2014 WIND POWER PROGRAM PEER REVIEW

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

Test Facilities

March 24-27, 2014

Wind Energy Technologies

PR-5000-62152

Contents

Test Facilities

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

Blade Test Facilities

Structural Test Facilities O&M and Massachusetts Large Blade Test Facility

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March 25, 2014

Budget, Purpose, & Objectives

NWTC Test Facility Capabilities

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- **Field**
  - Field test sites and infrastructure
  - DOE 1.5, Industry MW turbines
  - Controls Research Turbines (CART)
  - Research-grade inflow meteorological data
  - Small turbine testing
- **Drivetrain**
  - 225-kW, 2.5-MW, 5.8-MW dynamometers
  - Dynamic torque testing of fully integrated drivetrain systems or components (gearboxes, generators, PE)
  - HALT, condition monitoring
  - Model-in-the-loop, i.e., to simulate turbulence
  - Non-torque loading (NTL) to impart rotor loads
- **6.3-MW Controllable Grid Interface**

- **Structural**
  - Test stands, hydraulic actuators
  - Accredited (A2LA) fatigue (resonant) and static testing of blades (up to 50 m in length) to IEC standards
  - Modal and property measurements, profiling, NDT methods
  - Innovative test methodology R&D
  - Massachusetts large-blade test facility partnership
- **ISO 17025, A2LA accredited to IEC Standards**
  - Power performance, power quality, acoustic emissions, structural loads, duration, Safety and Function
- **Custom**
  - Testing to meet R&D needs (e.g., data for model validation, proof-of-concept)
  - Explore applicability of advanced sensors, DAS

Budget, Purpose, & Objectives

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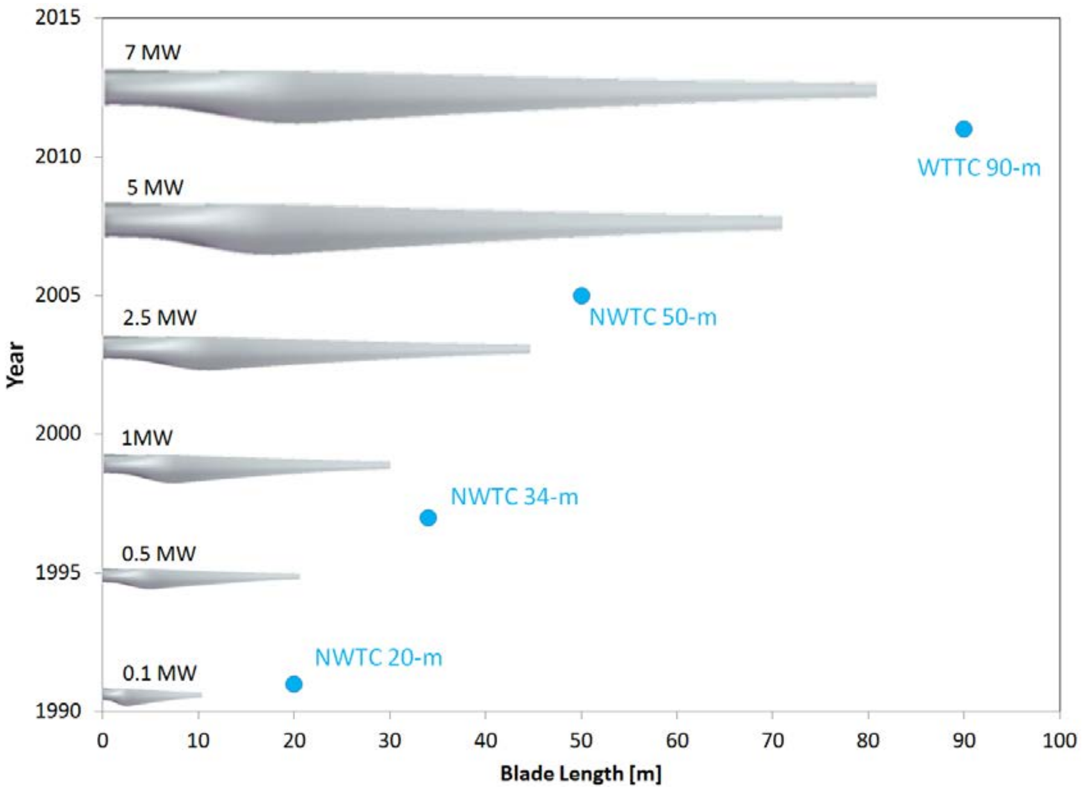
Problem Statement:

- Blade reliability continues to be a significant source of O&M costs
- Current test practices not representative of in-field loading
- Large gap in fidelity between coupon tests and full-scale testing
- Protracted time necessary to perform full-scale tests of large wind turbine blades
- Lack of U.S. capability to test large blades under more characteristic biaxial conditions
- Lack of sensing techniques needed to characterize and translate damage and structural performance from laboratory test articles to a blade fleet



Budget, Purpose, & Objectives

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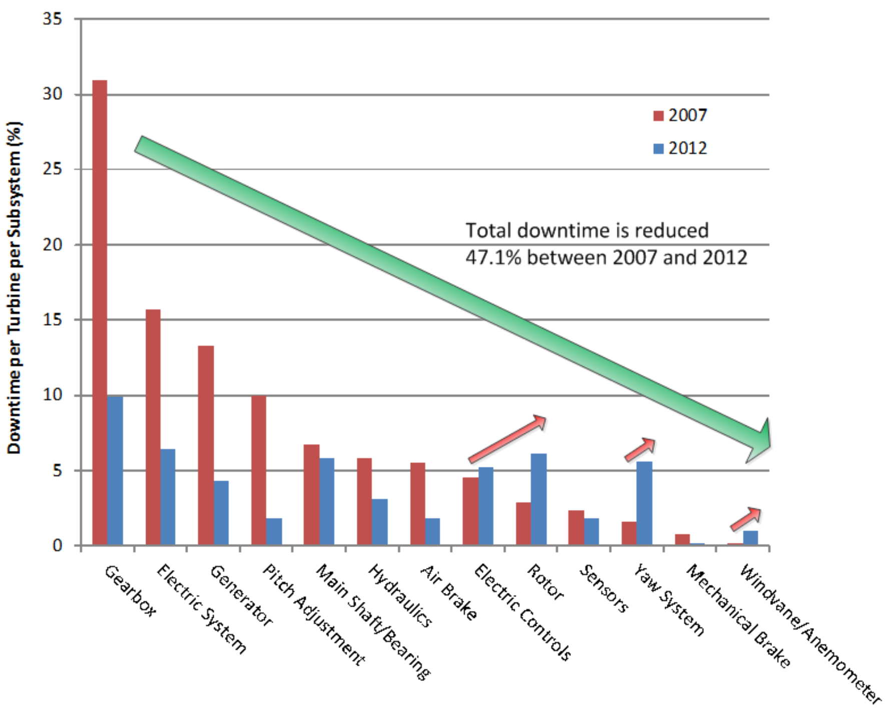
Impact of Project:

- Improved test capabilities will enable gains in blade reliability
- Reduce technical and financial risks of large-scale deployment
- Mission-ready facilities and expert staff for support research, development, and certification testing for industry and academia
- Reduce the time and cost of full-scale testing
- Improves value of laboratory tests to field results
- Informs development of international standards



Budget, Purpose, & Objectives

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Total DOE Budget[1]: $4.205M

Total Cost-Share[1]:$0.200M

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
- **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

Facilities O&M

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Buildings 251 and A-60

- 19-m blade test capability
- 1.35 MN-m root moment capacity
- 500-kN load frame

Structural Testing Lab

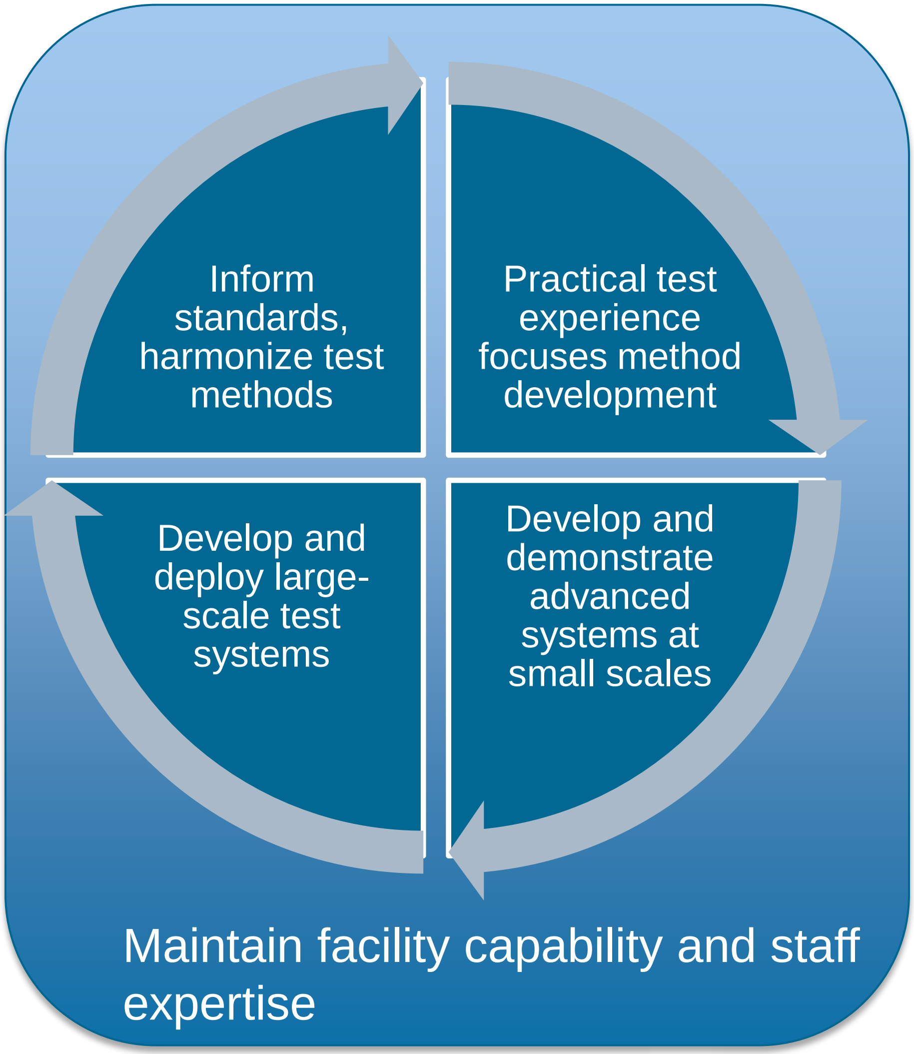
- 50-m blade test capability
- 16 MN-m root moment capacity
- Two test stands, outdoor static testing

- Support testing operations at WTTC with two full-time staff
- Support WTTC with “surge” support from NWTC staff
- Maintain facility safety and operations and staff competency
- Continuous improvements in quality management systems
- Maintain laboratory accreditation to IEC 61400-23 and NREL QA
- Participation in inter-laboratory comparison projects
- Improvements to blade test specific data acquisition capabilities

Technical Approach

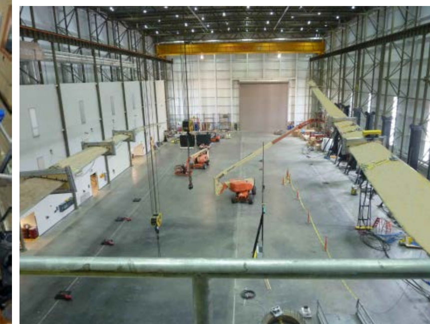
Test Method Development and Deployment

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



Technical Approach

History



Year	1990	1995	2000	2005	2010	2015

Challenges / Innovations → Development of normative methods → Precision control → Dual axis testing → Resonant testing → Advanced blades → Sensing → Resonant Dual Axis Testing

Goal: Improve fidelity, lower cost, and reduce the time necessary to perform full-scale testing

Accomplishments and Progress

WTTC Support

- Procured and commissioned DOE-provided test equipment to WTTC
- Transferred operating and certification test procedures to WTTC
- Trained MassCEC staff
- Guided development of data post-processing tools
- Developed report templates
- Supported commissioning of certification testing at the WTTC
- Assisted WTTC in achieving laboratory accreditation
- Lead technical role in execution of blade test programs
- Deployed new release of data acquisition system software
- Collaboration with WTTC and MTS to develop and deploy GREX (Ground-based Excitation) system

Accomplishments and Progress

Test Facility O&M

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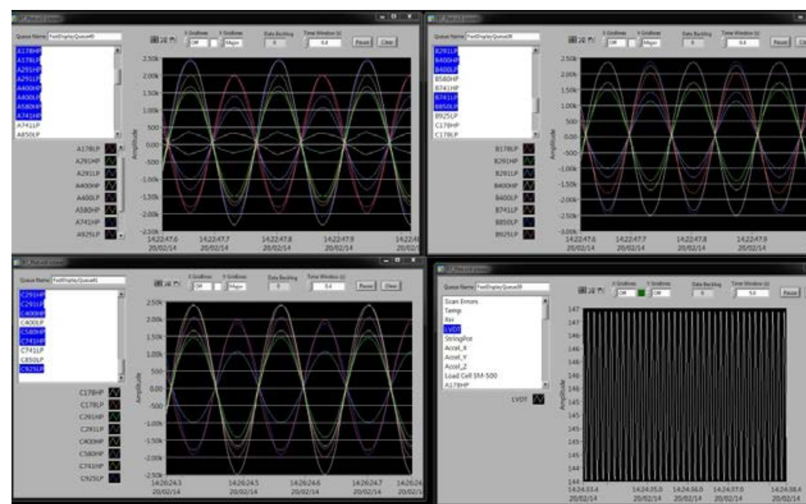
- Maintained mission-ready test capabilities, supporting testing of 33 blades
- Maintained safe operations
- Developed and demonstrated a highly scalable data acquisition system
- Coordinated and managed an inter-laboratory comparison of modal test methods with 11 international laboratories
- Completed a draft blade test measurement uncertainty guideline



Accomplishments and Progress

Innovative Test Methods

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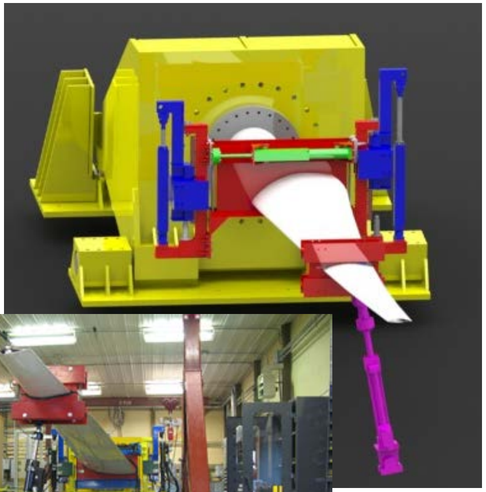
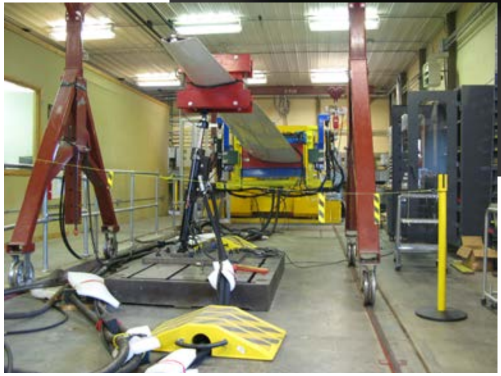
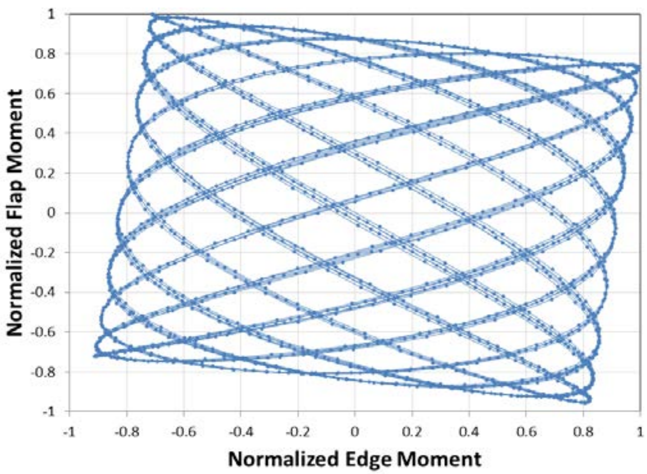
- Completed demonstration testing of multi-station UREX (Universal Resonant Excitation System) on a 50-m blade
- Completed demonstration testing of the PhLEX (Phased-Locked Excitation) prototype system on a 9-meter blade
- Completed demonstration testing of the quantum biaxial test method on a 50-m blade
- Co-authored a statement of work for IEA Task 35, Ground Testing of Wind Turbines and Their Components







Project Plan & Schedule

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Summary	
WBS Number or Agreement Number	1.1.2, 1.1.5, 1.1.7, 1.1.8
Project Number	21110
Agreement Number	22498

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

Task / Event	FY2012 Q1	FY2012 Q2	FY2012 Q3	FY2012 Q4	FY2013 Q1	FY2013 Q2	FY2013 Q3	FY2013 Q4	FY2014 Q1	FY2014 Q2	FY2014 Q3	FY2014 Q4
Project Name: Blade test facilities												
D&D, O&M - Release version 1.0 of DAQ software to WTTC and NWTC												
MA - Complete integration of DOE supplied capital test data acquisition												
D&D, O&M - Complete test plan for Phase-locked Excitation (PhLEX) scale test												
MA - Integration and validation of DOE - supplied static load system at WTTC												
D&D, O&M - Conduct readiness verification of PhLEX scale test												
MA - Complete transition and NREL audit of safety and operating protocols to WTTC												
D&D, O&M - Complete Base Excitation Test System reporting												
MA - Complete qualified engineer training of MA-NREL staff to NREL QA system												
MA E&A - Complete UREX training of WTTC staff												
O&M - Complete barcode equipment tracking of structural test equipment												
D&D - Complete PhLEX summary technical report												
MA E&A - Complete modal and data acquisition system training of WTTC personnel												
O&M - Complete test plan for Inter-Laboratory Comparison (ILC) modal test survey												
D&D - Complete readiness verification for biaxial quantum test												
MA E&A - Deploy blade testing data analysis tools at WTTC												
O&M - Release version 2.0 of DAQ software												
D&D - Complete hybrid fatigue test system test plan												
MA E&A - Define protocols for laboratories to participate in modal ILC												
O&M - Complete draft of blade testing uncertainty best practice guide												
D&D - Complete IEA Task 35 Statement of Work												
Current work and future research												
O&M - Release NREL produced test assessment report to modal ILC participants												
D&D - Prepare technical publication of biaxial quantum fatigue test												
MA - Complete GREX system training of WTTC staff												
D&D - Host a kick-off web conference for IEA Task 35												
MA - Develop a test plan for conducting a static blade test ILC program												
O&M, MA - Release version 3.0 of DAQ software at WTTC												
D&D - Complete readiness verification of the biaxial hybrid 9-m scale test												
O&M, MA - Final uncertainty guide, release analysis tool to WTTC staff												
D&D - Complete summary report of biaxial hybrid test												

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators:

- In FY12 and FY13, NREL staff led or supported testing of 33 blades
- Blades tested were represented by 12 different manufacturers
- Blade test procedures and practices transferred to WTTC
- Facilities supported SBIR test program for 3Tex, Inc.
- Facilities used for supporting university research, UML, MSU
- Facilities supported research from other national laboratories, SNL and LANL
- Reports for each of these test programs are provided to the test partner
- Demonstration of 3rd party sensing systems (acoustic emission, thermography, DIC, shearography)
- Demonstration of fiber optic strain systems in collaboration with Fraunhofer and Micron
- Participation in the new IEA Wind Task 35: Ground Testing for Wind Turbines and Their Components, includes collaboration with international blade testing organizations, including NaREC (UK), Fraunhofer (Germany), DTU (Denmark), and CENER (Spain).

Communications and Technology Transfer:

- Development and commercialization of the GREX and UREX systems in partnership with WTTC and MTS
- Patents for linear hydraulic test methods, biaxial quantum test methods, and base excitation test systems
- Development and demonstration work for the PhLEX and biaxial quantum test methods have been presented at the Sandia blade reliability workshop
- NREL technical reports for PhLEX and biaxial quantum testing are in progress

Next Steps and Future Research

FY14/Current research:

- Support operations at WTTC
- Support and maintain operations of NWTC facilities
- Demonstration of higher capacity GREX system
- 9-m scale demonstration of biaxial resonant method

Proposed future research:

- Large-blade biaxial resonant fatigue development
- Component and system-level test method development
- Large-scale health monitoring and sensing
- Effect of defect testing
- Improved test methods for small and mid-size turbine blades

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Massachusetts Large Blade Testing Facility

RAHUL YARALA

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March 25th, 2014

Budget, Purpose, & Objectives

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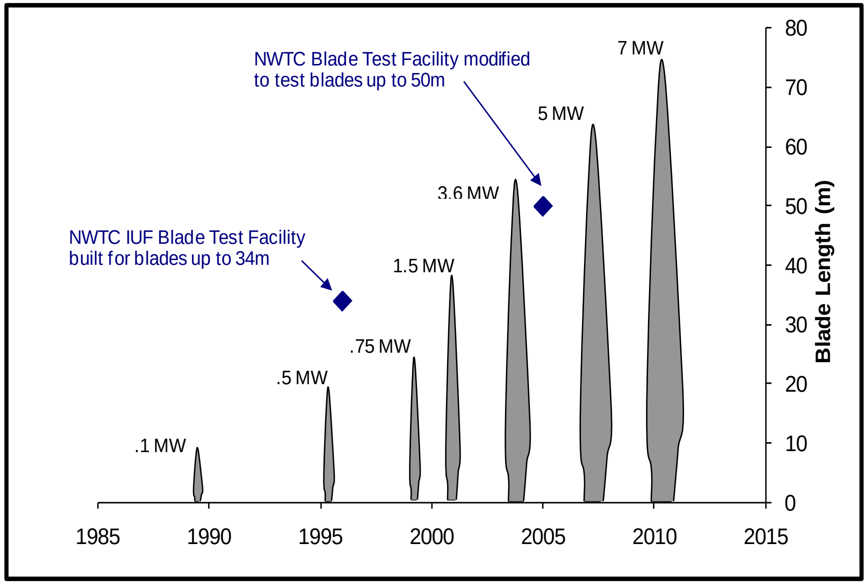
Total DOE Budget [1,2]: $0.000M

Total Cost-Share[1]:$0.000M

Massachusetts Large Blade Testing Facility

90

- Static strength testing and accelerated fatigue testing of wind turbine blades are required for
  - Turbine certification
  - Improve blade reliability. Reduce the risk of widespread failures
  - Reduce COE
- Blades over 50m could not be fatigue tested in the United States before this facility was operational, Blades 62m long are in production and longer blades are being designed/prototyped
- This facility will reduce COE by
  - Improving reliability of wind turbine blades
  - Introducing more efficient blades
  - Reducing technical and financial risk of large-scale deployment
  - Providing industry with cost effective test facilities to comply with certification &support value engineering

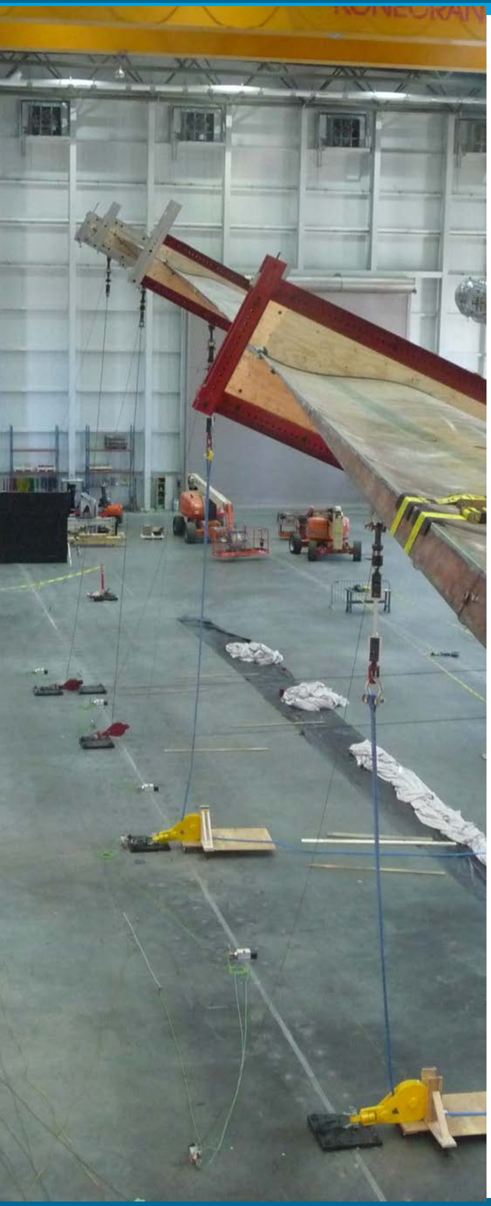


This project aligns with the following DOE Program objectives and priorities

__Reduce unsubsidized turbine LCOE to be cost-competitive with fossil fuels;
__Jumpstart a U.S. offshore wind industry
__Testing, advanced manufacturing, certifications, and standards

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

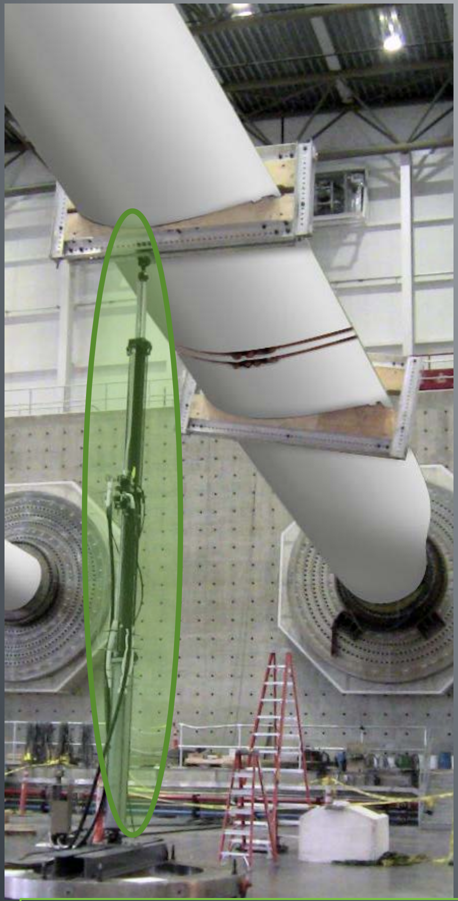
Technical Approach



- Continue to work with industry partners to maintain the latest technology for large blade testing per IEC 61400-23 and additional research testing including efficient ultimate tests to failure.

- Static testing is performed using a Hydraulic winch/actuator system that is flexible and expandable as blades get longer than 70 meters and need more than 8 locations for load application. All the load application points are synchronized to help achieve various bending moment targets and safely perform the static test and ultimate tests to failure

Fatigue Test – New testing techniques



– Fatigue test using our Ground based exciter system (GREX developed in 2013 and implemented at WTTC, for improved and faster fatigue (especially Flap fatigue) testing.

– Fatigue test using UREX developed by NREL (exciter on the blade)

Accomplishments and Progress

- Performed fifteen commercial blade tests since opening in Summer 2011. Static, Fatigue (edge and flap) using resonant exciter system on the blade and the new ground based exciter systems. Fatigue test using eccentric motor system provided by a customer. Natural frequency measurements and full modal analysis partnering with University of Massachusetts Lowell. Four blades were tested to ultimate failure per customer specifications.

- A2LA accredited. Participating in Inter Laboratory collaborations.

- 5 blades in queue to be tested over the next 12-18months

- Testing revenues in first two full fiscal years around 80% of yearly operating expenses. Testing revenues for next fiscal year are forecasted to be around $2.3million with yearly operating expenses forecasted to be around $2.5million

Project Plan & Schedule

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Comments

- MA large blade testing facility was constructed and commissioned on schedule in May 2011.

Next Steps and Future Research

Work with industry partners and other blade testing facilities to continuously improve testing efficiency and methods.

MA large blade testing facility plans to continue blade testing operations to support the wind industry with reduced or no DOE/NREL on-going support starting September 2014.

