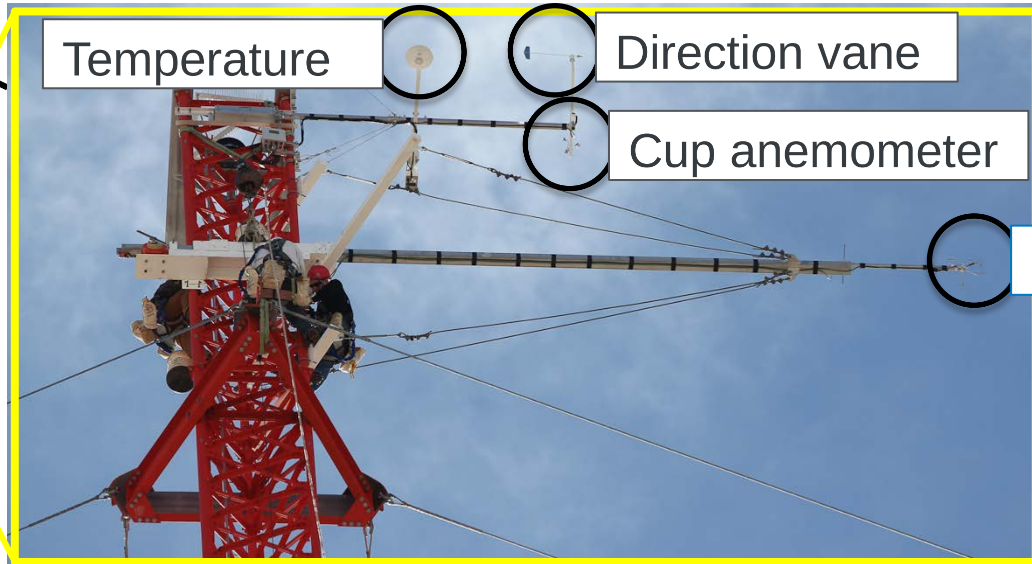
Technical Approach
NWTC Site 4.4

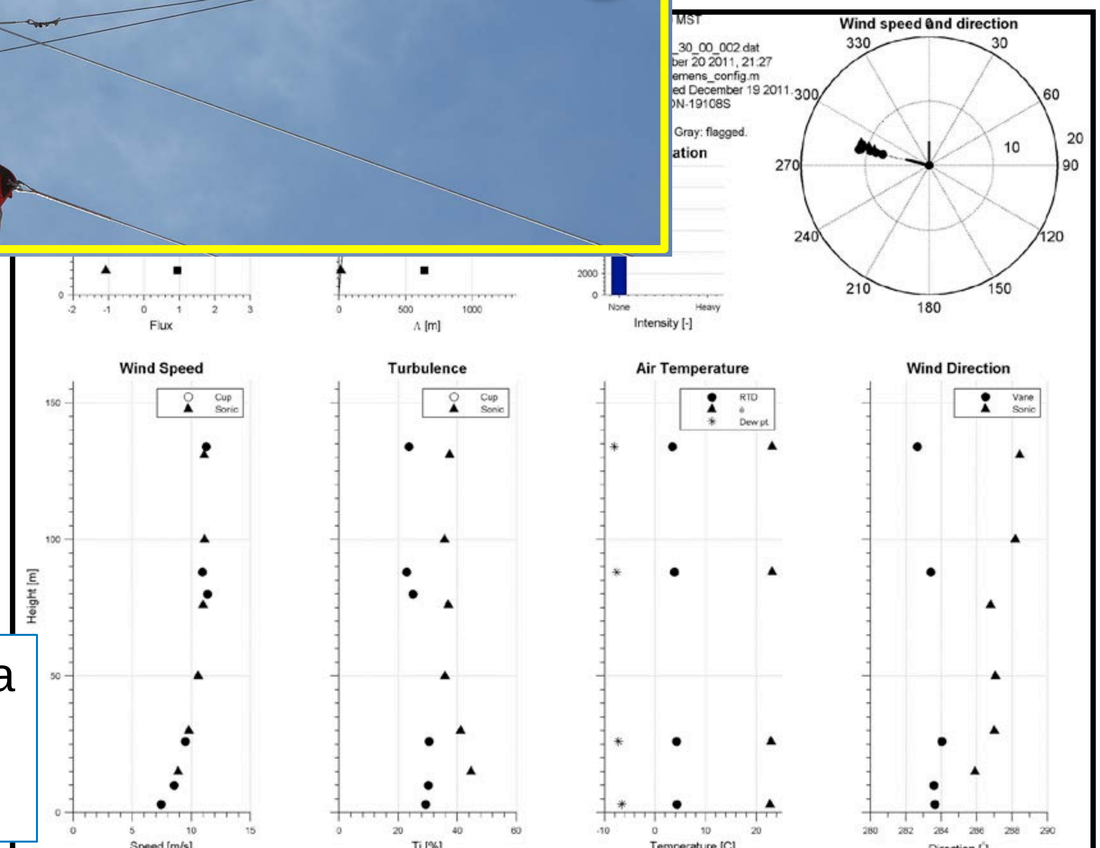


Technical Approach
135 m Meteorological Tower

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

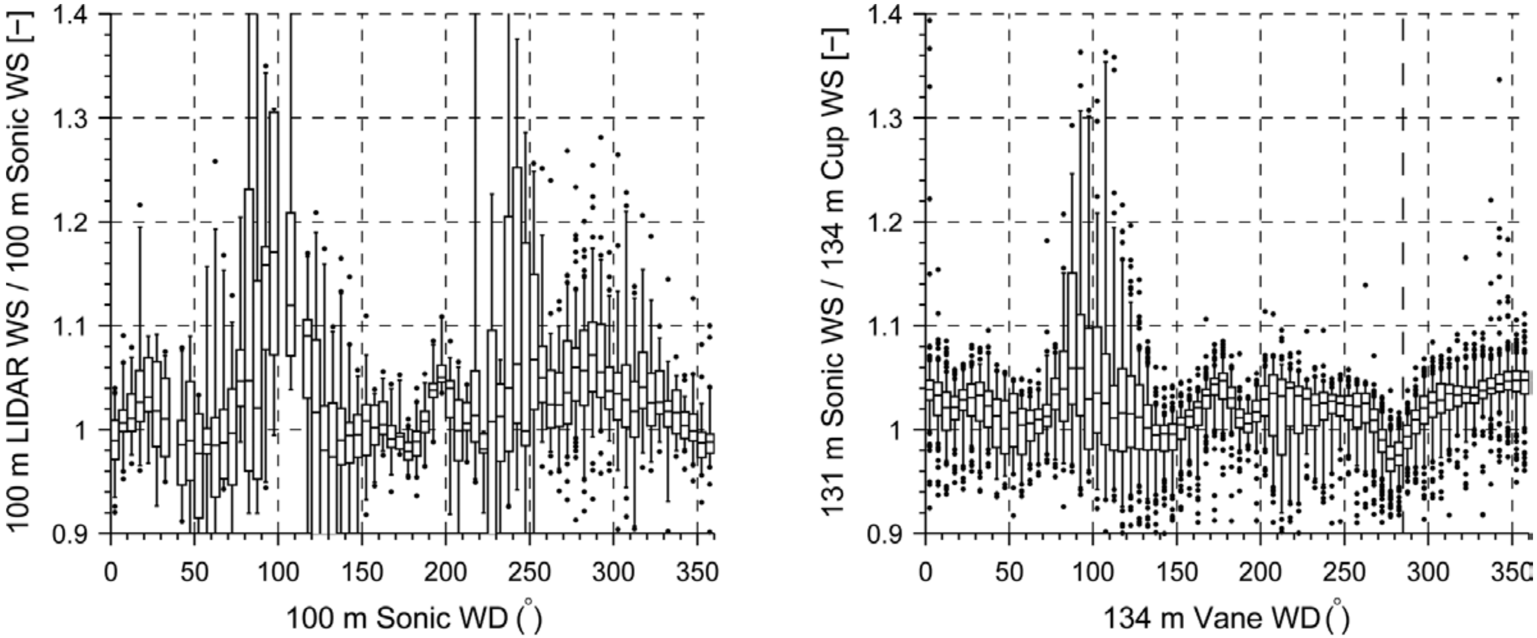






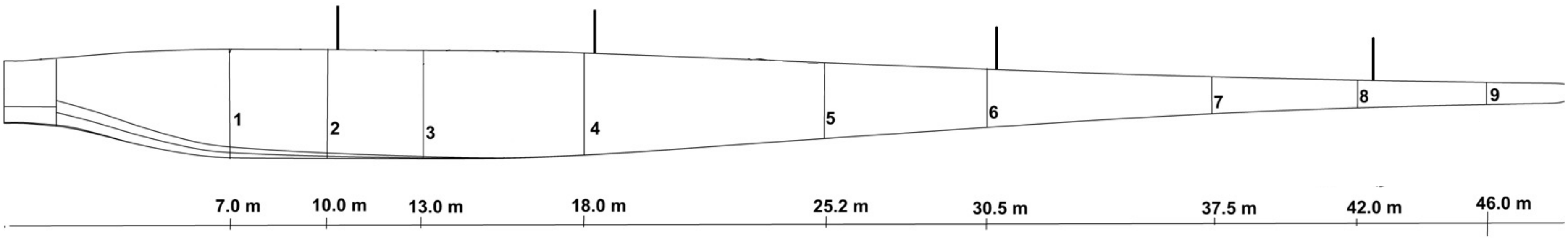
Automated data acquisition and archiving

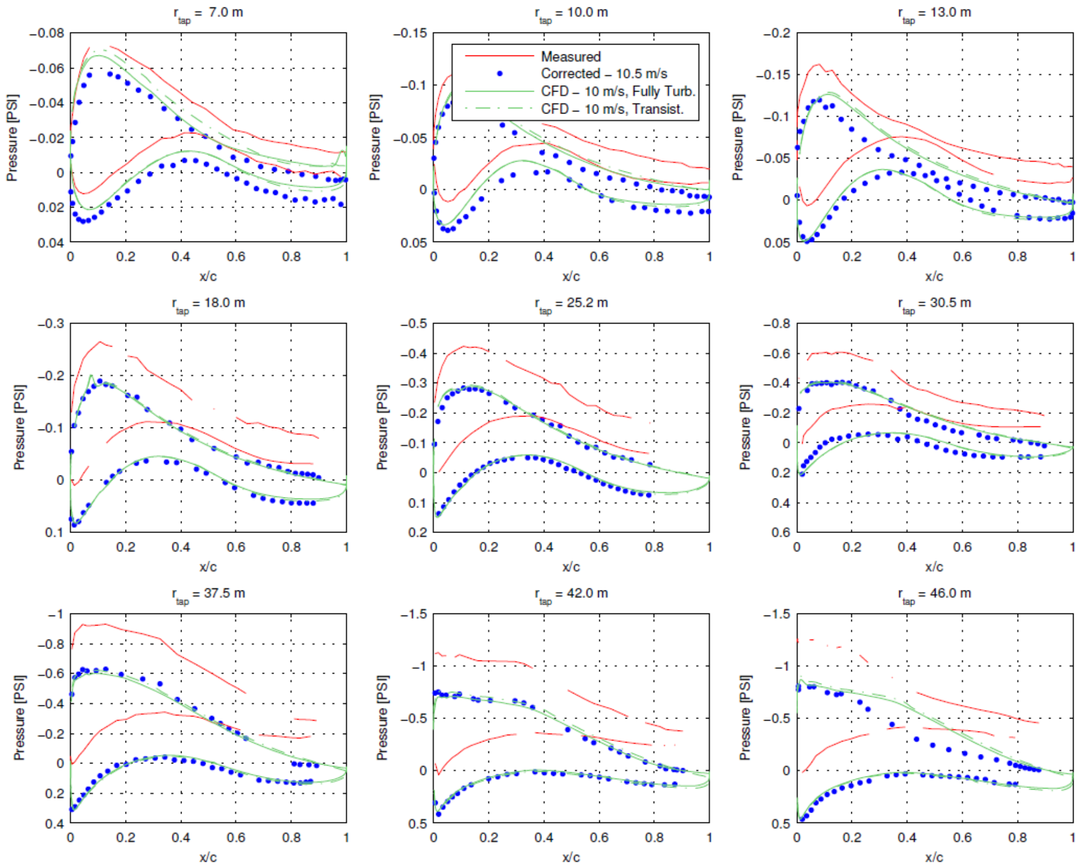
- 135 m meteorological tower at NWTC Site 4.4*
  - Instrumentation comparisons and validations
  - Windcube LIDAR vs. tower sonic anemometers
  - Windcube LIDAR vs. tower cup anemometers
  - Site inflow and tower characterization for user support



*Clifton, A.; Schreck, S.; Scott, G. "Turbine Inflow Characterization at the National Wind Technology Center," *J. of Solar Energy Eng.*, August 2013.

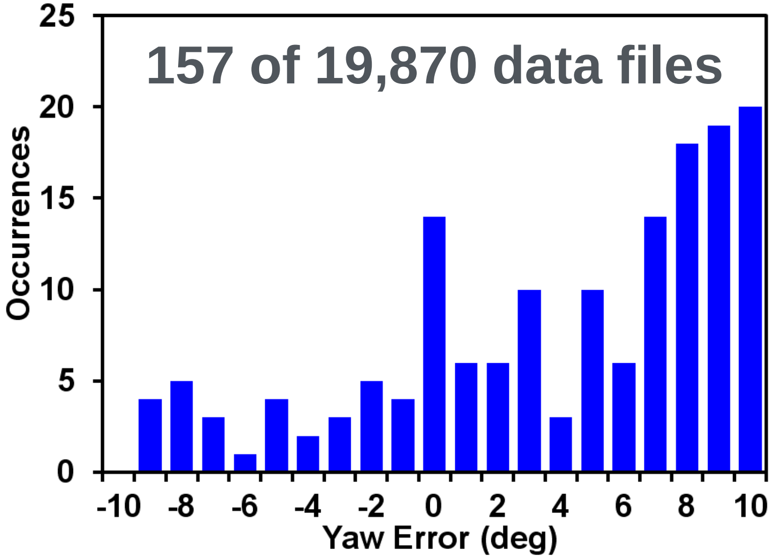
Technical Approach
Blade Pressure Measurements

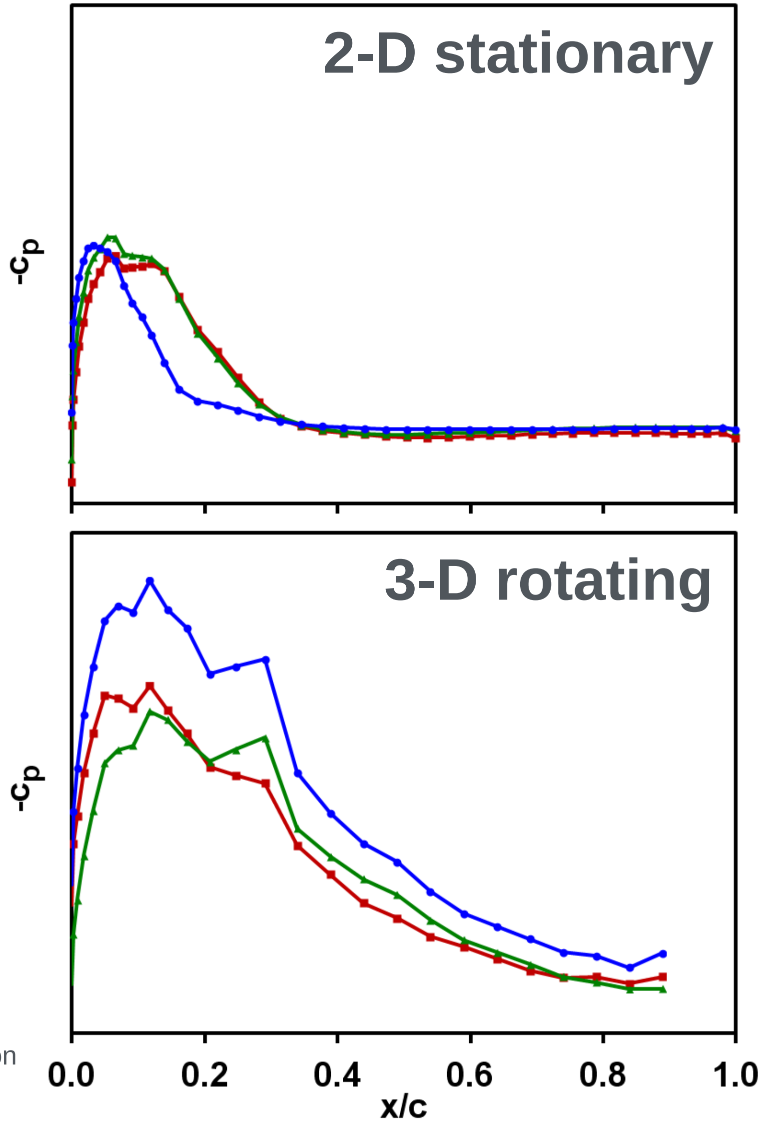




Accomplishments and Progress
Blade Aerodynamic Performance

- Rotational augmentation*
  - c_p and C_n amplified 2X – 3X
  - Persists in turbulent inflow
  - Occurs on thick flatback airfoils
  - Active at high Re

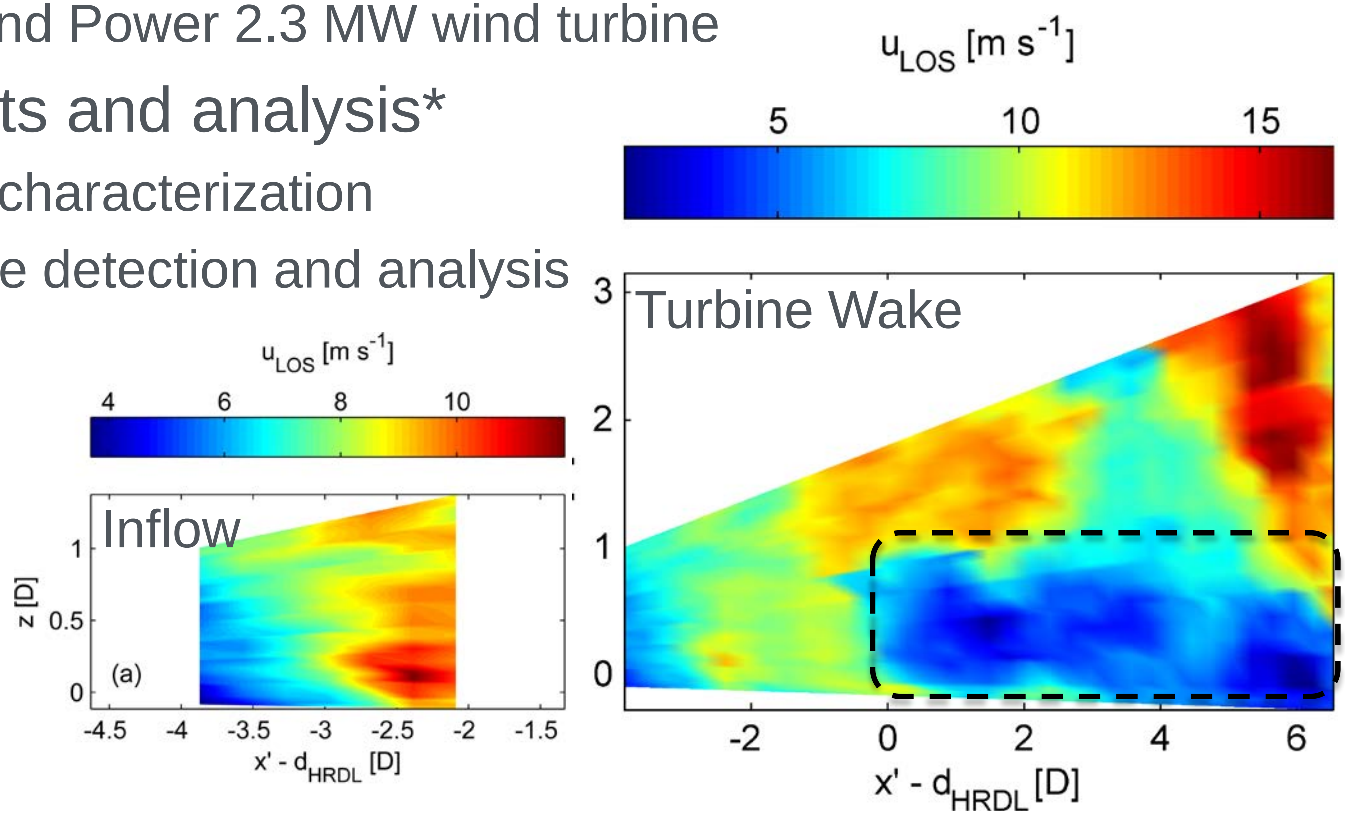




*Schreck, S.; Fingersh, L.; Siegel, K.; Singh, M.; Medina, P. "Rotational Augmentation on a 2.3 MW Rotor Blade with Thick Flatback Airfoil Cross Sections," AIAA-2013-0915, January 2013.

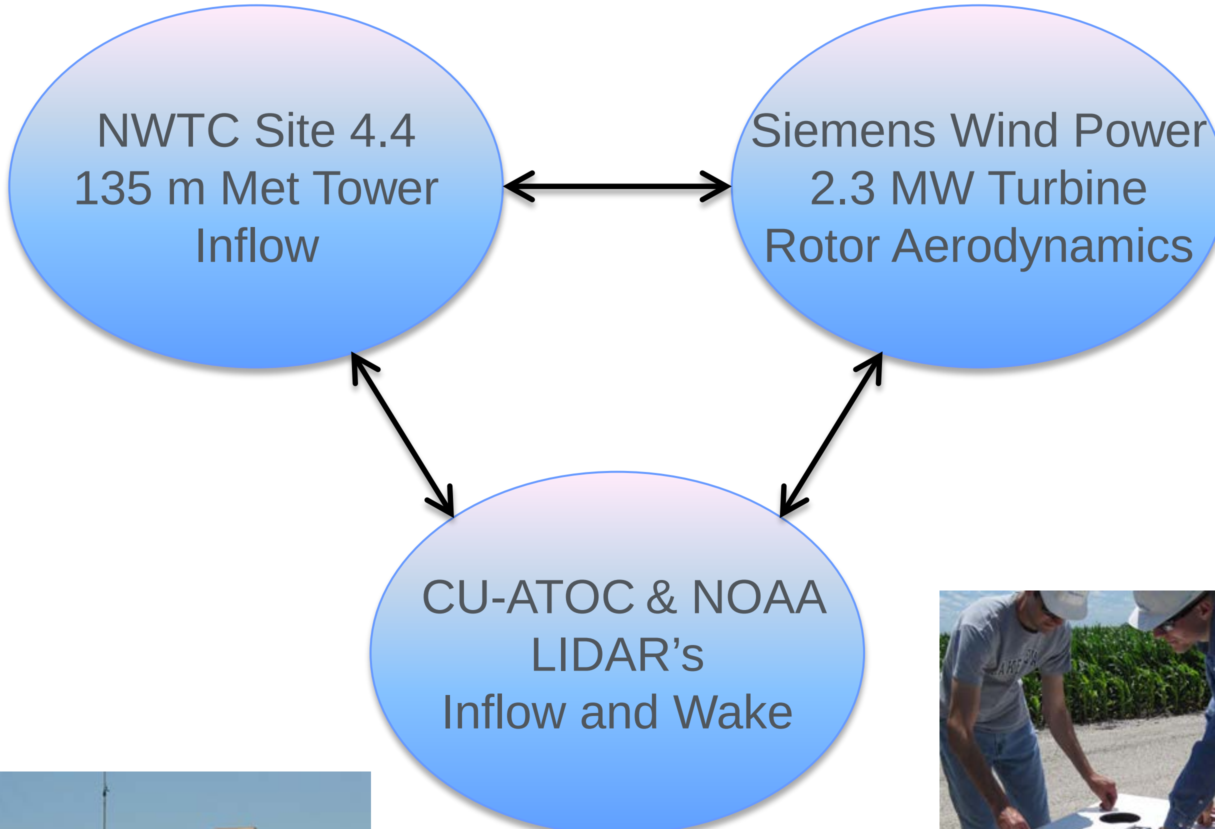
LIDAR Sensing of Inflow and Wake

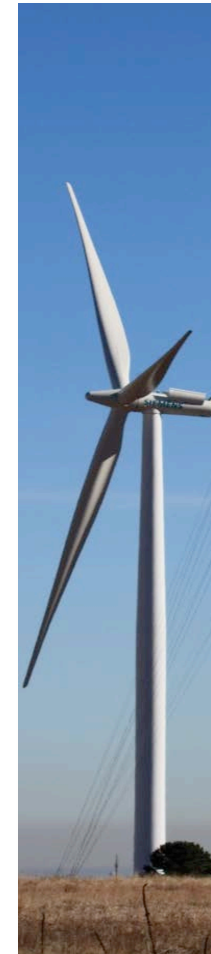
- Collaboration
  - University of Colorado (Lundquist – ATOC)
  - NOAA High Resolution Doppler LIDAR (HRDL)
  - Siemens Wind Power 2.3 MW wind turbine
- Measurements and analysis*
  - Wind inflow characterization
  - Turbine wake detection and analysis



*Aitken, M.; Lundquist, J.; Pichugina, Y.; and Banta, R. 2014. Quantifying wind turbine wake characteristics from scanning remote sensor data. *J. Atmos. Ocean Tech*. 10.1175/JTECH-D-13-00104.1

Accomplishments and Progress
Measurement Comparisons





Project Plan & Schedule

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

Summary	
WBS Number or Agreement Number	3.1
Project Number	3.1.8
Agreement Number	22503

Legend
- Work completed
- Active Task
- Milestones & Deliverables (Original Plan)
- Milestones & Deliverables (Actual)

Task / Event	FY2012 Q1 (Octt-Dec)	FY2012 Q2 (Jan-Mar)	FY2012 Q3 (Apr-Jun)	FY2012 Q4 (Jul-Sep)	FY2013 Q1 (Octt-Dec)	FY2013 Q2 (Jan-Mar)	FY2013 Q3 (Apr-Jun)	FY2013 Q4 (Jul-Sep)	FY2014 Q1 (Octt-Dec)	FY2014 Q2 (Jan-Mar)	FY2014 Q3 (Apr-Jun)	FY2014 Q4 (Jul-Sep)
Project Name: Advanced Rotor Systems Siemens CRADA Aerodynamics												
Q1 Milestone: Discussions with Siemens regarding potential turbine data release												
Q2 Milestone: Write paper/give talk on Siemens 2.3 MW inflow & aero data												
Q1 Milestone: Reduce/analyze previously acquired data for publication & planning												
Q2 Milestone: Publish paper, give presentation on rotational augmentation effects												
Q3 Milestone: Complete SWT data acquisition for 2013 wind season, for off-design												
Q4 Milestone: Complete blade design spec w/ SWP, for B53 surface pressure blade												
Current work and future research												
Q1 Milestone: Receive B53 blades at NWTC, commence final prep and check-out												
Q2 Milestone: Validation of surface pressure data acquisition system in Blade 1												
Q3 Milestone: Complete SWT data acquisition for 2013-2014 wind season												
Q4 Milestone: Site 4.4 instrumentation to be taken down and sent for recalibration												

Comments

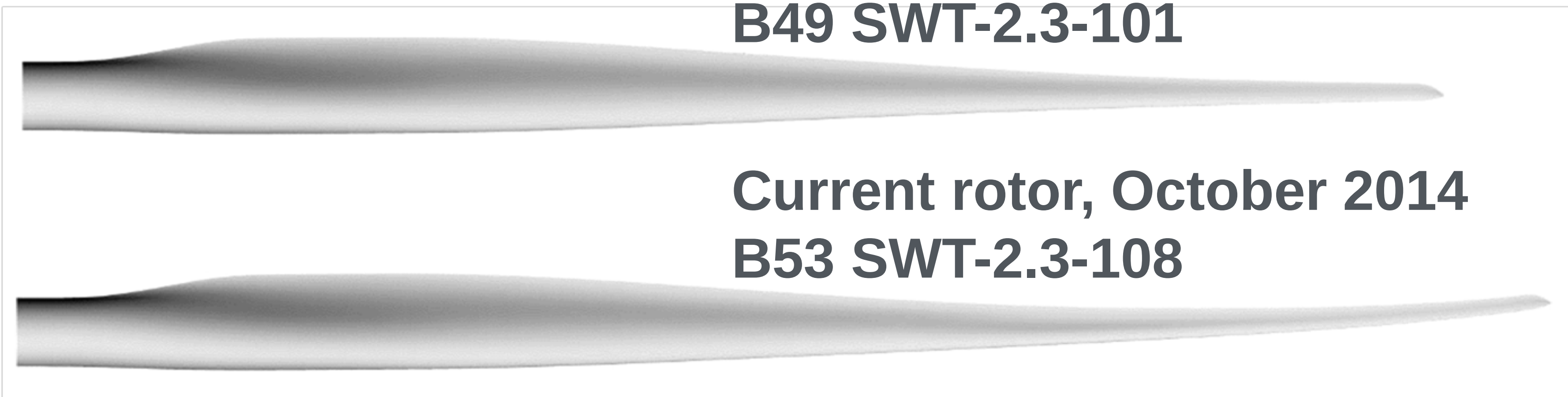
- CRADA originally executed January 2009
- CRADA extension executed September 2013

Partners, Subcontractors, and Collaborators

- Siemens Wind Power (SWP)
- Univ. of Colorado Dept. of Atmos. and Oceanic Sci. (CU ATOC)
- National Oceanic and Atmospheric Administration (NOAA)
- Lawrence Livermore National Laboratory (LLNL)

Communications and Technology Transfer

- 5 journal articles
- 3 conference papers
- 1 poster
- 16 presentations


Previous rotor
B49 SWT-2.3-101
Current rotor, October 2014
B53 SWT-2.3-108

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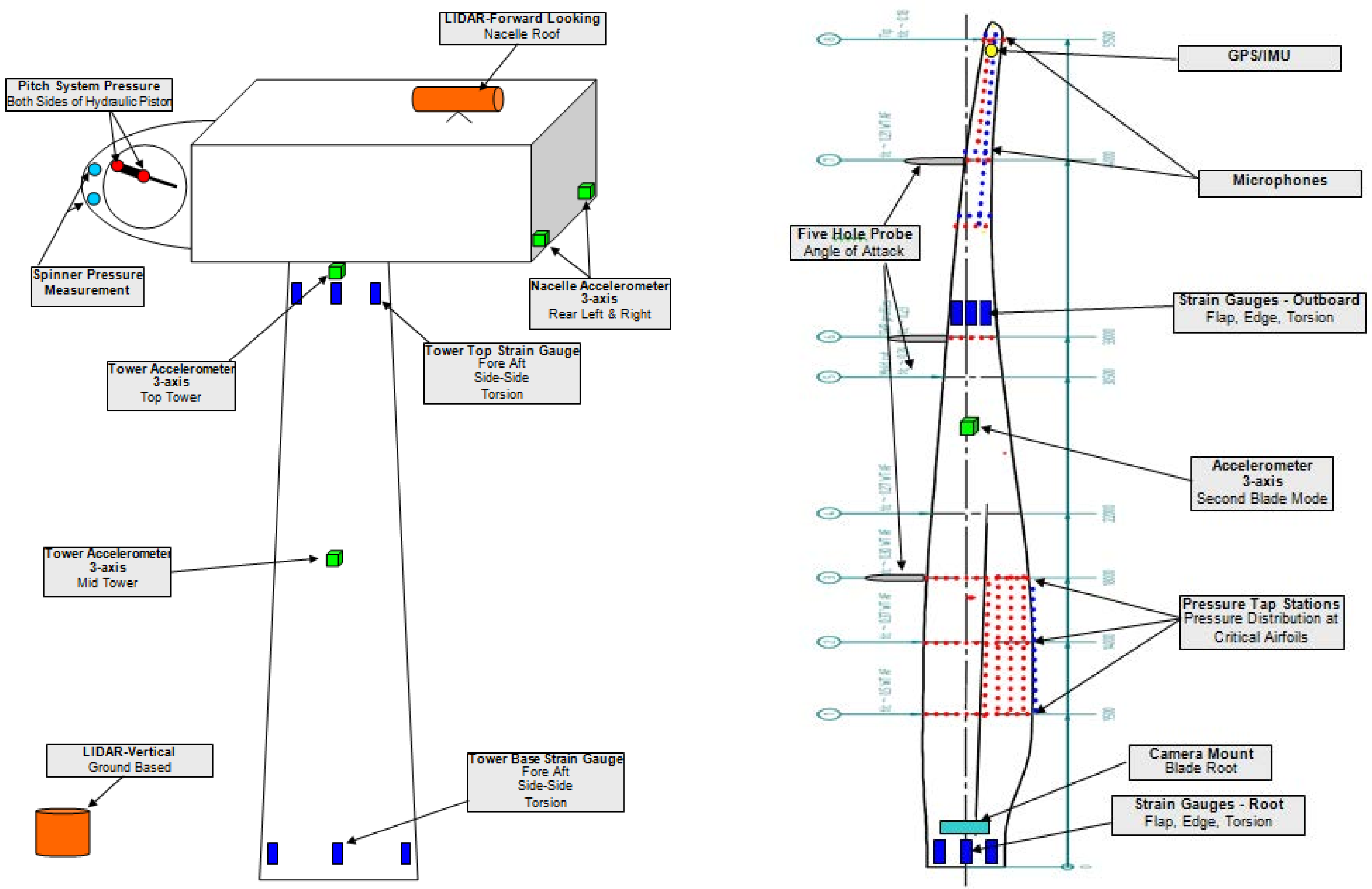
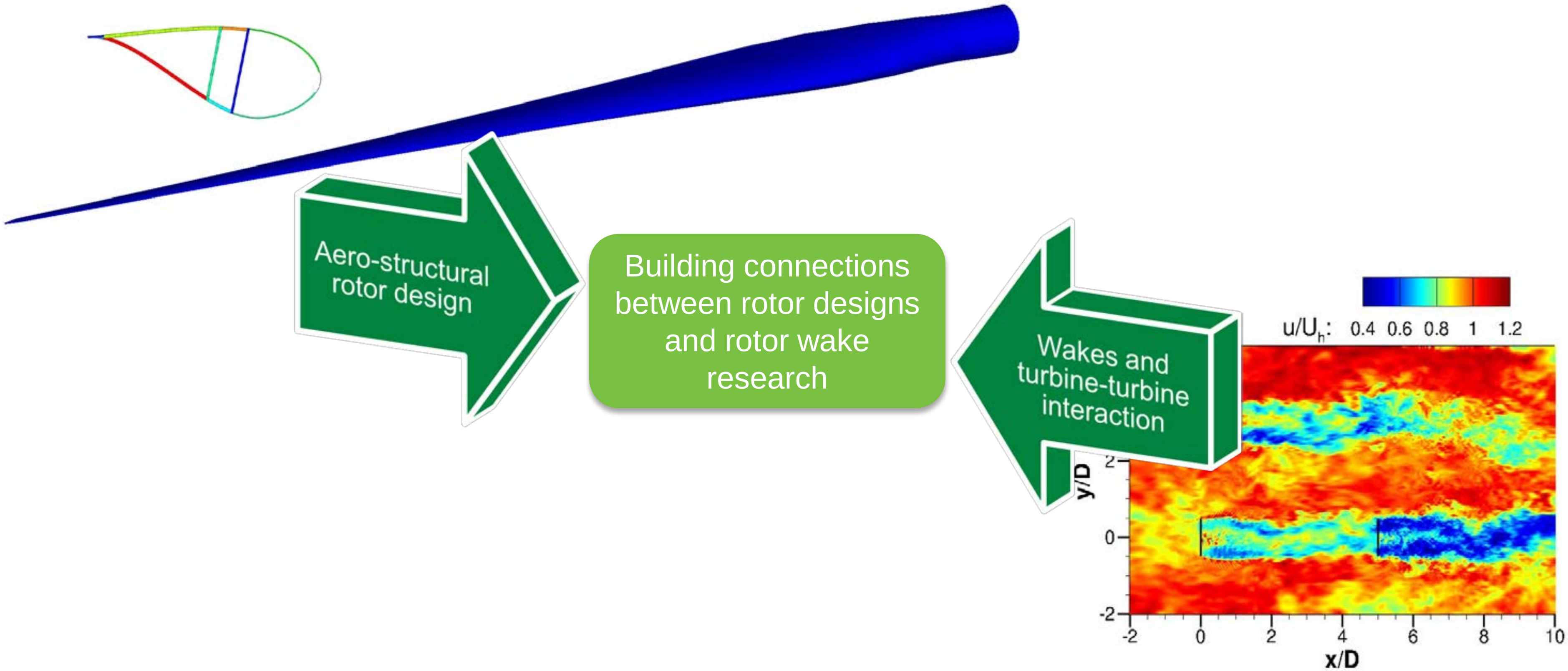
Current instrumentation, October 2014



Next Steps and Future Research

- Siemens – DOE/NREL collaboration
  - Designed/specified instrumentation
  - Participated in experiment planning
  - Supported fabrication/build-up/calibration
  - Data acquisition/reduction/validation
  - Understand/disseminate flow physics
  - Identify and extract validation data
  - Support CAE/CFD validation efforts
  - Make codes available to wind industry
  - Measured data archiving and release



The National Rotor Testbed

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

Brian Resor

Sandia National Laboratories

Brian.Resor@sandia.gov / 505-284-9879

March 26, 2014

Budget, Purpose, & Objectives

Total DOE Budget[1]: $1.800M

Total Cost-Share[1]:$0.000M

Problem Statement: In order to capitalize the SWIFT investment, a modern designed blade must be benchmarked. At the same time, the A2e Initiative is in need of unique rotor hardware at multiple size scales to support a long term (5-7 year) model validation campaign.

Impact of Project: This project will lead to improved understanding of the relationships between rotor design and wind plant performance in terms of dynamic power and loads related to array effects, wake recovery and turbine-turbine interaction. The ultimate impact is on increased wind plant AEP and wind plant reliability.

This project aligns with the following DOE Program objectives and priorities

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources
- **Testing Infrastructure:** Enhance and sustain the world-class wind testing facilities at Universities and national laboratories to support mission-critical activities
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

[1]***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical approach

Assumptions:

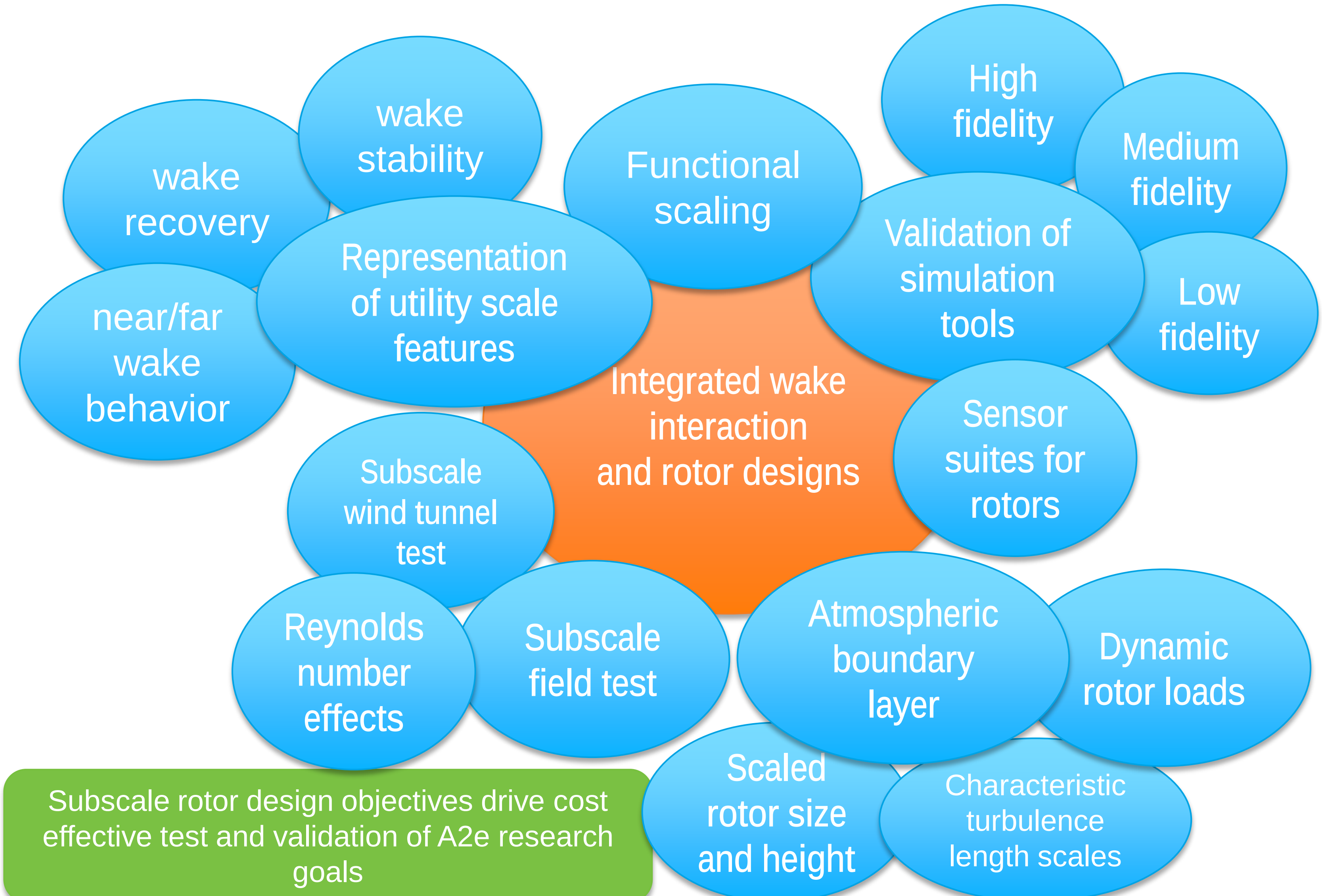
- A2e programs and wind plant performance is key to future industry success:
  - Increase wind plant AEP through better understanding of array effects, wake recovery and turbine-turbine interaction
  - Increase reliability through better understanding of dynamic loads related to array effects, wake recovery and turbine-turbine interaction
- A variety of functionally scaled tests will allow for complex structures and their physics to be isolated and to maximize efficiency of test budgets

Challenges associated with this problem include:

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

A2e has identified this project as central to future complex flow R&D and is expanding the goals and objectives of this project

Open research questions that drive rotor design



Subscale rotor design objectives drive cost effective test and validation of A2e research goals

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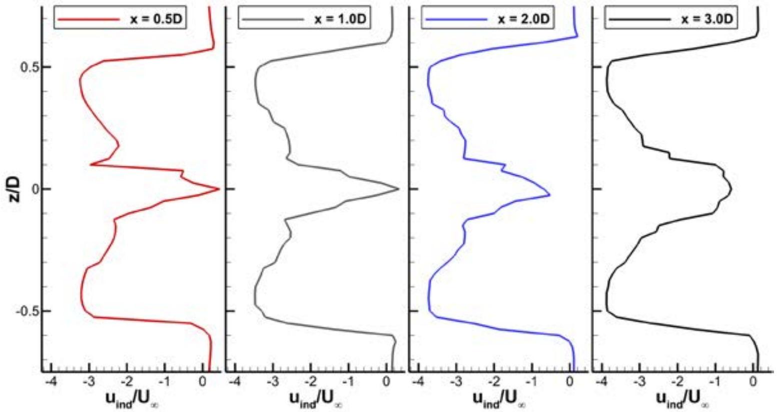
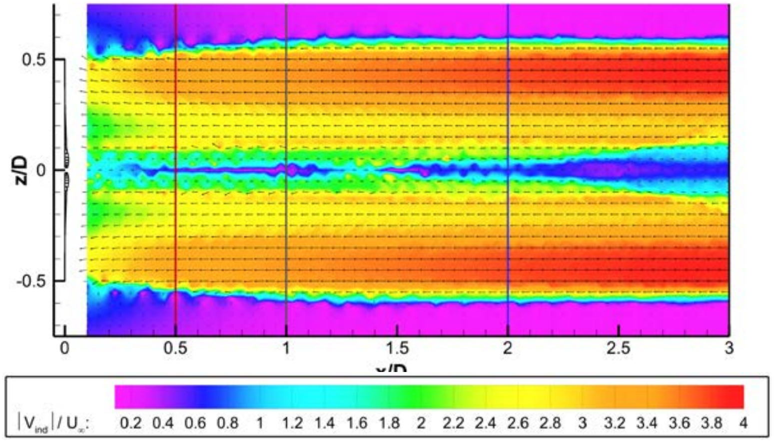
Instantaneous induced velocities



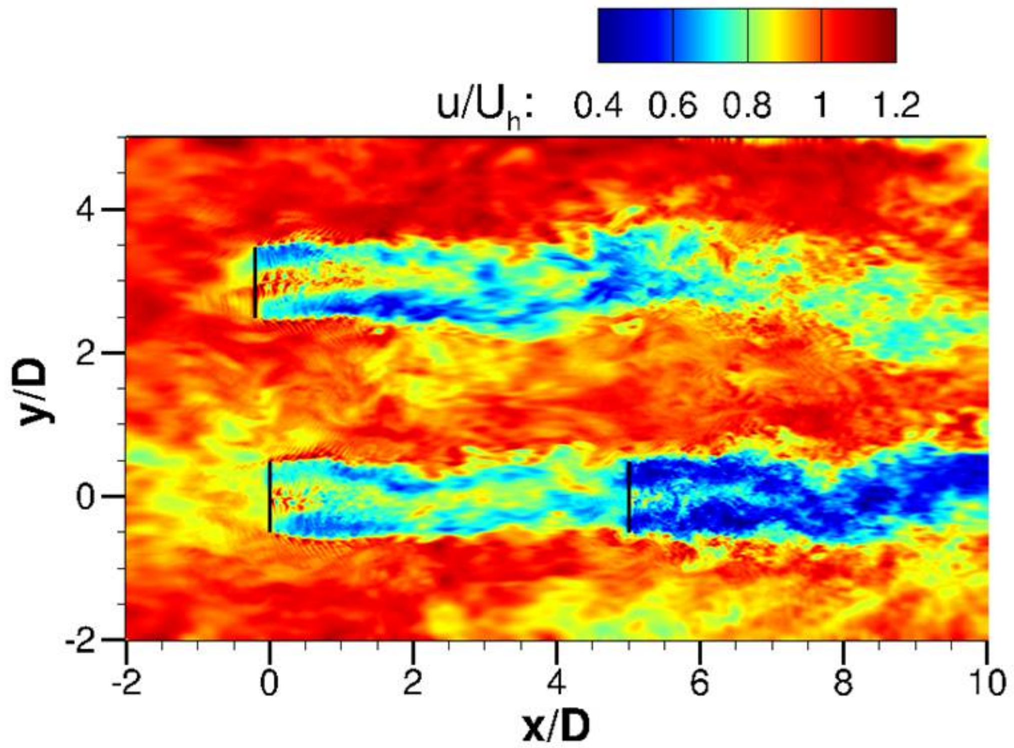


- Medium fidelity vortex wake methods are used to guide rotor design decisions in situations where
  - Blade element momentum may be incomplete or
  - Relationship between wake behavior and rotor design is needed

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

Wake character from LES

- High fidelity LES methods will be used to guide rotor design
- Key questions:
  - Are the wakes of a MW-scale turbine rotor and the SWIFT rotor similar ?
  - If different, how to translate scaled knowledge to full scale ?
  - How do changes in blade loading distribution resulting from NRT scaled design studies affect the development of the SWIFT wake?



Instantaneous contours of stream-wise velocity from a Large Eddy Simulation of the SWiFT test site using the University of Minnesota Virtual Wind Simulator.