Three major focus areas for future research are dual-axis testing, non destructive inspection systems and advanced instrumentation (like fiber optic sensor systems, strain mapping- digital image correlation)

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NREL Dynamometer Facilities

5 MW Dynamometer and Dynamometer Facilities O&M

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March 25, 2014

Budget, Purpose, & Objectives

NWTC Test Facility Capabilities

- **Field**
  - Field test sites & infrastructure
  - DOE 1.5, Industry MW turbines
  - Controls Research Turbines (CART)
  - Research-grade inflow meteorological data
  - Small turbine testing
- **Drivetrain**
  - 225kW, 2.5 MW, 5.8MW dynamometers
  - Dynamic torque testing of fully integrated drivetrain systems or components (gearboxes, generators, PE)
  - HALT, condition monitoring
  - Model-in-the-loop to i.e. simulate turbulence
  - Non-torque loading (NTL) to impart rotor loads
- **6.3MW Controllable Grid Interface**
- **Structural**
  - Test stands, hydraulic actuators
  - Accredited (A2LA) fatigue (resonant) and static testing of blades (up to 50m in length) to IEC standards
  - Modal and property measurements, profiling, NDT methods
  - Innovative test methodology R&D
  - Massachusetts large blade test facility partnership
- **ISO 17025, A2LA accredited to IEC Standards**
  - Power performance, power quality, acoustic emissions, structural loads, duration, Safety & Function
- **Custom**
  - Testing to meet R&D needs (e.g. data for model validation, proof-of-concept)
  - Explore applicability of advanced sensors, DAS

Budget, Purpose, & Objectives

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Total DOE Budget[1]: $4.350M

Total Cost-Share[1]:$0.000M

Problem Statement: Facilitate a cost-effective means to validate wind turbine drivetrain designs and prove new technologies in a controlled laboratory environment.

Impact of Project: Testing is essential to reduce deployment risk and increase reliability, leading to a lower overall cost of energy. NREL's dynamometer facilities have proven to be a cost-effective means to accomplish this testing.

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

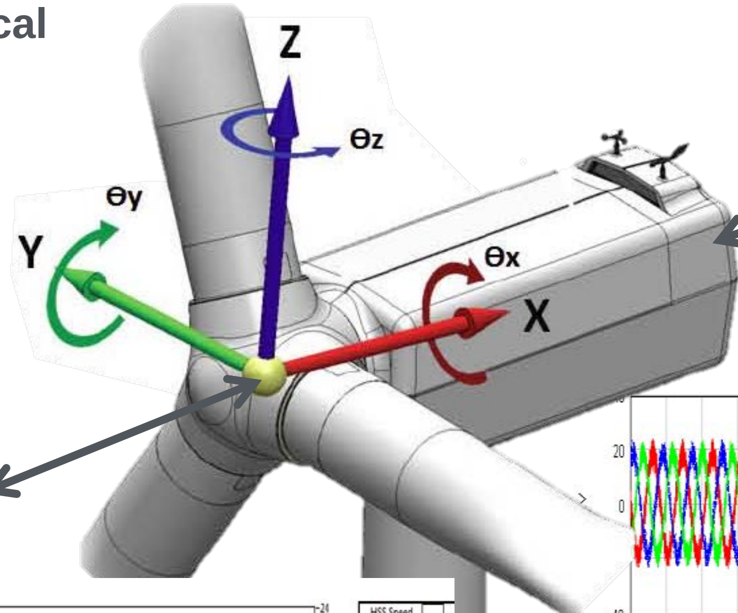
Testing Infrastructure: Enhance and sustain the world-class wind testing facilities at universities and national laboratories to support mission-critical activities.

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

Technical Approach
Testing Concept

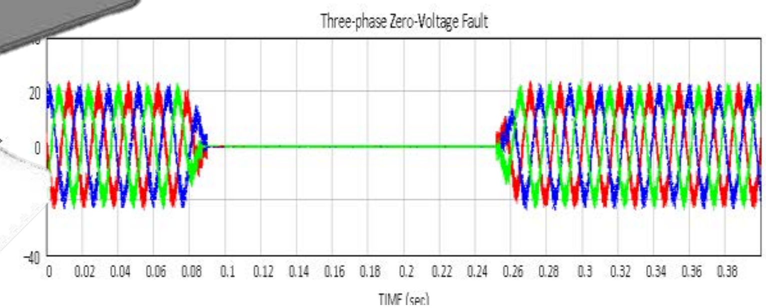
Dynamometer provides control of rotor interface mechanical parameters

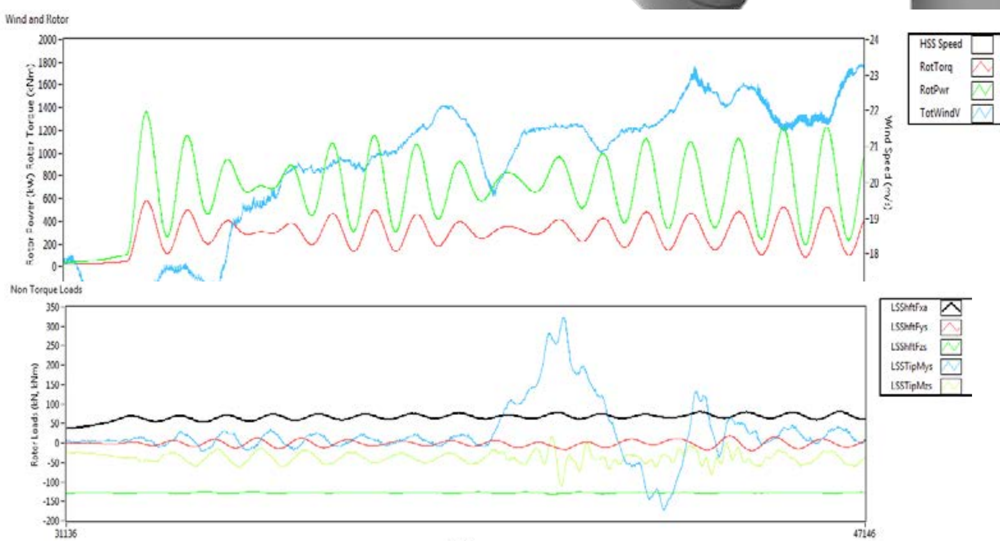
- Torque
- Bending moments
- Forces



Controllable Grid Interface (CGI)

Dynamometer





CGI provides control of grid interface electrical parameters

- Voltage
- Frequency
- Impedance

Technical Approach History

Zond Z-750

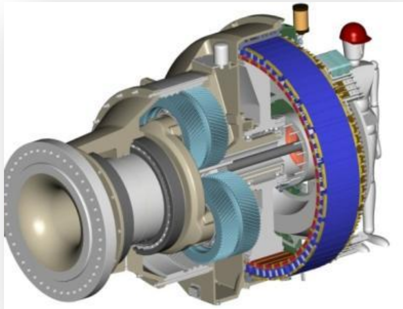
GE 1.5 MW

Clipper (8 Gen)

Clipper (4 Gen)

Northern 1.5 MW

Northern 2.3 MW



GEC 1.5 MW

NREL/DOE GRC 1&2

Samsung 2.5 MW

Clipper Liberty

NREL/DOE GRC 3

GE 2.75 MW

Technical Approach
Facilities and Specifications

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5 MW Dynamometer

- 5.8 MW low-speed shaft power
- 0-12 rpm rated torque, 12-24 rpm rated power
- 4.6 MNm maximum torque
- 5 DOF non-torque loads
  - 7.2 MNm bending
  - 3.5 MN force
- Dual 75-ton overhead crane, 14 m max hook height
- 12 x 20 m test bay
- 5 degree fixed drive line angle

2.5 MW Dynamometer

- 2.5 MW low-speed shaft power
- 0-22 rpm rated torque, 22-44 rpm rated power
- 1.1 MNm maximum torque
- 3 DOF non-torque loads
  - 1 MNm bending
  - .9 MN force
- 50-ton single crane, 9 m max hook height
- 12 x 15 m test bay
- 0-6 degree drive line angle

5 MW Dynamometer

Facility Aerial View

Controllable Grid Interface (CGI)

2.5 MW Dynamometer

Technical Approach
CGI

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Capabilities

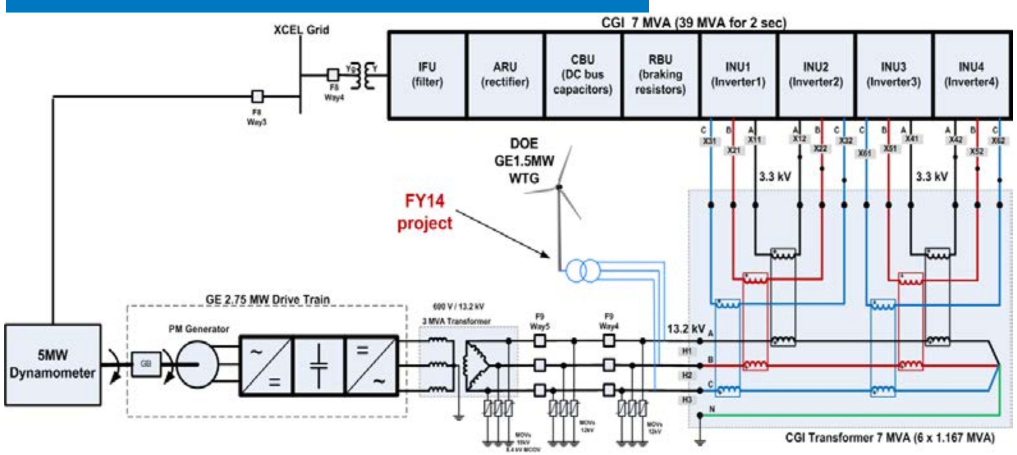
- Balanced and unbalanced over and under voltage fault ride-through tests
- Frequency response tests
- Continuous operation under unbalanced voltage conditions
- Grid condition simulation (strong and weak)
- Reactive power, power factor, voltage control testing
- Protection system testing (over and under voltage and frequency limits)
- Islanding operation
- Sub-synchronous resonance conditions
- 50 Hz tests

Power rating
- 7 MVA continuous
- 39 MVA short circuit capacity (for 2 sec)
- 13.2 kV output

Voltage control (no load THD <5%)
- Balanced and un-balanced voltage fault conditions (ZVRT and 130% HVRT) – independent voltage control in each phase
- Long-term symmetrical voltage variations (+/- 10%) and voltage magnitude modulations (0-10 Hz) - SSR
- Programmable impedance (strong and weak grids)
- Programmable distortions (lower harmonics 3, 5, 7)

Frequency control
- Fast output frequency control (+/- 3 Hz)
- 50/60 Hz operation
- Simulate frequency response of various power systems
- RTDS / HIL capable

Possible test articles
- Types 1, 2, 3 and 4 wind turbines
- Capable of fault testing of world's largest 6.15 MW Type 3 wind turbine
- PV inverters, energy storage systems
- Conventional generators
- Combinations of technologies



Accomplishments and Progress 5 MW Upgrade

- $9,950K American Recovery and Reinvestment Act project beginning FY09
- Design concept by NREL personnel based on experience gained operating 2.5 MW facility
- Ground breaking in September 2011
- Building construction and major equipment installation FY12
- No-load commissioning — March 2013
- GE 2.75 MW test article installation — August 2013
- Loaded commissioning with test article and CGI (NREL milestone) — September 2013


5 MW Groundbreaking


5 MW Building Construction


GE 2.75 MW Test Article Arrival

Accomplishments and Progress
2.5 MW Dynamometer

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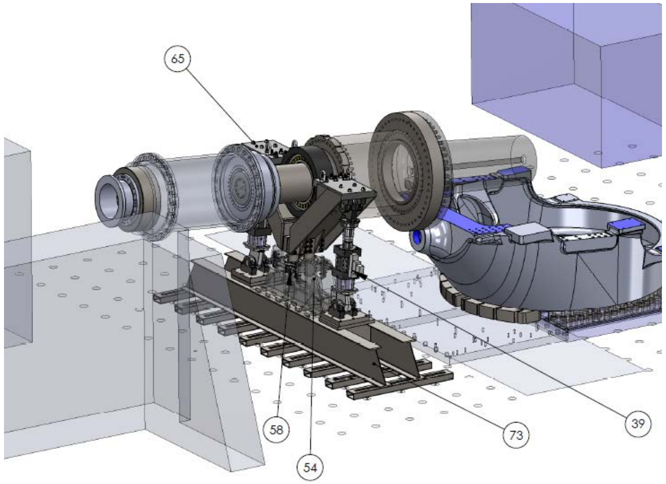
- Replaced obsolete variable speed drive system with high-performance ABB ACS2000 in FY13. New drive provides 100x improvement in speed and torque control
- Prepared and installed Gearbox Reliability Collaborative (GRC) phase 3 test article FY13
- Fabricated and tested additional gear ratio for dynamometer gearbox during FY12-13. New capability provides wider testing envelope to complement 5 MW facility
- Utilized NREL-designed non-torque loading system to test a Clipper C93 drivetrain during FY12

ABB ACS2000 Medium Voltage Variable Speed Drive



Non-torque loading system designed by NREL

Project Plan & Schedule

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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: Wind Energy Forecasting Methods and Validation for Tall Turbine Resource Assessment												
Q1 Milestone:Commission 2.5-MW two degree-of-freedom NTL System.												
Q2 Milestone:Complete CRADA Joint Statement of Work with IST Partner												
Q3 Milestone:Design review of 5-MW dynamometer control & DAS												
Q4 Milestone: Take delivery and install test article for the IST												
Q1 Milestone: Install 5 MW dynamometer facility PLC hardware												
Q2 Milestone: Commission 5 MW dynamometer control system												
Q3 Milestone: Test 2.5 MW dynamometer carrier and high speed stage gearing with no-load spin												
Q4 Milestone: Develop a draft Safe Operating Procedure (SOP) for the 5 MW dynamometer												
Current work and future research												
Issue a purchase order to S&C (vendor) for Vista switch remote operators												
Install and commission Vista switch remote operators												
Operate the new ACS2000 2.5-MW VFD at the NWTC using the GRC												
Complete barcode tagging of all the dynamometer testing equipment												

Comments

- Post IST CRADA support project: FY13-FY14. Dynamometer facilities O&M project is ongoing
- FY12 Q4 Milestone delayed due to change in IST partner (Clipper to GE)
- FY13 Q3 milestone delayed due to manufacturing error beyond NREL’s control

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators

- GE
- Clemson
- Lambert Engineer
- Windward Engineering
- Navarro
- GRC Annual Meeting
- IEA
- Testing for research and industry to promote reliable wind turbines for lowering the cost of energy.

Communications and Technology Transfer

- Facility fact sheets and video were created.
- Results were communicated by researchers and other facility users.

Next Steps and Future Research

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

FY14/Current research

- 5 MW and CGI characterization test and report
- Real-time “Model-in-the-loop” testing
- 5 MW flexible coupling model validation
- GE dynamometer test CRADA support

Proposed future research

- Enhanced model-in-the-loop capabilities with real-time grid simulation via RTDS

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Clemson University Wind Turbine Drivetrain Testing Facility

Dr. Nikolaos Rigas
Clemson University
nrigas@clemson.edu (843) 730-5072
March 25, 2014

Project Team

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

PI: Dr. Imtiaz Haque

Project Manager: James Tuten

Co-PI: Dr. Nikolaos Rigas

Research Scientist: Dr. Andrei Mander (Mechanical)
Research Scientist: Dr. Ryan Schkoda (Simulation)
Research Scientist: Dr. J. Curtiss Fox (Electrical)
Facility System Manager: James Tuten
Business Development: Elizabeth Colbert Busch
CU Research Associate: Konstantin Bulgakov
CU Research Associate: Open
CU Medium Voltage Technician: Mark Milcetich
CU Mechanical Technician: Open
CU Safety Manager: J.P. Hooks

Advisors: Dr. Vincent Blouin, Dr. John Wagner
Graduate Students:
Jake Hawkins: Large bearing test fixtures

Undergraduate Interns: Leigh Allison, Amber Solomon, Adam Broering, Eliot Hitchcock, Marquita Frazier, Alexandra Peterson, Phillip Meyer, Lucas Bryson, Omar Haque, Seth Strickland, Sarah Mercer, Dylan Sontag, Justin Moyland, Troy Hall

Budget, Purpose, & Objectives

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

Total DOE Budget [1,2]: $0.00M

Total Cost-Share[1]:$56.650M

Problem Statement: Ever larger and more advanced wind turbines require extensive testing to improve performance and reliability to lower the 'Levelized Cost of Energy' (LCOE), accelerate new innovations into the market and lower the risk of new technology introduction to the market. World-class, advanced testing infrastructure for wind turbines is capital intensive, high risk and requires specialized expertise making it difficult for individual innovators to develop stand alone facilities.

Impact of Project: State of the art, world-class 7.5 MW and 15 MW test rigs with non-torque loading systems with the capability of full electrical testing through a 15 MW Hardware-in-the-loop grid simulator will provide access to innovators at competitive costs to test new innovations and help educate the workforce of the future. Through collaboration with other similar facilities world-wide, new testing protocols and performance standards will be developed to reduce technology risk leading to lower LCOE.

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

- ✓ Reduce unsubsidized turbine LCOE to be cost-competitive with fossil fuels;
- ✓ Jumpstart U.S. offshore wind industry
- ✓ Testing, advanced manufacturing, certifications, and standards

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

Project Goals

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1. Design, construct and commission a 7.5 MW and 15MW wind turbine drivetrain testing facilities.

2. Provide full-scale testing and development services to industry through a ‘shared facility’ model to promote the rapid introduction of new technology in the energy market.

3. Develop system level expertise in wind turbine testing and validation.

4. Use facilities to educate the workforce of the future and promote public/private partnerships in research and development related to wind industry.

5. Develop long-term sustainable business model for facilities.

Scope of Project

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Shared facilities model giving open access to all Innovators.
7.5 MW Dynamometer with Static Off-axis load applicator (Upgradeable to dynamic) • 4-6 degree tilt • 100 ton lifting capability augmented by Charleston Port heavy lift infrastructure
15 MW Dynamometer with Dynamic Off-axis load applicator (Upgradeable to higher forces) • 6 degree fixed tilt • 125 ton lifting capacity augmented by Charleston Port heavy lift infrastructure • 7 meter center line of connection hub to base of dynamometer
Direct Drive and Geared Turbine Testing
50 and 60 Hz System Testing with capability to recycle power within each dynamometer
Electrical access to 15 MW Hardware-in-the-Loop (HIL) Grid Simulator Laboratory for full electrical testing.
Accessibility by ship, rail or road
High-speed Secured Data Acquisition System with Real-time Monitoring Capability
Develop system level expertise in advanced testing and multi-body simulation

Technical Approach

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- Industrial and Technical Advisory Board established to provide input on the key design parameters of the facility.
- Equipment purchased as turn key systems to minimize risk.
- A/E and Construction managed through Construction Management at Risk Model.
- Equipment utilizes proven and commercially available components to reduce costs and risk, increase flexibility and to maximize interchangeability between systems.
- Data acquisition system designed for security and real-time sharing of data.
- Logistic plan leverages Charleston Port Infrastructure.
- Maximize the use of existing building infrastructure.
- University adopts IP model to meet Industry's needs.
- Collaborate with existing and new facilities for exchange of information.
- 6 DOF measurement flanges added to project scope of work.
- Calibration fixture designed and built for 7.5 MW system.
- Real-time multi-body simulation models developed of test rigs to improve testing results while decreasing risks.

Key Issues

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- Design and operate facility to ensure protection of personnel and environment.
- Industry input strongly urged installation of non-torque loading system on 7.5MW test rig and measurement flanges not originally specified in proposal.
- Accommodating large diameter turbine specimens on 15MW dynamometer required deconstruction of portion of building to install wider and taller test bay triggering requirement that building be brought up to new seismic and wind codes.
- Construction of large dynamic foundations near deep water channel in poor soil conditions, hurricane wind loads and high earthquake risk zone.
- Electric isolation of facility as required by SCE&G necessitated the need for a dedicated 28mVa transformer.
- Coupling of 15 MW Hardware in the loop Grid Simulator required extensive electrical control system to manage power flows.

Accomplishments and Progress

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- Safety program developed and training completed.
- Building infrastructure construction completed. Gold LEED Certification.
- Electrical infrastructure complete.
- 7.5MW test unit 100% assembled.
- 15 MW test unit ~ 85% assembled.
- Water , hydraulic and lubrication systems commissioned.
- Calibration system for 7.5MW designed and built.
- Commissioning plans complete.
- First test run plans complete.
- First test article at site.
- Multi-body simulation models of test rigs complete.
- Staffing plan complete.

Project Plan & Schedule

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

	Milestone	Original Date	Revised Date	Status
1	Renk preliminary design review	12-10-10	12-10-10	Complete
2	A&E selection completed	12-21-10	12-21-10	Complete
3	A&E design work initiated	01-10-11	03-04-11	Complete
4	Start of hardware procurement	01-03-11	01-19-11	Complete
5	SCDHEC Dig Permits issued	01-17-11	04-01-11	Complete
6	Minor demolition started)	01-17-11	09-20-10	Complete
	Major Building demolition started, old sections		04-1-11	Complete
	Major Building Demolition, new sections		09-19-11	Complete
7	Data acquisition system prototypes ordered	01-17-11	03-15-11	Complete
8	Construction Management Company selected	2-28-11	04-21-11	Complete
9	Motors and Drives ordered/ Electrical transformers ordered	3-7-11/ 3-7-11	04-01-11 05-01-12	Complete Complete
10	Cranes specified/ ordered/installed	4-15-11 11-15-11	08-15-11 10-01-11 07-05-13	Complete

Project Plan & Schedule

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

	Milestone	Original Date	Revised Date	Status
11	7.5 MW Foundation work initiated/completed	04-18-11/ 12-30-11	08-16-11/ 06-29-12	Complete
12	Rail Spur started/ completed	06-13-11/ 09-16-11	05-14-12/ 08-31-13	Complete
13	7.5MW testing equipment delivery started	12-09-11	02-15-13	Complete
14	Temporary electrical infrastructure functional	12-01-11	06-15-13	Complete
15	15 MW Foundation work initiated/completed	04-18-11	09-01-13	Complete
16	Cooling Equipment Installed		12-15-13	Complete
17	Final electrical infrastructure installed		01-01-14	Complete
18	Automation and Data System Ready for install	02-17-12	12-15-13	7.5 MW installation complete, 15 MW system delivered
19	7.5 MW Unit commissioning start	03-05-12	04-15-14	Ongoing
20	15MW testing equipment delivery	03-09-12	10-3-13	Complete
21	7.5MW test stand operational	07-09-12	03-10-14	Complete
22	Facility dedication	07-16-12	11-21-13	Complete
23	15 MW Unit commissioning start	09-17-12	05-01-14	Ongoing

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

Savannah River National Laboratory
Renk Test Systems Labeco
Choate Construction
SM&E
SC Public Rails
University of Aachen
NREL NWTC CRADA
AEC Idom Engineering
NREL NWTC GBX Collaborative
SCE&G
IEA Task #35
LORC

Communications and Technology Transfer:

- >600 national and international media stories on project.
- Webinars held for IAB, TAB and other interested parties.
- 6 papers/posters presented on project at conferences.
- 167 presentations given to companies, technical/education organizations , business organizations, elected officials, and non-profit groups.
- November 21, 2013 Industry Technical Workshop
- November 22, 2013 Dedication
- Website developed (clemsonenergy.com) .

Start of Brownfield Site

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Finished Energy Innovation Center

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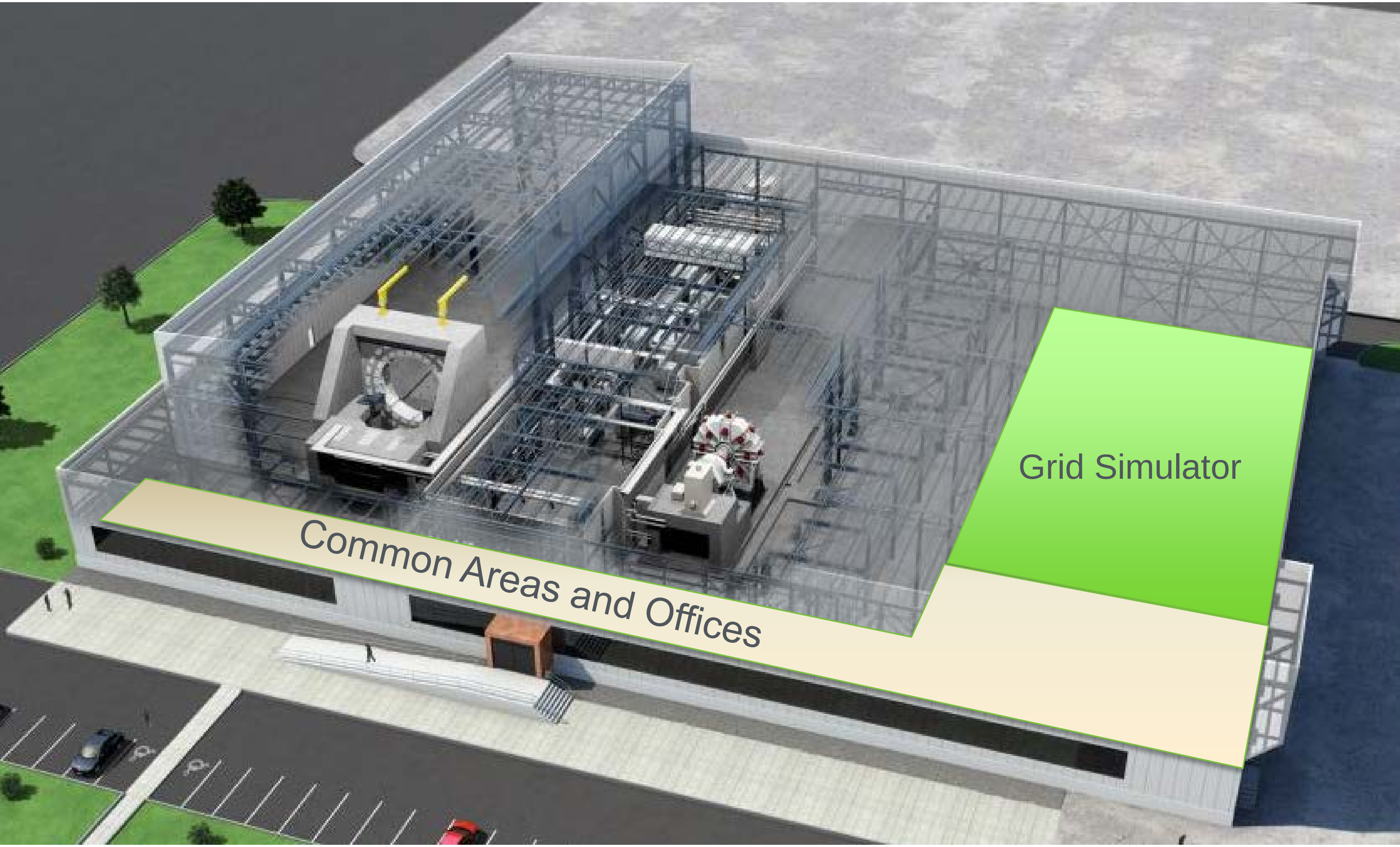
Building Layout



Finished Energy Innovation Center

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7.5 MW Test Rig

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7.5 MW Test Rig

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15 MW Test Rig

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15 MW Test Rig

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Hydraulic Room

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Utility Bay

Control Room

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Next Steps and Future Research

Milestone	Targeted Date
Load calibration test stand on 7.5MW test rig.	March 2014
Install nacelle on 7.5 MW test rig.	April 2014
Complete assembly of 15 MW test rig.	May 2014
Start Commissioning of 15 MW test rig.	July 2014

Challenges:

- Large test article for 15 MW unit.
- Utilization of facilities.
- Exchange of information with similar facilities.