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

Functional scaling drivers for Concept 1

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Prioritized design drivers for a scaled rotor:

1. Design within allowable rotor loads for the SWiFT turbines
2. Recreate the shape of the circulation distribution along the rotor span
3. Match absolutes:
   – Tip speed ratio of the full scale rotor
   – Tip velocity of the full scale rotor
   – Campbell diagram in the lowest frequency range
4. Match aerodynamics features:
   – Delta between $C_{l,max}$ and design C_l values along the span of the blade
   – Steady – ensure that inboard blade does not operate in a stalled or high drag condition
   – Dynamic – ensure that inflow gusts translate to equivalent dynamic loads

Concept 1 designs chart a path forward

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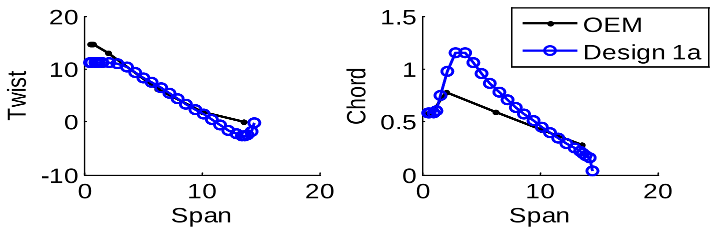
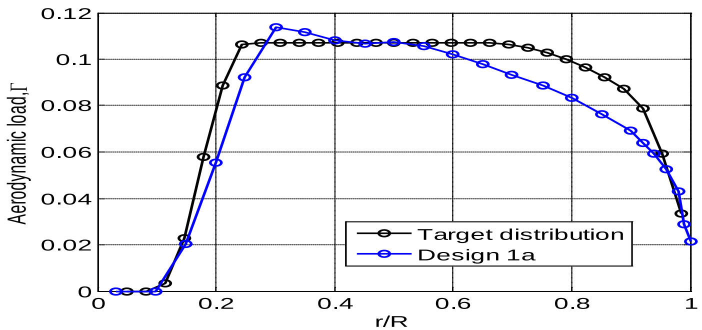
Design 1a

“best practice”

- Wetzel Engineering, Inc. with guidance by Sandia
  - 29 m rotor
  - 78 m/s max tip velocity
  - DU-airfoils
- Rotor loads fall within desired limits
- Designed with process for maximum AEP
- TSR is approximately matched
- No control over circulation distribution

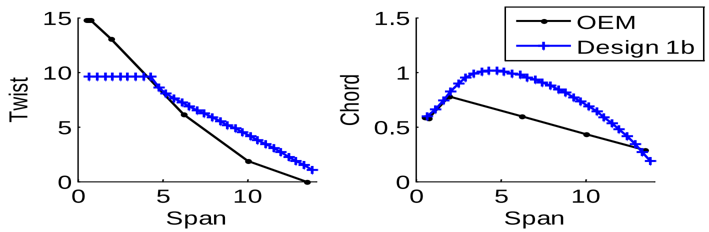


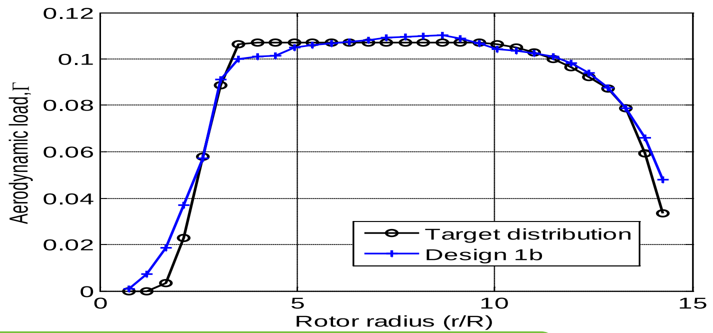


Design 1b

“perfect scaled match”

- Sandia design using a framework of publicly available tools (HARP_Opt, WT_Perf, CoBlade, NuMAD)
  - 29 m rotor
  - 78 m/s max tip velocity
  - DU-airfoils
- Aerodynamic load (circulation) distribution is matched
- Specified TSR is matched
- Rotor loads exceed desired limits





Rotor designs show that initial rotor specifications need to be revisited

Technical Accomplishments

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- Defined functional scaling methodology which is a new paradigm for design of subscale rotors relevant to full scale
- Completed full scale analysis of the DOE GE 1.5sle to define requirements and specifications for subscale rotors
- Applied multi-objective rotor design optimization tools for the NRT designs
- Completed 29m rotor design for the SWIFT turbines with Concept 1a/b rotors
- Compiled feedback on the functional scaling methodology from: Siemens, GE, Vestas, Wetzel, NREL, UC-Davis, U.Minnesota
  - Consensus is that this functional scaling approach has reopened some minds to the possibilities of subscale testing, especially at SWIFT scale
- The activities secured a clear path for scaled rotor testing with key consensus from partners

Work done in FY13 prepared the project to define the technical approach being executed in FY14

Project Plan & Schedule

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

Summary	Legend	
WBS Number 2.3.0.6		Work completed
Agreement Number 26911		Active Task
		Milestones & Deliverables (Original Plan)
		Milestones & Deliverables (Actual)

Task / Event	FY2013 Q1 (Octt-Dec)	FY2013 Q2 (Jan-Mar)	FY2013 Q3 (Apr-Jun)	FY2013 Q4 (Jul-Sep)	FY2014 Q1 (Octt-Dec)	FY2014 Q2 (Jan-Mar)	FY2014 Q3 (Apr-Jun)	FY2014 Q4 (Jul-Sep)
Project Name: Wind Energy Forecasting Methods and Validation for Tall Turbine Resource Assessment								
FY13 Q1: Define of nominal state-of-the art megawatt-scale rotor and turbine								
FY13 Q2: Draft SAND Report on aero-servo-elastic scaling of wind turbine systems								
FY13 Q3: Design review of aeroelastically scaled 27-meter rotor design concept								
FY13 Q4: Report on final detailed design of the National Rotor Testbed hardware								
FY14 Q1: Gather feedback on functional scaling and resulting NRT design								
Current work and future research								
Report on recommendation for Sandia rotor design tool plan and verification plan								
Complete verification of a Sandia rotor design tool								
Complete rotor scaling study and NRT design study using VWM and LES								
Preliminary design review of proposed rotor hardware at the Sandia Blade Workshop								

Comments

- Initial project objective was to outfit the SWIFT machines with modern rotors; goal was to deliver blades for flight tests in late FY14
- Current project objective is the result of a project expansion in FY13 Q3/Q4 to rotors for A2e
  - FY13 Q3/Q4 milestones related to final steps of blade manufacture are delayed
  - FY14 Q2+ work is currently being adjusted in an AOP modification (proposed tasks are shown above)

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

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

Communications and Technology Transfer:

- Numerous one-on-one meetings with OEMs and researchers on the topic of functional scaling
- 2014 AIAA ASME Wind Energy Symposium presentation
- A first significant public review of all NRT work will occur during meetings at the Sandia Blade Workshop in August 2014.

Next Steps and Future Research

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FY14/Current research:

- Re-visit and closeout current rotor design specifications
- Rotor design
  - Assembly and verification of aero-structural rotor design tool to enable unconventional design objectives for functionally scaled rotors
- Wake simulations to guide rotor design
  - Vortex wake simulations
  - LES wake simulations (U.Minnesota)
- Airfoils
  - Specification of airfoil families for mid and small scale rotor designs
- SWIFT loads envelope
  - Formal calculation of SWIFT turbine loads envelope to remove conservatism in rotor design
- Sensors
  - Lab and field test of aero sensing strategies to increase confidence of implementation in the field
- Public Review
  - Final rotor design concept(s) for public review at the Sandia Blade Workshop (August 2014)

Next Steps and Future Research

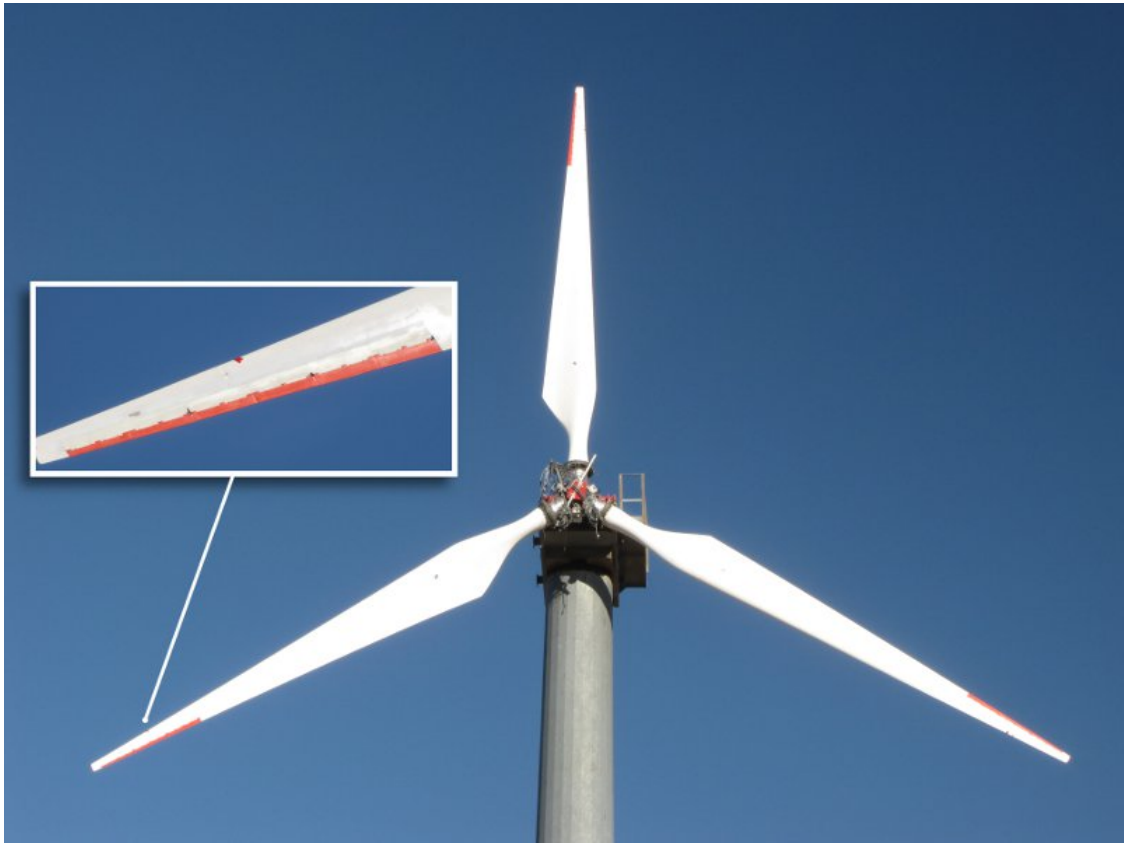
FY15:

- Comprehensive review of entire test campaign by A2e science panel
- Detailed blade design in preparation for manufacture
- Blade and tooling manufacture, manufacture blades, ground test blades, flight test blades

Proposed future research:

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

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



SMART Rotor Test & Data Analysis

Advanced Rotor Technology Development

Jonathan Berg

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26 March 2014

Budget, Purpose, & Objectives

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

Total DOE Budget[1]: $1.225M

Total Cost-Share[1]:$0.000M

Problem Statement:

Validation of Active Aerodynamic Load Control (AALC) modeling is needed. The simulations have shown how the technology can reduce damaging loads from wind gusts, wind shear, and yaw misalignment.

This project demonstrates the practical use of flaps and progresses the engineering methods needed for successful technology transfer to industry.

Impact of Project:

- Improved simulation accuracy can be used to assess load control approach and reduce commercialization risk
- Rotor balancing by active control can reduce wear-and-tear on entire machine
- A larger rotor, enabled by AALC, improves capacity factor for a given turbine size

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

[1]*Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Technical Approach

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Design & Build (FY10-11)

- Three research scale blades
- Integrated trailing edge flaps

Field Test (FY12)

- Demonstrate the control capability of the trailing-edge flaps at Bushland test site
- Evaluate the accuracy of simulation tools in predicting results of active rotor control
- Develop procedures for characterizing an operating wind turbine with active rotor control

Data Analysis (FY13)

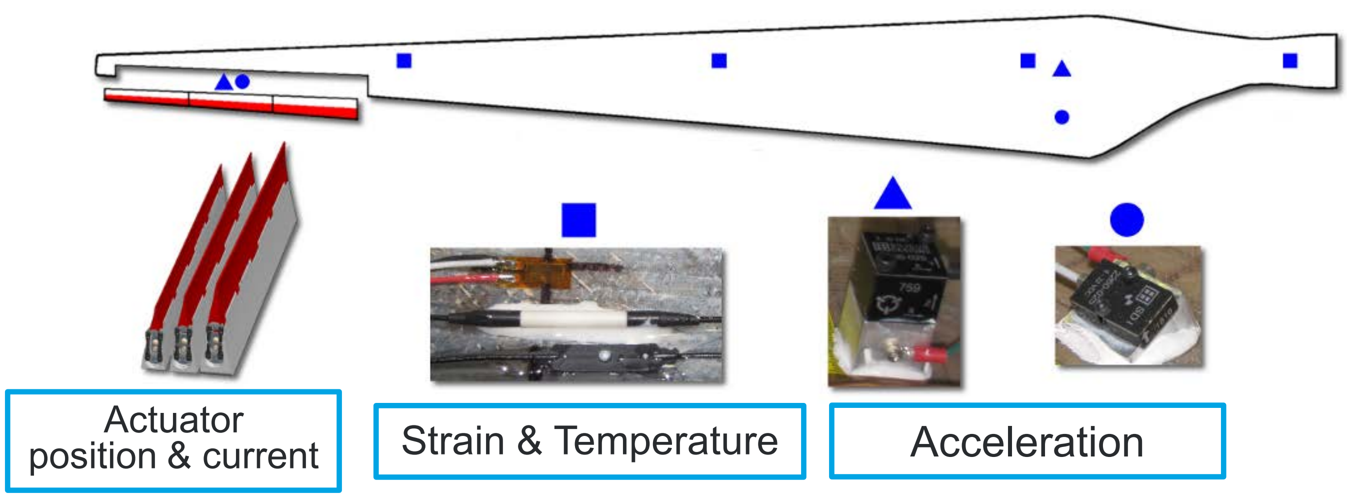
- Ensure the time-accuracy and alignment of signals
- Translate observed load responses to fundamental aerodynamic blade and wake time scale for future engineering models

Process	Time Scale Definition	Time Scale
AALC Device Actuation	Actuation Period	0.09 – 1.1 sec
Response to Rotationally Sampled Wind	1P,2P,3P periods	0.3 - 1.1 sec
Dynamic Structural Response	Period of First Two Blade Flap Modes	0.09 - 0.22 sec
Local Section Flow	Chord / Relative Flow Velocity	0.004 sec
Local Section Flow Adjustment	5-10x Section Flow Time Scale	0.02 - 0.04 sec
Wake Response	Rotor Radius / Wind Speed	1.2 sec

Estimated time scales for test turbine at Bushland site.

Technical Approach

- Leverage Sandia's previous experience integrating sensors in blades
- Optimize number and location of sensors to enable estimation of other quantities not measured directly
- Work with partners to integrate state-of-the-art sensors



Sandia has 9 years of experience with in-blade sensing systems

Field Tests, State-of-the-Art

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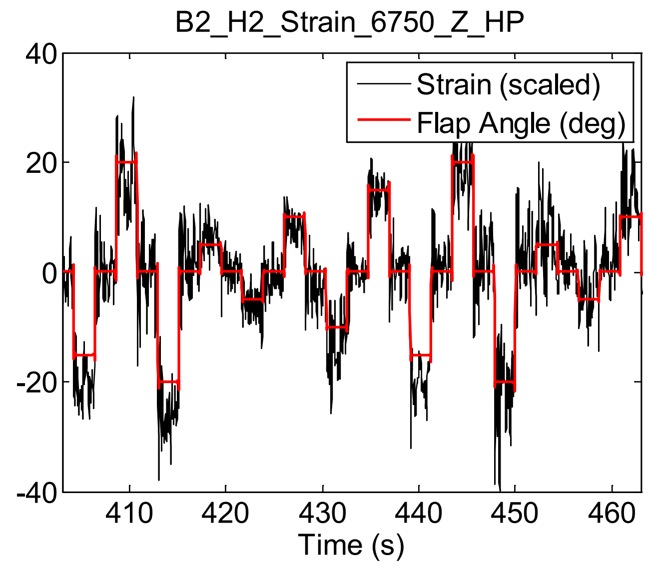
	DTU, Vestas	DTU, Vestas	SNL
Year Published	2010[1]	2013[2]	2013[3]
Turbine	V27	V27	Micon 65/13M
rotor diameter	27 meter	27 meter	19 meter
pitch	variable	variable	fixed
Number of Active Blades	1	1	3
Device (TEF = Trailing Edge Flap)	flexible TEF	hinged TEF	hinged TEF
percent of span, installed	15%	15%	20%
percent of span, functional during test	15%	5%	20%
Structural Sensors	strain, accel	strain, accel	strain, accel
Aerodynamic Sensors	Pitot tubes (3)	Pitot tubes (3)	no
Achieved closed-loop control?	no	yes	no

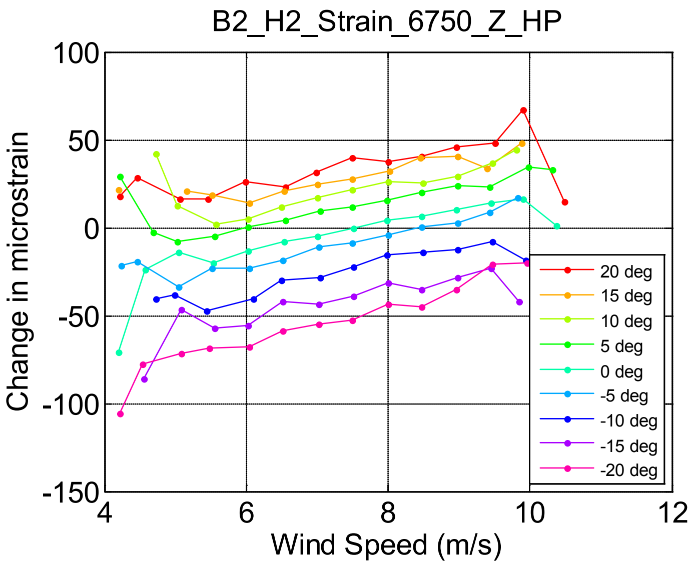
1. D. Castaignet, et al., "Results from the first full scale wind turbine equipped with trailing edge flap", 2010 AIAA Applied Aerodynamics Conference
2. D. Castaignet, et al., "Full-scale test of trailing edge flaps on a Vestas V27 wind turbine: active load reduction and system identification", 2013 Wind Energy Journal
3. J. Berg, et al., "Field Test Results from the Sandia SMART Rotor", 2013 ASME Wind Energy Symposium / AIAA Aerospace Sciences Meeting

Control Capability Demonstrated

- Response captured over a range of flap angles and wind speed
- At 3/4 span with -20 and 20 degree flap, strain magnitude changed by 50 and 33 microstrain
- These changes are 114% of the strain induced by normal power production

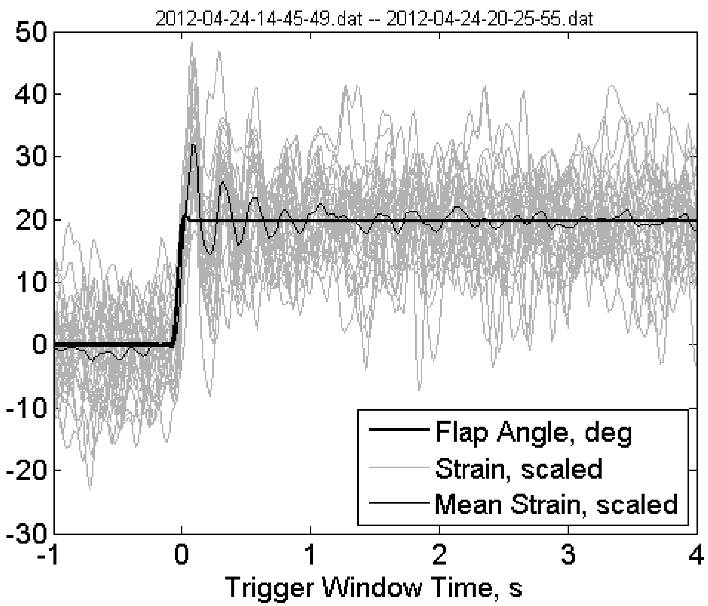
The flap control authority ranged from completely unloading to doubling the load on the flapped section of the blade



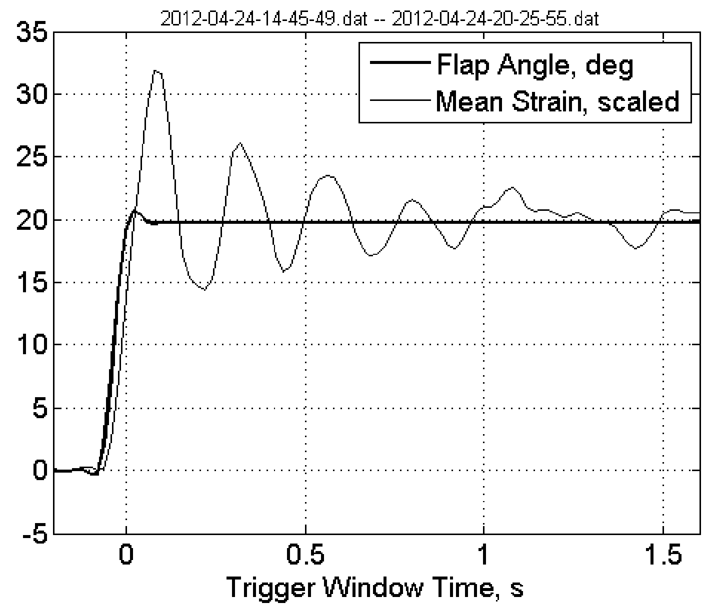


Advanced signal processing allowed concise quantification

- Wind inflow is highly variable which makes every test run different
- Ensemble average of many responses to the same flap motion uncovers the repeatable behavior
- The result enables fundamental time scale and damping identification



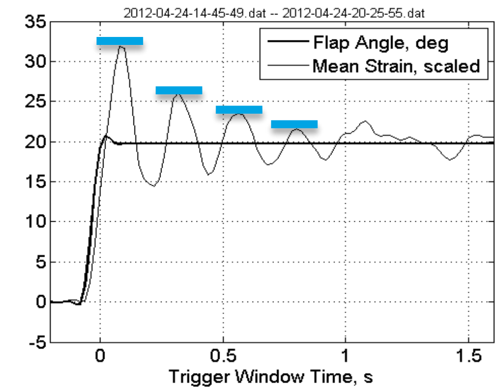
29 individual responses (gray)



Ensemble average response

Observed Combined Aero-Structural Damping

- Damping added by aerodynamic forces is typically difficult to quantify
- Combined damping estimated to be 1.3-3.2% of critical damping
- Amount of damping appears to depend on amplitude of blade motion

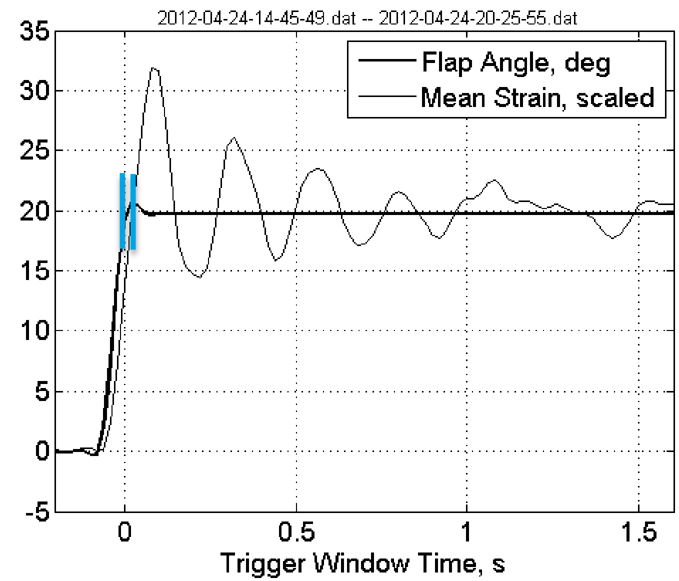


Peak	Maximum	Time, s		Peaks	Log Decrement	Damping Ratio	Time Difference, s	$1/\Delta T, s^{-1}$
u_1	30.38	0.0799		$u_2 - u_1$	0.202	0.032	0.2396	4.17
u_2	24.83	0.3195		$u_3 - u_2$	0.097	0.015	0.2397	4.17
u_3	22.54	0.5592		$u_4 - u_3$	0.080	0.013	0.2396	4.17
u_4	20.81	0.7988						

Flaps can be used to characterize turbine dynamics and calibrate fundamental aerodynamics properties

Observed Response Time Delay

- Observed 0.02 second delay in structural response
- Local section airflow adjustment can be related to structural response
- Evaluate accuracy of simulation tools

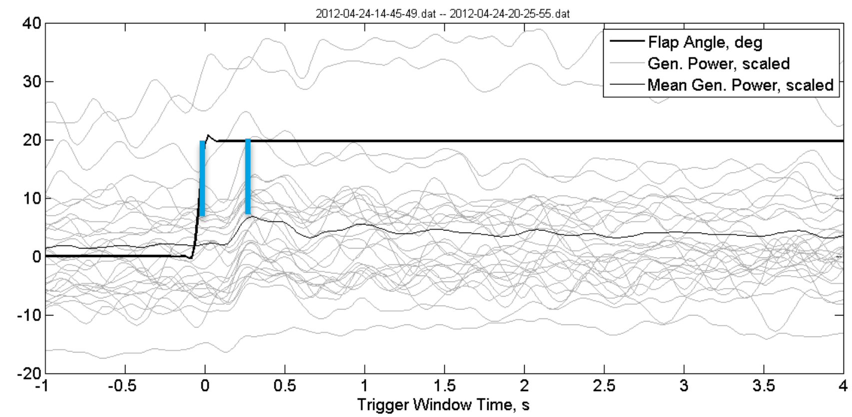


Process	Time Scale Definition	Time Scale
AALC Device Actuation	Actuation Period	0.09 – 1.1 sec
Response to Rotationally Sampled Wind	1P,2P,3P periods	0.3 - 1.1 sec
Dynamic Structural Response	Period of First Two Blade Flap Modes	0.09 - 0.22 sec
Local Section Flow	Chord / Relative Flow Velocity	0.004 sec
Local Section Flow Adjustment	5-10x Section Flow Time Scale	0.02 - 0.04 sec
Wake Response	Rotor Radius / Wind Speed	1.2 sec

Observed 0.02 second delay in strain response

Observed Power Response

- Important to capture power output accurately in simulation
- Observed 0.3 second delay in power response
- Power response and wake response are closely related, and flaps can be used to investigate the relation



Process	Time Scale Definition	Time Scale
AALC Device Actuation	Actuation Period	0.09 – 1.1 sec
Response to Rotationally Sampled Wind	1P,2P,3P periods	0.3 - 1.1 sec
Dynamic Structural Response	Period of First Two Blade Flap Modes	0.09 - 0.22 sec
Local Section Flow	Chord / Relative Flow Velocity	0.004 sec
Local Section Flow Adjustment	5-10x Section Flow Time Scale	0.02 - 0.04 sec
Wake Response	Rotor Radius / Wind Speed	1.2 sec

Observed 0.3 second delay in power response

Project Plan & Schedule

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Summary	
WBS Number or Agreement Number	WE 3.1.7 (FY13)
Project Number	21112
Agreement Number	22527

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

Task / Event	FY2012 Q1 (Octt-Dec)	FY2012 Q2 (Jan-Mar)	FY2012 Q3 (Apr-Jun)	FY2012 Q4 (Jul-Sep)	FY2013 Q1 (Octt-Dec)	FY2013 Q2 (Jan-Mar)	FY2013 Q3 (Apr-Jun)	FY2013 Q4 (Jul-Sep)	FY2014 Q1 (Octt-Dec)	FY2014 Q2 (Jan-Mar)	FY2014 Q3 (Apr-Jun)	FY2014 Q4 (Jul-Sep)
Project Name: Wind Energy Forecasting Methods and Validation for Tall Turbine Resource Assessment												
Q1 Milestone: Complete AIAA conference papers												
Q2 Milestone: Complete SMART open-loop testing												
Q3 Milestone: Complete draft report on SMART field test												
Q4 Milestone: Submit conference abstract on AALC test/model comparison												
Q1 Milestone: Complete SAND report documenting field test & data sets												
Q2 Milestone: Progress update memo on data analysis												
Q3 Milestone: Submit article to peer-reviewed journal												
Q4 Milestone: Publish SAND report detailing conclusions from data analysis												
Current work and future research												

Comments

- FY13 Q1&2 saw decrease in available staff time as resources were devoted to SWiFT installation.