Future Research: Dynamic Simulation Time and Frequency Domain

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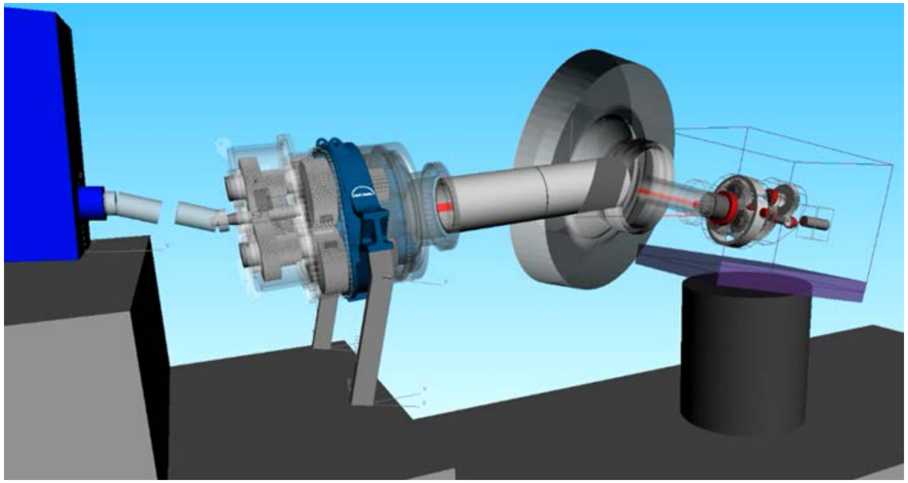
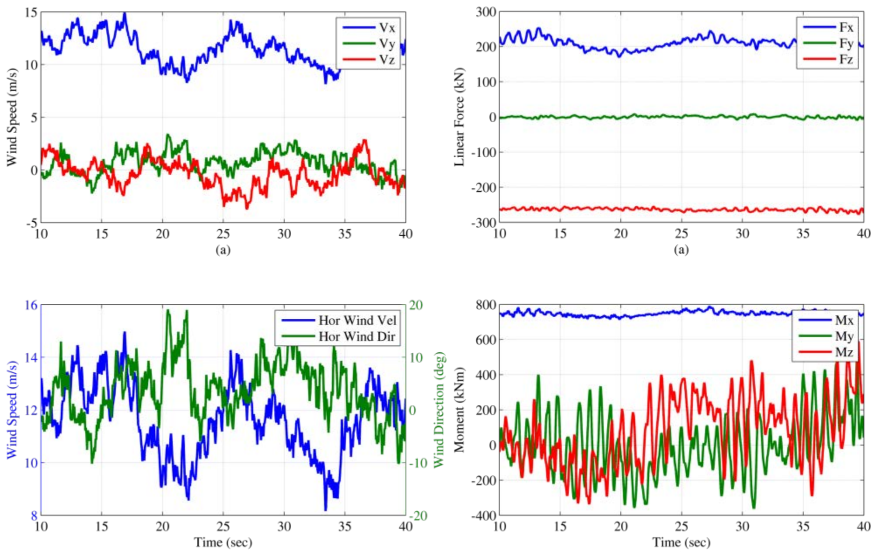
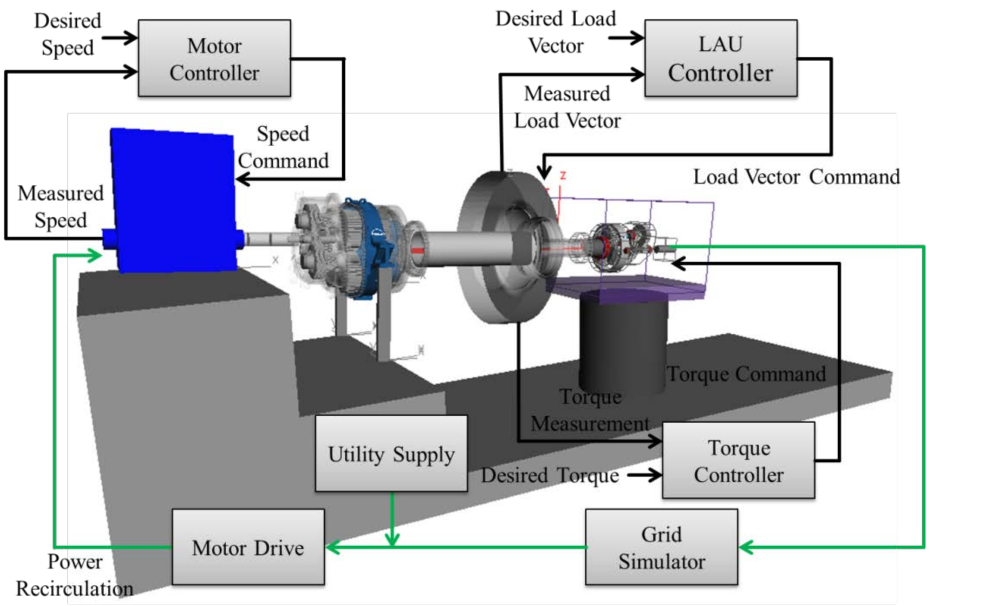
System level Dynamic Simulation

- Multi-body dynamics
- Control systems
- Electrical/power systems
- Real-time execution
- Wind load simulation
- Test profile development and evaluation
- Third party tool integration



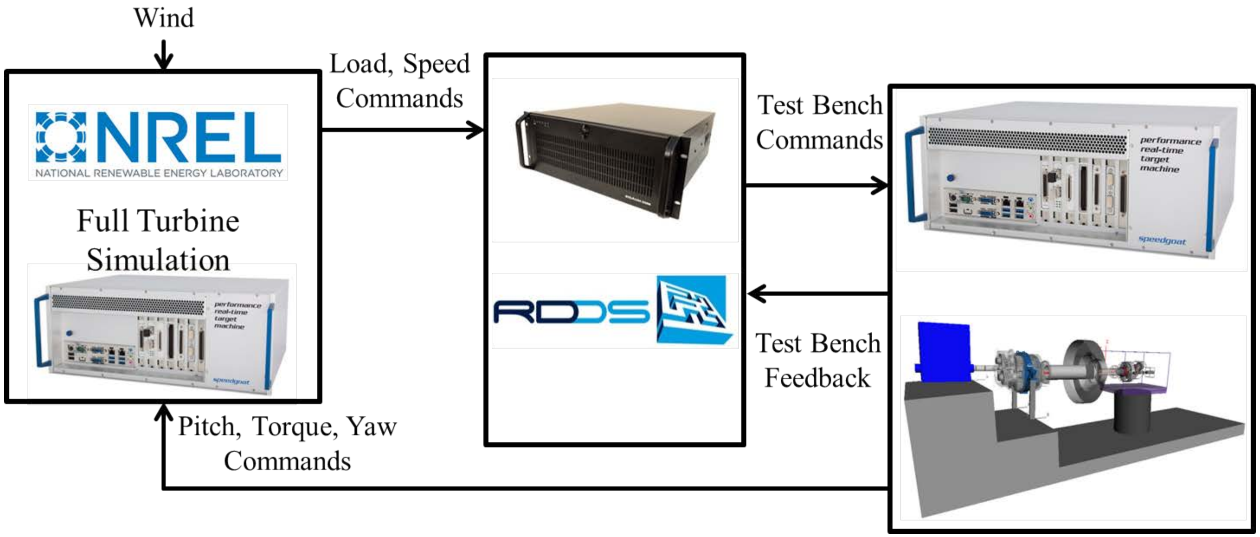
Wind and Main Shaft Load Simulation

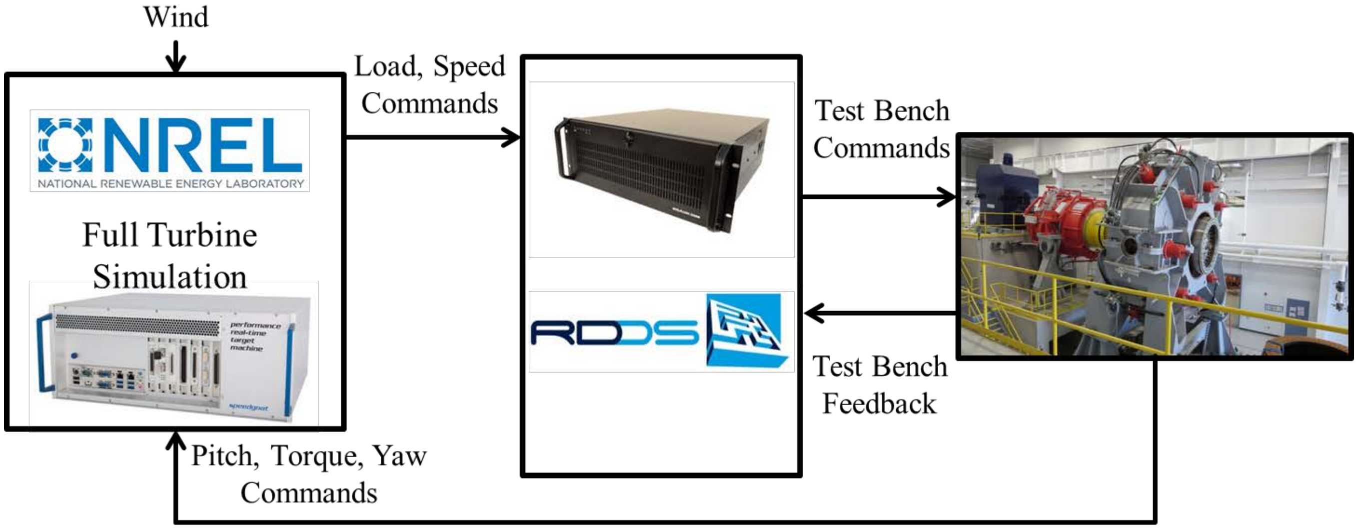




Future Research

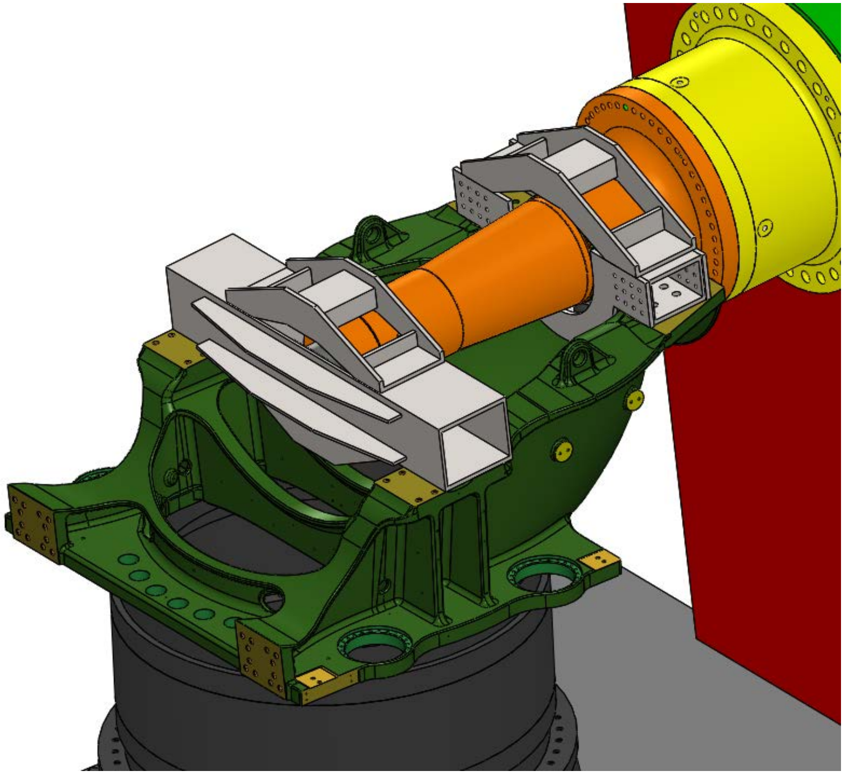
Closed loop Simulation to develop advanced testing strategies and integrate third party models.

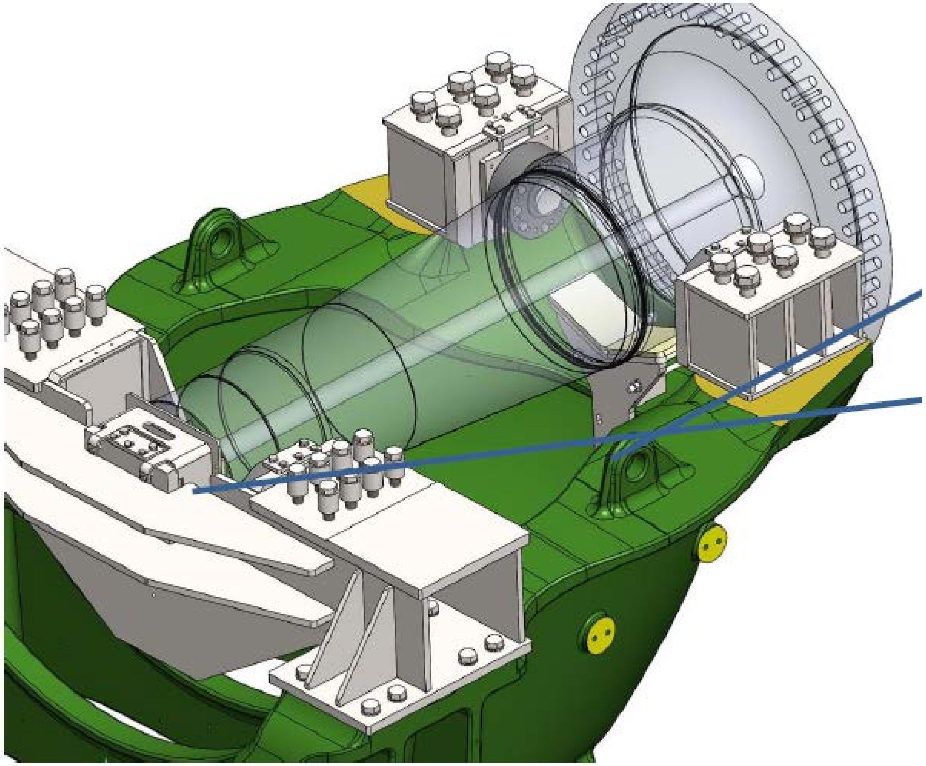




Closed loop Operation to execute advanced testing strategies, highly accelerated life testing and control system testing.

Future Research: Rigid Commissioning Stand





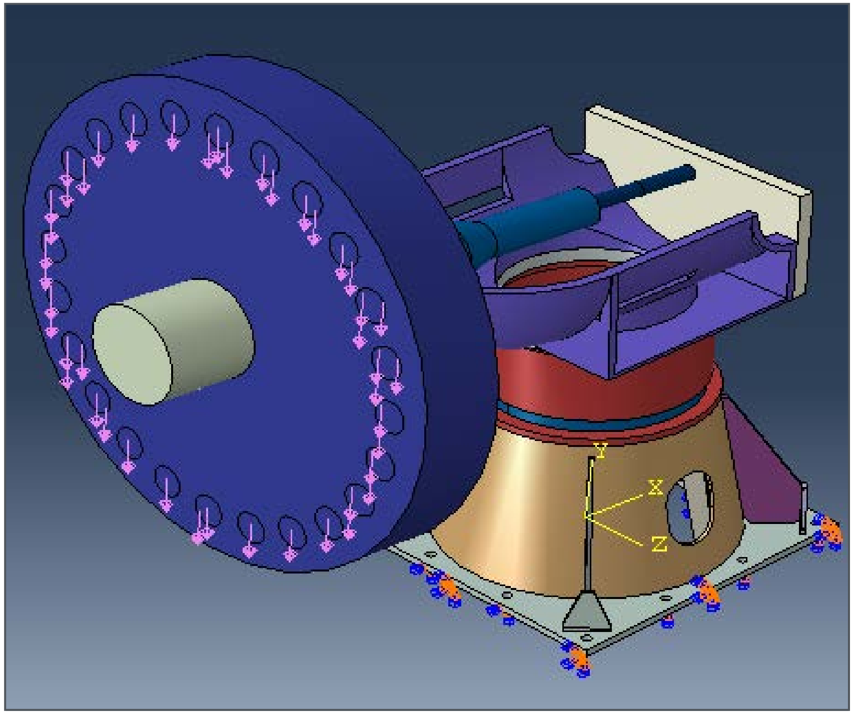
<u>Main Objectives:</u>

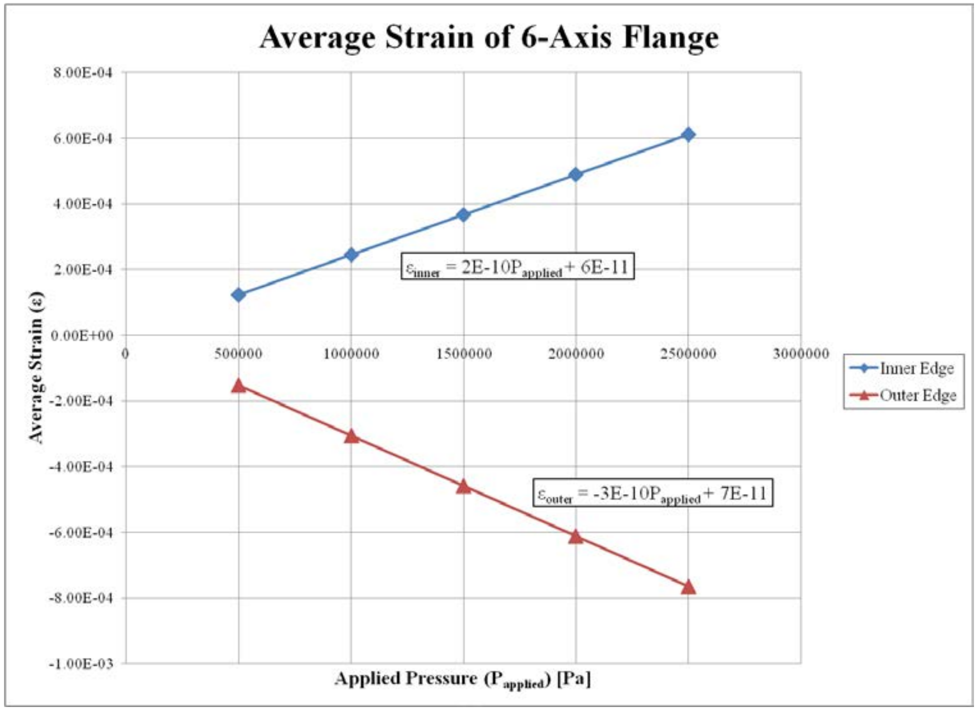
- Minimize safety risks
- Test Bench Accuracy
- Calibration for Certification Studies
- Long Term Preventive Maintenance

Future Research: Structure Modeling

Advisor: Dr. Vincent Blouin
MS Student: Jake Hawkins

Thesis Work:
Predictability of the RCS (Rigid Commissioning Stand) deflection by performing Shear & Thrust Linearity Analysis and FEAs Studies





Future Research: Lubricants

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Shell / Exxon Mobil

	DIRECTION 1 Product Efficiency	DIRECTION 2 Product Reliability	DIRECTION 3 Product Noise
Variables under investigation	1. Oil type 2. Oil temperature 3. Operational load matrix	1. Oil type 2. Oil temperature 3. Operational load matrix	1. Oil type 2. Oil temperature 3. Operational load matrix
Test methodology	1. Optimized calorimetric methodology with mirror set up and advanced measurement system	1. Advanced Reliability protocols 2. To inject and reproduce field failure mode 3. Cold starts (-20C) , heat runs (70-80C) , cold runs (5-10C)	1. Standard acoustic HW and SW packages
Test results and value	1. Accurate efficiency value 2. Efficiency vs oil type 3. Efficiency vs oil temperature 4. Efficiency vs speed map 5. Efficiency vs torque map	1. Reliability vs oil type 2. Quantitative Reliability value 3. Failure mode reproduction 4. Design and specification change to avoid failure	1. 3D noise model around product 2. Noise vs oil type 3. Noise vs oil temperature 4. Meshing frequency GBX change vs oil type. Noise sources
Business value	1. Better power output 2. Optimized operation and lower heat losses 3. Better cost of energy	1. Proven and optimized Reliability 2. Reduced operational and service costs	1. Certification requirements support 2. HSE improvements

Controllable Grid Interface (CGI)

Mark McDade

NREL/NWTC Testing

Mark.McDade@nrel.gov /(303) 384-6961

March 25, 2014

Budget, Purpose, & Objectives
NWTC Test Facility Capabilities

- **Field**
  - Field test sites & infrastructure
  - DOE 1.5, Industry MW turbines
  - Controls Research Turbines (CART)
  - Research-grade inflow meteorological data
  - Small turbine testing
- **Drivetrain**
  - 225kW, 2.5 MW, 5.8MW dynamometers
  - Dynamic torque testing of fully integrated drivetrain systems or components (gearboxes, generators, PE)
  - HALT, condition monitoring
  - Model-in-the-loop to i.e. simulate turbulence
  - Non-torque loading (NTL) to impart rotor loads
- **6.3MW Controllable Grid Interface**
- **Structural**
  - Test stands, hydraulic actuators
  - Accredited (A2LA) fatigue (resonant) and static testing of blades (up to 50m in length) to IEC standards
  - Modal and property measurements, profiling, NDT methods
  - Innovative test methodology R&D
  - Massachusetts large blade test facility partnership
- **ISO 17025, A2LA accredited to IEC Standards**
  - Power performance, power quality, acoustic emissions, structural loads, duration, Safety & Function
- **Custom**
  - Testing to meet R&D needs (e.g. data for model validation, proof-of-concept)
  - Explore applicability of advanced sensors, DAS




Budget, Purpose, & Objectives

Total DOE Budget[1]: $3.700M

Total Cost-Share[1]:$0.000M

Problem Statement: The wind industry is limited by grid transmission technology. To date, grid performance testing has been limited to occurrences on field turbines. Controllable Grid Interfaces (CGI) allow for rapid testing in laboratory situations with lowered costs and risks.

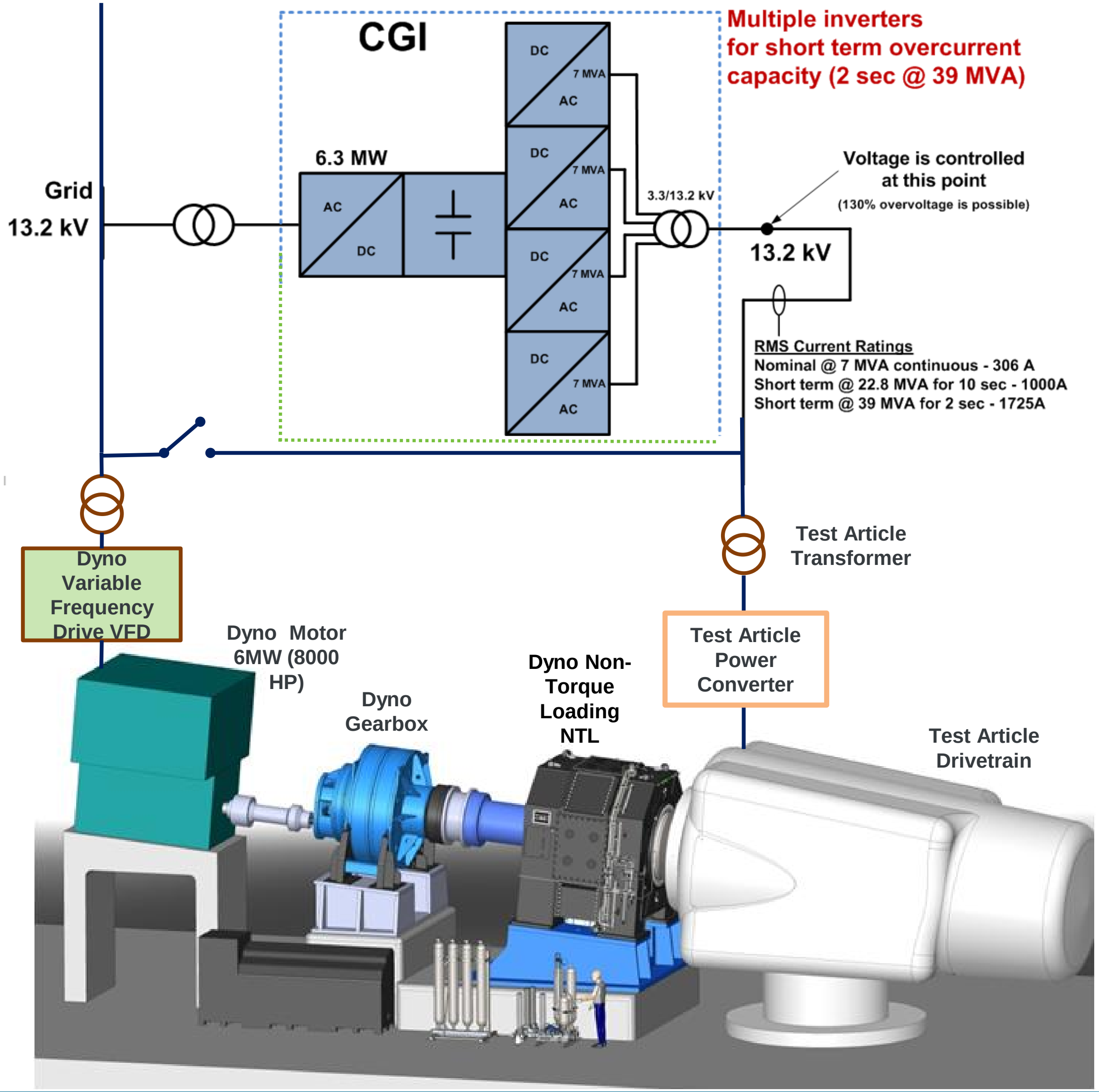
Impact of Project: CGI testing will speed turbine electrical code compliance assurance and increase basic knowledge of grid interactions as renewable penetration increases.

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

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***

Budget, Purpose, & Objectives
CGI and Dynamometer Testing



Technical Approach

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Methods

- Customized variable frequency drive power electronics
- ~7MVA continuous power throughput at <3% thd
- Up to 2-second short-circuit testing at ~39MVA
- Isolates grid from disturbances caused during testing
- Allows testing of variable voltage and frequency systems

Technical Approach

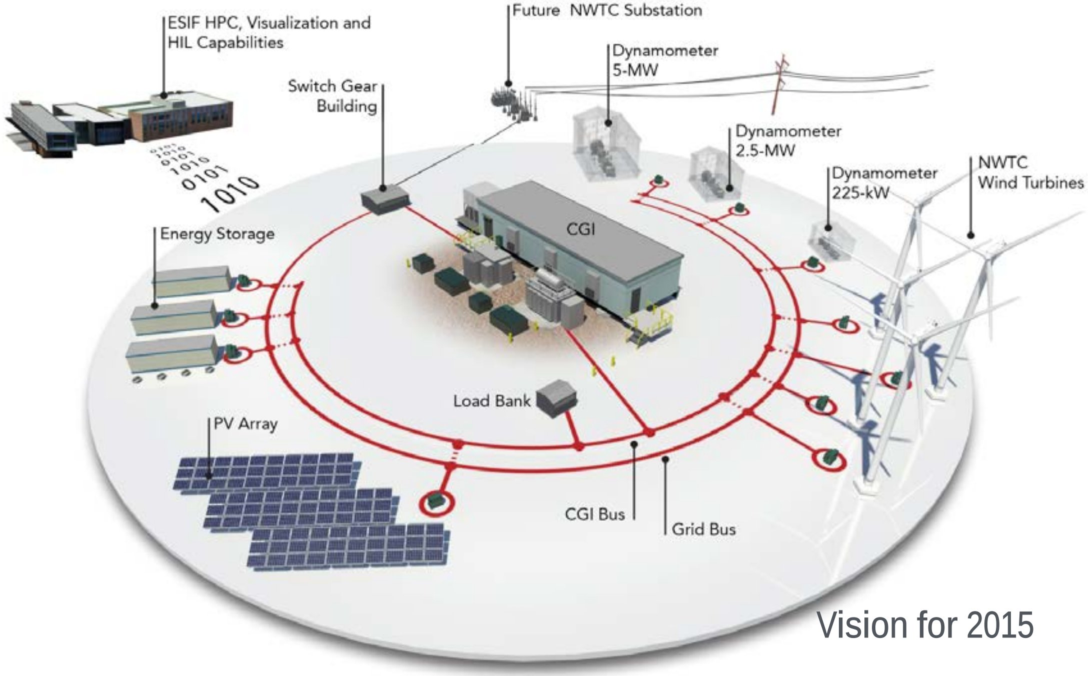
Key Issues

- Current work is focused on characterizing system under various conditions of frequency, voltage, load, balance, unbalance, etc. System is being tuned and proven throughout the range of conditions it can generate.