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators:

- USDA-ARS staff at Bushland Test Site
- University research collaboration
  - University of California, Davis (C.P. van Dam)
  - TU Delft (Thanasis Barlas, Jan-Willem van Wingerden, Lars Bernhammer)
- Subcontract: Creaform, blade surface geometry scan

Communications and Technology Transfer:

Sandia Project Reports

- J.C. Berg, M.F. Barone, and N.C. Yoder. "SMART Wind Turbine Rotor: Data Analysis and Conclusions." Sandia Report SAND2014-0712, January 2014.
- J.C. Berg, B.R. Resor, J.A. Paquette, and J.R. White. "SMART Wind Turbine Rotor: Design and Field Test." Sandia Report SAND2014-0681, January 2014.

Conference Proceedings

- J.C. Berg, M.F. Barone, and B.R. Resor. "Field Test Results from the Sandia SMART Rotor." Proceedings of the 51st AIAA Aerospace Sciences Meeting, Grapevine, TX, January 2013.
- J.C. Berg, D.E. Berg, and J.R. White. "Fabrication, Integration, and Initial Testing of a SMART Rotor." Proceedings of the 50th AIAA Aerospace Sciences Meeting, Nashville, TN, January 2012.

Next Steps and Future Research

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Proposed future research:

- Based on the acquired experience, develop updated models that advance the state of the art and allow for design optimization of future active load control rotors.
- Utilize lessons learned and updated models to produce second generation AALC rotor.
- Implement closed-loop control utilizing a variety of controls approaches and sensors to progress TRL for technology transfer to industry.

High Efficiency Structural Flowthrough Rotor With Active Flap Control

Mike Zuteck

Zimitar, Inc.

MikeZuteck@ZimitarWind.com

March 26th, 2014

Budget, Purpose, & Objectives

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

Total DOE Budget[1]: $0.700M

Total Cost-Share[1]:$0.178M

Problem Statement: Conduct engineering studies for a lightweight rotor that reduces specific weight to about half of conventional offshore designs

Impact of Project: Recent study suggests a 6 MW 160-180 m structural flowthrough rotor could improve LCOE by 21-23% as compared to existing offshore designs

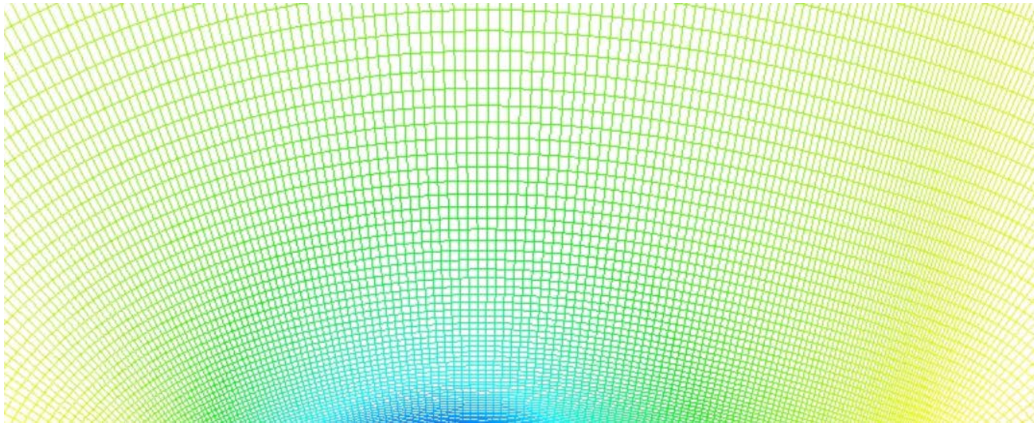
This project aligns with the following DOE Program objectives and priorities:

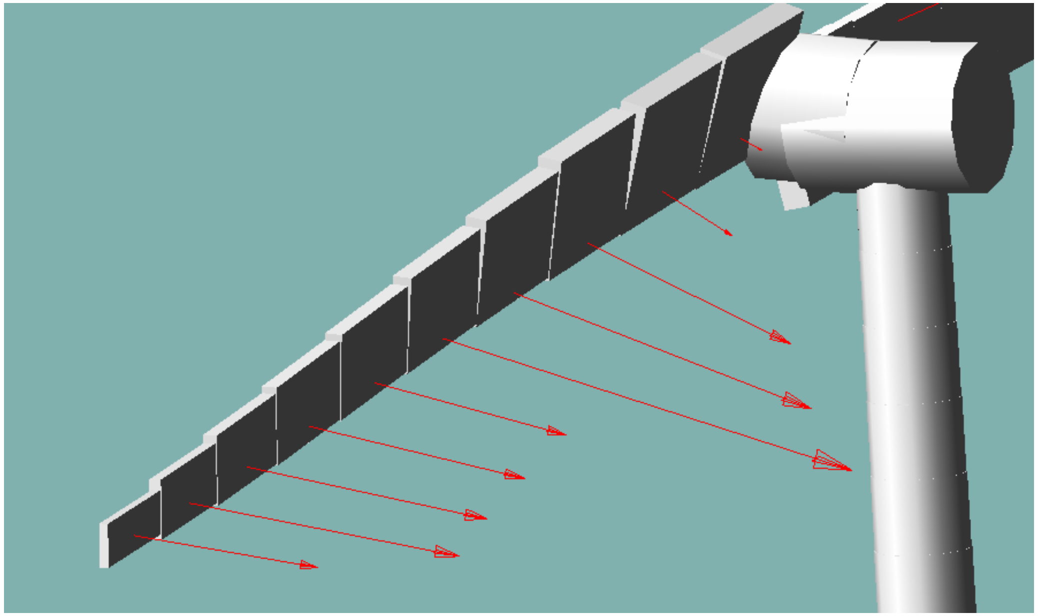
- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)

[1] *Budget/Cost-Share for Period of Performance FY2012 – FY2013*

Technical Approach

- SolidWorks for 3D CAD & Stress Contour Maps
- Section Analysis for Rotor Structural Properties
- XFOIL and OVERFLOW2 for Airfoil/Flap Investigations
- WTPerf, AeroDyn, CurveFAST, & ADAMS for Loads
- AeroSolve Multi-Disciplinary System Integration





Technical Approach

MAJOR DESIGN VARIATIONS

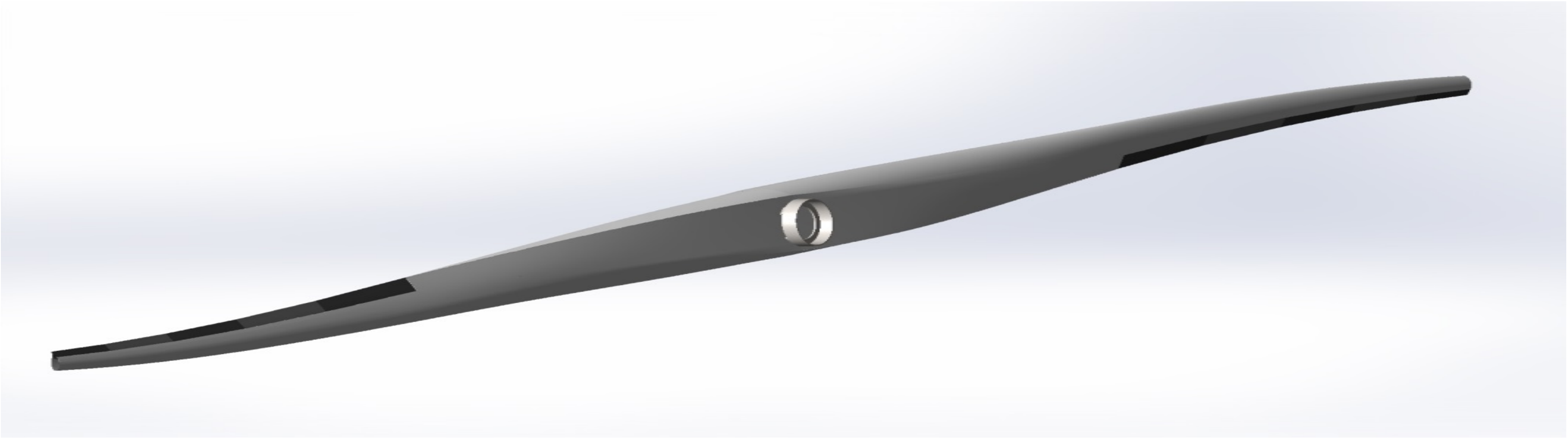
Single Spar vs Double Spar Primary Rotor Structure

Flap Locations Investigated:

- 30-70% Span -> 50% to Tip

Outboard Airfoils Studied:

- FX Series: Normal design Cl and flap hinge moments
- Modified TL 190: High Cl, >flap moments and float angles



Single Spar Geometry With Mid-Span Flaps

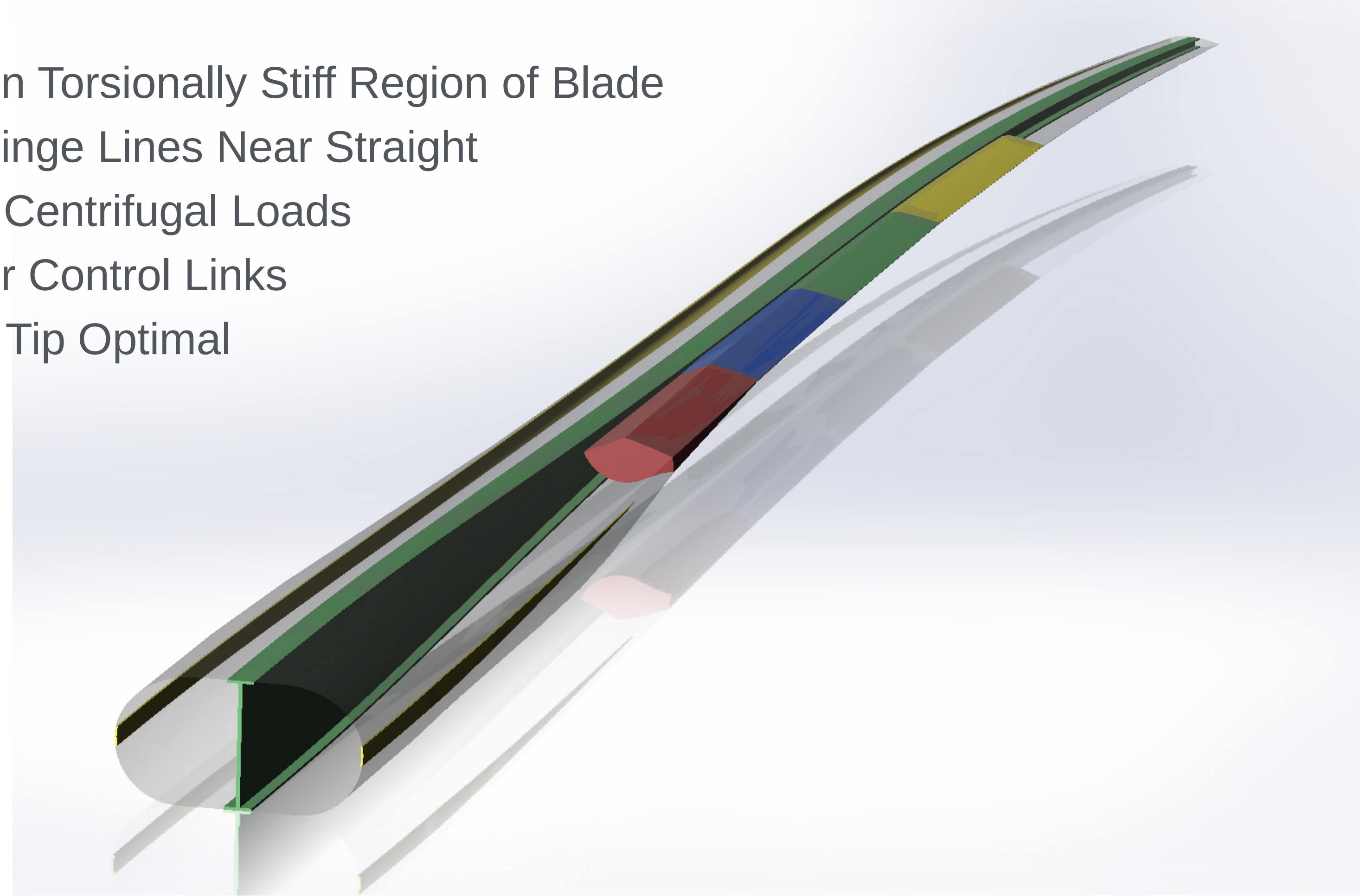
Flaps in Torsionally Stiff Region of Blade

Flap Hinge Lines Near Straight

Lower Centrifugal Loads

Shorter Control Links

Swept Tip Optimal



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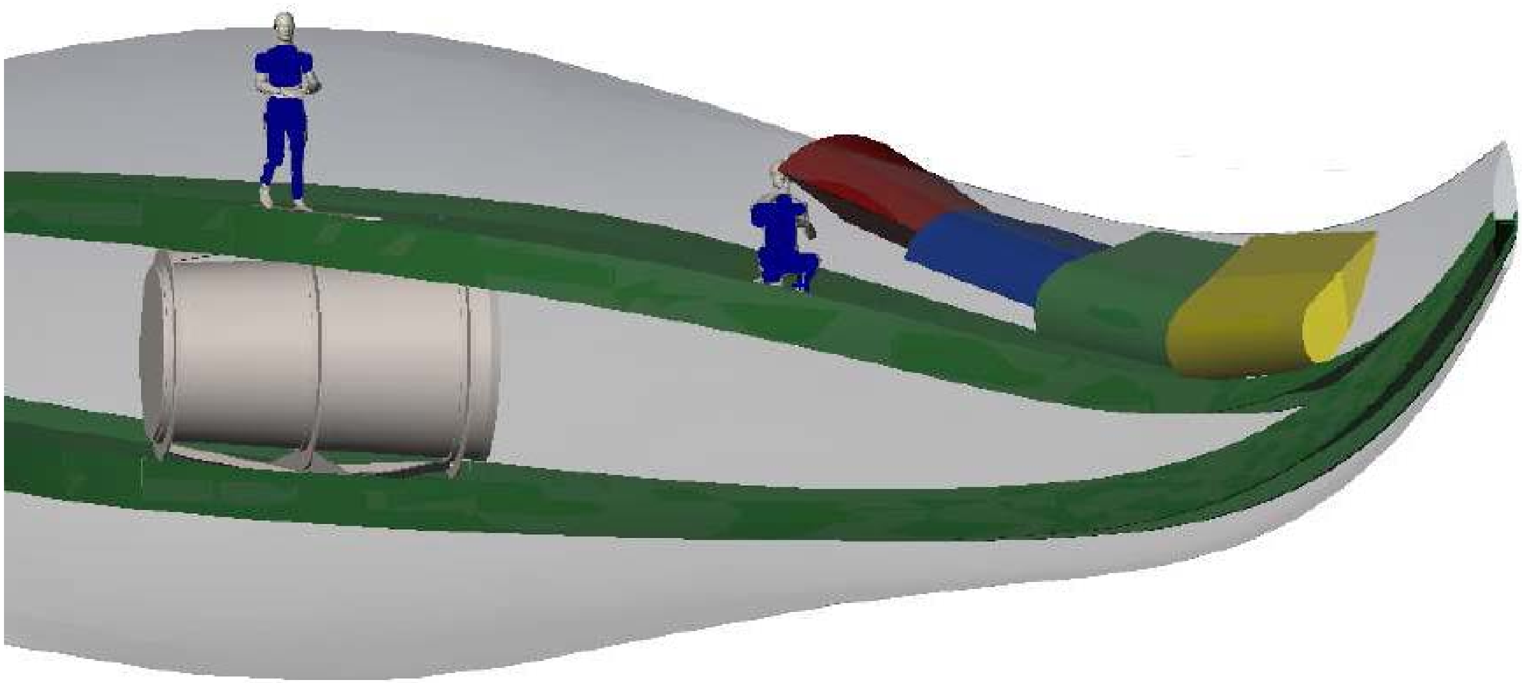
Double Spar With Mid-Span Flaps – Good Crew Access



Technical Challenges

Mid-Span Flaps Difficulties

Inadequate Power Control and Stopping Authority

Large Flap Angles Required During Operation

- Flaps forced into separated flow regime
- Large pull toward stop system required

Single Spar Edgewise Spline Ends Too Far Inboard

Double Spar Interferes with Size of Inboard Flaps

One-Piece Rotor with Mid-Span to Tip Flaps

Curved or Segmented Hinges Needed

Chordwise Centrifugal Flap Loading

Flaps Fit Behind Spars Easily

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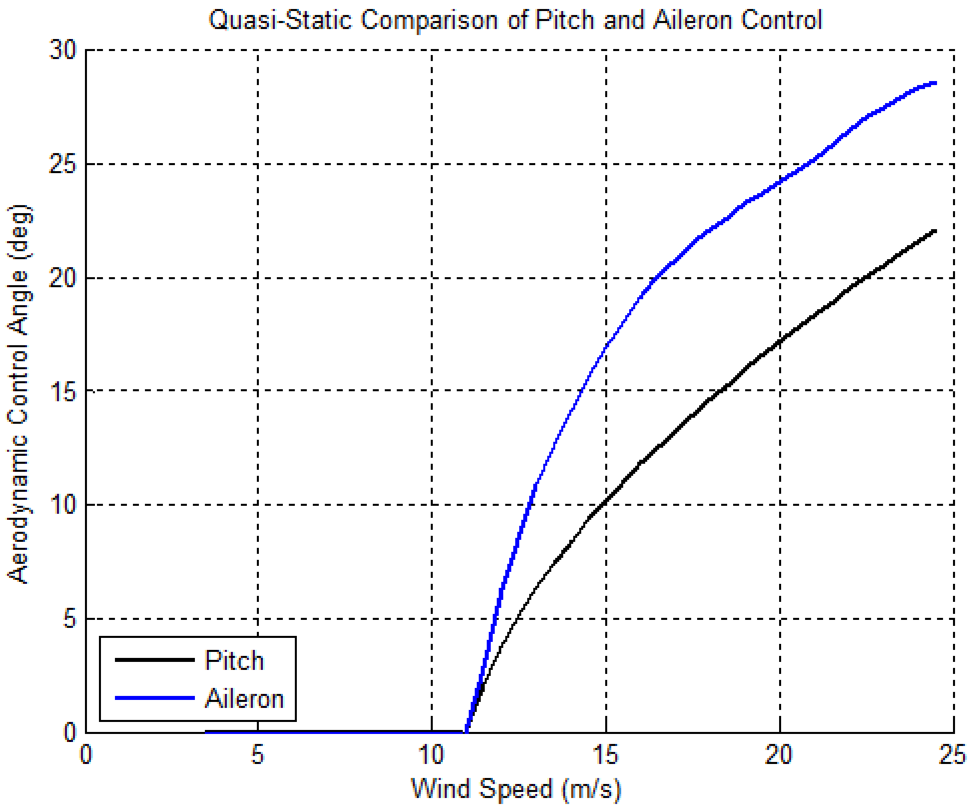
Rotor Now Behaves Similarly To Full Span Pitch



Technical Challenges

Flaps to Tip Caused Large (7°) Adverse Tip Twist

High GJ Design:

- Add DB Shell Fabric and Move Spar Aft
- ~3x torsional stiffness at 90% r/R
- Cut flap deploy twist about in half

Low Tip Chord Design:

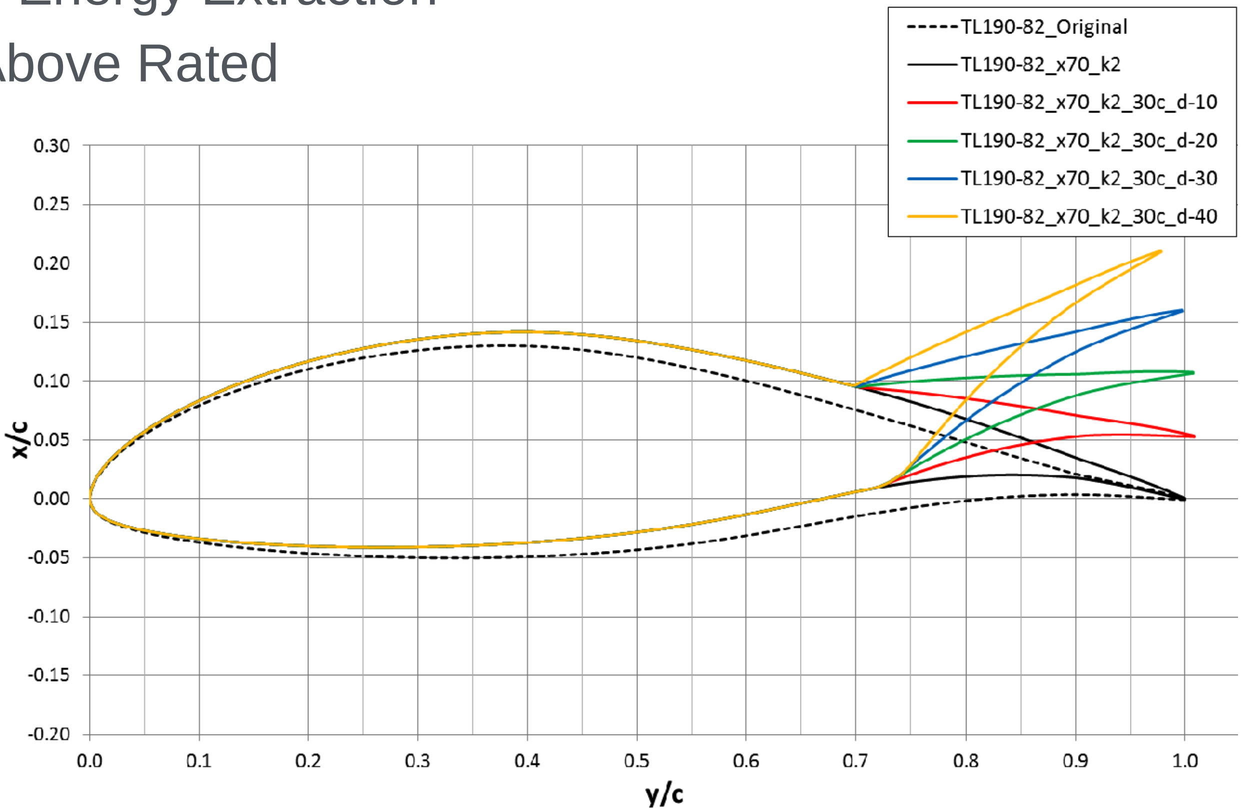
- Tip chord from 1.7m -> 1.2m
- Pitching moment goes as square of chord
- High Cl airfoil required to compensate chord loss
- Cut flap deploy adverse twist ~ 1/3 additional

Highly Flap Aft Loading -> Large Actuator Loads

Larger Flap "Aero Only" Float Angle Desired

Inner Rotor Aerodynamic Challenges

- Efficient Below-Rated Energy Extraction
- Limit Excess Power Above Rated



Technical Differentiation

Largest Loads Flow Across Hub, Not Via Joints/Bearings

Mass of “Pitching” Structure Greatly Reduced

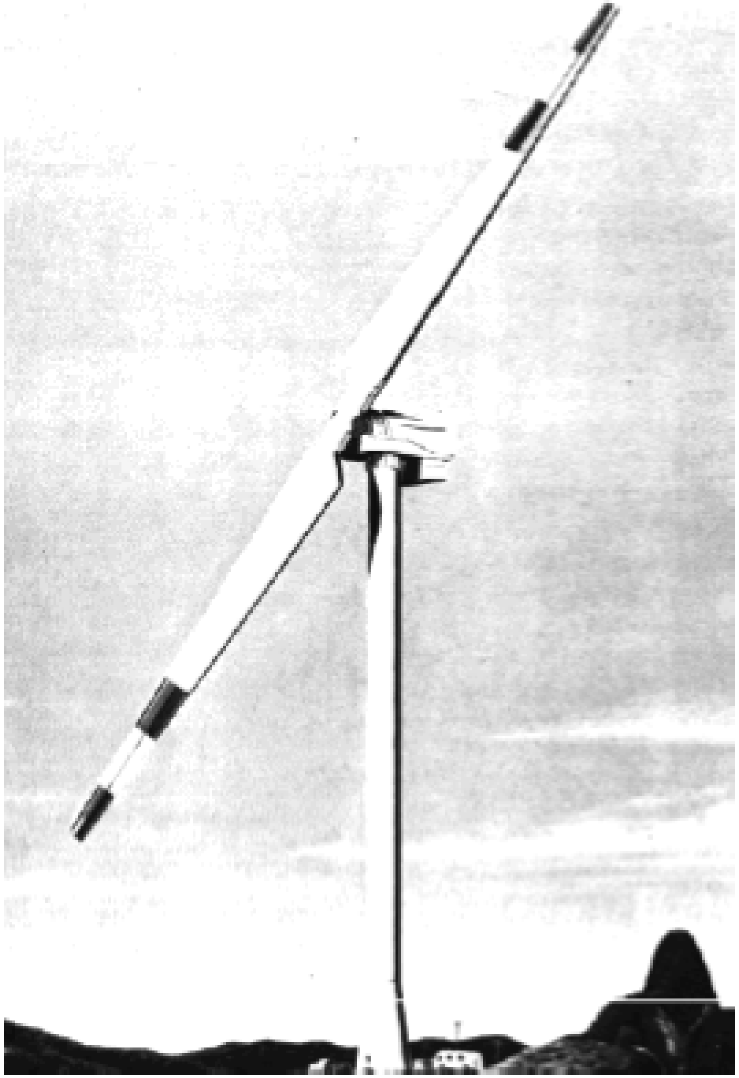
Self-feathering To Safe Stop

Easy to Raise the Rotor

Technical Differentiation

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

- 7.3 MW NASA/GE Mod-5A Design Was One-Piece
- Update to Modern Materials and Airfoils Successful
- Bottom Line – A Path To Cut Rotor Weight In Half



Accomplishments and Progress

Zimitar completed conceptual design studies in FY2013 Q4 and completed preliminary design in FY2014 Q2.