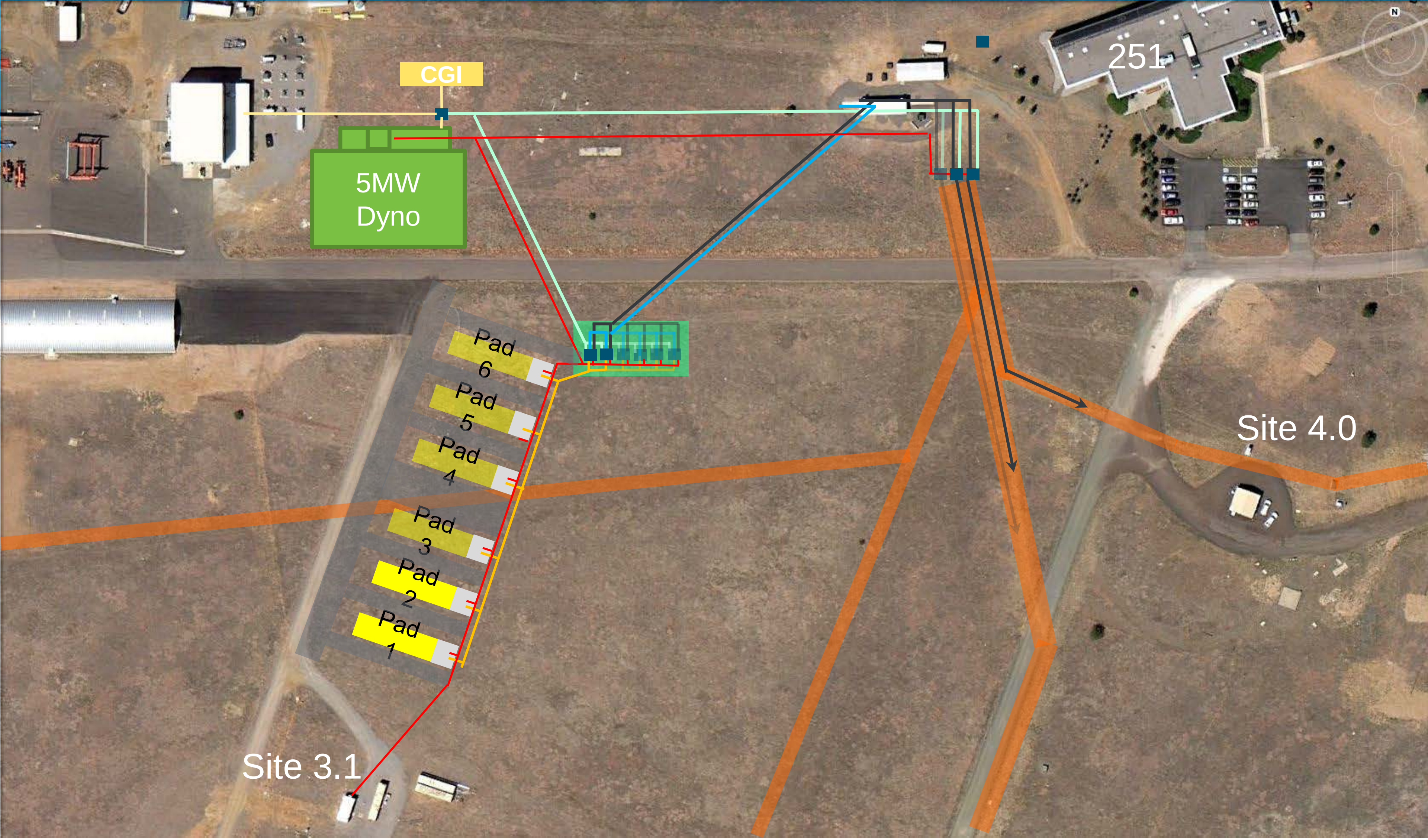
- A project is underway to connect the system to the large turbines at the NWTC to extend testing from the laboratory into the field.

Unique Aspects

- Largest fully functional controllable grid interface for renewable energy
- Only controllable grid interface that will be connected to both dynamometer and multi-technology field test articles



Vision for 2015



Electrical & facility infrastructure for Grid Energy Storage (GES) test pads and Row 4 turbine interconnection to Controllable Grid Interface (CGI)

Accomplishments

- Design completed and subcontract awarded to ABB for provision of equipment
- All equipment installation and cabling completed at the NWTC during FY13
- System commissioned under load using GE 2.75MW test article in the 5MW dynamometer on 9/30/13

Project Plan & Schedule

Summary	
WBS Number or Agreement Number	
Project Number	
Agreement Number	

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 purchase of grid simulator electronic hardware												
Q2 Milestone: Award subcontract for purchase of CGI modular enclosure												
Q3 Milestone: Award subcontract for CGI electrical infrastructure												
Q4 Milestone: Completion of CGI modular enclosure with two inverters installed												
Q1 Milestone: Complete installation of modular enclosure												
Q2 Milestone: Complete engineering, manufacture and testing of power transformers												
Q3 Milestone: Complete engineeering, manufacture and testing final output inverters												
Q4 Milestone: Final installation and testing of CGI												
Current work and future research												
Complete testing of connection of CGI to Row 4 turbines												

Comments

- Project initiated June 2010
- Computer simulation modeling was successfully used to inform design
- Completion September 2013, meeting all DOE milestones

Research Integration & Collaboration

Partners, Subcontractors, and Collaborators:

- BEW subcontracted to design the system in partnership with NREL.
- ABB was subcontracted to deliver CGI system based on NREL specifications.
- ACS was subcontracted to provide physical installation of enclosure, cabling, transformers, etc.

Communications and Technology Transfer:

1st annual International Workshop on Grid Simulator Testing of Wind Turbine Drive Trains initiated by NREL (Gevorgian) June 13-14, 2013 with 40 attendees.

See: http://www.nrel.gov/docs/fy14osti/60246.pdf

Next Steps and Future Research

FY14/Current research: Goal in FY14 is to connect the CGI to the >1MW turbines in the field at the NWTC and to verify use of the CGI with a field turbine.

Proposed future research: CRADA is under development with multiple wind energy partners for use of CGI to research grid management strategies using NWTC field turbines as small dedicated grid. NREL has initiated procurement of a megawatt-scale energy storage facility to be integrated with the CGI, MW turbines and dynamometer facilities.

Wind Power Peer Review

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

15 MW Hardware in the Loop Grid Simulator

Dr. Nikolaos Rigas

Clemson University

nrigas@clemson.edu 843-730-5072

March 25, 2014

Project Team

PI: Dr. Nikolaos Rigas
Co-PI: Dr. Randy Collins

Technical Lead: Dr. J. Curtiss Fox
Project Manager: James Tuten

Research Scientist: Dr. Mark McKinney, Assoc. Professor EE, Citadel
Research Scientist: Dr. Thomas Salem, Assoc. Professor EE, US Naval Academy
Research Scientist: Recruiting
Post Doctoral Associate: Recruiting

CU Research Associate: Ben Gislason
CU Medium Voltage Technician: Mark Milcetich
CU Safety Manager: J.P. Hooks

Advisors: Dr. Randy Collins, Dr. Keith Corzine, Dr. Elham Makram
Graduate Students:

- Nikitas Zagoras: Ancillary Services for Energy Storage Devices
- Lindsey Stephens: Harmonic controller
- Vahid Dargahi: Real-time Power System Dynamics
- Pasmal Saraf: Real-time Power System Dynamics
- K. Balasubramarian: Parallel transient simulator for control
- Puspal Hazra: Power system stability

Undergraduate Interns: Nicholas Willis, Ben Gislason, Tyler Shake, Diana Argest

Budget, Purpose, & Objectives

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Total DOE Budget[1]: $2.800M

Total Cost-Share[1]:$13.000M

Problem Statement: Access to powerful electric grid testing infrastructure that can (1) replicate real-world transient events, (2) validate and certify new technologies, and (3) investigate power quality and performance without putting the existing grid at risk in order to seamlessly integrate new technologies into the distribution and transmission infrastructure is needed by wind turbine innovators.

Impact of Project: Reducing the LCOE by:

- lowering the risk of new technology introduction into the market.
- accelerating the introduction of new technologies into the market.
- helping to establish new performance driven standards that increase value of energy. (i.e. ancillary services)

This project aligns with the following DOE Program objectives and priorities

- Optimize Wind Plant Performance
- Accelerate Technology Transfer
- Mitigate Market Barriers
- Advanced Grid Integration
- Testing Infrastructure

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

Project Goals

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

1. Design, construct and commission a state-of-the-art 15 megawatt (MW) HIL Grid Simulator that supports full-scale grid compatibility testing of multi-megawatt wind turbines.

2. Integrate 15 MW HIL Grid Simulator with 7.5 MW and 15 MW wind turbine drivetrain testing dynamometers.

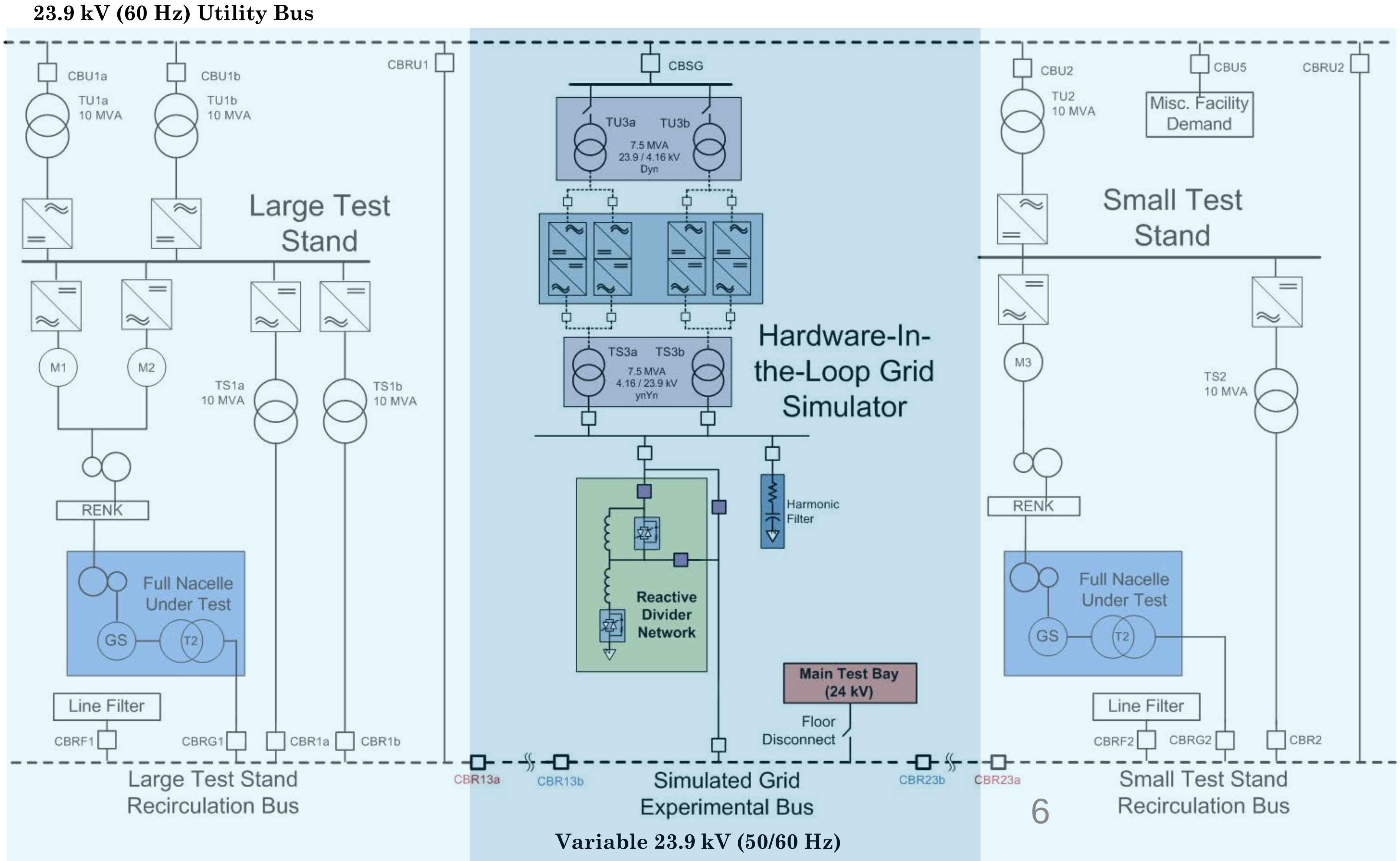
3. Provide full-scale testing and development services to industry through a 'shared facility' model to promote the rapid introduction of new technology in the energy market.

4. Develop competitive power systems program for education and support K-12 STEM education.

Accomplishments and Progress

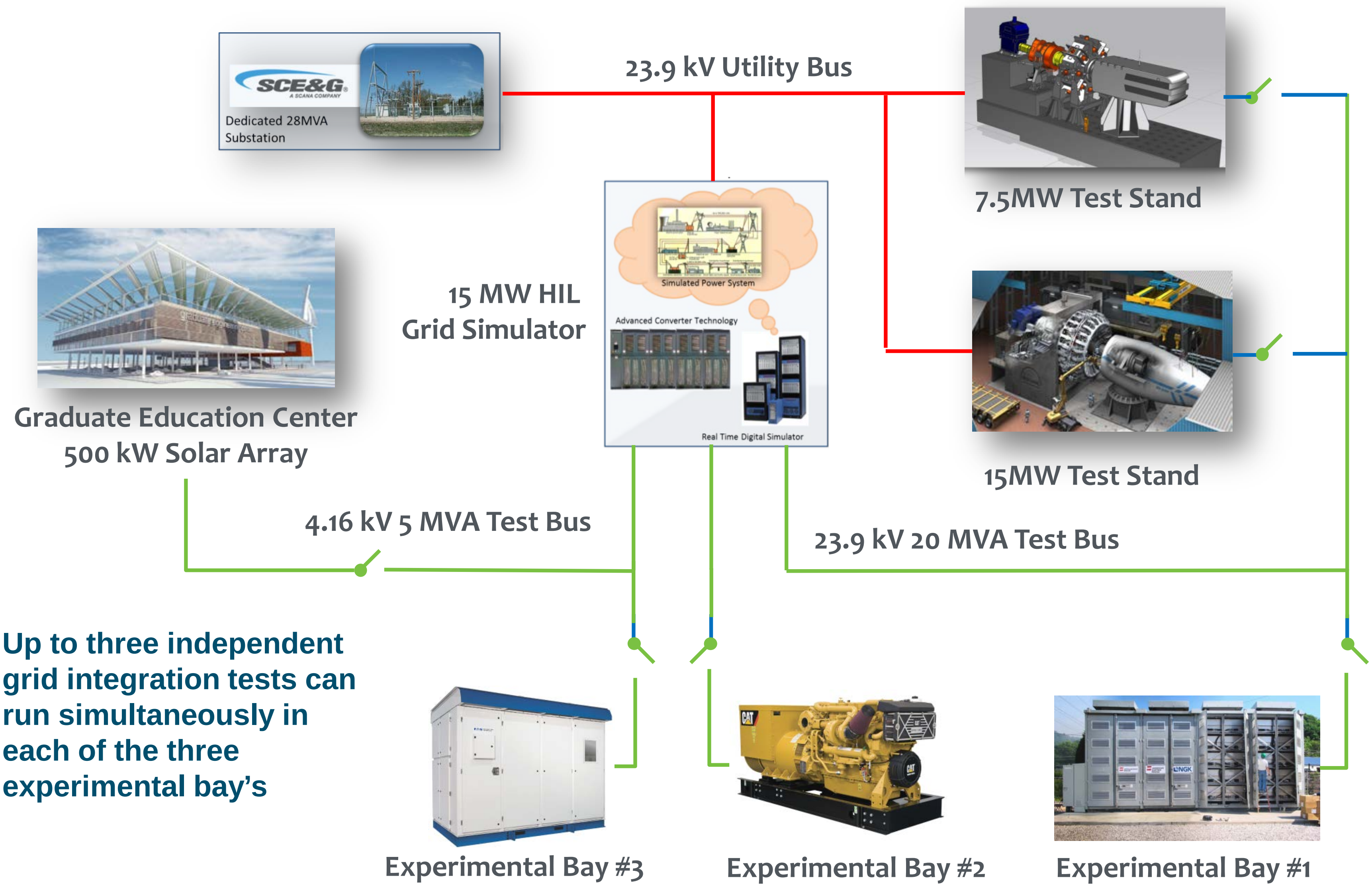
- Completed design and construction per the targeted time frame.
- Expanded the capability of the system into three separate test beds.
- Improved the safety of reactive divider network through automation.
- Increased resolution of HIL capability through in-house developed hardware and software.
- Utilized RTDS system and developed simulation model of facility to validate all interface protocols.
- Developed design for DC power source to mimic PV array and support DC power research.

Interface with WT DTF



15 MW HIL Grid Simulator

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



Up to three independent grid integration tests can run simultaneously in each of the three experimental bay's

Targeted Capabilities

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Steady State and Envelope Evaluations	• Power Set Points • Voltage and Frequency Variations • Controls Evaluation
Power Quality Evaluations	• Voltage Flicker • Harmonic Evaluations • Anti-Islanding (Software)
Ancillary Services	• Frequency Response • Active Volt-VAR Control • Active Frequency Regulation
Grid Fault Ride-Through Testing	• Low Voltage Ride-Through • Unsymmetrical Fault Ride-Through • High Voltage Ride-Through
Open Loop Testing	• Recreation of field events with captured waveform data
Hardware-In-the-Loop Testing	• Simulated dynamic behavior and interaction between grid and the device under test

Increasing level of difficulty

Hardware-in-the-Loop Testing

15 MW TECO-Westinghouse Power Amplifier

CU / National Instruments Interface Controller

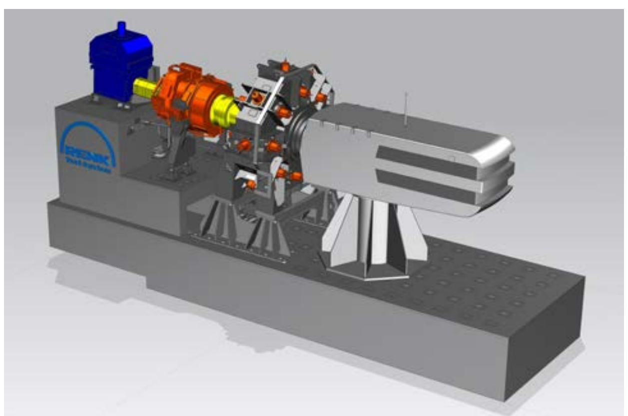
Voltage and Current Set Point Commands

'Real' Power System Model

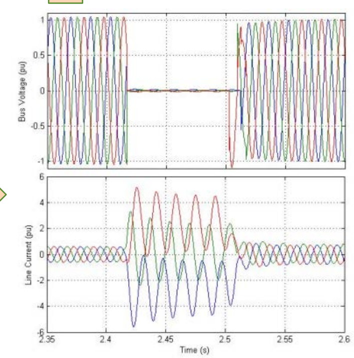
RTDS®

Turbine is BUS #N In the Model
Voltage and Current Information

Real Voltages and Currents associated with ***BUS #N***



Turbine on Adjacent 7.5MW Test Stand
*"I am connnected at **Bus #N in the Power System Model**"*



Real Voltage and Current Measurements

HIL connects the DUT into a replicated power system where disturbances are evaluated in real-time with a closed-loop dynamic system response. The DUT actually influences the simulated environment , which is critical for testing interactions with "soft grids"

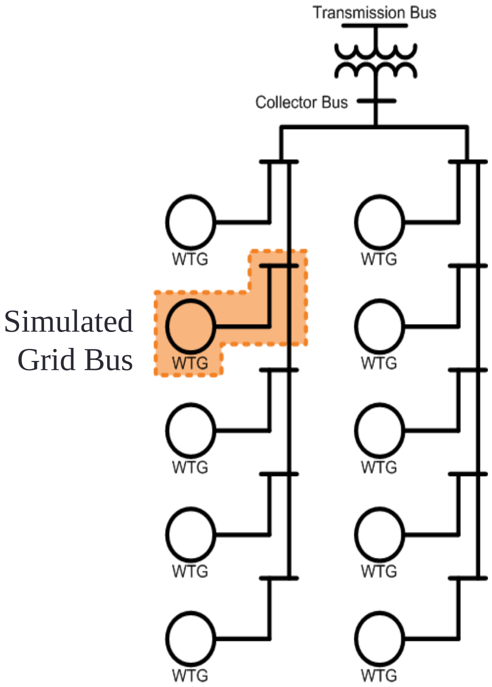
HIL Testing Capabilities: Wind Energy Applications

Wind Farm Modeling
- Classic lumped WTG stability study
- Disturbances external to the farm

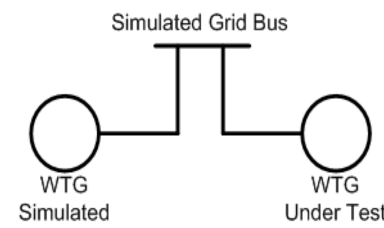
Collector Bus Modeling
- Model several WTGs in parallel
- Disturbances internal to the farm

Parallel Model Verification
- Present the same test case to both a simulated machine and the actual WTG under test

Application Specific Issues
- Offshore versus land based
- Harmonics
- Stiff versus weak grid conditions



Wind Farm and Collector Bus Experiments



Parallel Model Verification

Fault-Ride Through (FRT) Testing

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Reactive Divider Network Method

- ABB Factory Testing (2009)
- FGH Test Systems Field Testing (2006)

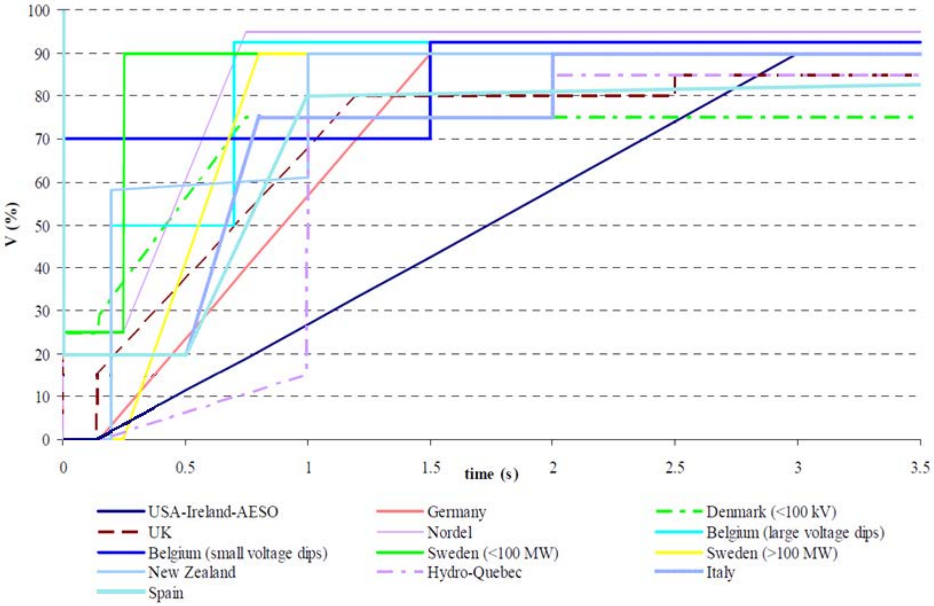
Variable Voltage Source Method

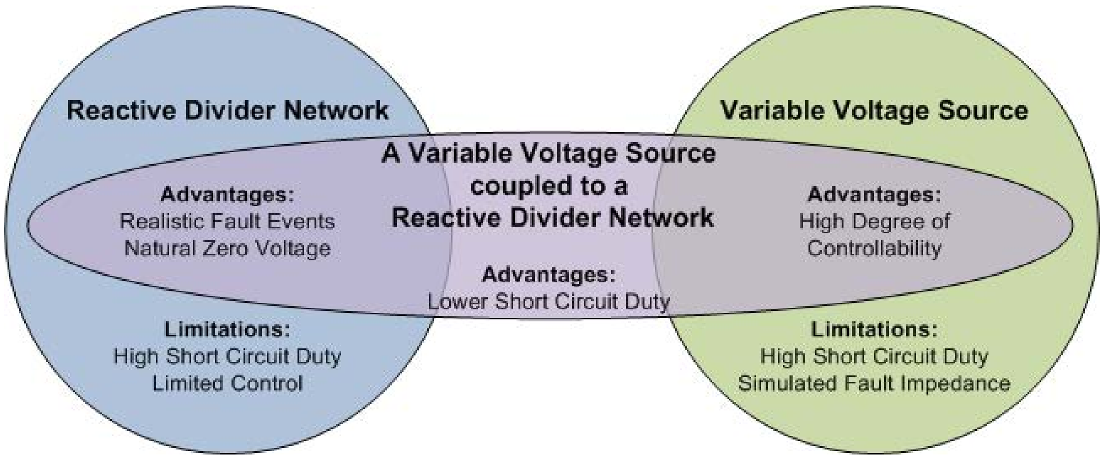
- **GE Power Conversion** (Fr. Converteam)
  - Vestas V164 Test Bench (2013)
  - NAREC 15 MW Test Bench (**Hybrid?**)
- **ABB Test Systems**
  - NWTC at NREL (4Q-2013)

Hybrid Method

- Clemson University

World Wide FRT Withstand Curves

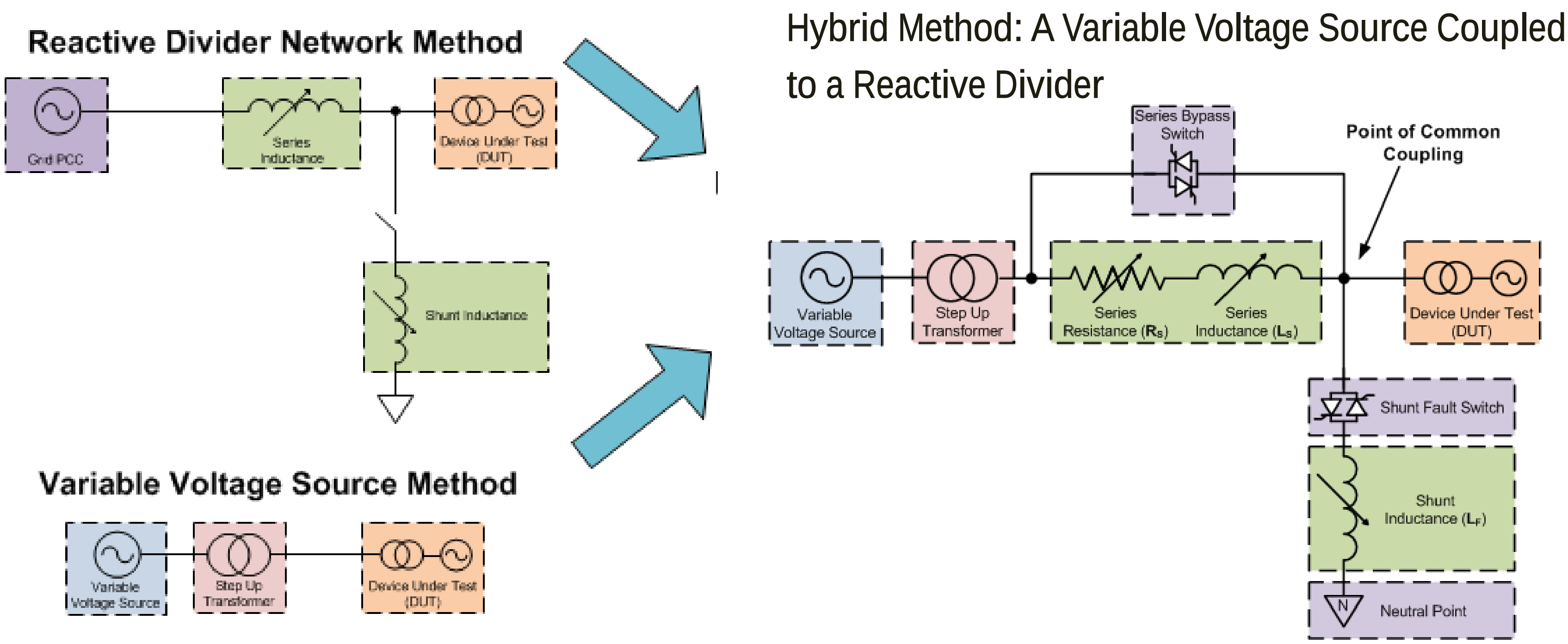




Why a Hybrid Method?

The Hybrid Method has more flexibility with FRT evaluations

- Faulted at the point of common coupling (PCC)
- True zero voltage faults (ZVRT)
- Magnetic decoupling between transformers
- Real inductive loading for sub-transient and transient time constant analysis



Fault Induced Delayed Voltage Recovery (FIDVR)

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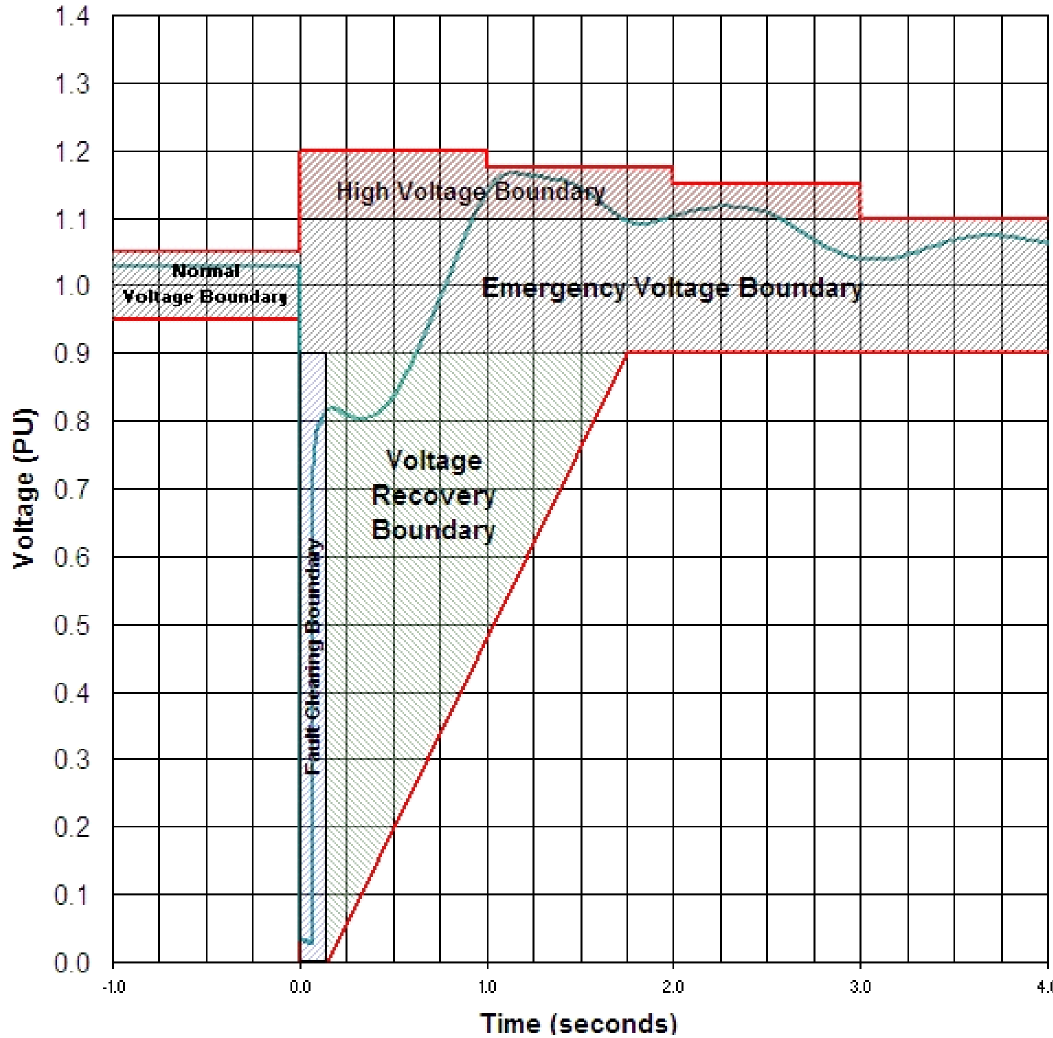
- Predominately caused by the stalling and subsequent tripping of a high penetration of line connected induction motors.

- Built in HVRT capabilities makes simulation of this type of event possible

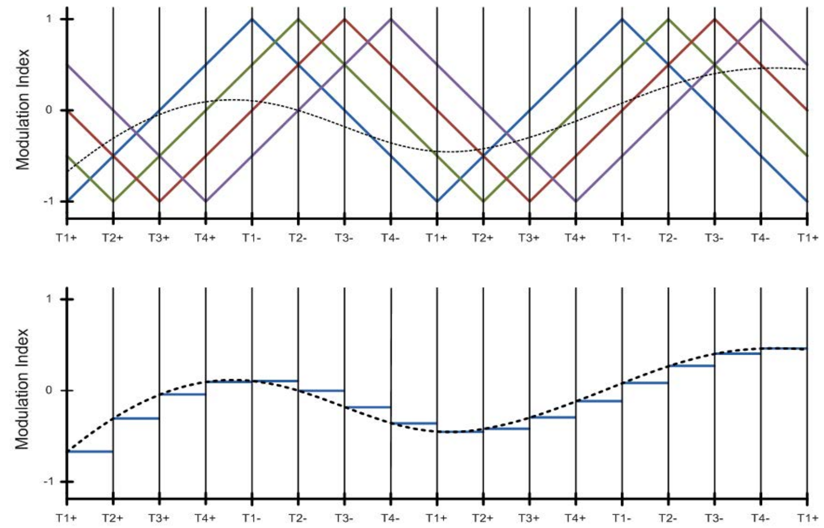


WECC Fault Ride-Through boundaries

13

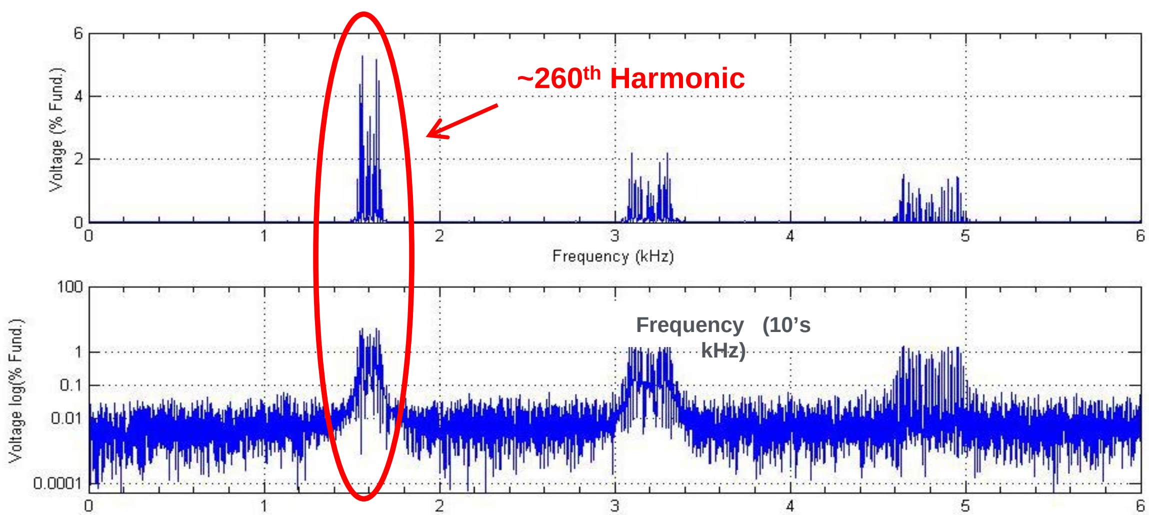
Power Quality Testing

- Phase Shifted Carrier PWM
  - High degree of harmonic cancelation due to multilevel architecture
  - Increased reference sampling fidelity
- Sampling fidelity is further increased by using asymmetrical sampling of each individual carrier



Synchronous Sampling up to 12 kHz

Power Amplifier Output Harmonic Spectrum (Fs = 2 kHz)



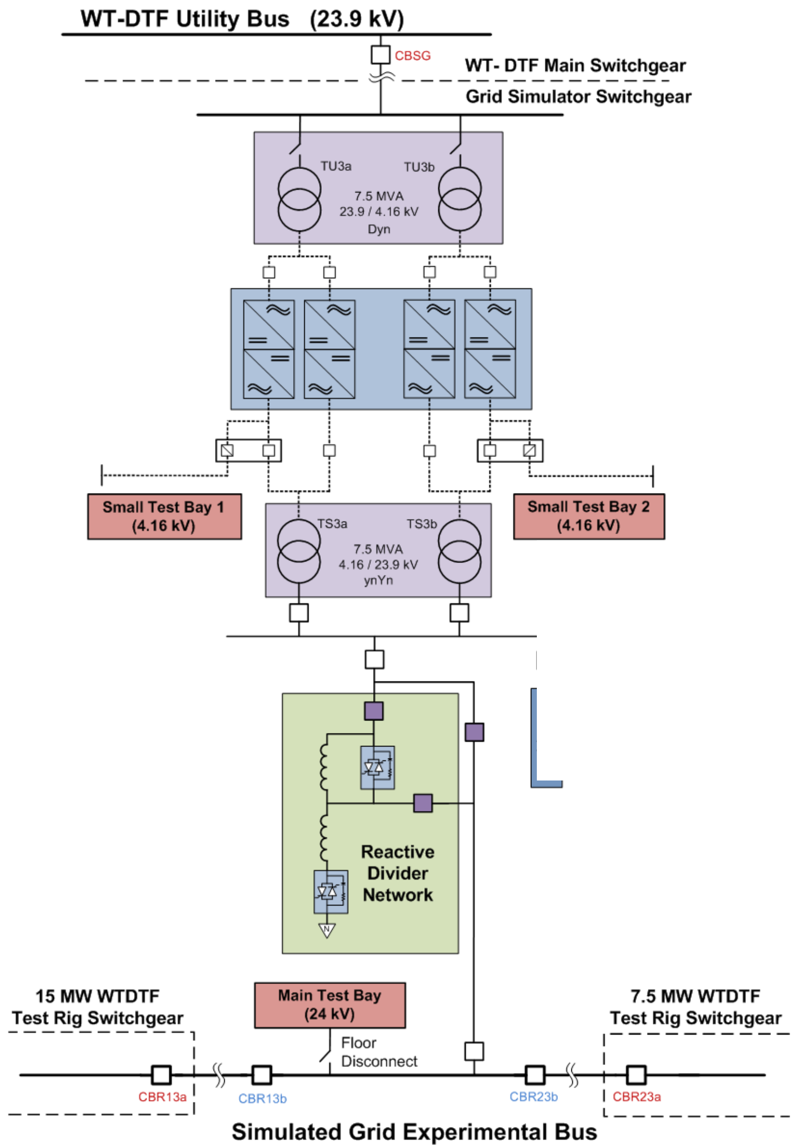
Preliminary simulations show excellent results with 2 kHz switching frequencies

First noise mode is at 16 kHz (Fs x 2 x Carriers) , 8 times the switching frequency

Reference resolution also at 12 kHz using asymmetrical sampling

System Specifications: Three independent test cells that can be recombined into full system capacity of 15 MW.

Overall Facility Electrical Capabilities	
Main Test Bay	
Nominal Voltage	24 kV (50/60 Hz)
Nominal Power	15 MVA (7.5 MVA)
Frequency Range	45 to 65 Hz
Sequence Capabilities	3 and 4 wire operation
Overvoltage capabilities	133% Continuous Overvoltage
Fault Simulation	Yes (includes Reactive Divider)
Hardware-In-the-Loop	Yes
Small Test Bay 1	
Nominal Voltage	4160 V (50/60 Hz)
Nominal Power	3.75 MVA (3 MW @ 0.8 PF)
Frequency Range	0 to 800 Hz
Sequence Capabilities	3 and 4 wire operation
Overvoltage capabilities	133% Continuous Overvoltage
Fault Simulation	Limited to Converter Only
Hardware-In-the-Loop	Yes
Small Test Bay 2	
Nominal Voltage	4160 V (50/60 Hz)
Nominal Power	3.75 MVA (3 MW @ 0.8 PF)
Frequency Range	0 to 800 Hz
Sequence Capabilities	3 and 4 wire operation
Overvoltage capabilities	133% Continuous Overvoltage
Fault Simulation	Limited to Converter Only
Hardware-In-the-Loop	Yes

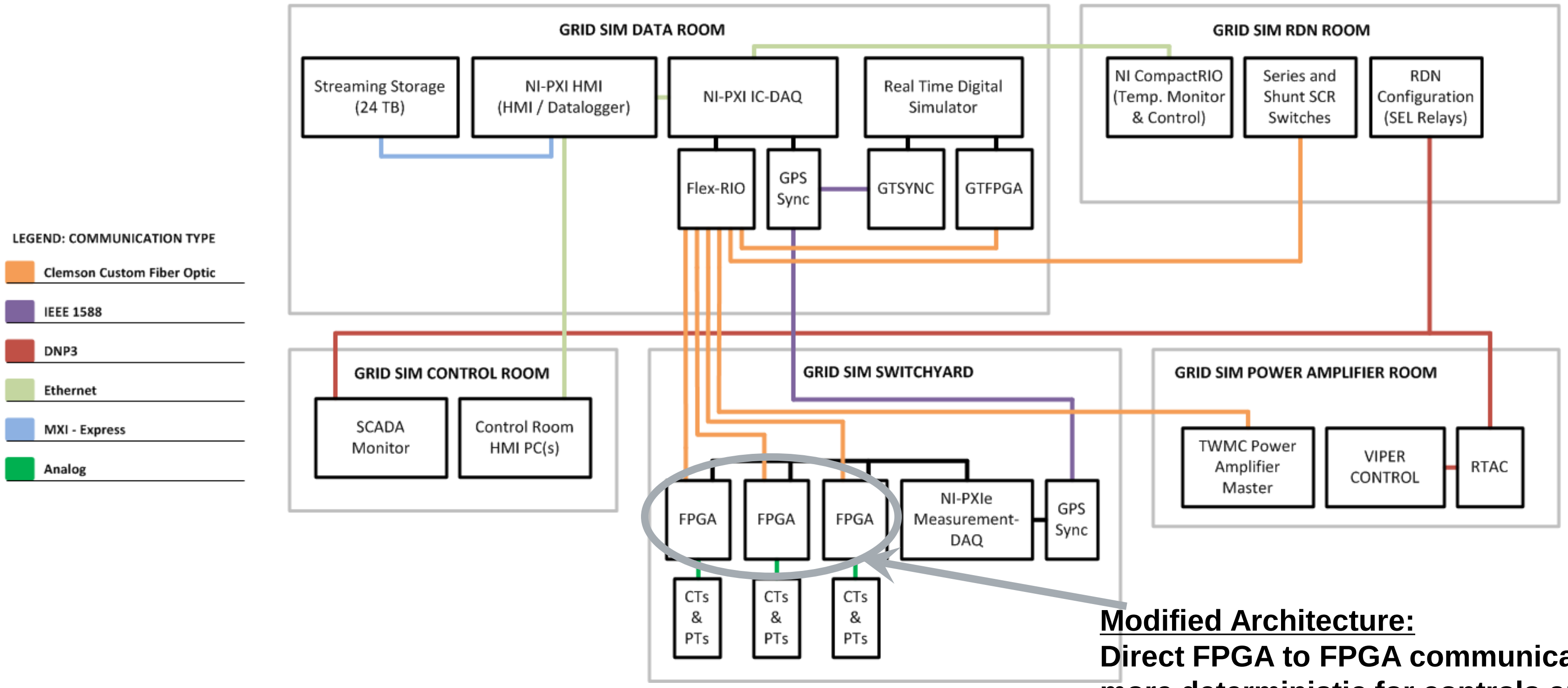


Control & Data Acquisition

- Detailed specifications developed through coordinated efforts between:

Savannah River National Laboratory	Clemson University	National Instruments

- Significant amount of hardware and software shared with the WTDTF systems
- Provides a powerful and flexible platform for the development of custom control systems to meet the various grid integration evaluation scenarios



Modified Architecture:
Direct FPGA to FPGA communication, more deterministic for controls applications.

Amplifier Room

Reactive Divider

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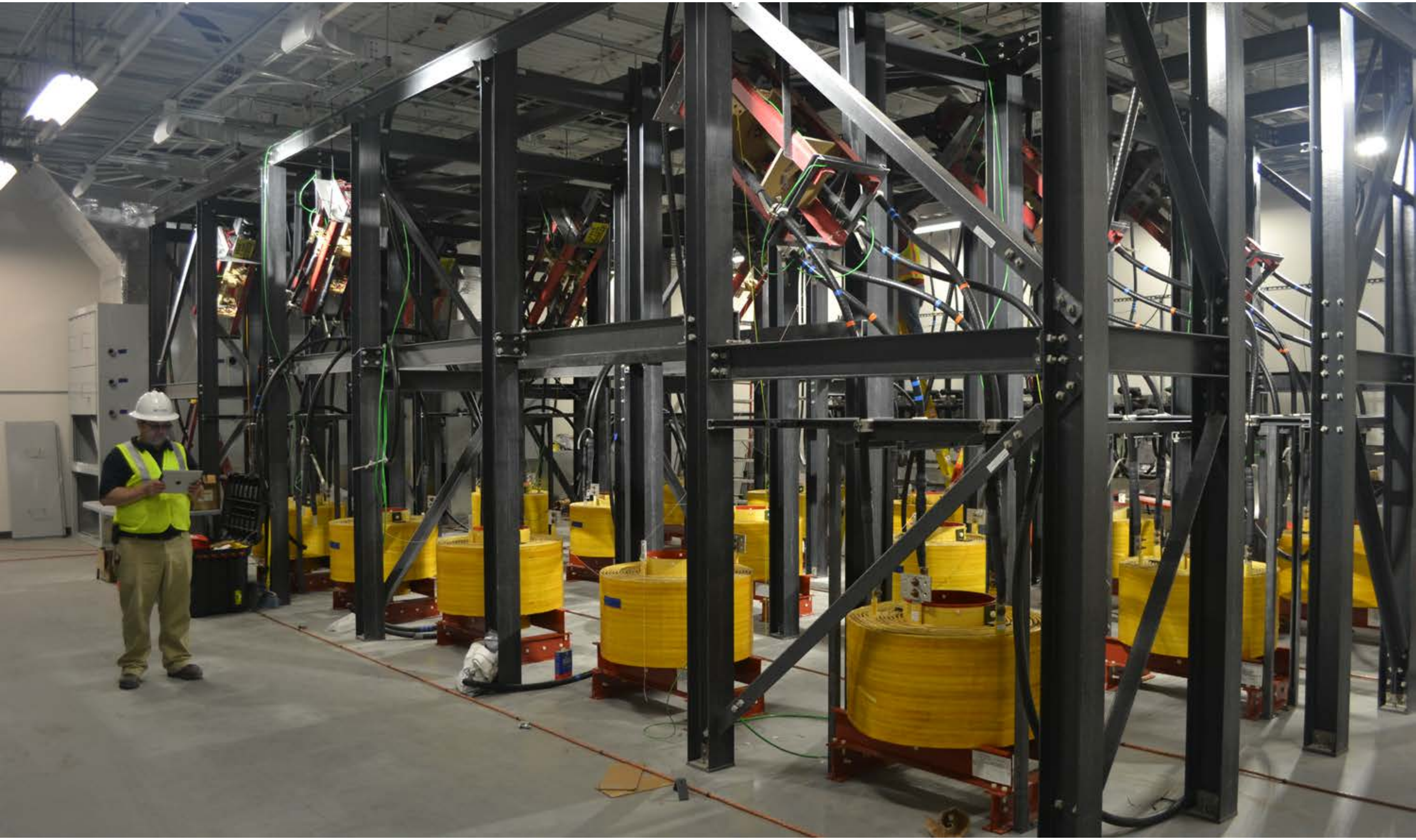

Substation

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Project Plan & Schedule

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Summary	
WBS Number or Agreement Number	
Project Number: DE-EE0005723	
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: 15 MW HIL Grid Simulator												
Task 1: Develop 15 MW HIL grid simulator specification												
Task 2: Complete detailed design of system topology												
Task 3: Complete the basis of design of facility infrastructure												
Task 4: Facility staffing												
Task 5: Complete detailed design of facility infrastructure												
Task 6: Construction of facility												
Task 7: Develop safety program												
Task 8: Commissioning of facility												
Task 9: Facility accreditation												
Task 10: Facility business plan												
Current work and future research												
Complete commissioning of equipment												
Integrate DC power source into system												
Integrate new harmonic controller for more robust power quality testing												

Project Plan & Schedule

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Comments

- Original scope called for a single test bay (connection). Based on input from industry, scope was revised to include 3 separate test bays that can be reconfigured into one if full 15 MW power level is required.

- Original scope called for manual configuration of tap switches for reactive divider. Based on input from industry and safety consultants, reactive divider network was redesigned for automatic setting of tap switches for safety purposes.

- Construction of facility did not begin as planned due to complex design of reactive divider room taking longer than anticipated.

- Commissioning of full system delayed by 2 months due to delay in arrival of key equipment and final wiring of system.

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators:

TECO Westinghouse Motor Company
Savannah River National Laboratory
AEC IDOM Engineering
MC Dean
Duke Energy
Santee Cooper
National Instruments
Choate Construction
Underwriters Laboratory
Prysmian Cables
SCANA
NREL NWTC

Communications and Technology Transfer:

- US Patent Application #13943200 Hybrid Reactive Divider Network
- Website Developed (clemsonenergy.com)
- > 150 national and international media reports on project.
- 79 presentations given to industry, academia and interested organizations.
- 5 technical papers submitted to industry conferences.
- 4 webinars held for industry, US DOE and academia.
- Hosted Technical Workshop on 11/21/13 with 115 participants.
- Co-hosted Technical Workshop with NWTC on 06/13 with 45 participants.
- Hosted management teams from Duke Energy, SCANA, Santee Cooper, Hydro-Quebec, Excelon, Shanghai Electric, Southern Company and others.

FY14 Tasks

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- Complete wiring of grid simulator.
- Complete planned commissioning activities.
- Begin FRT with wind turbine specimen.
- Hardware in the loop base case scenario development.
- Developing new testing protocols for harmonics.
- Prototype novel harmonic controller that will reflect true harmonic impedances for onshore and offshore wind turbine applications.
- Design and build a 2.5MW DC power supply front end that can utilize a portion of existing inverter capacity.
- Integrate maximum power point tracking (MPPT) PV array emulation on the DC supply.

Future Research: Coupling of Technologies

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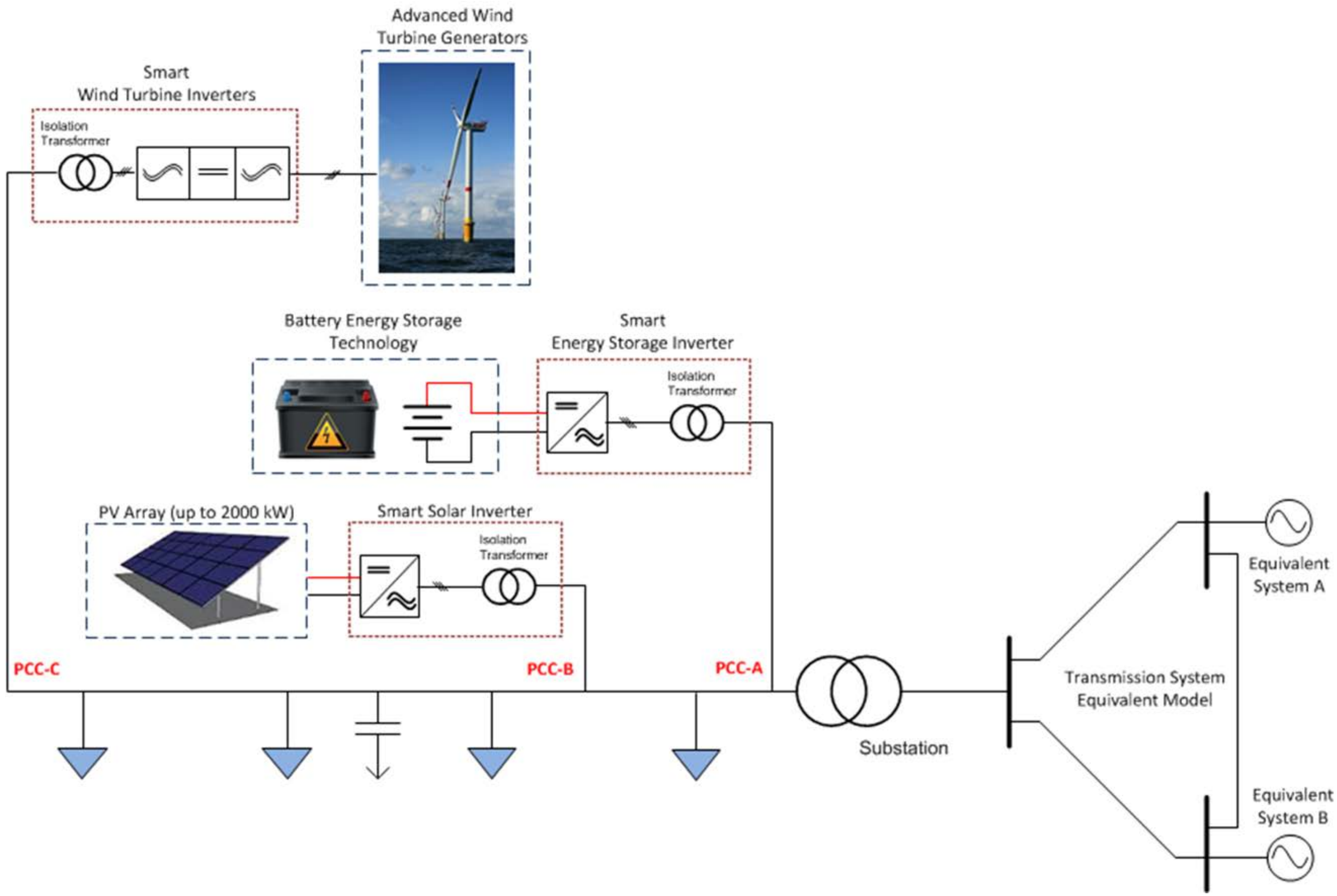
Representative model of a system consisting of wind power , solar and energy storage



Future Research: Coupling of Technologies

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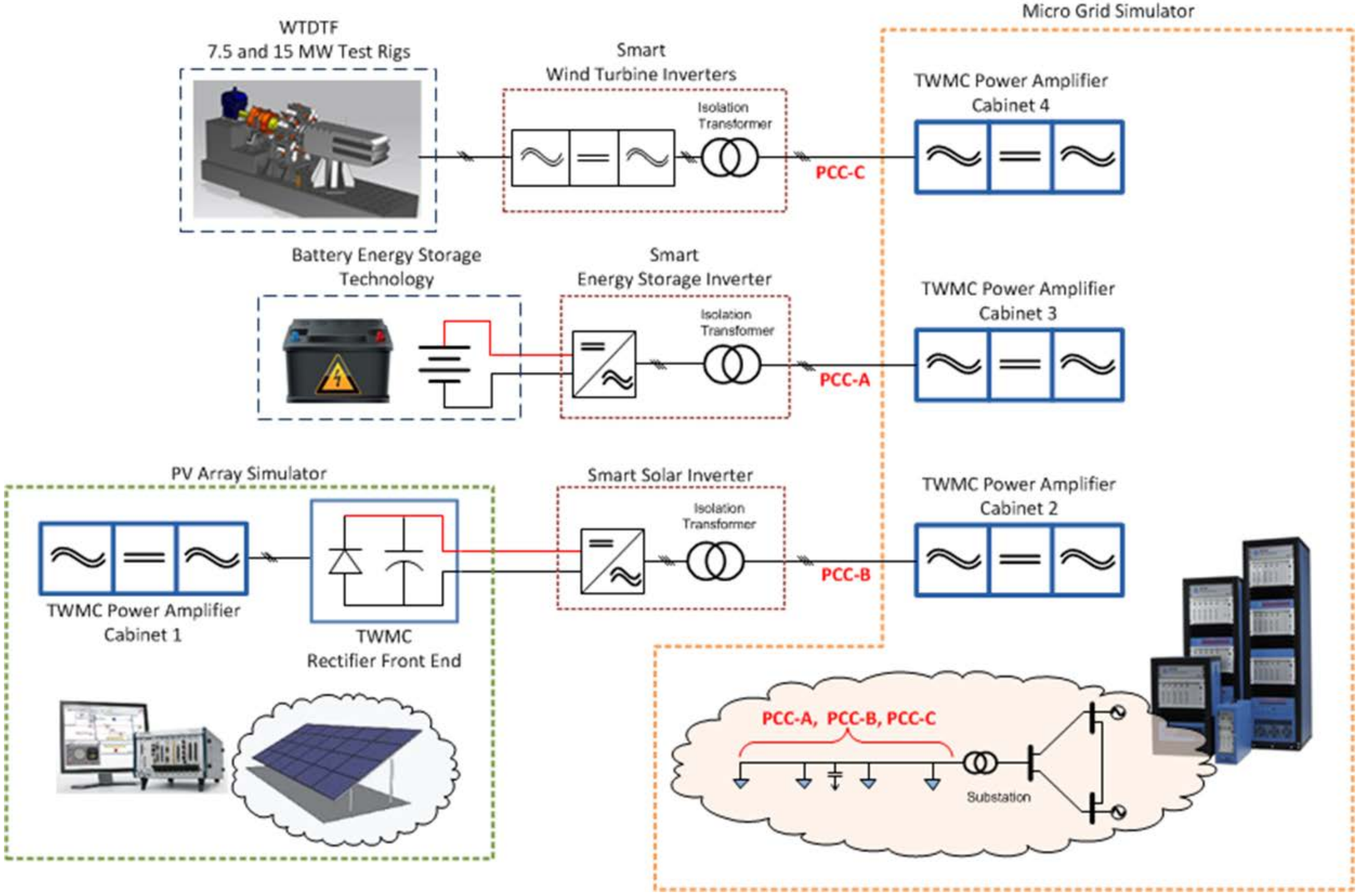
Configuration of grid simulator for HIL studies.