Analysis results suggest total rotor weight is about half of currently operating offshore rotors, which met expectations for the key design goal. LCOE improvements were estimated to be 21-23% compared to the existing offshore fleet.

Dynamic models of the rotor have been used to run thousands of simulations. Analysis results show that aileron deployment angle is functionally similar to conventional pitch control.

Engineering of the flap actuator system has successfully identified commercially available components and estimated their cost. An actuator and other hardware were purchased for laboratory testing. Critical tooling needed to fabricate field test articles was transported to the manufacturing facility.

Project Plan & Schedule

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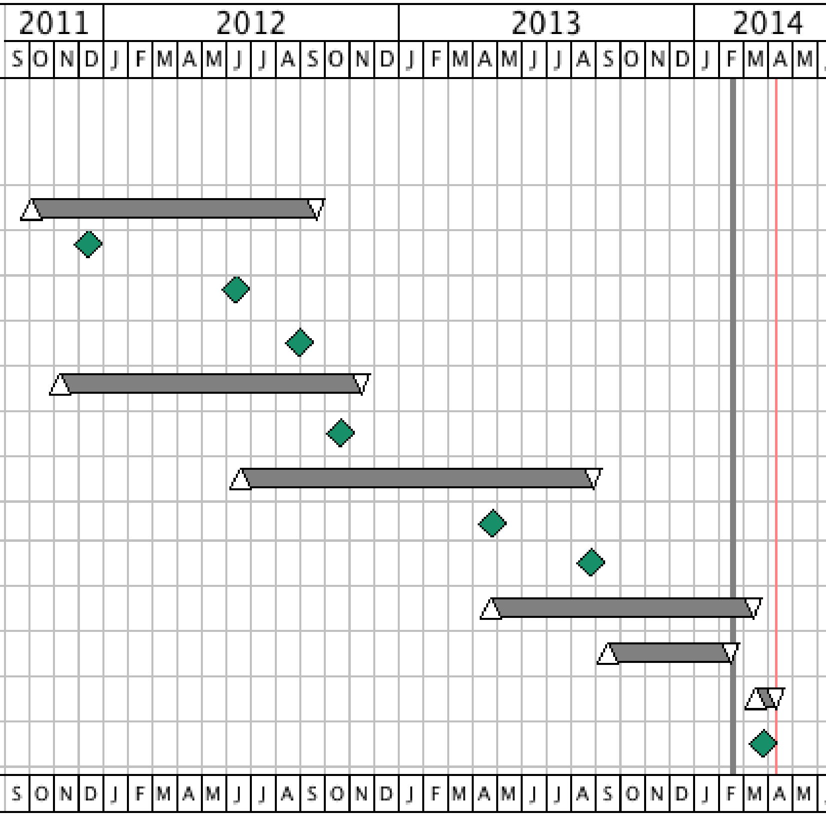
Activity Name	Start Date	Finish Date	Duration (Work Days)
High Efficiency Structural Flowthrough Rotor With Active Flap Control Budget Period 1			
Project Planning	***10/3/11***	***9/21/12***	***255***
M1 – Initial Project Meeting	12/14/11	12/14/11	0
Award Approved by DOE	6/12/12	6/12/12	0
D1 – Project Work Plan	8/31/12	8/31/12	0
Define Technical Approach	11/7/11	11/16/12	270
M2 – Conceptual Design Plan Review	10/22/12	10/22/12	0
Conceptual Design	6/18/12	8/30/13	315
M3 – Blade Shell Review Meeting	4/26/13	4/26/13	0
D2 – Conceptual Design Presentation	8/26/13	8/26/13	0
Preliminary Design	4/22/13	3/14/14	235
Laboratory and Field Test Planning	9/16/13	2/14/14	110
Preliminary Design Review	3/17/14	4/11/14	20
D3 – Preliminary Design Presentation	3/26/14	3/26/14	0



Comments

- Detailed project planning began in FY2012 Q1 with DOE
- DOE approved agreement 5492:BP1 in FY2012 Q3 for 24 months
- BP1 on schedule with BP2 Go/no-go decision point in April 2014

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

Field Test Rotor: Blades: TPI Composites (MA & RI)
Field Test Rotor: Flaps: Clear Carbon & Components (RI)
Field Test Rotor: Tooling: Heron Wind Manufacturing (MI)
Rotor Design: Composite FEA: NSE Composites (WA)
Flap Actuator Design: California Maritime Academy (CA)
Aero CFD & Wind Tunnel Testing: UC Davis (CA)
Field Testing: NextEra Cabazon (CA)
Field Testing: TerraGen Tehachapi (CA)

Communications and Technology Transfer:

Zuteck: Presentation at Cal Maritime, September 2013

Next Steps and Future Research

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

FY14/Current research:

Currently in project continuation review.

DOE approval leads to BP2 starting in FY2014 Q4 for 36 months. Plans include field testing of the flap system at sub-scale on a 750 kW wind turbine. Manufacturing of three blade test articles will occur in FY2015 Q2. The flap system will be assembled, bench tested, and integrated with the field test articles. The field test rotor will be installed in southern California in FY2016 Q2.

The BP2 field test effort is critical to measure aerodynamic response characteristics and confirm flap actuator dynamic loading. These data will be used to verify model predictions for loads on the rotor and actuator components.

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Offshore 12-MW Turbine Rotor with Advanced Materials and Passive Design Concepts

Kevin Standish

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March 26, 2014

Budget, Purpose, & Objectives

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

Total DOE Budget[1]: $0.569M

Total Cost-Share[1]:$0.699M

Problem Statement: Despite growing commercialization, the Cost of Energy from Offshore Wind Power continues to be expensive when compared with fossil fuel sources.

Impact of Project: This project is focused on reducing the Levelized Cost of Energy from Offshore Wind Power by 20% through passive rotor design technologies.

This project aligns with the following DOE Program objectives and priorities [select best fits & delete others]:

To be provided at a later date. Please leave this section blank until further guidance is provided

[1] ***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Technical Approach

Phase 1 Focus: computationally demonstrate a cost of energy reduction of offshore wind power through advanced materials, and passive design concepts.

Passive design concepts:

- relatively simple, high likelihood of success, low cost of commercial implementation

Rotor Growth Through Load Alleviation:

By lowering extreme and fatigue loads on an offshore wind turbine with passive design concepts it should be possible to fit larger rotor blades on existing machinery, thus increasing energy capture, and lowering the levelized cost of energy from wind power.

Aeroelastic / Material Advancements:

- Investigated 6 passive technologies that focused on weight reduction, and flap-twist coupling.

Aerodynamic Devices:

- Investigated 6 passive technologies that focused on load reductions (fatigue, extreme) & performance increase

Target: 20% reduction to the LCOE of Offshore Wind Power

To Date: Achieved 6% on a 2.3MW Onshore Wind Turbine

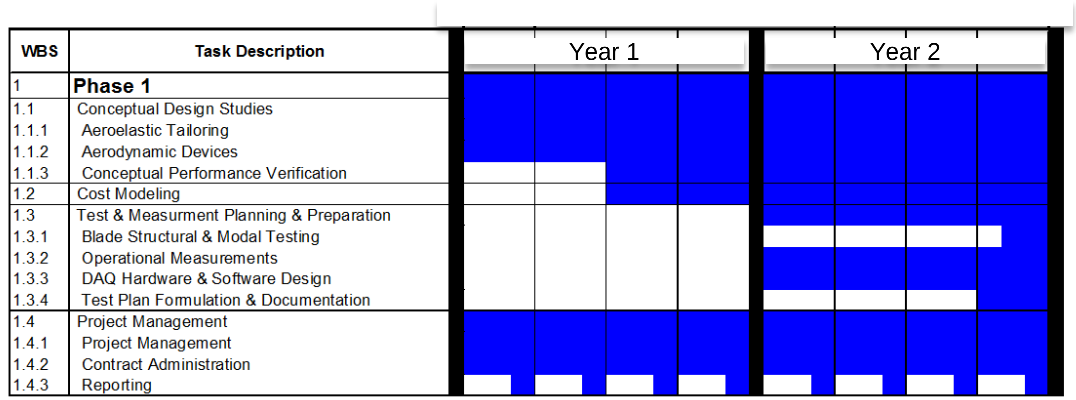
Intellectual Property: 5 Invention Disclosures Submitted

Project Plan & Schedule

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

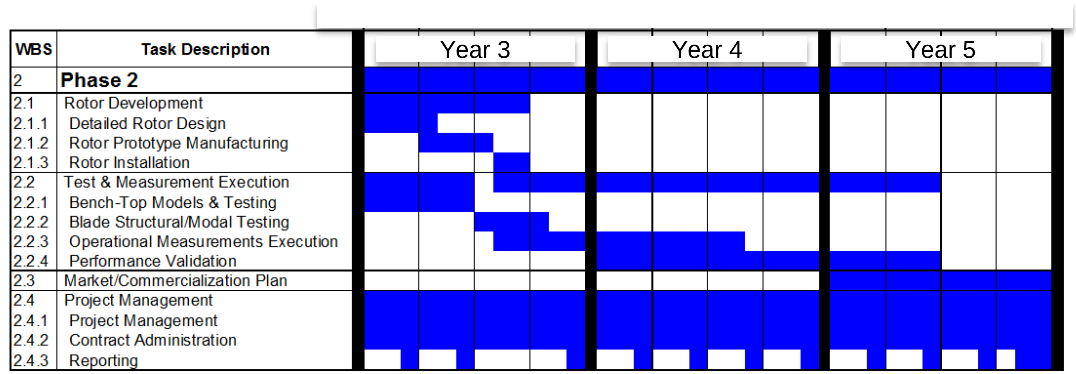
Original Project Plan:

- Shifted by 6 months due to late start



Phase 2:

- Aligning project scope with internal objectives



Comments

- Award Announcement: Oct. 2011 --- Original Completion Date: Sept. 2013
- No-Cost Extension Granted through Mar. 2014 --- Project did not formally start until Aug. 2012
- 2nd extension being sought (through Sept. 2014) in order to align project scope w/ internal objectives

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

Partners in this project:

- Nat'l Wind Tech. Cent. (NWTC): Cost modeling work, Test & Measurement Planning & Preparation
- Det Nortske Veritas (DNV): Provided independent validation of key COE-reducing technologies

Communications and Technology Transfer:

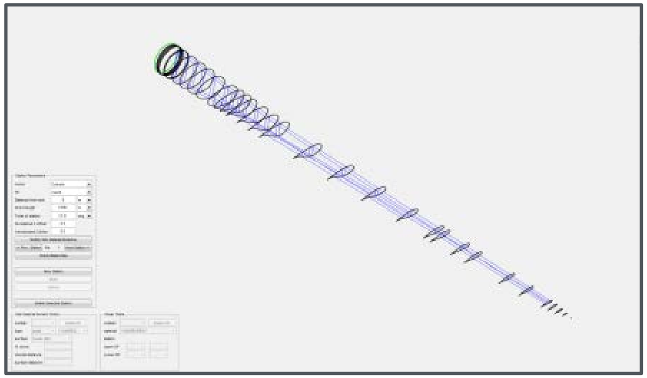
Work has not been presented on this project to date.

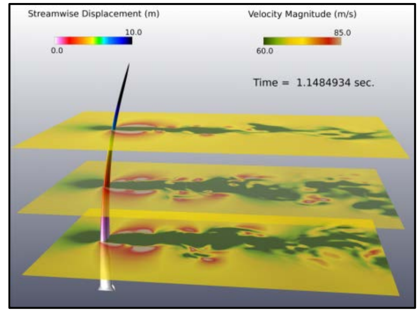
Next Steps and Future Research

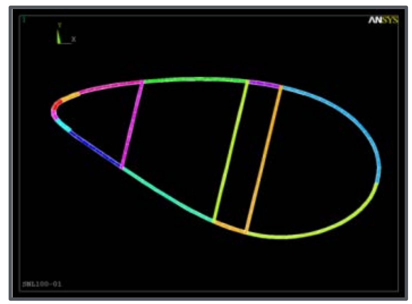
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY14/Current research: This project is currently moving into Phase 2, in which the technologies demonstrated computationally in Phase 1 will be incorporated into a new design & field tested on a 2.3MW machine at NWTC.

Proposed future research: Much of the future of this work will include design, testing, and validation of current technologies, as well as new, attractive passive technologies.







WE 5.1.3 Offshore Wind RD&T: Large Offshore Rotor Development

D. Todd Griffith, PhD

Sandia National Laboratories

dgriffi@sandia.gov (505) 845-2056

March 26, 2014

Budget, Purpose, & Objectives (1/2)

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

Total DOE Budget[1]: $0.470M

Total Cost-Share[1]:$0.000M

Problem Statement:

A dominant trend and major driver of cost reduction in wind energy technology has been growth in turbine rotor size. Research is needed to address key technology, manufacturing, economic, and logistical challenges associated with larger and larger turbines.

Impact of Project:

The over-arching objectives:

- Enable large rotor technology
- Identify and assess the large blade barriers
- Develop their mitigation

From the beginning, the project was designed to be an entirely public domain project – filling an important gap.

[1]***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

Budget, Purpose, & Objectives (2/2)

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

This project aligns with the following DOE Program objectives and priorities:

- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

This research has provided a public domain database of large turbine (13.2 MW) and large blade (100m) detailed design models that did not exist, and that would not otherwise be made available by industry.

Technical Approach (1/2)

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The technical approach:

1. Perform large blade design studies
2. Make public the lessons-learned reports/documentation
3. Make public the actual blade design models
   – Enable research by graduate students and industry
4. Perform research to mitigate the challenges
   – Flutter studies & tool development
   – Manufacturing cost model
   – Carbon spar blade
   – Advanced core blade
   – Thick flatback airfoils

Phase One:

SNL100-00 All-glass 100-meter Baseline Blade in FY11

- ID upper limit of conventional blade technology
- ID technical concerns (weight & cost, gravitational fatigue, panel buckling, aero-elastic instability (e.g. flutter))
- Provide a baseline public domain detailed design layup

Phase Two (FY12-FY13, FY14)

Prioritize and pursue follow-on studies with the goal to mitigate the identified barriers; **Sandia selected these:**

- Flutter parameter study and improvements to flutter tool
- Sandia Blade Manufacturing Cost Model (version 1.0)
- Carbon spar design (SNL100-01)
- Advanced core material and strategy (SNL100-02)
- Flatback airfoils and blade slenderness study (SNL100-03)

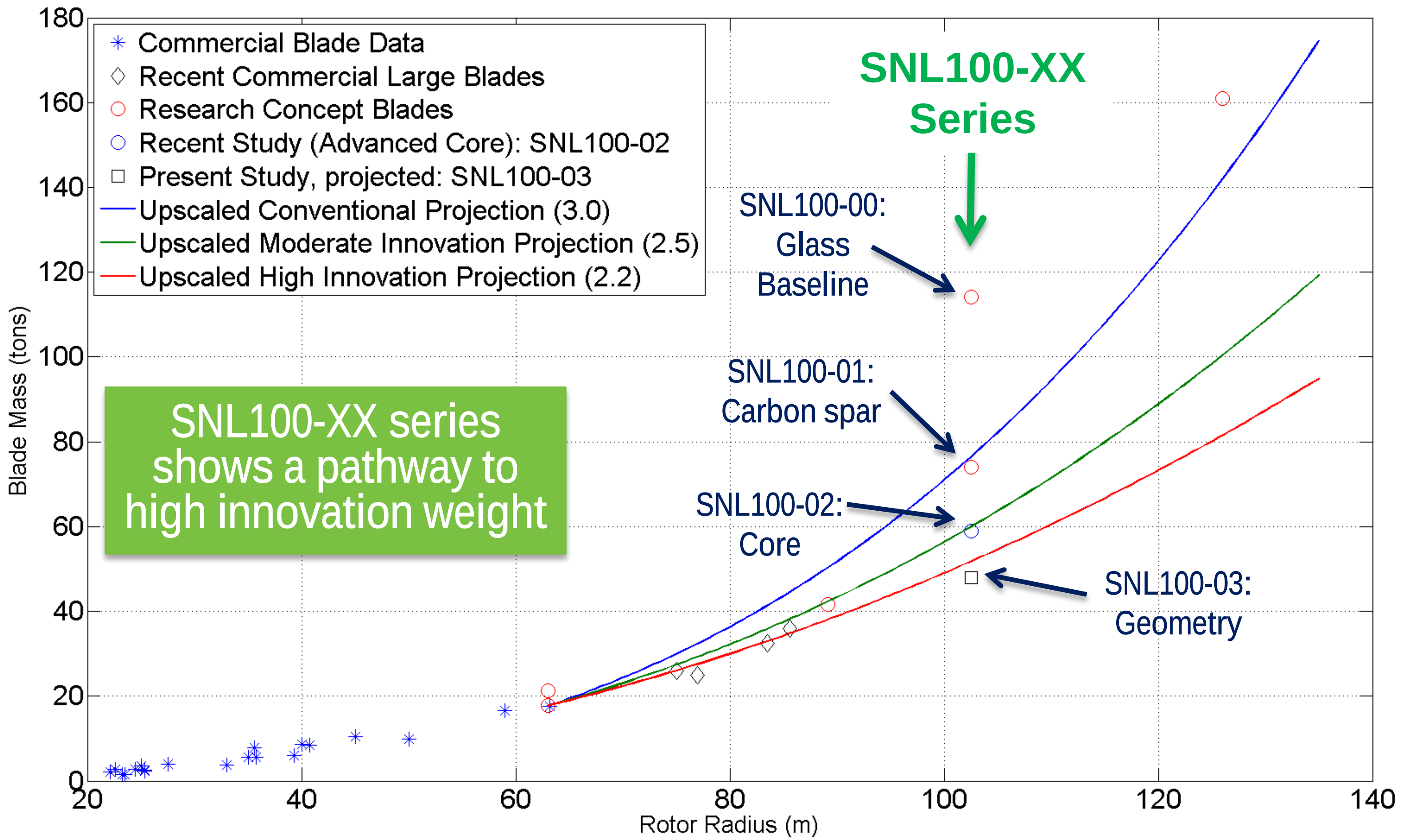
Most important technical accomplishments:

- Carbon Blade with 35% weight reduction
- Core blade with additional 20% reduction (48% total)
- Published Blade Manufacturing Cost Model (MS Excel)
- Final design with ~46 tons weight (~60% total weight reduction from baseline blade)
  - **A light-weight, manufacturable, aero-elastically stable 100-meter design**

Benchmarking of accomplishments:

- Original goals were met/exceeded in identifying challenges and opportunities for large blades
- Wide dissemination of reports and 4 detailed design models in public domain

Industry survey of blade mass: **Commercial blades (20-60 meters), recent large prototype blades (73-83 meters), and research concept blades (61.5, 86, 100, 123 meters)**



Accomplishments and Progress (3/7)

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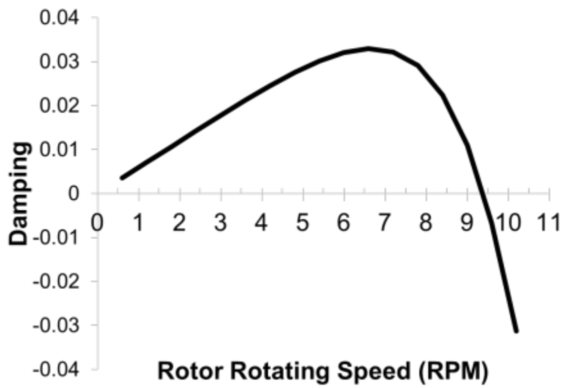
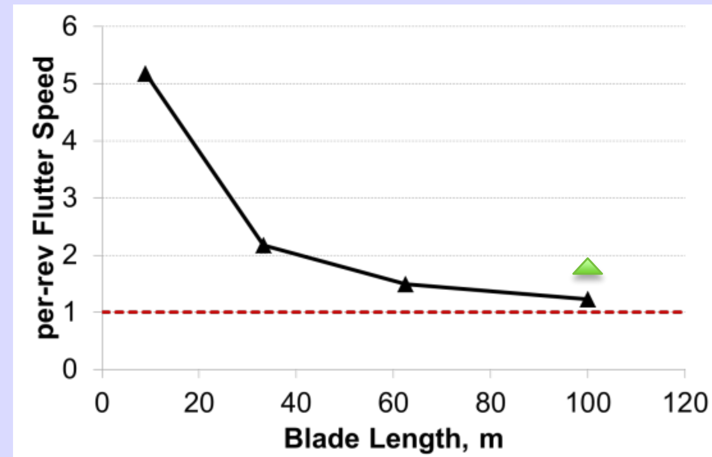
1. Flutter parameters study and improvements to flutter tool



Data shown are from classical flutter analyses:

- SNL CX-100; 9-meter experimental blade
- WindPact 33.25-meter 1.5MW concept blade
- SNL 61.5-meter blade (preliminary design)
- SNL100-00 Baseline Blade



1. Resor, Owens, and Griffith. “Aeroelastic Instability of Very Large Wind Turbine Blades.” Scientific Poster Paper; EWEA Annual Event, Copenhagen, Denmark, April 2012.
2. Owens, B.C., Griffith, D.T., Resor, B.R., and Hurtado, J.E., “Impact of Modeling Approach on Flutter Predictions for Very Large Wind Turbine Blade Designs,” Proceedings of the American Helicopter Society (AHS) 69th Annual Forum, May 21-23, 2013, Phoenix, AZ, USA, Paper No. 386.