Future Research: Distributed Control and Cyber Security

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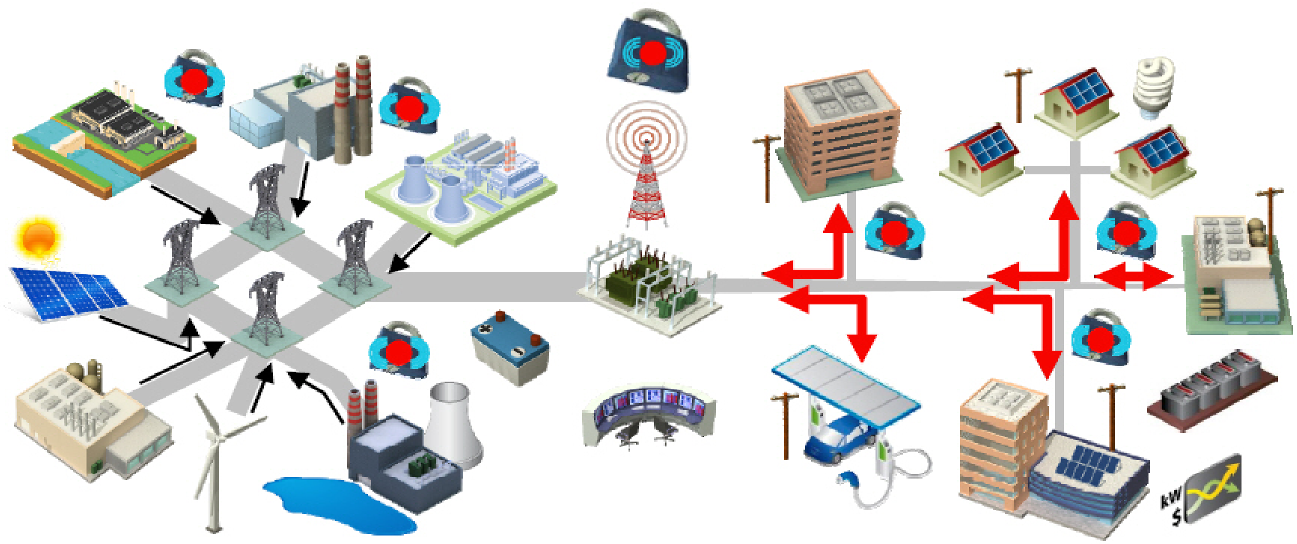
How the grid simulator can aid in development and demonstration:

- Advanced Hardware-in-the-Loop testing can simulate power system events with full scale devices attached to the simulated power system
    - Distributed control hardware, software and communication elements can be deployed on the simulated power system
        - Cyber attacks, communication losses and equipment disruptions can be evaluated on the distributed control devices integrated with the HIL power system simulations



Tomorrow's Power System: A Smart Grid

Figure Source: EPRI

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

National Wind Technology Center

Test Facilities – Field: DOE Turbine Facilities and Test Sites O&M

Dave Simms

NREL

david.simms@nrel.gov

Budget, Purpose, & Objectives

NWTC Test Facility Capabilities

- **Field**
  - Field test sites and infrastructure
  - DOE 1.5, Industry MW turbines
  - Controls Research Turbines (CART)
  - Research-grade inflow meteorological data
  - Small turbine testing
- **Drivetrain**
  - 225 kW, 2.5 MW, 5.8 MW dynamometers
  - Dynamic torque testing of fully integrated drivetrain systems or components (gearboxes, generators, PE)
  - HALT, condition monitoring
  - Model-in-the-loop to simulate turbulence
  - Non-torque loading (NTL) to impart rotor loads
- **6.3 MW Controllable Grid Interface**
- **Structural**
  - Test stands, hydraulic actuators
  - Accredited (A2LA) fatigue (resonant) and static testing of blades (up to 50 m in length) to IEC standards
  - Modal and property measurements, profiling, NDT methods
  - Innovative test methodology R&D
  - Massachusetts large blade test facility partnership
- **ISO 17025, A2LA accredited to IEC Standards**
  - Power performance, power quality, acoustic emissions, structural loads, duration, Safety & Function
- **Custom**
  - Testing to meet R&D needs (e.g., data for model validation, proof-of-concept)
  - Explore applicability of advanced sensors, DAS

Budget, Purpose, & Objectives

NWTC Field Test Sites

NWTC is a terrific extreme-event field test site

- Full-scale turbine testing under extreme conditions
  - Data to test design margins and validate code extrapolation
  - Exceptionally high turbulence, frequently exceeds IEC Class A
- Highly variable and diverse winds October to May
  - Quickly fill test matrices
- Mild winds in the summer
  - Allows for test article and test apparatus installation, calibration, reconfiguration
- Meteorologically, perhaps the best characterized wind test site in the world
- Accredited testing
- Comprehensive safety
- Experienced testing staff, international reputation for excellence
- Supporting infrastructure and equipment
- Efficient resource sharing

Budget, Purpose, & Objectives

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

Total DOE Budget[1]: $2.750M

Total Cost-Share[1]:$0.000M

Problem Statement: Ensure safe and reliable operation and maintenance of field test facilities at DOE's NWTC.

Impact of Project: Provides field test facilities to support R&D and industry.

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

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
MW Turbines at the NWTC

DOE 1.5 MW
- Model: GE 1.5-SLE
- Tower height: 80 m, Rotor diameter: 77 m
- DOE owned—to be used for research and education
- Turbine commissioned Sept 2009 at Site 4.0

DOE Owned, Operated and Maintained

Siemens 2.3 MW
- Model: SWT-2.3-108
- Tower height: 80 m, Rotor diameter: 108 m
- Siemens owned and operated
- Multi-year, cost-shared R&D CRADA—aerodynamics and rotor performance
- 101 m turbine commissioned Oct 2009 at Site 4.4, rotor change to 108 m November 2013

Industry Partner Owned, Operated and Maintained

Alstom 3 MW
- Model: ECO 110
- Tower height: 90 m, Rotor diameter: 110 m
- Alstom owned and operated
- Multi-year Funds-In Agreement—testing, R&D
- 100 m turbine commissioned April 2011 at Site 4.1, rotor changed to 110 m February 2013

Gamesa 2 MW
- Model G97
- Tower height: 90 m, Rotor diameter: 97 m
- Gamesa owned and operated
- Multi-year Funds-in Agreement—testing, R&D
- Class III Turbine commissioned November 2011 at Site 4.5, removed and replaced with G97 Class II machine and commissioned March 2013

Technical Approach

NWTC Controls Research Test Facilities CARTs

- Two DOE-owned 600 kW turbines
  - Custom-configured to satisfy Program and industry controls RD&T needs
  - All turbine, met, and site information available and unrestricted public domain (i.e., machine properties, airfoil shapes, structural models, control, and DAS systems)
- Unique capabilities
  - Demonstrate the performance of advanced multi-variable control algorithms through field testing (i.e., load-mitigating state-space independent blade pitch algorithms; advanced sensors, including integrated remote inflow-sensing devices such as LIDAR)
  - Each with an upwind meteorological tower extending above rotor height
  - Full turbine system structural, drivetrain, and inflow <u>data available as real-time control parameters</u> (more than120 channels per turbine at ~100 Hz data rate)
  - High-rate pitch and full power conversion systems
  - Real-time in-the-loop turbine control simulation
  - Overriding supervisory turbine control systems enable safe testing of advanced prototype control concepts
- Many R&D partners

Technical Approach
NWTC Meteorological Towers

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- Two 135 m and one 80 m met towers
  - Research-grade inflow measurements at multiple heights
  - Wind speed (sonic and cup anemometers), direction, temperature, humidity, pressure used to derive wind shear, turbulence, air density, stability
  - Characterize atmospheric conditions that affect turbine responses
  - Reference for ground-based LIDAR and SODAR comparison
  - Service lifts ease instrument access and replacement
  - 80 m tower has 12-year Web-based archive
- Additional towers at test sites (~12)
  - Custom-configured to support turbine testing
  - Typically located two rotor-diameters in the predominant upwind direction—often height extends above rotor plane

Technical Approach

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- Keep DOE-owned turbines maintained and operating safely
  - Mechanical and structural (e.g., blades, rotors, pitch and yaw drives, hydraulics, elevators)
  - Electrical (e.g., generators, power converters, electrical switch gear, slip rings, UPS systems)
  - Control systems, computers and data acquisition systems, and integrated safety systems
- Keep research-grade instrumentation and data acquisition systems on DOE-owned turbines and meteorological towers calibrated and operational to obtain high-caliber R&D test data in accordance with researcher and DOE/ NREL QA requirements
- Engineering design, analysis, and verification of custom equipment and instrumentation

Accomplishments and Progress

- DOE 1.5
  - Completed design, specification and installation of research-grade mechanical loads measurement system, including rotor fiber-optic rotary coupling, foundation instrumentation
  - Annual and semiannual maintenance and repair by GE Field Service Maintenance
- Unconventional operation of custom CART machines
  - Frequent inspections, troubleshooting/repair/rebuilding of components due to service hours, stock/replace worn, failed, obsolete, or damaged components (e.g., extreme testing, weather)
- Met Towers
  - Maintained required calibrations of Site 4.0, Site 4.4, M2, and CARTs instrumentation
  - Inspections after extreme events (i.e., wind, lightning)
- Maintain annual certifications on the CART turbine elevators and met tower personnel lifts
- Repairs and upkeep of the NWTC site data sheds and field-site testing infrastructure, including electrical
- Maintain field-testing data acquisition/ processing/ analysis methods and tools to keep up with changing researcher needs, IEC standards
- Supported DOE roll-out of small turbine IEC testing to Regional Test Centers

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: NWTC Field Testing Operations & Maintenance												
Q1 Milestone: Complete the annual scheduled elevator certifications on the CARTs												
Q2 Milestone: Complete required annual maintenance on the DOE 1.5 MW turbine												
Q3 Milestone: Components for DOE 1.5 MW DAS/instrumentation upgrade												
Q4 Milestone: Complete yearly scheduled maintenance on the CARTs												
Q1 Milestone:Complete cal/change out of all instrumentation on the M-2, Site 4.0, and Site 4.4 met towers												
Q2 Milestone: Complete required annual maintenance on the DOE 1.5 MW turbine												
Q3 Milestone: Complete upgrade of DOE 1.5 MW DAS/instrumentation												
Q4 Milestone: Complete yearly scheduled maintenance on the CARTs												

Comments

- All milestones completed on time and within budget

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators

- Industry partners
- Subcontractors supporting field test O&M
  - Mountain States Crane Services
  - Navarro Engineering—mechanical engineering and data acquisition programming support
  - Windward Engineering—mechanical test engineering and technician support
  - TCB—data acquisition system programming support
  - GE—turbine maintenance and repair

Communications and Technology Transfer

- Historical archive of 12 years of NWTC site meteorological data from 80 m M2 tower
- Support industry partners
  - Specialized field test methods (i.e., flow visualization, turbine instrumentation)
  - IEC field-testing methods
- Field-testing results inform development of standards

Next Steps and Future Research

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NWTC Test Facility Schedule – Large and Small Turbine Field Test Sites

FY 2014: Jan, Feb, Mar, Apr, May, Jun, Jul, Future

DOE GE 1.5MW (Site 4.0)
- Turbine operated & maintained for electrical power generation (curtailed to remain within NWTC 10MW limit)
- Gearbox oil condition monitoring

Alstom 3MW (Site 4.1)
- IEC S&F, noise testing
- IEC Power Performance testing with flow modifiers
- Flow Visualization Phase II

CART 3 600kW (Site 4.2)
- Active power control testing (CU Boulder)
- Zephir nacelle-mounted LIDAR testing
- Opto-Atmospheric nacelle-mounted LIDAR preliminary evaluation
- Zephir hub-mounted LIDAR testing and verification for feed-forward controls (DTU-Wind)
- Independent pitch control testing for blade load mitigation

CART 2 600kW (Site 4.3)
- Field testing of improved closed-loop System Identification algorithm (CENER)
- Upgraded Avent LIDAR testing for feed-forward collective pitch control
- Aeroacoustic array noise identification and reduction (CSM)

Siemens 2.3MW (Site 4.4)
- 108m rotor aerodynamic, structural & atmospheric inflow data acquisition

Gamesa 2MW (Site 4.5)
- IEC PP testing on G97 Class II with updated controls

Xzeres (Site 1E)
- Xzeres product line RDD&D

Small Turbines (Site 3.2)
- Anemergonics SBIR tower testing on Skystream, Air Dolphin, Air Breeze & Pika turbines

Small Turbines (Site 3.3)
- Genuine 20kW VAWT IEC testing
- Urban Green Energy Site 3.3a (DWT R&D VAWT)

NPS 100 kW (Site 1.2)
- Turbine operated & maintained for electrical power generation

Activity Key: DOE- EERE Program | Cooperative Agreement | Funds-In Agreement

Wind Power Peer Review

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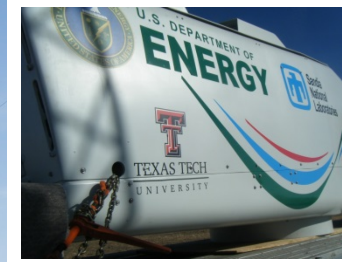

DOE/SNL SWiFT Facility

Development of the DOE/SNL Scaled Wind Farm Technology Facility

Jonathan R. White, Ph.D.

Sandia National Laboratories

jonwhit@sandia.gov, 505-284-5400

3/25/14

Budget, Purpose, & Objectives

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Total DOE Budget[1]: $1.859M

Total Cost-Share[1]:$3.250M

Problem Statement: A world-class, public, open-source testing facility is required to develop wind-plant technology from basic research up to commercialization.

Impact of Project: Lower cost of energy with innovative advancements to wind energy, developed in the most rapid and cost-efficient process possible.

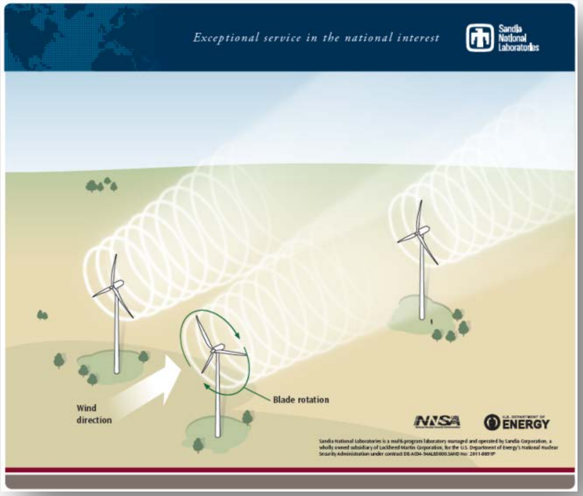
This project aligns with the following DOE Program objectives and priorities:

- ✓ **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
- ✓ **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 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*

Relevance to Industry

Provide a public, open-source, experimental wind-plant facility with a validated model that can be used by international consortia of industry, academia, and national laboratories to:



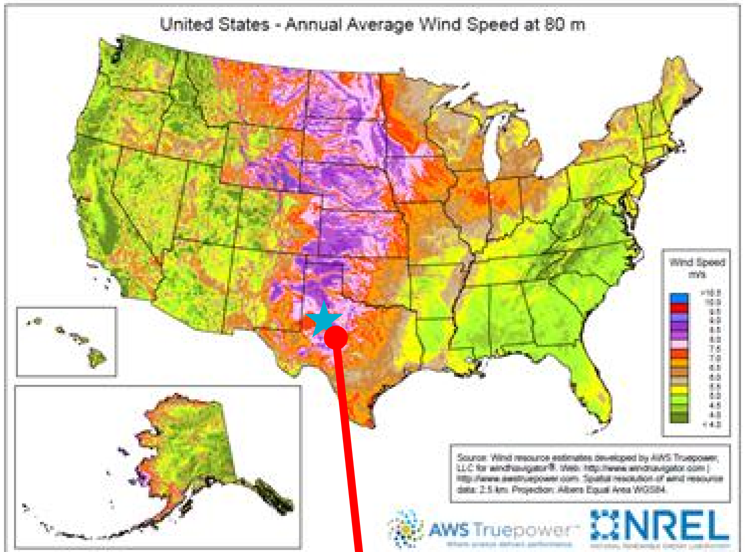
1. Reduce power losses and damage caused by turbine-turbine interaction through study of complex wake flows
2. Enhance wind-plant energy capture by developing the next generation of rotor technology
3. Perform rapid, cost-efficient research in aeroacoustics, aeroelasticity, aerodynamics, and reliability

Technical Approach

Innovating wind-energy plants requires:

1. High winds in a consistent direction to minimize measurement time
2. Flat terrain to minimize uncertainty for validation campaigns and to allow the discrete addition of well-understood, man-made terrain features.
3. Open-source wind turbines that do not have restrictions to enable cross-cutting collaborative research between laboratories, industry, and academia
4. An on-site, research-quality assembly building to prepare experiments and create rapid-response testing components
5. An open-source, variable-speed controller that is integrated with data acquisition system to facilitate collaborative research
6. A site-wide time-synchronized control and data-acquisition network to allow direct, time-based data analysis, instead of statistical representations
7. Cost efficient testing required to enable high-risk early-stage technology
8. A functional scaling methodology (including limitations) to transfer technology development to current and <u>future</u> utility-scale

High, Consistent Wind Is Key to Rapid Research Execution

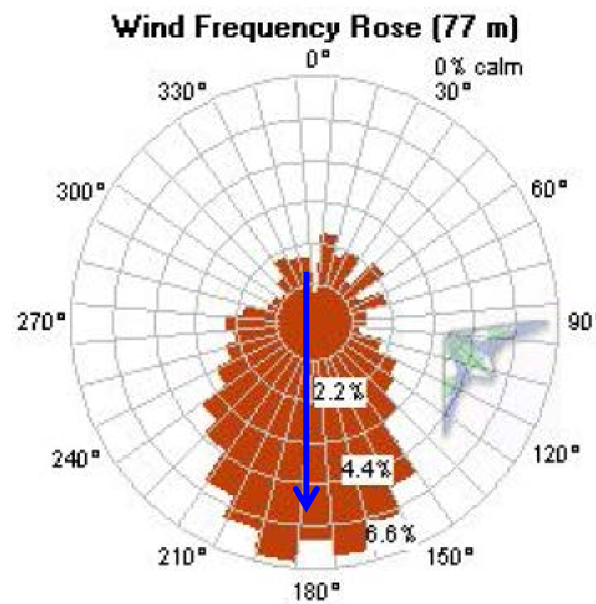


Location is in the best part of the US wind corridor—with favorable weather year-round and the most US wind installations: 12 GW and continued growth.

TEXAS TECH UNIVERSITY

Consistent high data rate and efficient research execution due to:

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



Taking Advantage of Consistent Wind Direction

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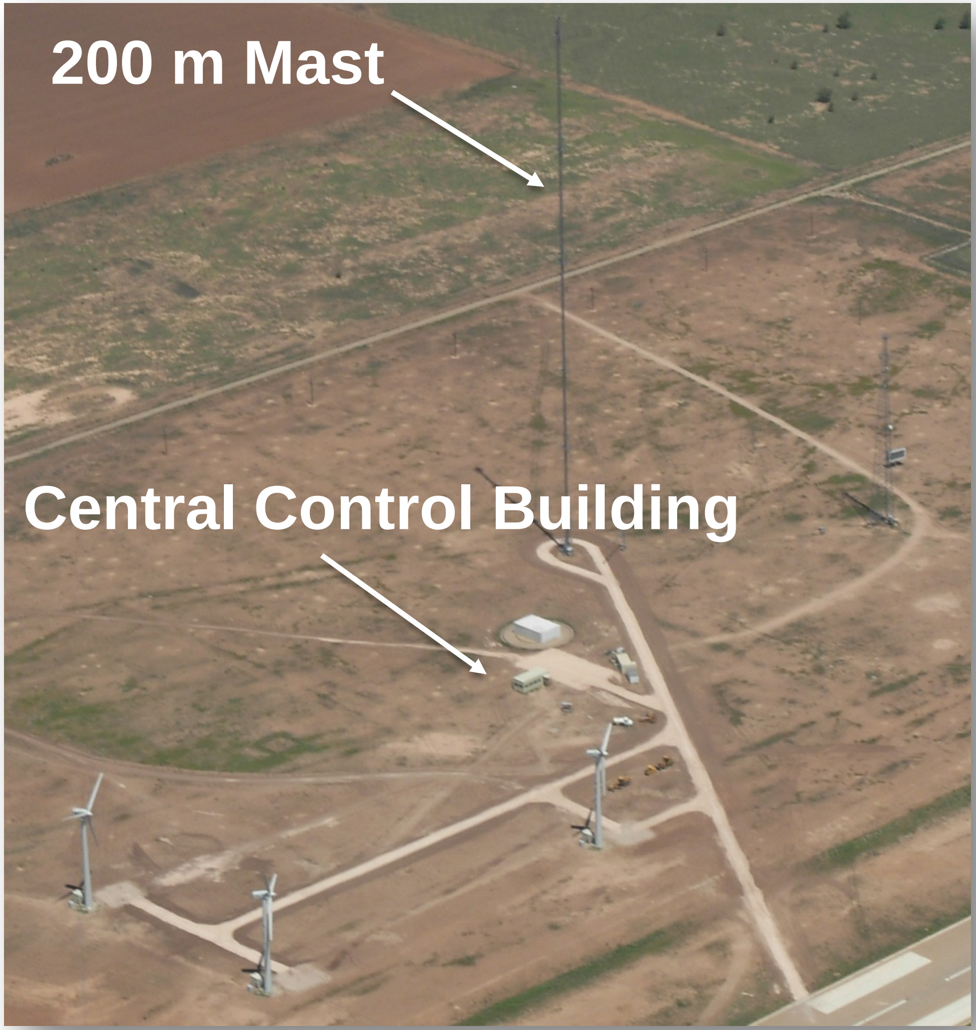
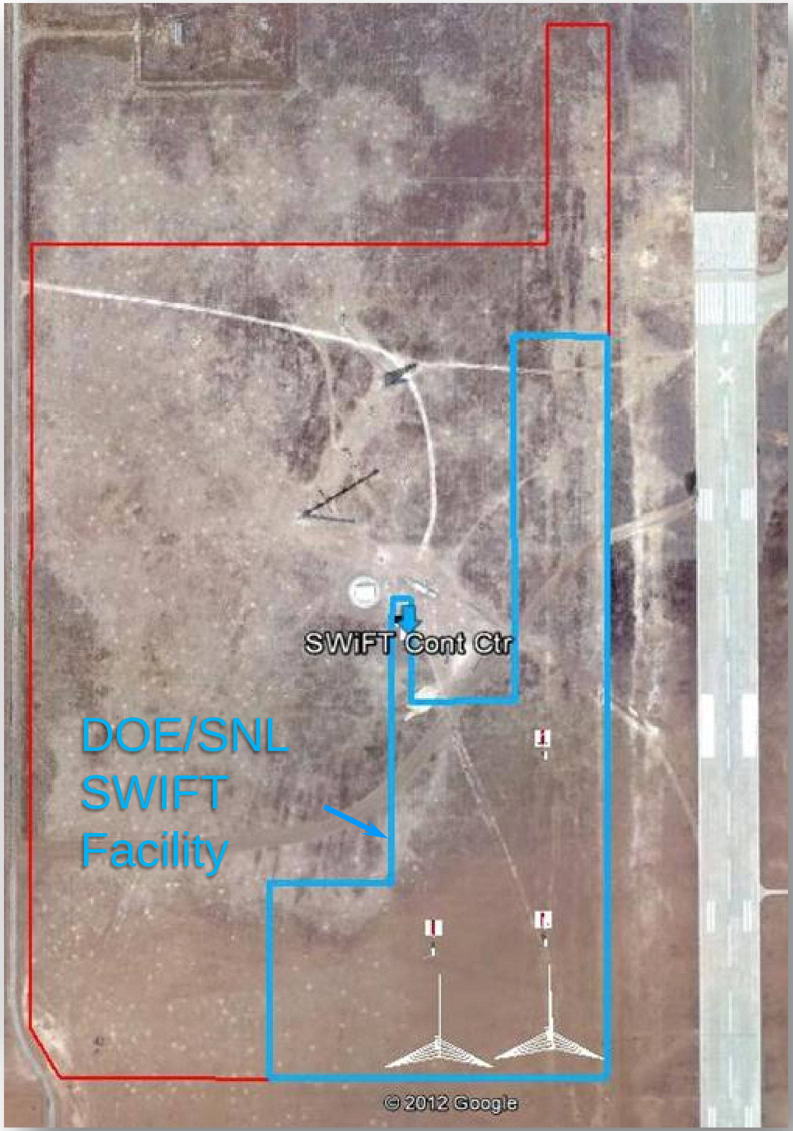
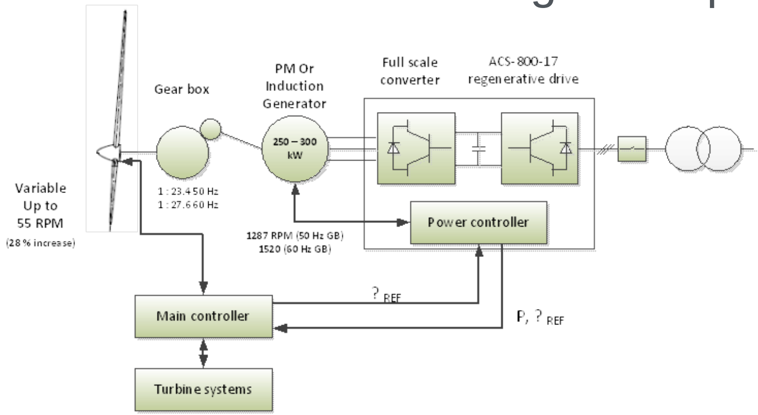




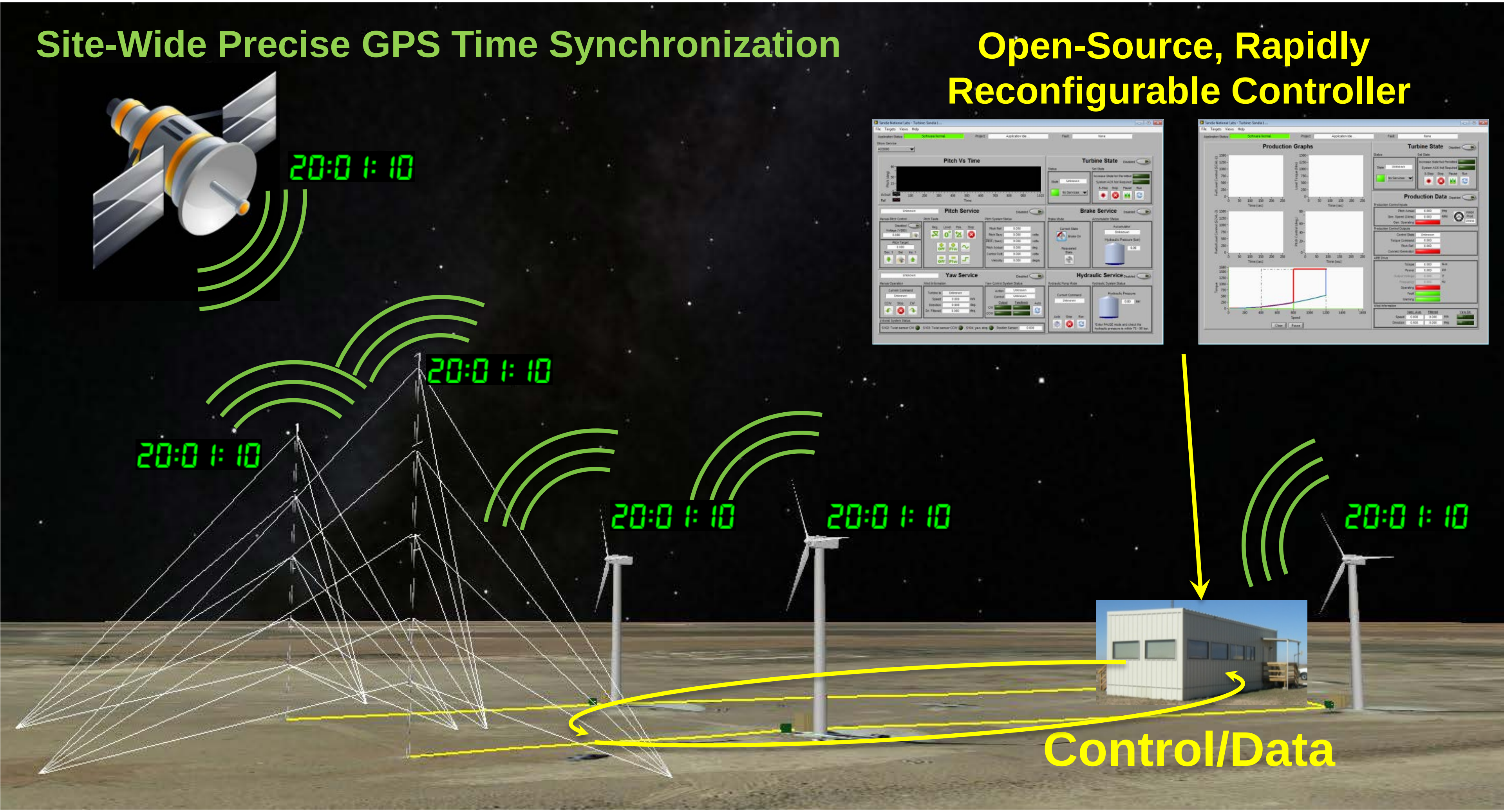
Open-Source Wind Turbines

Fully documented open source hardware, developed in collaboration with Vestas

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



Comprehensive and Easy Controls Integrated with Site-Wide Measurement System



On-site Workshop Allows Fast Turn-around and Rigorous Preparation

- 4,500 sq. ft. high-bay for experimental rotor preparation and calibration
- 1,000 sq. ft. machine shop to produce unique, critical, and rapid-turnaround parts
- Environmentally controlled, with high-intensity lighting

Accomplishments and Progress

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

- Developed public, open-source variable-speed controller for SWiFT
- Installed three wind turbines & two meteorological masts without (safety) incident
- Performed rigorous characterization tests on component and full-system scales, to ensure the accuracy of a public wind-turbine model
- Commissioned three wind turbines—are being readied for open-source R&D
- Trained and employed technician and operational staff, in partnership with Texas Tech
- Refurbished a comprehensive on-site workshop for research preparation

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: Scaled Wind Farm Testing Facility Development												
SNL/USDA Bushland Facility												
Q2 Milestone: SMART Rotor Test and Data Collection												
Q3 Milestone: SNL/LANL SHM Rotor Test												
Q4 Milestone: Decomission USDA-Bushland Facility												
SWiFT Facility												
Q1 Milestone: Detailed Facility Planning												
Q1 Milestone: Procure and Refurbish Wind Turbines												
Q2 Milestone: SWiFT Construction												
Q1 Milestone: SWiFT Commissioning												
Current work and future research												
SWiFT Baselining, Verification and Validation												
Wake Imaging System Preliminary Field Testing												

Comments

- Facility technical capabilities and agreements designed through 2022
- Two unsuccessful turbine procurements and a protracted refurbishment accounted for most significant four-quarter delay
- Outstanding refurbishment issues added one quarter to construction

Research Integration & Collaboration

Partners, Subcontractors, and Collaborators:

2 OEMs: Vestas*, GE**

15 Companies: Group NIRE*, ATA Engineering*, Micron Optics*, National Instruments*, GL-DNV*, Broadwind*, ABB*, CC Jensen*, Cascade, Baker, Met One, Thies, ATI Inc., Rohn, GearWorks, Halus

3 Laboratories: NREL, SRNL, LANL

5 Universities: TTU, U-Minnesota, UC-Davis, Texas A&M, Purdue

*Providing cost-share **Providing advisory guidance

Communications and Technology Transfer:

Technical Presentations: 2014 AIAA ASME Wind Energy Symposium, 2013 SNL Reliability Workshop, 2012 SNL Blade Workshop

Technology Transfer: Rotor Fiber Optic Instrumentation methods to Vestas, Variable Speed Controller to ABB, SWiFT Facility Commissioning, Public SWiFT Wind Turbine Model, Public Open-Source Variable Speed Controller

Next Steps and Future Research

FY14/Current Research:

- SWiFT Baselining Project: Verify and validate instrumentation/data, site operations, and turbine performance in preparation for future DOE and collaborative R&D projects. Create a website to transfer SWiFT models, documentation and data to collaborators.
- Wake Measurement System: Preliminary field deployment of high-resolution wake-imaging measurement system.

Proposed Future Research:

- Development of functional scaling methods in partnership with National Rotor Testbed, TTU Ka-band Radars and OEMs
- Detailed characterization and control of scaled wake structures to increase wind-plant performance
- Wake merging, meandering, and complex deep array studies
- Advanced rotor designs with passive and active load control
- Rotor aero-acoustic generation and propagation measurements

Basic Turbine to Turbine Interaction

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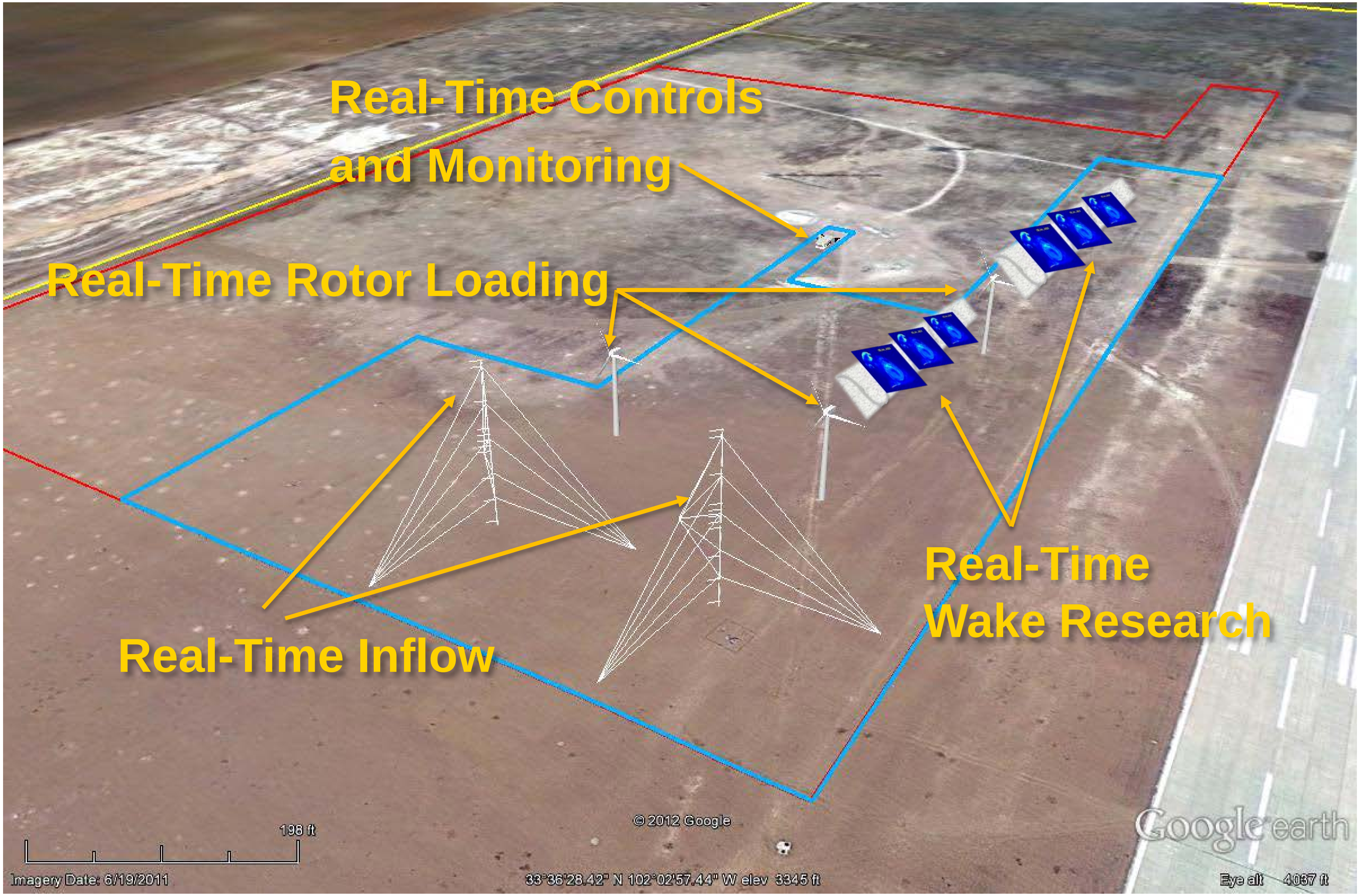

Deep-Row Wake Deficit and Meandering Studies

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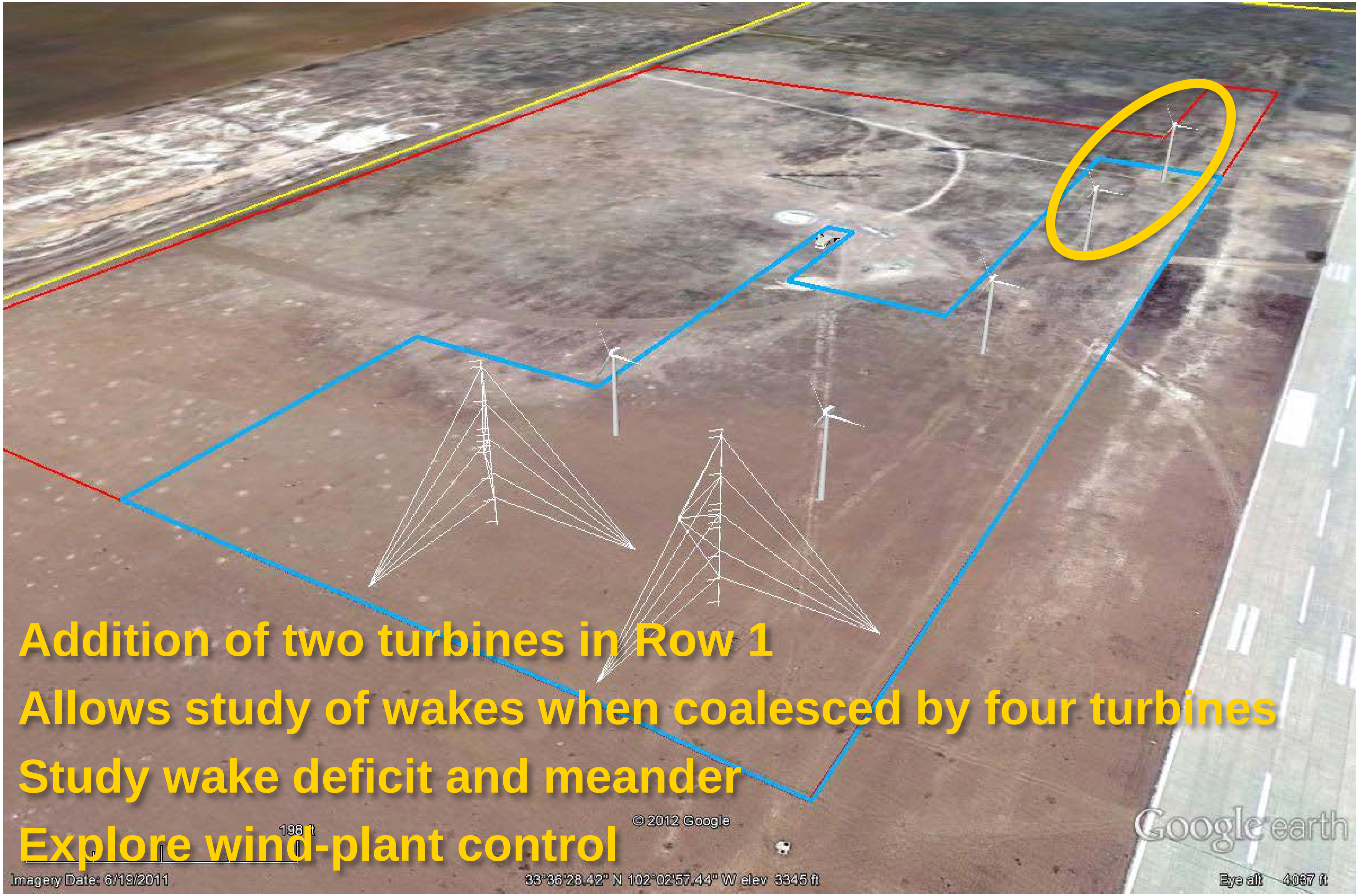

Addition of two turbines in Row 1

Allows study of wakes when coalesced by four turbines

Study wake deficit and meander

Explore wind-plant control

Complex Lateral Wake Merging and Meander

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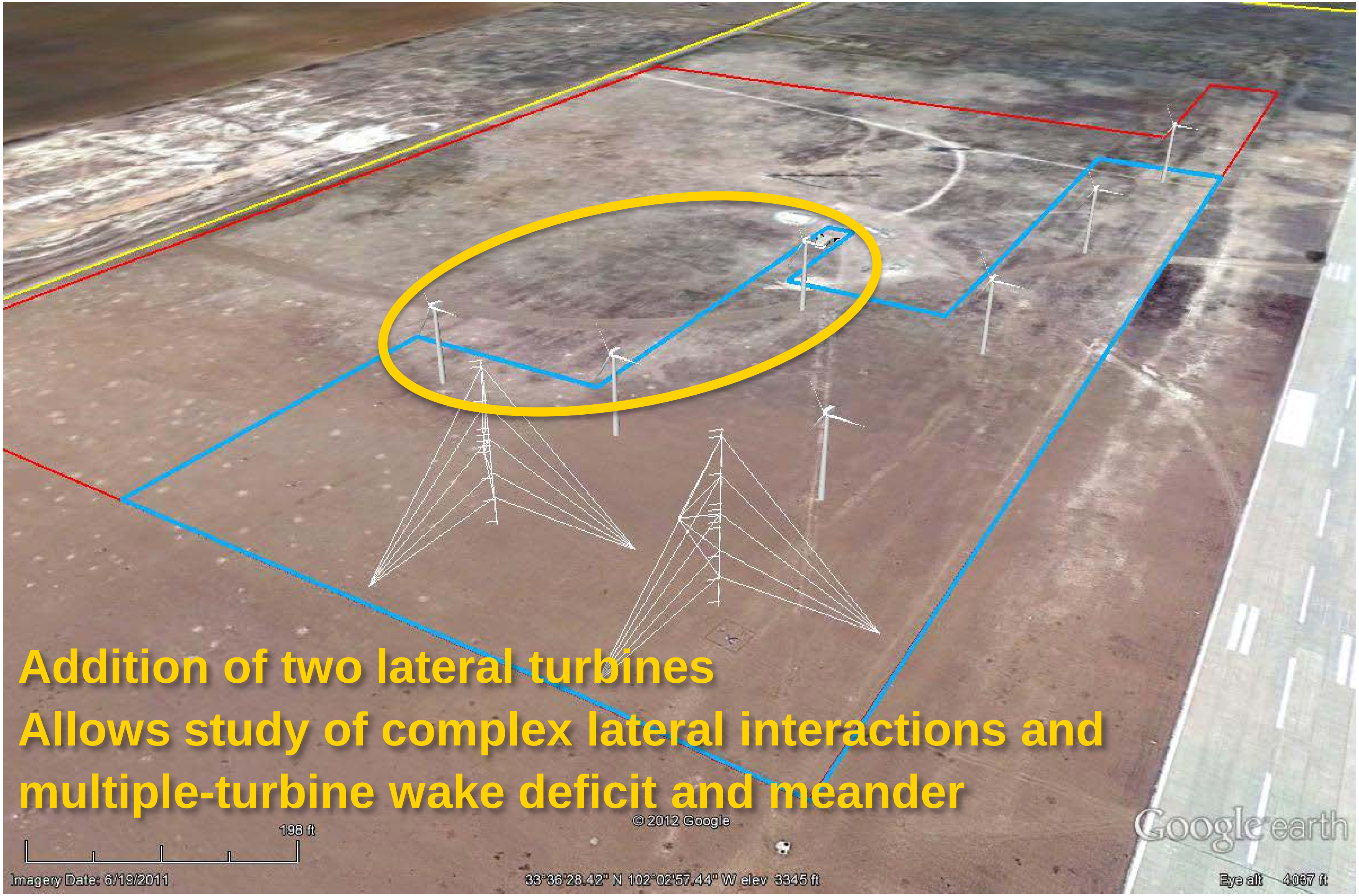
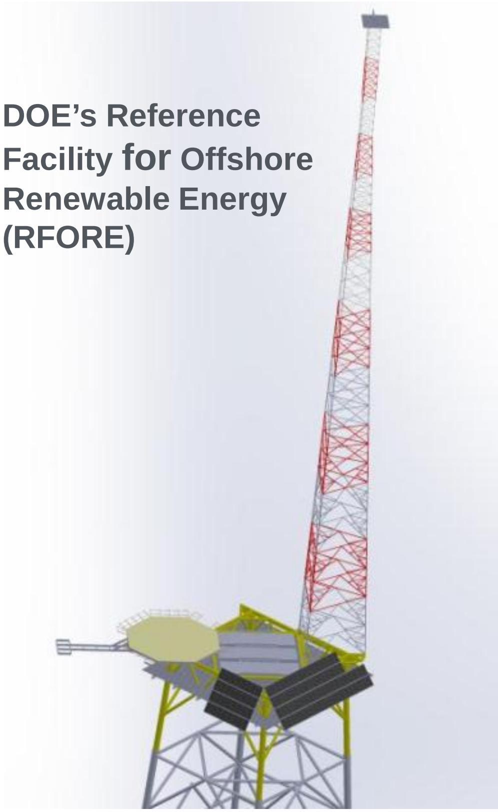


Addition of two lateral turbines

Allows study of complex lateral interactions and multiple-turbine wake deficit and meander



Reference Facility for Offshore Renewable Energy: Chesapeake Light Tower

Jim Green, NREL
jim.green@nrel.gov – 303-384-6913

Will Shaw, PNNL
will.shaw@pnnl.gov – 509-372-6140

March 24, 2014

Budget, Purpose, & Objectives

Total DOE Budget[1]: $4.150M

Total Cost-Share[1]:$0.000M

Problem Statement

- No continuing wind resource data at hub height in U.S. coastal waters
- Lack of data for evaluation of offshore wind and turbulence models
- Lack of environmental data to facilitate permitting
- Lack of confidence in metocean conditions to use as the design basis for offshore renewable technologies
- No current means to validate cost-effective technologies for measuring wind speed offshore

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

Impact of Project

This project reduces barriers to developing offshore renewable energy sources by providing:

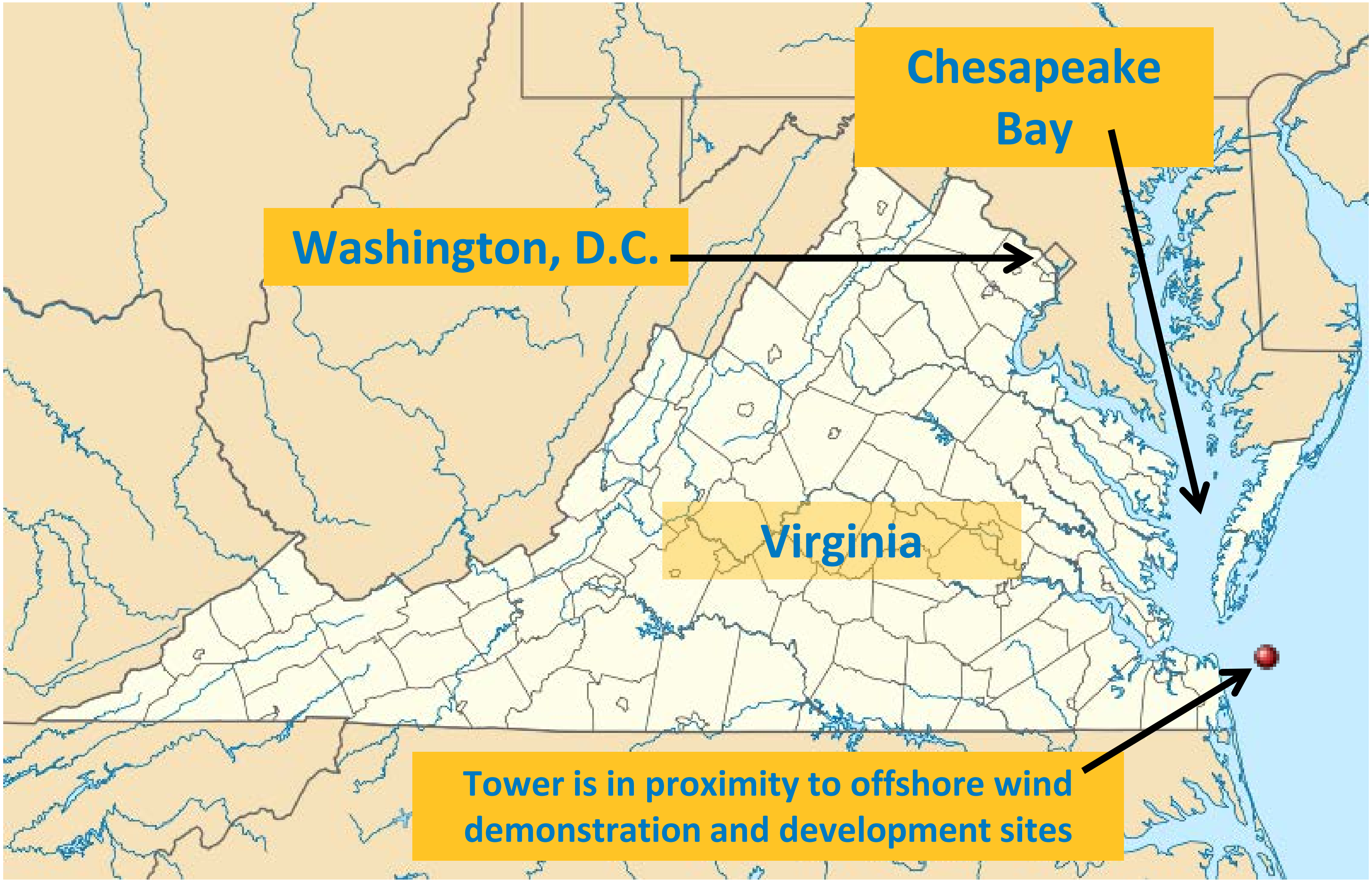
- Facility support for research and for validation of new, cost-effective resource measurement technologies
- Extensive and continuing meteorological, oceanographic, and environmental data that will
  - Advance understanding of metocean conditions in U.S waters
  - Advance the ability to characterize the offshore wind resource
  - Inform international standards regarding U.S. conditions
- Baseline environmental data to assess ecological effects of offshore renewable installations
- Open access to data collected with U.S. public funds for industry and researchers

Budget, Purpose, & Objectives

This project aligns with the following DOE Program objectives and priorities

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

Chesapeake Light Tower



Technical Approach

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NREL Approach

- Repurpose the Chesapeake Light Tower (CLT) as DOE's Reference Facility for Offshore Renewable Energy (RFORE)
- Develop and implement a project management plan
- Conduct engineering and environmental assessments of the CLT and assess feasibility of life extension
  - Platform is 49 years old with visible structural liabilities
- Develop a conceptual design for the RFORE renovation
- Develop and implement safe work procedures for current tower users

NREL Issues

- The underwater survey of the CLT in September 2013 observed subsidence of ocean floor below CLT — required additional analysis

Accomplishments and Progress

NREL

- Project kick-off with NREL, PNNL, and DOE staff — October 2012
- Completed project management plan — December 2012
- Completed NEPA documentation for all activities to date — FY 2013
- Initiated contact with numerous regulatory agencies to determine jurisdictions having authority and permit requirements — FY 2013
- Safe work permit issued for current CLT users — October 2013
- Developed conceptual design for the reconfiguration and upgrade of the CLT into RFORE — FY 2013
  - Power budget
  - Concept for a renewable (PV) power system
  - Concept for self-supporting met tower, 111 m above sea level
- Obtained metocean conditions for the CLT site — April 2013
  - Design basis for future engineering analysis and design

Accomplishments and Progress

NREL

- Completed initial qualitative assessment of the CLT — March 2013
  - Life extension of the jacket and substructure appears feasible
  - Main deck has severe deterioration — recommended to remove and replace

Chesapeake Light Tower Demolition

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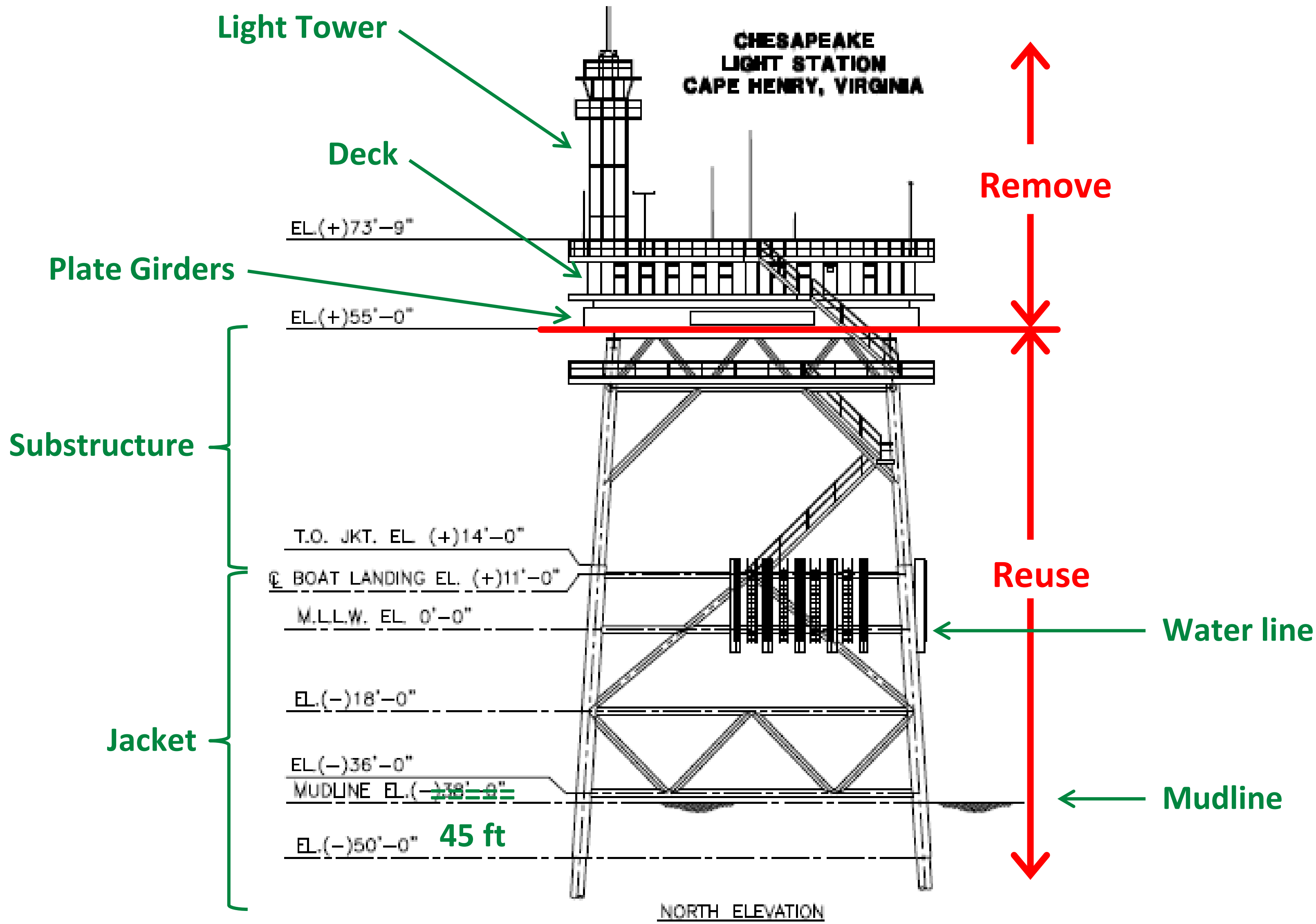
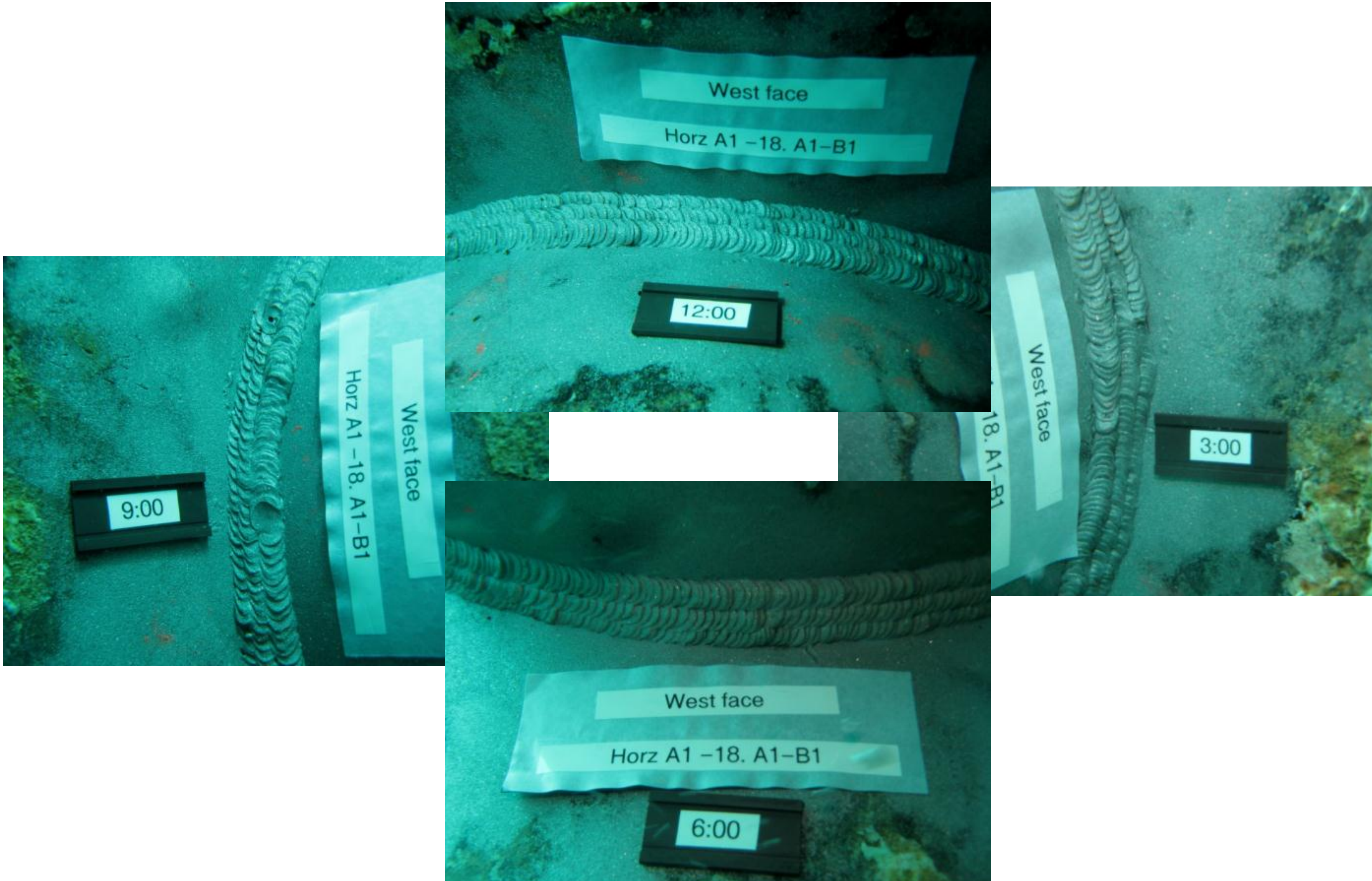