Design impacts identified & SNL Flutter Tool Improved

Accomplishments and Progress (4/7)

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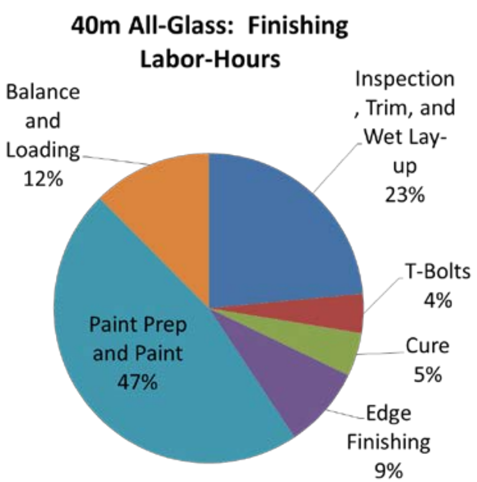
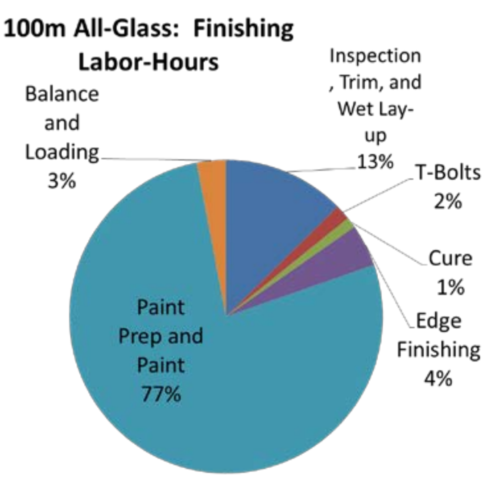
2. Sandia Blade Manufacturing Cost Model (version 1.0)

- Components of the Model:
  - Materials, Labor, Capital Equipment
  - Detailed Labor Breakdown by major operation
  - Reports: SAND2013-2733 & SAND2013-2734

Important Study of Labor Operations Trends with Scale



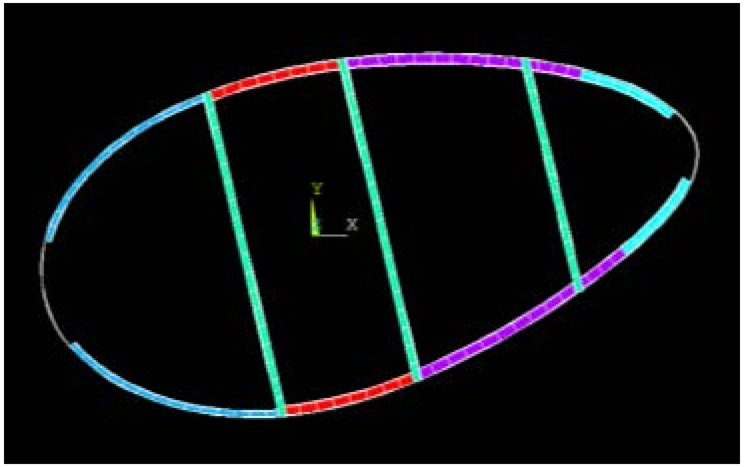


One example: An analysis of labor costs shows the growth in labor hours for area-driven manufacturing tasks such as paint prep and paint as blades grow longer.

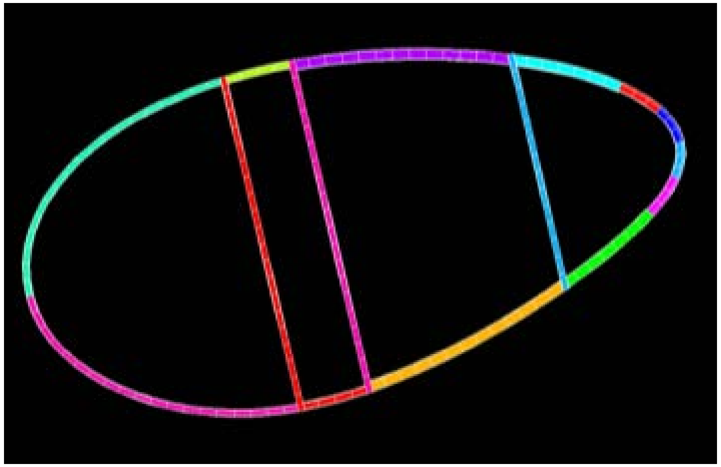
3. Carbon spar (SNL100-01)

Cross-sections at 14.6m station

SNL100-00: Glass Spar



SNL100-01: Carbon Spar



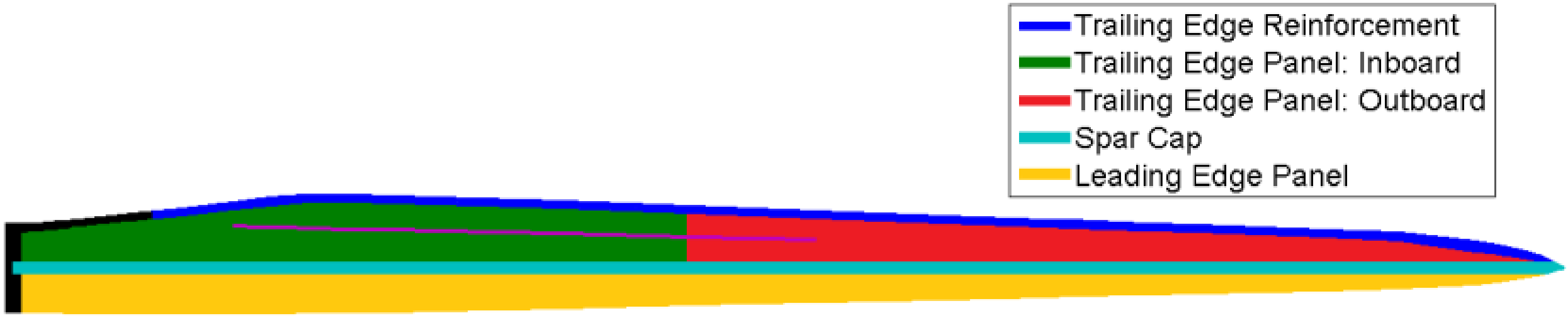
Carbon blade weight and cost baseline established (using SNL Blade Cost Model)

- **Spar width reduced by 50%**
- **Shear web thickness reduced by 25%**
- **35% weight reduction**

4. Advanced core material (SNL100-02)

Performance Focus:
- Balsa in critical buckling areas
- PET foam (recyclable) in non-critical buckling areas and shear webs
- ~20% additional weight reduction

Secondary Benefit:
- Eco-friendly core materials approach (regrowable and recyclable)



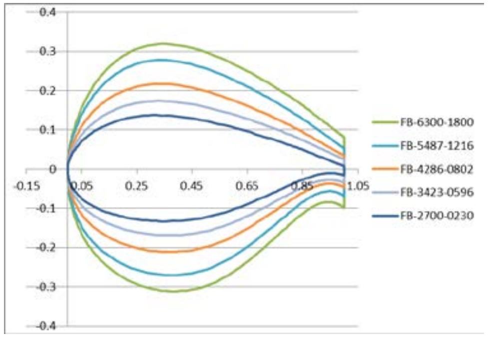
Primary and secondary weight reduction benefits;
Recyclable foam has good potential for large blade applications

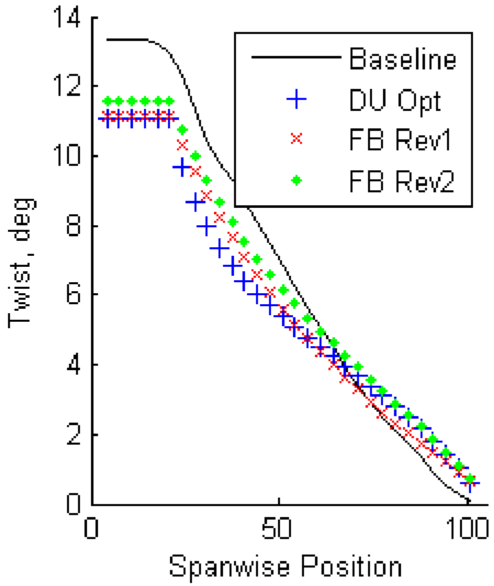
5. Flatback airfoils (SNL100-03)

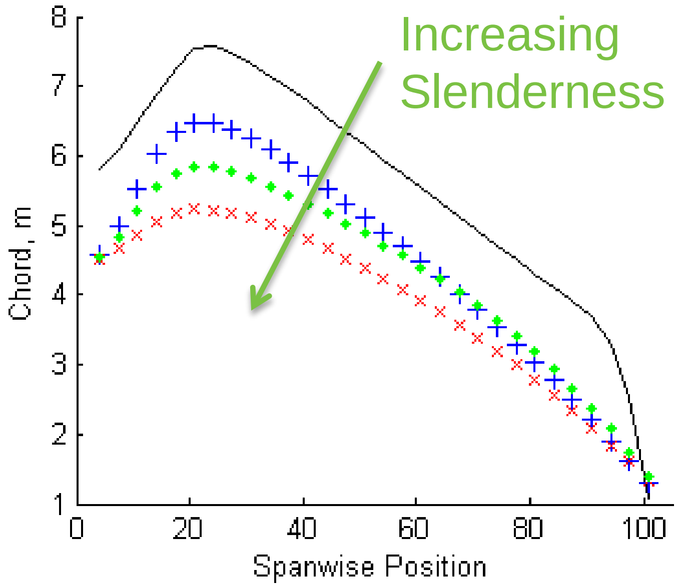
Focused on effect and limits of blade slenderness

Opportunity to reverse many trends, including:

- Weight growth – *innovative weight projection anticipated*
- Buckling
- Flutter, Deflection, Fatigue
- Surface Area Driven Labor Operations







Increased blade slenderness has advantages and disadvantages – these design studies aid in better understanding the trade-offs

Project Plan & Schedule

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Summary	
WBS Number or Agreement Number	WE 2.5.0.3
Project Number	
Agreement Number	26901

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

Task / Event	FY2012				FY2013				FY2014			
	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: WE 5.1.3 Large Offshore Rotor Development												
Q1 Milestone: Public release of aero-elastic turbine model & blade structural model												
Q2 Milestone: Develop draft of 13.2 MW land-based reference model report												
Q3 Milestone: Publish 13.2 MW land-based reference model report												
Q4 Milestone: Complete engineered core study												
Q1 Milestone: (1) Public release of SNL100-01 carbon blade, (2) Submit long-range plan to DOE												
Q2 Milestone: (1) Survey document, (2) Release Sandia Blade Manufaturing Cost Model												
Q3 Milestone: Initial report on trade-offs for thick airfoils												
Q4 Milestone: FY13 Final Report												
Current work and future research												
Complete project final report and SNL100-03 blade design and make public												

Comments

- Project start in FY10
- All milestones met on schedule, with exception of FY13/Q4 milestone that was re-directed for completion as element of FY14 project final report

Research Integration & Collaboration

Partners, Subcontractors, and Collaborators:

In-kind collaborations: Altair Software, Inc. (CFD), Univ. of Bristol (structural efficiency), Univ. of Stuttgart (bend-twist coupling), ECN (thick airfoils)

Communications and Technology Transfer:

- Project website with models and reports: (http://largeoffshorerotor.sandia.gov)
- Large external dissemination: 18 total publications (13 reports/papers + 5 presentations/posters)
- 4 detailed blade reference models (SNL100-00, SNL100-01, SNL100-02, SNL100-03) made available by request to over 60 researchers
- Design models in use in Wind Energy curriculum at ETH-Zurich (Switzerland)

Research Integration & Collaboration

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

Communications and Technology Transfer:

Publications Summary: 13 reports/papers to date

5 Sandia Technical Reports (SAND reports)
8 conference papers

- EWEC 2012, EWEC 2014
- AIAA 2012 (2), 2013, 2014
- AWEA WindPower 2012
- AHS 2013

Next Steps and Future Research

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FY14/Current research:

Current FY14 effort focused on project close-out: final series of design studies and final report showing a pathway to a large, light-weight, cost-effective, manufacturable, and aero-elastically stable blade.

Proposed future research:

1. Spin-off research on flatbacks and/or carbon
2. Large Blade Manufacturing Study (e.g. Blade Manufacturing Cost Model version 2.0) – manufacturing trends and needs assessment
3. Larger rotor design studies (>> 100 meters)
4. System-level design trade-offs
5. Validation of flutter tools (code comparison and experimental validation)
6. Large blade substructure testing

Pivot Offshore Wind Turbine

Geoff Sharples PI

Clear Path Energy

Geoff@ClearpathenergyLLC .com 415 307 3562

March 26, 2014

Purpose & Objectives

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Problem Statement: The big cost drivers of offshore wind are installation, maintenance, the support structure and the NIMBY resistance to near shore installations.

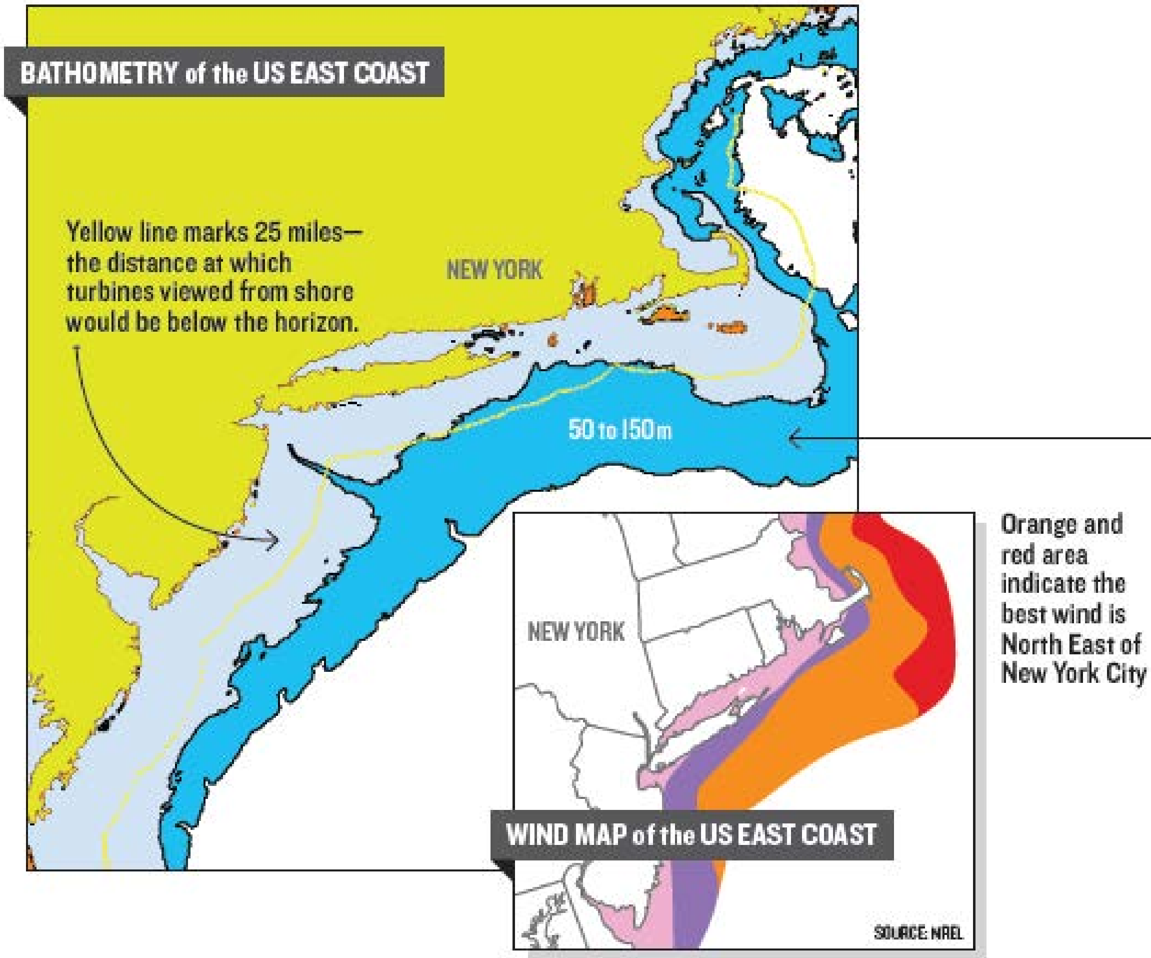
Impact of Project: This turbine can be installed with standard tugs and barges out of sight of land to deliver energy 25% below current costs.

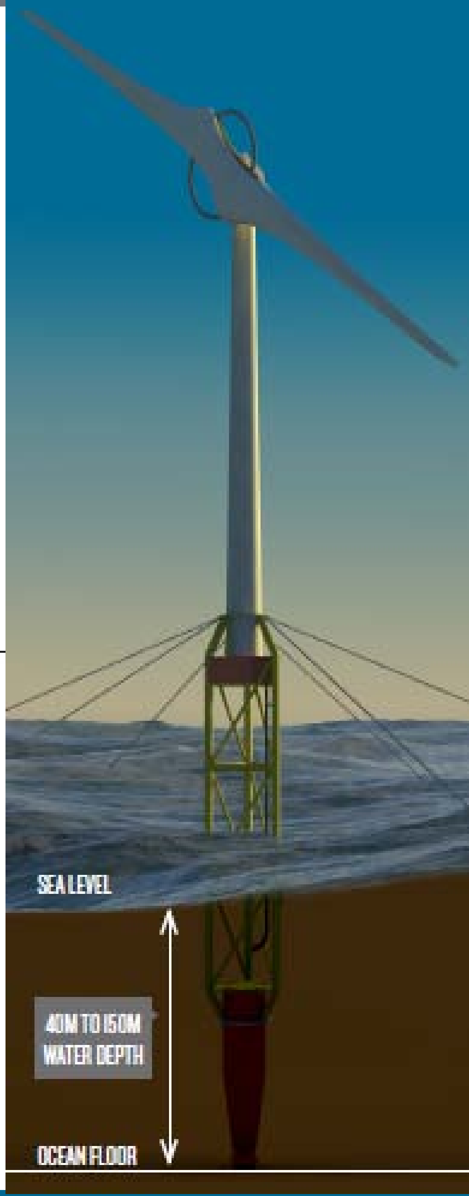
This enables Jones Act compliance, avoids NIMBY and other near shore issues and delivers power at a competitive price opening up the US East Coast to offshore wind power.

This project aligns with the following DOE Program objectives and priorities

- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries

Out of sight but close to load





Technical Approach

Market driven, holistic design included redesigning the drive train, rotor and support structure.

Most floating offshore wind turbine structures are more expensive than fixed foundations and require deep water to operate. There is a market gap in the 40m to 100m range.

The light weight robust generator enabled the light weight rotor. Both enabled the light weight flip up support structure.

The flip up structure and light weight components avoid the need for heavy lift cranes and specialized vessels reducing the cost of installation and maintenance.

The Principal Characteristics

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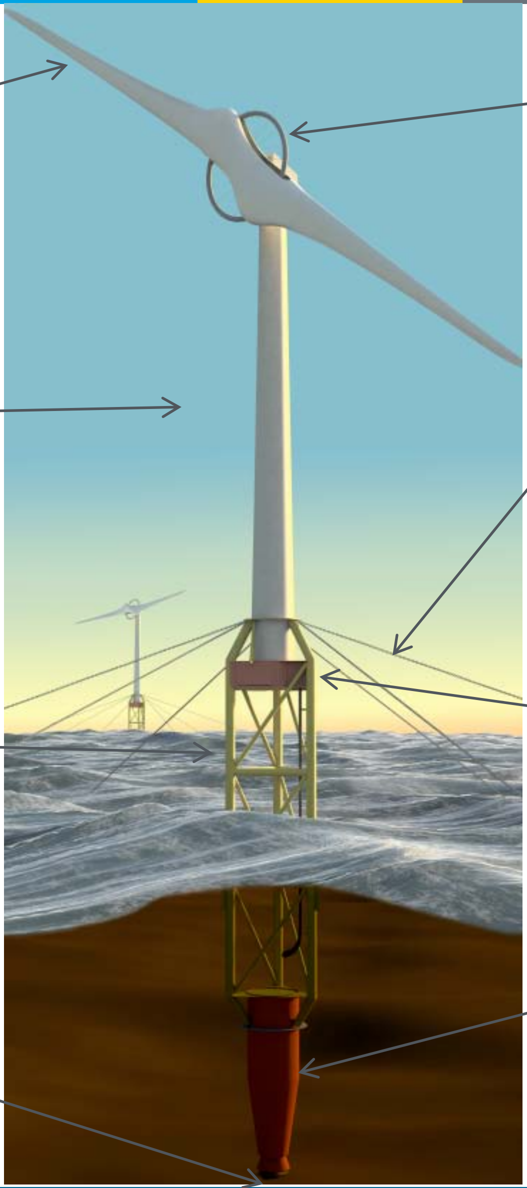


Two bladed partial pitch rotor 30% lower mass than incumbent turbines

Tethered tower structure half to one third the mass of "floating" platforms

Water line structure allows waves to pass through easily

Articulated joint transfers load to tethers and anchors.

Ring generator is 50% the mass of incumbent drive trains

Tethers provide stability

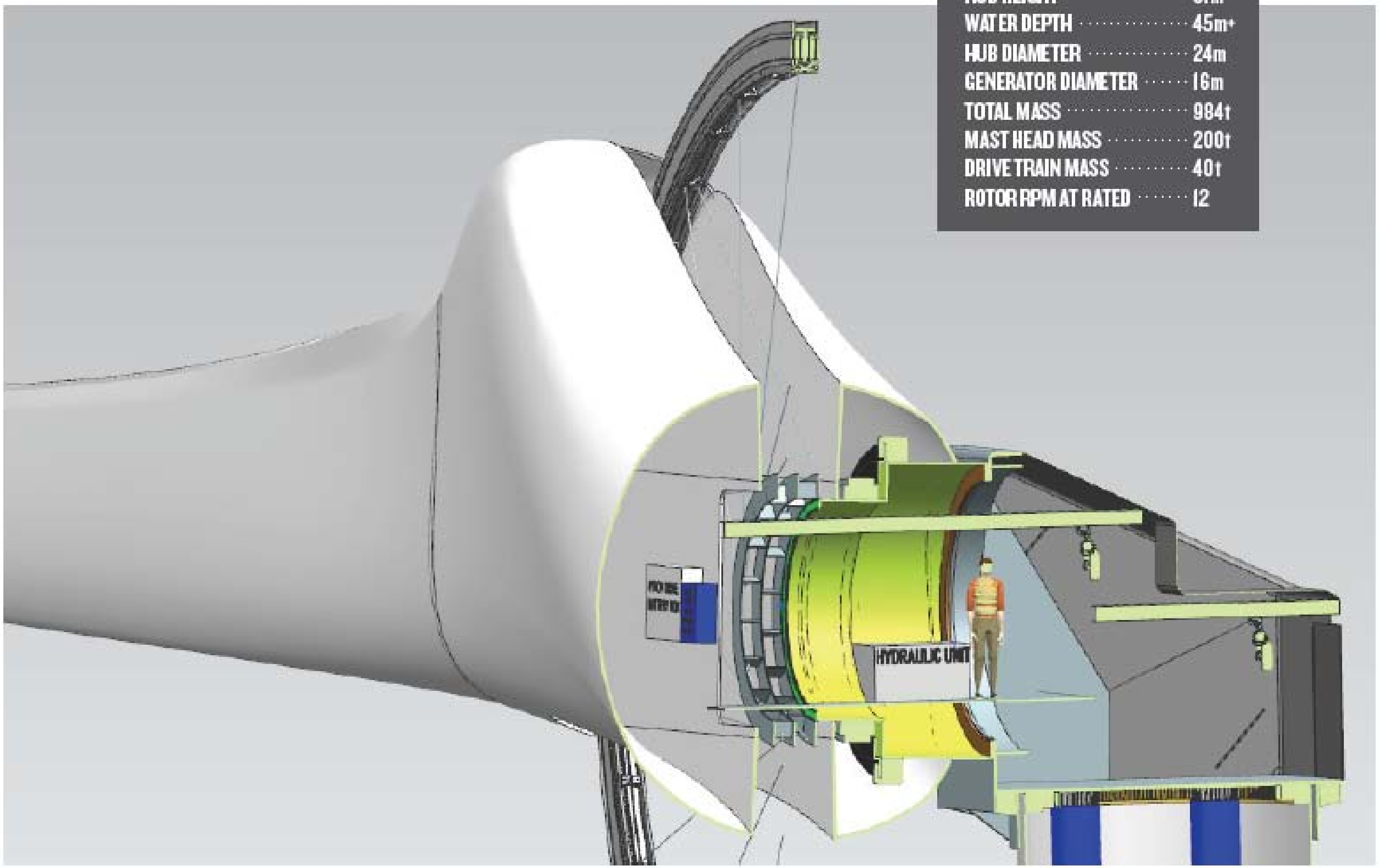
Easy access to power electronics for reduced O&M cost.

Buoyancy reduces load on seabed and articulated joint.

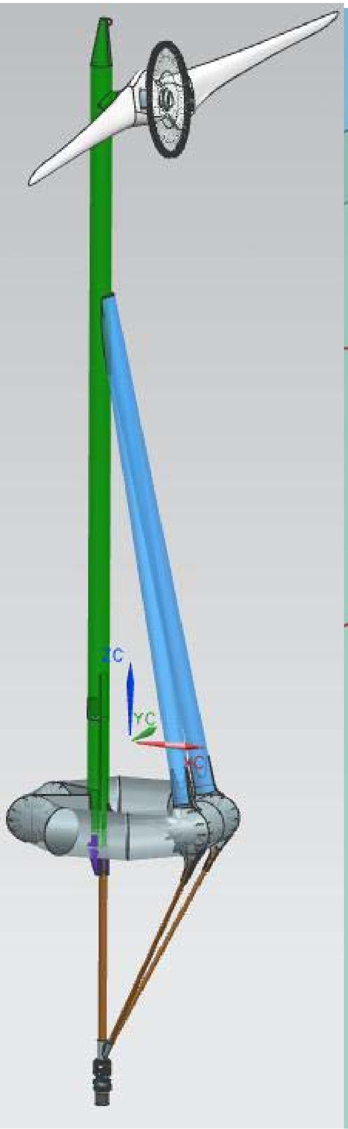
The Flip

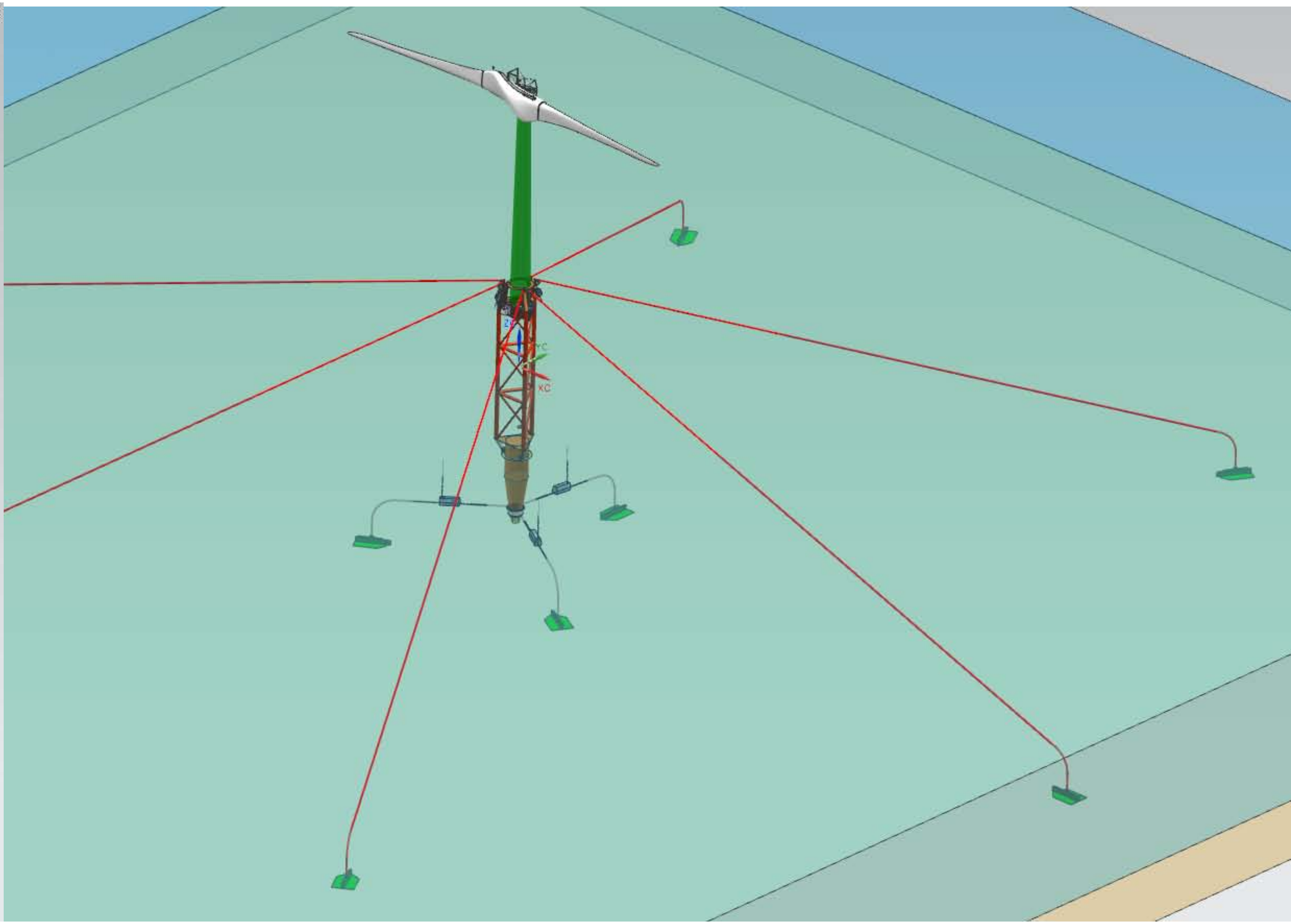
The ‘Nacelle’

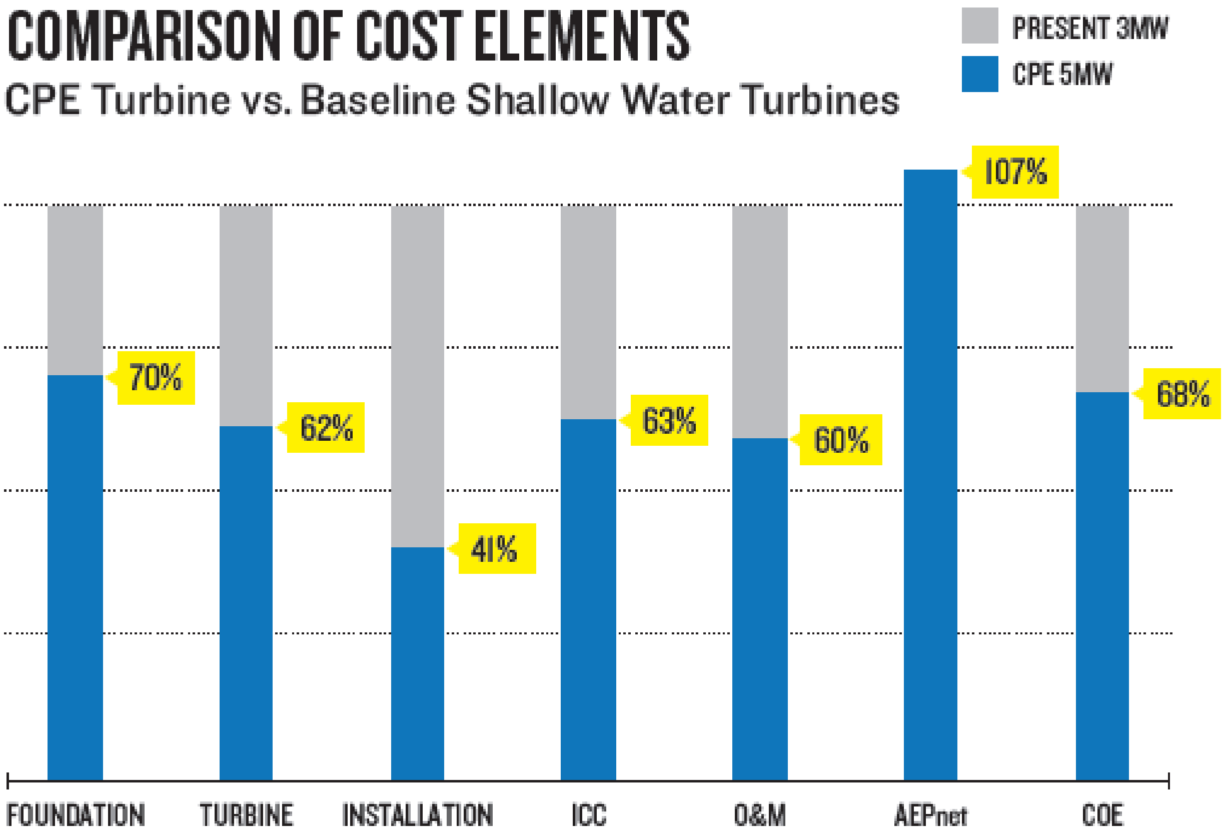
ROTOR DIAMETER	135m
HUB HEIGHT	91m
WATER DEPTH	45m+
HUB DIAMETER	24m
GENERATOR DIAMETER	16m
TOTAL MASS	984t
MAST HEAD MASS	200t
DRIVE TRAIN MASS	40t
ROTOR RPM AT RATED	12



The Pivot







Although installed in deeper water, the foundation is lower cost than shallow water driven pile foundations.

Installation is dramatically lower in cost.

An increase in energy from stronger winds also lowers cost of energy.

Capital Cost Comparison

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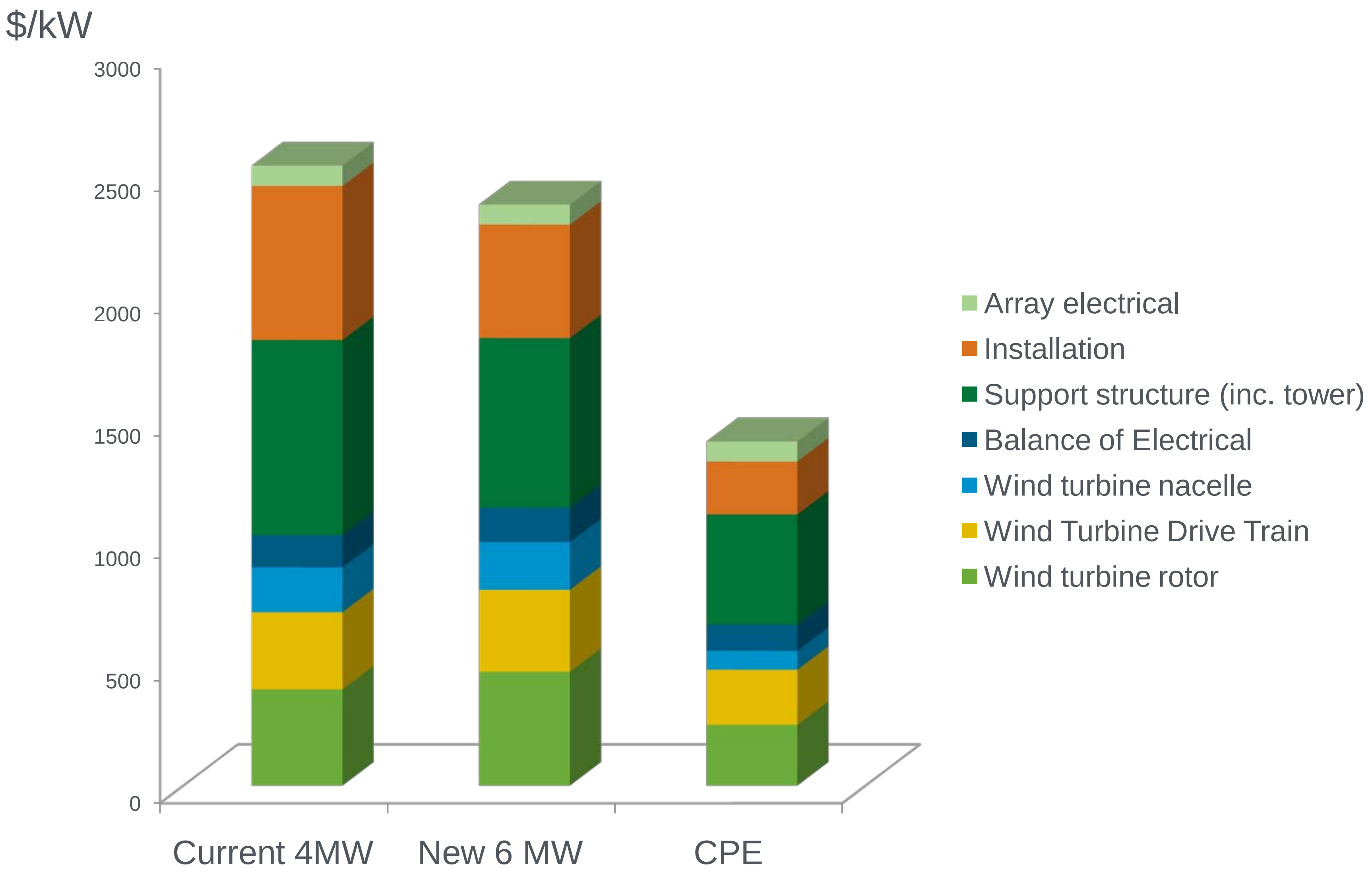

Accomplishments and Progress

The team created an installation technique that does not require the use of large cranes or specialized vessels.

The turbine can be installed in 40 to 150 meters of water.

A support structure was designed for a 5 MW turbine that weighed less than 1000 tons.

A generator was designed for a 5 MW generator that weighed less than 40 tons.

The ideal of the original plan was to have a turbine that could operate in 35 meters or deeper. The depth band is narrower but still meets the target market.

Tethers rather than buoyancy were used as the primary stabilizing mechanism.

Project Plan & Schedule

Comments

- The project was completed ahead of schedule in October 2013
- At the end of 2012, following the DOE review, the design team decided to “pivot” from buoyancy stabilized to tether stabilized.

Project Budget

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Budget History					
FY2012		FY2013		FY2014	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$209,375	$65,313	$290,625	$90,751	0	0

- All of the budget has been expended.
- The project is complete.

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators: DNV-Kema, Advanced Prototype Engineering, Oak Engineering, Erik Nielsen, KLC Electronics, McCleer Power, Chris Tracy, Jeff Minnema Consulting, Henri P. Gavin and Santos Wind Tech.

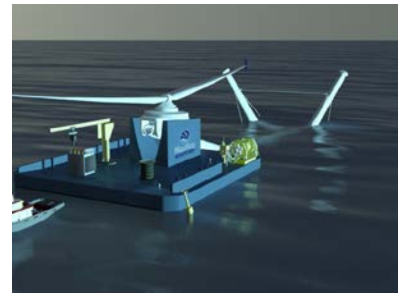
Communications and Technology Transfer: At the EWEA offshore conference Nov 2013 the PI met with major and minor players including OEM's. Positive feedback on the market need and technical aspects of the design.

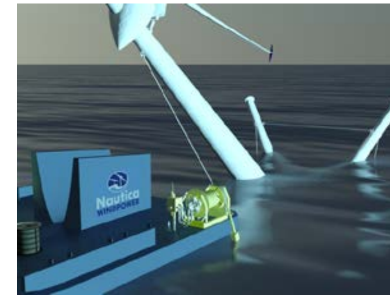
Major Effusive Thanks to: The DOE Michael Hahn, Greg Matzat, Alana Smentek-Duerr and Yelena Onnen for their guidance on monthly calls and everyone else at DOE who created this opportunity for leading edge research.

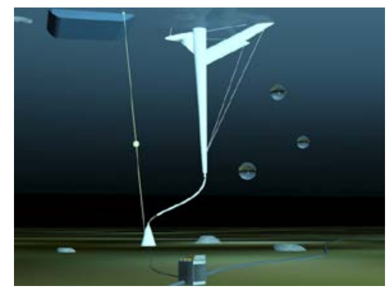
Next Steps and Future Research

FY14/Current research: 2014 is focused on finding a commercial partner to take the design to the next stage.

Proposed future research:
Building a prototype is the next major step.
Minor steps include extensive modeling, detailed design and continued development of manufacturing and installation techniques.







Advanced Floating Turbine

Larry Viterna, Ph.D., P.E.

Nautica Windpower

info@nauticawindpower.com (440) 427-8598

26 March 2014

Budget, Purpose, & Objectives

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

Total DOE Budget [1,2]: $0.000M

Total Cost-Share[1]:$0.238M

Problem Statement: **Commercial success for offshore wind will require significant reductions in cost of energy (COE) as well as the ability to operate in greater water depths, winds & waves.**

Impact of Project: **A next generation of integrated wind plant system, optimized for the offshore environment, could achieve a levelized COE of less than $0.10 per kW-hr and provide access to high quality wind resources at water depths of 35 to 700 m.**

This project aligns with the following DOE Program objectives and priorities

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Mitigate Market Barriers:** Reduce market barriers to preserve or expand access to quality wind resources

[1] *Budget/Cost-Share for Period of Performance FY2012 – FY2013*
[2] *Project remained active using DOE funds received prior to FY2012*

"Digital Prototype" Engineering: Design, Simulate, Visualize & Cost

Concept Design

Model:

- In-house / commercial
- Physics-based, time domain
- Multi-rigid body, elastic mooring
- Free surface, statistical waves

Uses:

- Deployment method/stability
- Extreme wind & wave motion

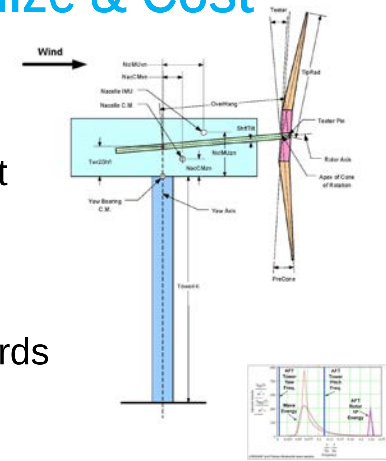
Loads Analysis

Model:

- NREL FAST / Wamit

Uses:

- Design loads
- Control assessment
- International standards



SYSTEM TRADE-OFF & DESIGN CYCLE

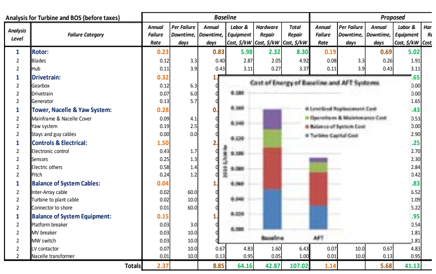
Cost of Energy

Model:

- NREL & In-house

Uses:

- Levelized COE
- Capital costs
- O&M costs
- Replacement Costs
- Availability



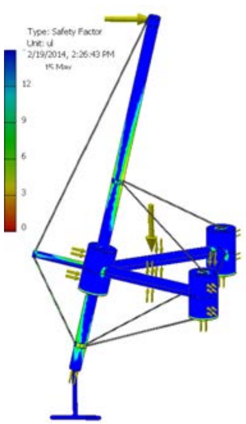
Detail Design

Model:

- Commercial CAD
- 3D solid / FEA models

Uses:

- Natural frequencies
- Stress analysis



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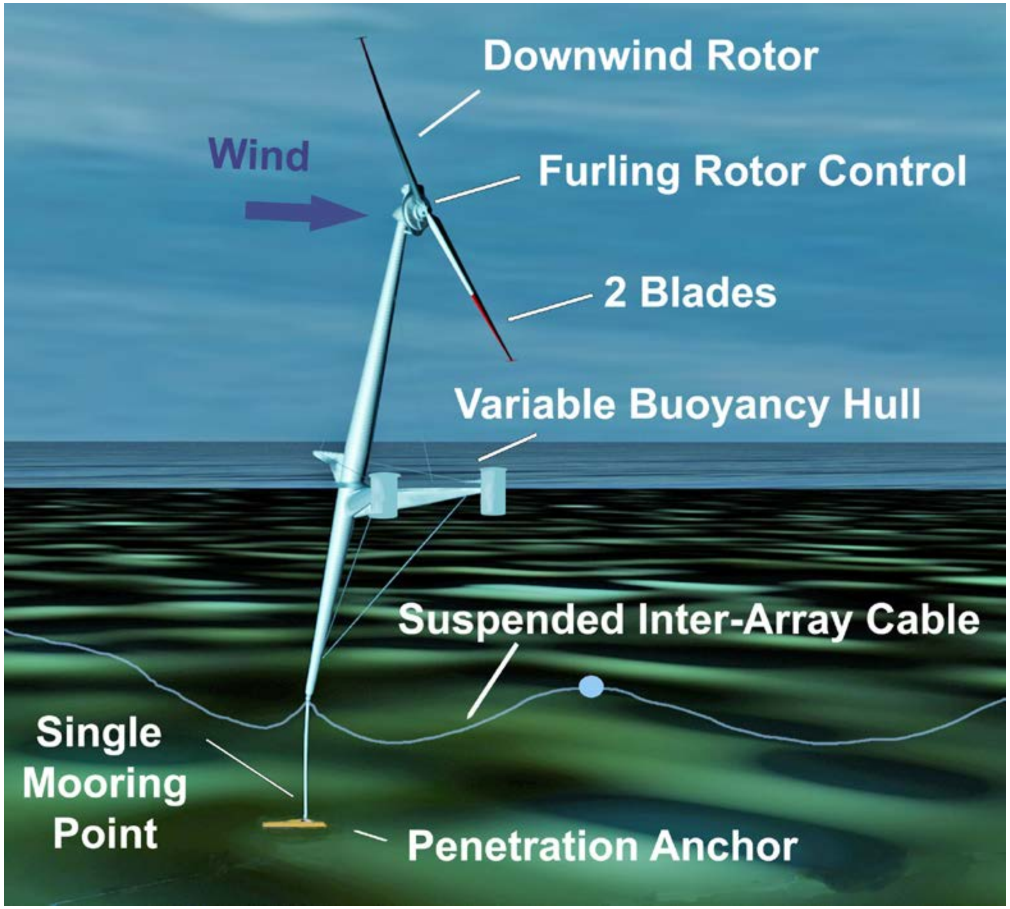
AFT Design Innovations / Cost Benefits



Downwind Rotor
- Aligns Without Yaw Drive System
- Reduces Tower Mass (external guys)
- Enables Lower Cost Flexible Blades

Furling Rotor Control
- Eliminates Multiple Actuators
- Increases Survivability in Hurricane

2 Blades
- Eliminates a Blade & Reduces O&M
- Reduces Transport/Deploy Limitations
- Reduces Drivetrain Costs (>RPM)

Variable Buoyancy Hull
- Horizontal Assembly & Float to Site
- Raises & Lowers Without Cranes at Sea

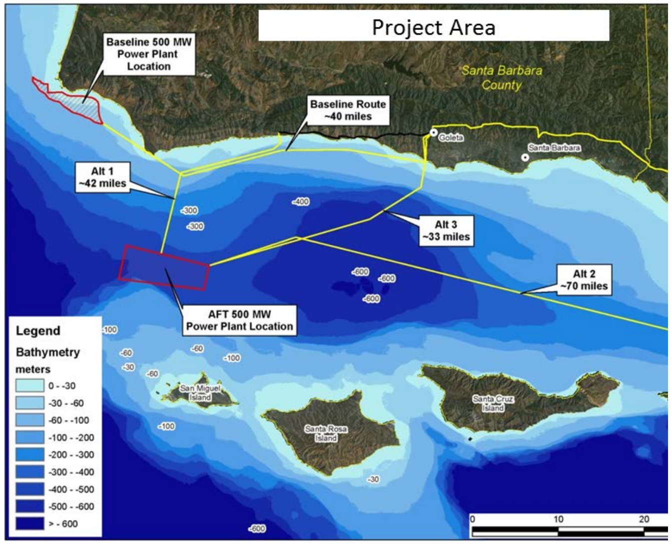
Suspended Inter-Array Cable
- Eliminates Burial
- Reduces Cable Lengths

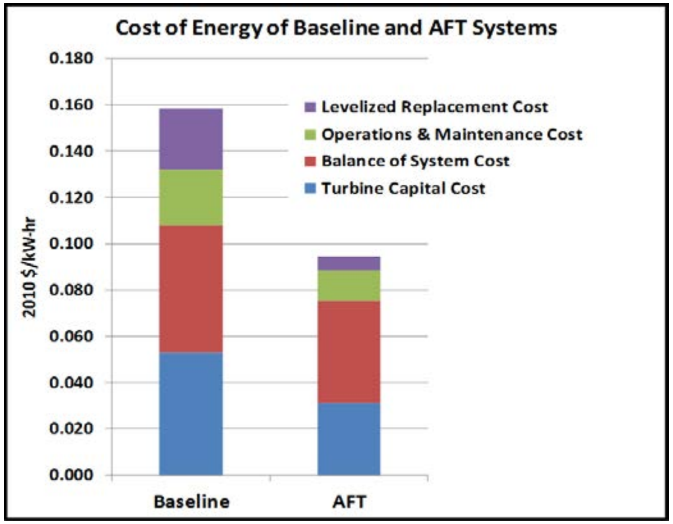
Single Mooring Point
- Simplifies Installation & Removal
- Minimizes Cables & Seafloor Impact

Penetration Anchor
- Simplifies installation
- Minimal materials / End-of-life Removal

DOE support for this project enabled:

- Siting study for U.S. west coast (wind resource, offshore geology, extreme wind & wave, navigation, etc.)
- Selected Reference & AFT sites west of Santa Barbara, CA (50 m & 500 m water depths)
- Digital prototype simulations of 126 m diameter AFT operating & under extreme wind / wave (video: http://www.nauticawindpower.com/achievements/)
- Projected AFT cost of energy of $0.095 / kW-hr
- Additional modeling that extended the AFT applicability to water depths as shallow as 35 m
- New technology disclosure / patent application for furl control innovation





Project Plan & Schedule

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

Summary	
WBS Number or Agreement Number	DE-EE0005487
Project Number	
Agreement Number	DE-EE0005487

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

Task / Event	FY2012 Q1 (Octt-Dec)	FY2012 Q2 (Jan-Mar)	FY2012 Q3 (Apr-Jun)	FY2012 Q4 (Jul-Sep)	FY2013 Q1 (Octt-Dec)	FY2013 Q2 (Jan-Mar)	FY2013 Q3 (Apr-Jun)	FY2013 Q4 (Jul-Sep)	FY2014 Q1 (Octt-Dec)	FY2014 Q2 (Jan-Mar)	FY2014 Q3 (Apr-Jun)	FY2014 Q4 (Jul-Sep)
Project Name: Advanced Floating Turbine												
Q1 Milestone: Definition of Baseline (reference) turbine and power plant												
Q2 Milestone: Selection of Baseline and Proposed AFT site in California												
Q3 Milestone: Acquire and develop hydrodynamic model												
Q4 Milestone: Developed AFT digital prototype & verified furl control												
Q1 Milestone: Completed site report (environmental, geotechnical etc.)												
Q2 Milestone: Optimization of AFT floating platform geometry												
Q3 Milestone: Completed Balance of Plant Concept Design Report												
Concept Design Review with DOE												

Comments

- Project original initiation date: 9/30/2011 Project planned completion date: 9/29/2014
- Two unexpected bugs found in commercial rigid body dynamics software required work around as well as redesign of AFT and delay of initial digital prototype
- Concept Design Review delayed 6 weeks due to personnel schedule conflicts

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

Nautica Windpower — Prime contractor, Principal Investigator, Turbine / Floating Platform Trade-offs & Design

Ocean and Coastal Consultants | COWI — Subcontractor, Balance of System Trade-offs & Design

The University of Toledo — Collaborator, 2 Blade Turbine Modeling

The Maritime Alliance — Collaborator, California Siting & Industry Support

Communications and Technology Transfer

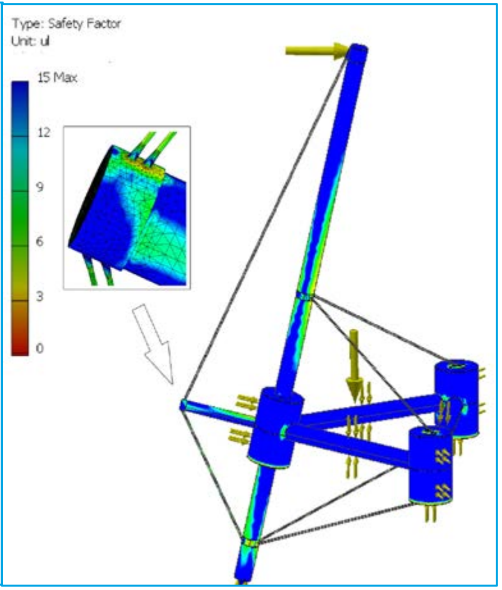
Conference/Workshop/Forum Presentations	Date
NREL/DOE Modeling Workshop, Virginia Beach, VA	Oct 2012
DOE Manufacturing Workshop, Toledo, OH	June 2013
Great Lakes Wind Collaborative Annual Meeting, Columbus, OH	Sept 2013
AWEA Offshore Wind Conference, Providence, RI	Oct 2013

Next Steps and Future Research

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

FY14/Current research:

- Detailed design / stress analysis of AFT innovative structure - verifying weight, strength & reliability of innovative structure (similar to large cable-stayed bridges)
- Design of furl control system for shutdown case
- Update cost of energy & prepare final report



Proposed future research:

The AFT's significant innovations have the potential to reduce the levelized cost of energy for offshore wind energy to less than $0.10/kW-hr in water depths of 35 – 700 m. A scaled physical prototype is now required to validate this innovative system and reduce perceived risks for the industry prior to commercial development.

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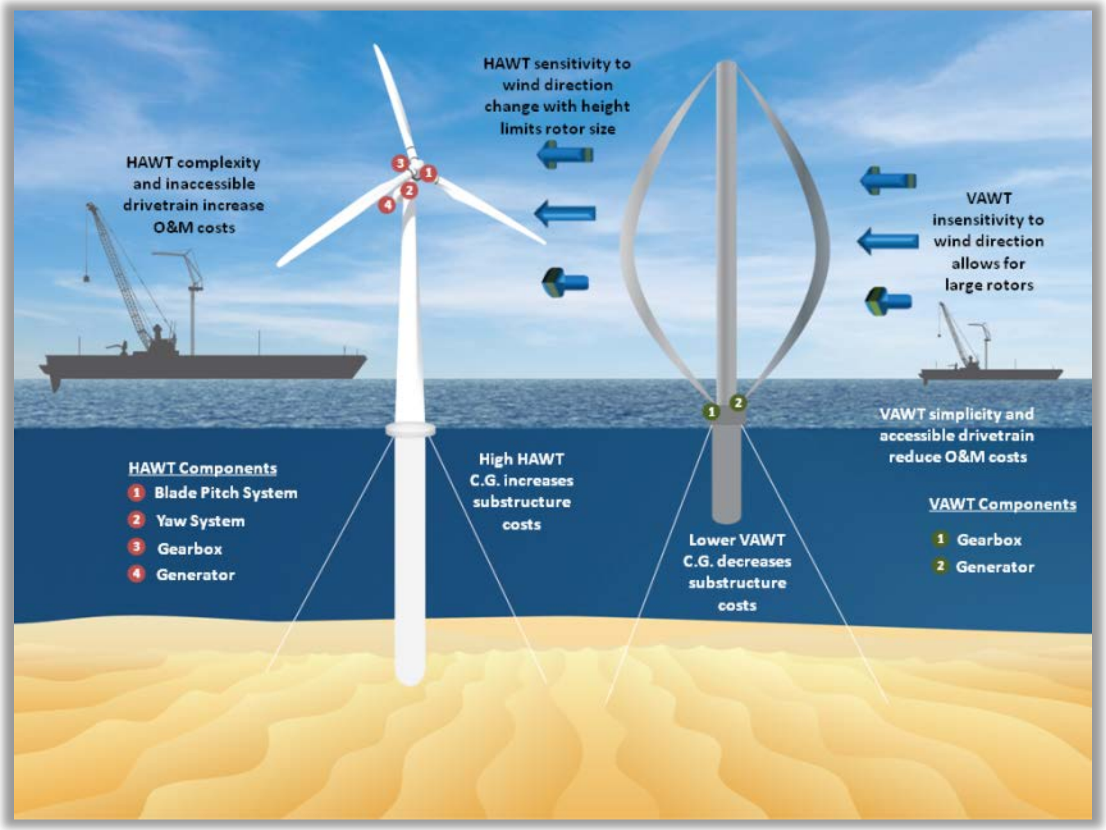

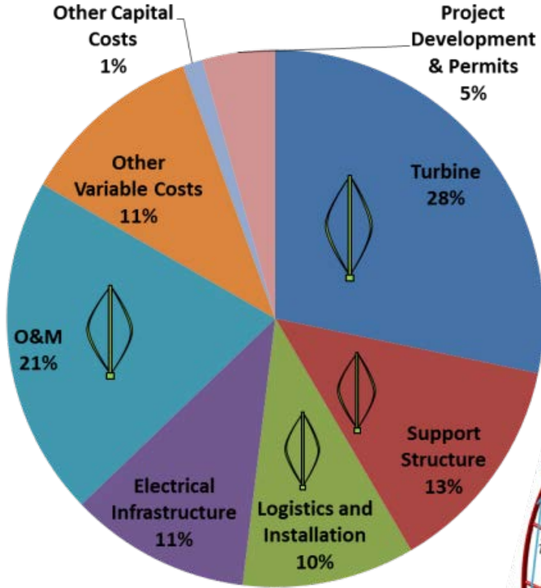

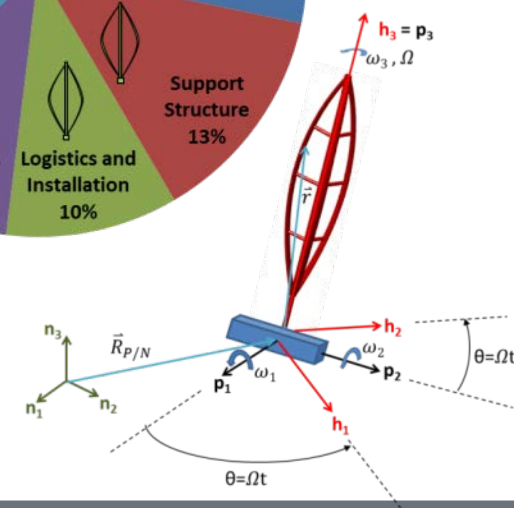

OSWind FOA #2 Offshore Technology Development

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Joshua.Paquette@sandia.gov
Daniel.Griffith@sandia.gov
March 26th, 2014

Budget, Purpose, & Objectives

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

Total DOE Budget[1]: $1.550M

Total Cost-Share[1]:$0.170M

Problem Statement:

Offshore wind deployment in the U.S. is hampered by high cost of energy and incremental improvements to an already mature technology will likely be insufficient.

Impact of Project:

Vertical-axis wind turbines have the potential to produce significant cost reductions for offshore wind applications.

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Testing Infrastructure:** Enhance and sustain the world-class wind testing facilities at Universities and national laboratories to support mission-critical activities
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

[1]***Budget/Cost-Share for Period of Performance FY2012 – FY2013***

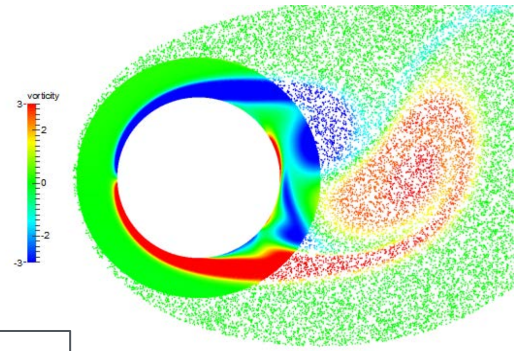
Technical Approach

- FOA project divided into two phases
- Phase I
  - Develop and validate necessary structural, aerodynamic, and platform design and analysis codes
  - Analyze design configurations to determine optimal concepts
  - Determine effect of rotor on platform design
  - Determine materials and manufacturing hurdles
- Phase II
  - Wind tunnel testing of innovative rotor concept prototypes
  - Design-build-test of critical manufacturing details
  - Detailed paper design of large floating VAWT
  - Wind/wave tank testing of floating VAWT prototype

Accomplishments, and Progress Airfoils and Aerodynamic Modeling

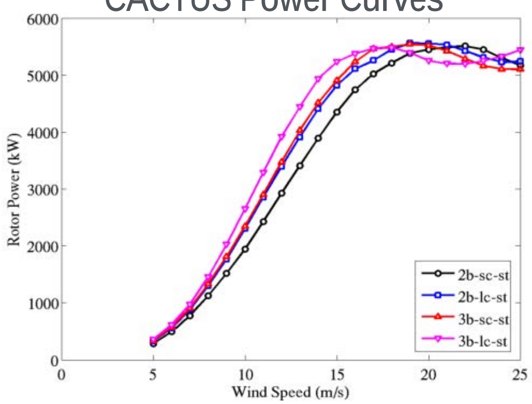
- **Partnership with TU-Delft**
  - Hybrid CFD code for VAWTs developed and verified
  - TU-Delft developed new thick VAWT-specific airfoils
- **Aerodynamic Design**
  - SNL CACTUS code applied to predict power and rotor loads for preliminary rotor designs

Hybrid Code Simulation

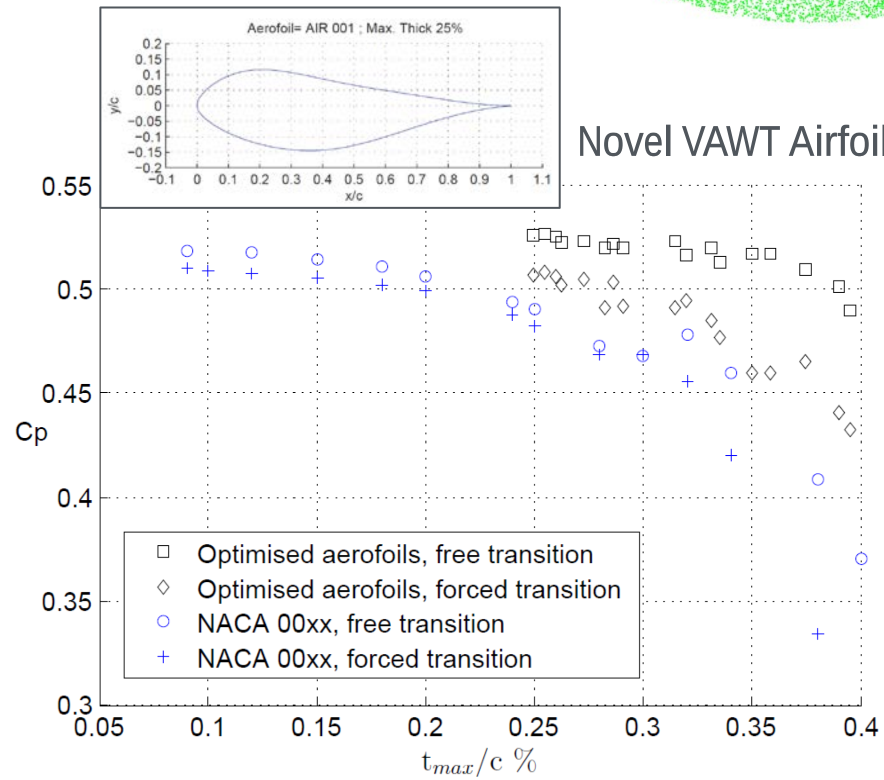


TU Delft
Delft University of Technology

CACTUS Power Curves



Novel VAWT Airfoils



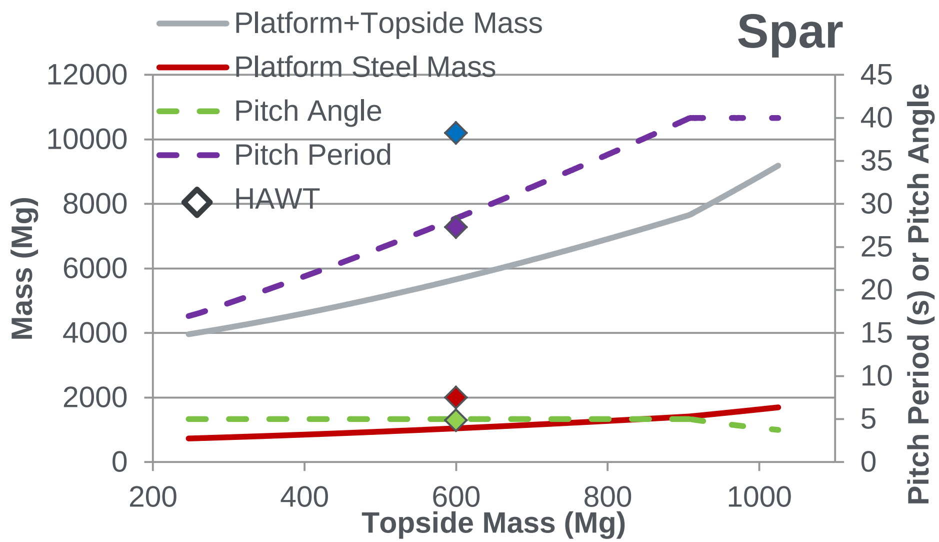
Accomplishments and Progress Platform Design and Analysis

- Platforms: Spar and Semi-Sub
  - Found that platform size/cost is highly dependent upon *topside mass* & *COG*, with MOI's, center of pressure, and aerodynamic load also a factor
- Anchor & Mooring: 3-line spread
  - Performed high fidelity (OrcaFlex) and low fidelity (static offset + WAMIT) analysis
- WavEC2Wire: Hydrodynamics
  - Upgraded Lisbon code for platforms and *exhibited floating platform dynamics coupling with OWENS*
- Capital Costs: BoS
  - Determined *cost as a function of topside mass*

BoS cost ($1000) comparison between a 5MW HAWT and a 5MW VAWT each with a topside mass of 600tons.

	Spar		Semi-Sub	
	HAWT	VAWT	HAWT	VAWT
Platform	12,500	6,531	19,430	11,444
Mooring	483	1,184	575	1,766
Installation	2,328	3,002	635	610
Total	15,311	10,718	20,640	13,819

BoS costs for VAWT < HAWT !!



A 5MW VAWT could be considerably lighter !!

Accomplishments and Progress Rotor Design and Analysis

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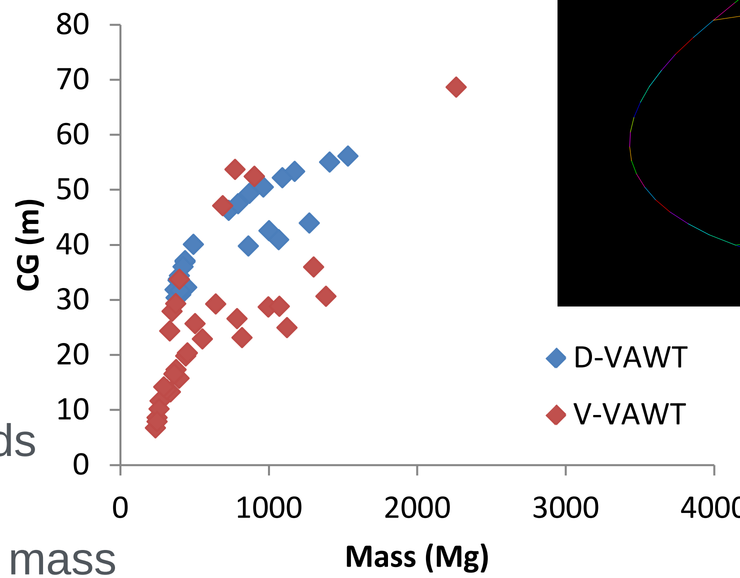
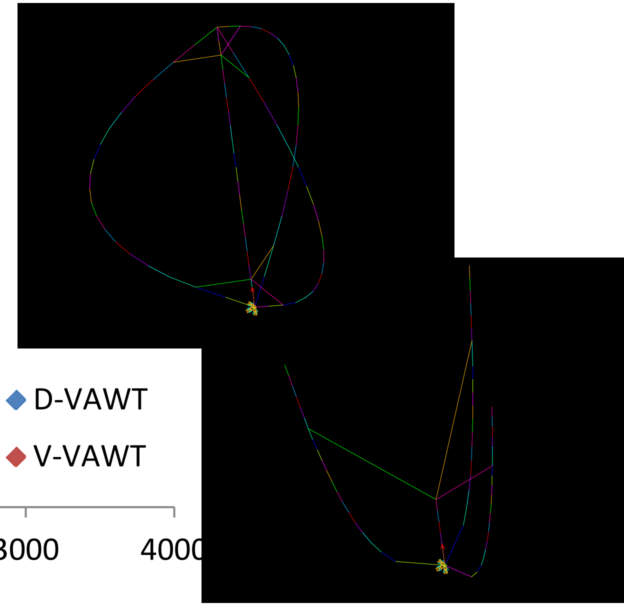
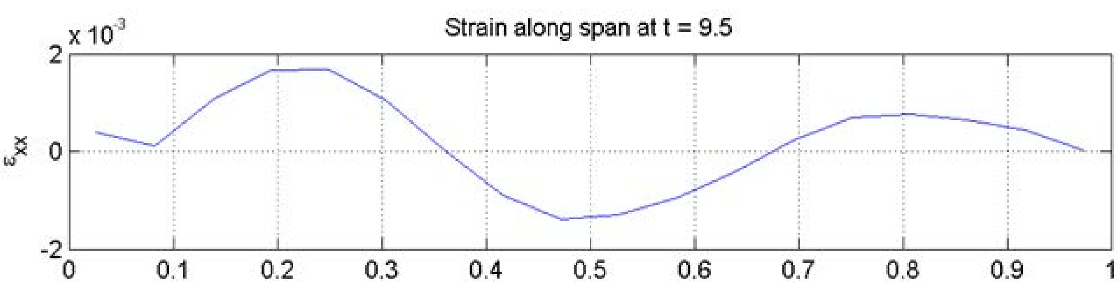
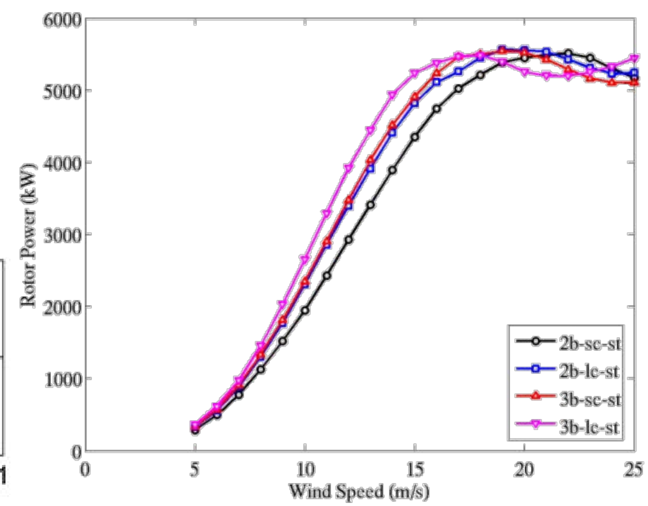
- Analyzed over 50 5MW Darrieus and V-shaped VAWT configurations
- Used ANSYS, OWENS, CACTUS
- Designs evaluated by
  - Operational Structural Dynamics
  - Parked & Operating Loads
- Results:
  - V-VAWTs have desirable mass properties but are difficult dynamics
  - Use of thick airfoils and carbon seems very likely









Project Plan & Schedule

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Summary	
WBS Number or Agreement Number	2.5.0.9
Project Number	
Agreement Number	22662

Legend
Work completed
Active Task
Milestones & Deliverables (Original Plan)
Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: OSWind FOA #2 Offshore Technology Development												
Q1 Milestone: Develop a VAWT performance design tool.												
Q2 Milestone: Identify two to three candidate VAWT rotor designs												
Q3 Milestone: Define the design space andparameters for design studies												
Q4 Milestone: Develop a cost-of-energy model for offshore VAWTs.												
Q1 Milestone: Validation of aero-elastic design code for offshore VAWTs												
Q2 Milestone: Definition of 5 MW baseline VAWT models												
Q3 Milestone: Preliminary materials and manufacturing concepts												
Q4 Milestone: Rotor design report												
Current work and future research												
Q1 Milestone: Report on platform comparison study												
Q2 Milestone: Report on validated VAWT aero-elastic design tool												
Q3 Milestone: Report on materials and manufacturing issues												
Q4 Milestone: Test plan model for VAWT wind tunnel test												

Comments

- Project started in mid 2012
- Currently finishing with Phase I work
- Design report delayed due to problems with some configurations
- Awaiting approval of Phase II work

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators:

tpi | THE UNIVERSITY OF MAINE 1865 | A|M | STATE | TU Delft

Communications and Technology Transfer:

Publications

- "An Energy Preserving Time Integration Method for Gyric Systems: Development of the Offshore Wind Energy Simulation Toolkit," EWEA 2013.
- "Aeroelastic Modeling of Large Offshore Vertical-axis Wind Turbines: Development of the Offshore Wind Energy Simulation Toolkit," AIAA SDM 2013
- "Modal Dynamics and Stability of Large Multi-megawatt Deepwater Offshore Vertical-axis Wind Turbines: Initial Support Structure and Rotor Design Impact Studies," AIAA SciTech 2014
- "Theoretical Developments and Practical Aspects of Dynamic Systems in Wind Energy Applications". Ph.D. Dissertation (Texas A&M University), 2013.
- "The Design Challenges of Large, Deep-Water, Vertical-Axis Wind Turbine Blades", NAWEA Symposium 2013.
- "Hydrodynamic Module Coupling in the Offshore Wind Energy Simulation (OWENS) Toolkit," OMAE 2014

Patent:

- **"Aeroelastically Coupled Blades for Vertical Axis Wind Turbines", Submitted, Under Review**

Next Steps and Future Research

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FY14/Current research:

- Rotor Design Report
- Economic Analysis Report

Proposed future research:

Phase II effort will include:

- Optimized, detailed design of offshore rotor
- Manufacturing detail demonstration
- Wind tunnel test of airfoils and scaled prototype
- Combined wind/wave tank test of scaled prototype