Accomplishments and Progress

NREL

- Completed engineering/environmental assessment — December 2013
  - No evidence of fatigue damage
  - No evidence of corrosion underwater
  - Cathodic protection system active — depletion ~ 50%
  - Severe corrosion damage to structural members in the “splash zone,” first 15 ft above sea level — repairs required
  - Only moderate corrosion damage elsewhere above water
- Structure, if repaired, has adequate strength
- Unexpected finding of ocean floor subsidence
  - 45-ft water depth compared to original 38-ft depth in 1963

Underwater Joint & Weld Detail



PNNL Approach

- Develop RFORE research agenda with input from multi-stakeholder RFORE Steering Committee and industry user groups
- Develop and operate RFORE data management facility (DMF) to receive RFORE data, perform quality checks, maintain a permanent archive, and disseminate data to all interested users
- The research agenda and DMF are location-agnostic and ongoing work is applicable for any RFORE site

PNNL Issues

- Completed evaluation of the DMF prototype with surrogate data from the DOE/SC ARM Program — need to extend this evaluation to actual RFORE instrumentation when available at NREL

Accomplishments and Progress

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

PNNL

- Engagement of R&D community via American Meteorological Society (AMS) presentation — January 2013
- Engagement of industry in a post-UVIG presentation in Salt Lake City (February 2013) and via AWEA Offshore Working Group
- Detailed suite of proposed RFORE instrumentation with R&D justification — June 2013
- Initial meeting of interagency RFORE Steering Committee in D.C. — July 2013
- Delivery of draft RFORE data management plan — September 2013
- Engagement of Danish and German offshore research experience via RFORE presentation to DTU (Denmark) and invited talk at bi-annual FINO Conference — October 2013
- Meeting with DFG (German Research Foundation) in D.C. to explore German-supported collaborative R&D at the RFORE — November 2013

Planned Core Instruments

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Wind

- Class 1 (or better) cup anemometers and vanes; 8 levels from 40 m to mast top (≥ 100 m MSL); sampling interval of 1 s (3 booms at each level)
- Doppler LIDAR (continuous wave) for vertical wind profiles
- Scanning Doppler LIDAR (pulsed)

Turbulence

- Sonic anemometers sampling u, v, w, T_v at 3 levels; possibly fast-response q as well

Thermodynamic Information

- Mean T, q at three levels to mast top (in situ)
- Microwave radiometer for T, q
- Barometric pressure

Precipitation

- Rain gauge (tipping bucket)

Cloud base/boundary layer depth

- Ceilometer

Planned Instruments (cont.)

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Sea Conditions

- Infrared and in situ sea surface temperature
- IR video camera for breaking waves, up to 30 s^{-1} frame rate
- Two-dimensional wave spectrum and current (ADP)
- CT profile

Measurement Continuity

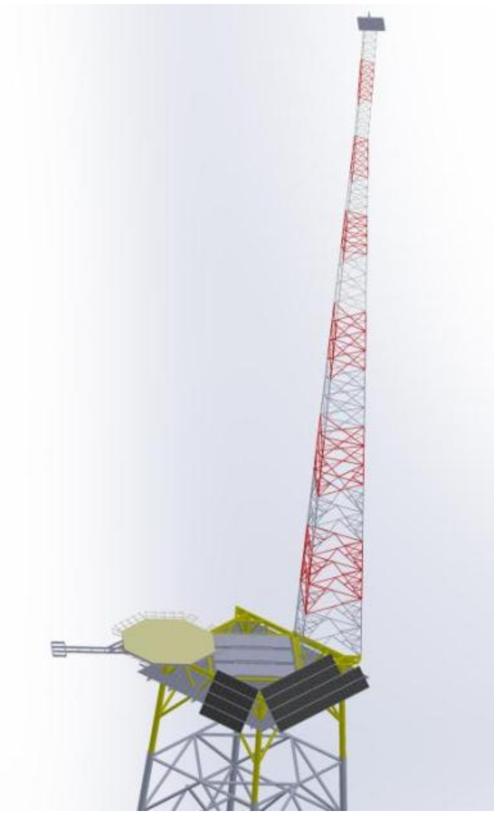
- NOAA and NASA existing measurements

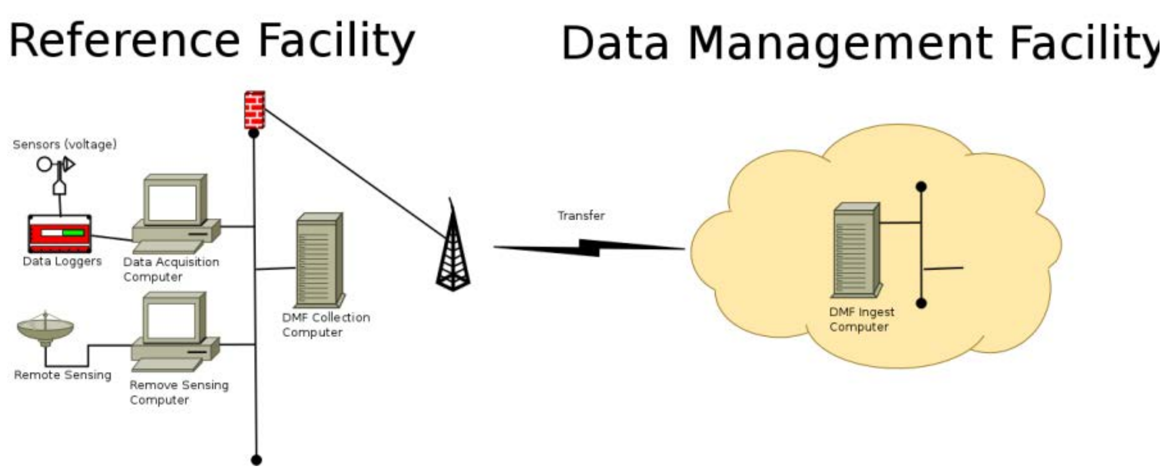
Environmental Measurements (likely later)

- Active bird/bat detection (radar)
  - Could also provide sea-state information
- Passive bird/bat detection
  - Microphones
  - Visible/IR video
- Marine mammal detection
  - Hydrophones
  - Echolocation system
  - 3-D acoustic camera
  - Sub-surface video

RFORE DMF

- Reports
  - Status
  - Monitoring
- Search
  - Browsing
  - Keyword/Advanced
  - Referential Standards
- Catalog Editor
  - Create, Read, Update, Delete (CRUD)
  - Administration
- Activity Tracking
  - Maintenance
  - Problem Reporting
  - Quality Assurance
  - Change Request





Project Plan & Schedule

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

Summary		Legend	
WBS Number or Agreement Number			Work completed
Project Number			Active Task
Agreement Number			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)
DOE obtains custody of the Chesapeake Light Tower												
NWTC: RFORE Infrastructure and Operations												
Q1 Milestone: Complete project execution plan												
Q2 Milestone: Complete qualitative structural assessment of the CLT												
Q3 Milestone: Initiate engineering & environmental assessment of the CLT												
Q4 Milestone: Complete facility status report for FY2013												
Q1 Milestone: Decision Gate #1: Proceed to engineering design												
PNNL: RFORE Research Agenda and Date Management Facility												
Q1 Milestone: Deliver an initial research and data management plan outline												
Q2 Milestone: Establish leadership structure/composition for RFORE research agenda												
Q3 Milestone: Draft suite of specific RFORE instruments defined with R&D rationale												
Q4 Milestone: Draft data RFORE management plan												
Q1 Milestone: Summary report of research lessons learned from European colleagues												

Comments

- DOE obtains custody of the Chesapeake Light Tower in September 2012
- Decision gate #1: *Proceed to engineering design*, Q2 of FY 2014 [This milestone slipped from Q1 due to unexpected finding of ocean floor subsidence below the tower.]
- Decision gate #2: *Proceed to RFORE construction*, FY 2015
- Planning for construction and operational commissioning of RFORE in FY 2016

Research Integration & Collaboration

CLT Users

- Coast Guard – aids to navigation
- NASA – CERES Ocean Validation Experiment
- NOAA – wind speed for the National Buoy Data Center
- Stantec – bat detection system

Subcontractors for CLT structural assessment

- MMI Engineering
- Keystone Engineering

Comparable Facilities - the FINO towers in the North and Baltic Seas

- FuE-Zentrum Fachhochschule in Kiel, Germany
  - Technical discussions, September 10-11, 2013
  - Trip to the FINO3 platform in the North Sea, September 11, 2013
- GL-Garrad-Hassan, Hamburg, Germany, September 10-11, 2013
- DEWI, Germany, September 12, 2013

Next Steps and Future Research

FY14/Current activities

Assess impact of 45-ft water depth

- Storm waves larger in deeper water
- Additional engineering analysis completed; February 2014
- Structure has adequate strength to survive 25-yr storm
- Compliant with the U.S. standard for “unoccupied” offshore structures

Determination on Decision Gate #1: *Proceed to engineering design?*

- Development and testing of the research system and data management facility

Research Integration & Collaboration

RFORE Steering Committee Representation

- DOE
- PNNL and NREL
- NASA, NOAA, BOEM, Navy
- State of Virginia

Conferences/Presentations

- American Meteorological Society Conference
  - January 2013 and February 2014
- German Wind Energy Institute (DEWI)
  - RFORE research agenda, Wilhelmshaven, September 2013
- FINO Conference 2013
  - Kiel, Germany, October 30, 2013
  - Presentation given on the RFORE research agenda
  - Presentation given on the engineering assessment of the CLT and conceptual design of RFORE
- Danish Technical University
  - October 2013
- American Geophysical Union
  - December 2013

Next Steps and Future Research

Proposed future research

- Full implementation of DMF
- Workshop to engage community to collect suggestions for RFORE-centered research
- Evaluation of in situ RFORE instrument performance characteristics, including any flow distortion effects
- Demonstration validation of floating lidars
- Analysis of emerging RFORE data for resource characteristics, including extreme events for wind and sea state
- Evaluation of wind resource modeling and associated physics over spectrum of varying conditions

Chesapeake Light Tower

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Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Wind Power Peer Review

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

National Wind Technology Center

Test Facilities – Overarching Site-wide Equipment, Safety, Environmental Compliance, and Accreditation

Dave Simms

NREL

david.simms@nrel.gov

Purpose & Objectives
NWTC Test Facility Capabilities

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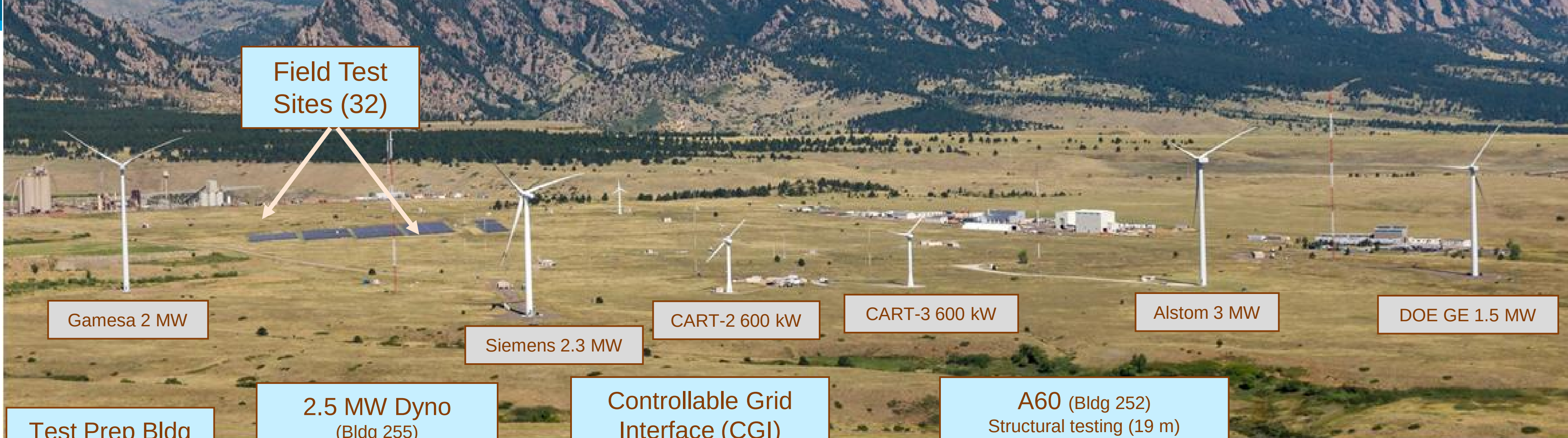
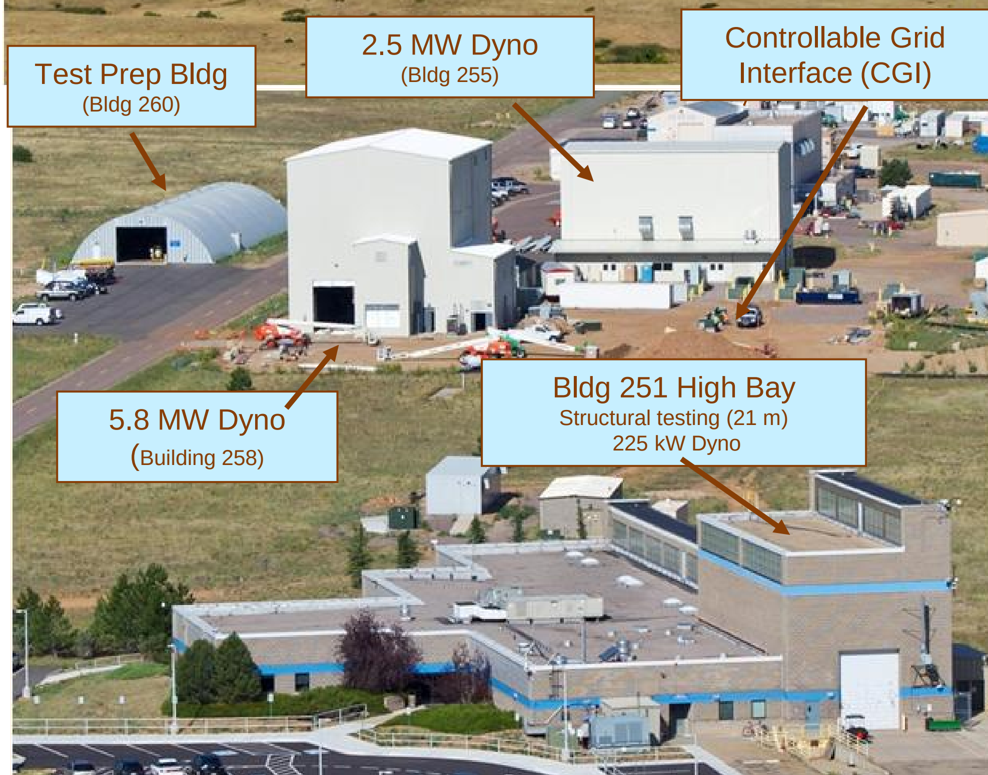
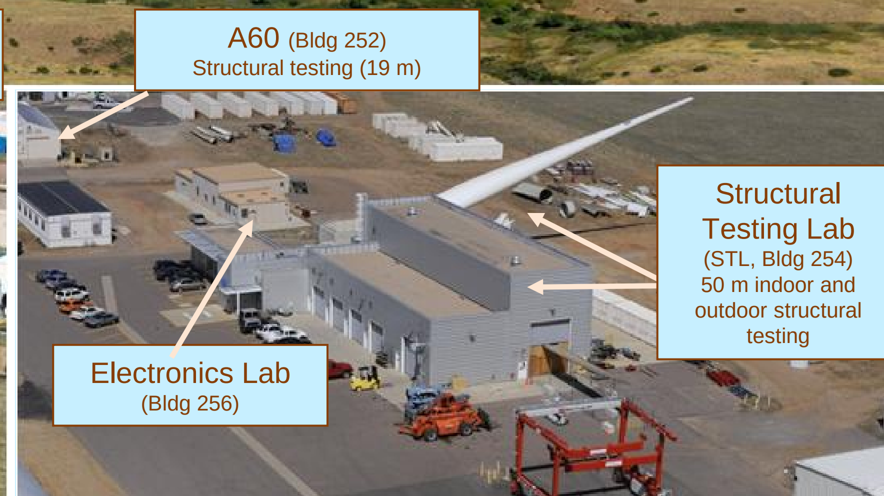
- **Field**
  - Field test sites and infrastructure
  - DOE 1.5, Industry MW turbines
  - Controls Research Turbines (CART)
  - Research-grade inflow meteorological data
  - Small turbine testing
- **Drivetrain**
  - 225 kW, 2.5 MW, 5.8 MW dynamometers
  - Dynamic torque testing of fully integrated drivetrain systems or components (gearboxes, generators, PE)
  - HALT, condition monitoring
  - Model-in-the-loop to simulate turbulence
  - Non-torque loading (NTL) to impart rotor loads
- **6.3 MW Controllable Grid Interface**
- **Structural**
  - Test stands, hydraulic actuators
  - Accredited (A2LA) fatigue (resonant) and static testing of blades (up to 50 m in length) to IEC standards
  - Modal and property measurements, profiling, NDT methods
  - Innovative test methodology R&D
  - Massachusetts large blade test facility partnership
- **ISO 17025, A2LA accredited to IEC Standards**
  - Power performance, power quality, acoustic emissions, structural loads, duration, safety and function
- **Custom**
  - Testing to meet R&D needs (e.g., data for model validation, proof-of-concept)
  - Explore applicability of advanced sensors, DAS

NWTC Field, Dyno and Structural Testing Facilities







NWTC Site Layout

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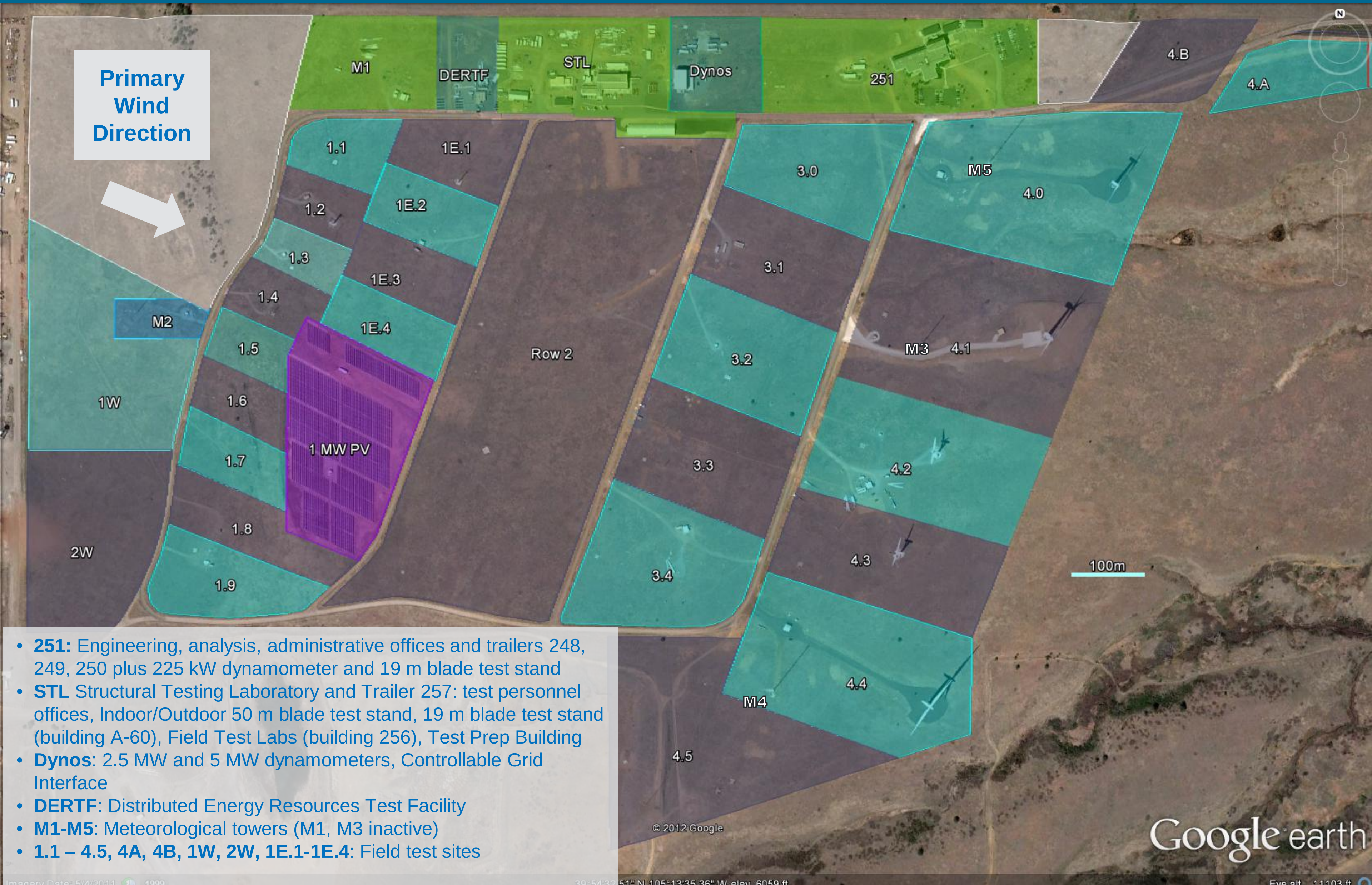

- **251:** Engineering, analysis, administrative offices and trailers 248, 249, 250 plus 225 kW dynamometer and 19 m blade test stand
- **STL** Structural Testing Laboratory and Trailer 257: test personnel offices, Indoor/Outdoor 50 m blade test stand, 19 m blade test stand (building A-60), Field Test Labs (building 256), Test Prep Building
- **Dynos**: 2.5 MW and 5 MW dynamometers, Controllable Grid Interface
- **DERTF**: Distributed Energy Resources Test Facility
- **M1-M5**: Meteorological towers (M1, M3 inactive)
- **1.1 – 4.5, 4A, 4B, 1W, 2W, 1E.1-1E.4**: Field test sites

Budget, Purpose, & Objectives

Total DOE Budget[1]: $3.622M

Total Cost-Share[1]:$0.000M

Problem Statement: Minimize risk of personnel exposure to NWTC hazards. Comply with essential overarching requirements associated with all NWTC testing (not covered under individual test projects or under specific facility operations and maintenance activities).

Impact of Project: Ensures safe operation of DOE's world-class test facilities located at the NWTC in accordance with DOE requirements.

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

- **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***

Budget, Purpose, & Objectives
Minimize Risk of Exposure to NWTC Hazards

NWTC Hazards

- Extreme winds, blowing debris
- Electrical—up to 13,200 V (shock, electrocution, arc-fault, and arc-blast)
- Aerial lifts, tower climbing, working at height
- Towers, turbines, and associated falling/flung/blown objects, debris, ice
- Confined spaces
- Noise
- High pressure (hydraulics, compressed gas, cooling and heat exchange systems)
- Burn/fire (overheating, welding, abrasive grinding, smoking)
- Cranes, suspended loads, hoisting, and rigging
- Mechanical oscillating/rotating apparatus and machinery, shop and power tools
- Fork lifts, snow plows, heavy equipment operation
- Environmental—blizzards, hail, icy conditions, lightning, wildfire, snakes and other critters
- Testing to failure (i.e., purposely breaking blades to quantify extreme load handling)

Budget, Purpose, & Objectives
NWTC Operations and Testing Challenges

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- The NWTC is a 305-acre outdoor test laboratory
  - Turbines are often custom-configured for R&D and testing
    - Operated outside of normal parameters, sometimes to extreme limits
    - Not a conventional wind farm (i.e., may be operated under limited or selective conditions to obtain specific data—power generation is not a priority)
  - Large component testing (i.e., blades, drivetrains)
    - Often outdoors, or may protrude out of laboratories
  - Unique test apparatus may be attached to turbines and components
- Challenging safety and confidentiality issues due to:
  - Atypical operations and test activities, purposely testing to failure
  - Curiosity attraction of large turbines, tall towers
  - Proximity to office workers unfamiliar with field and laboratory hazards
  - Industry Work-For-Others test projects and associated test article intellectual property (IP) requirements


Technical Approach

Ensure Compliance with All Overarching DOE and NREL:

- Safety Requirements
  - Safety reviews and inspections, handling and tracking of all required site safety documents in accordance with DOE requirements (e.g., Safe Operating Procedures, Safe Work Permits, Readiness Verifications, DOE Integrated Safety Management System, maintenance and inspection tracking, safety and environmental compliance audits)
  - Training to ensure all workers possess required technical qualifications (e.g., high-voltage electrical compliance, hydraulic system safety, hazardous material handling, climbing and fall protection, and hoisting and rigging)
  - Operation and maintenance of site-wide safety support systems (e.g., site-wide warning sirens, Web display of NWTC weather conditions, lightning protection monitoring systems, and more)
  - Annual simulated disaster-response exercises with local fire and police emergency responders, especially MW-scale turbines
- Quality Assurance Requirements
  - Overarching records of procurement, calibration, operation, tracking, inspection, and maintenance of data acquisition systems, sensors, and other government-owned test apparatus (e.g., meters, voltage sources). Managing proper documentation, analysis, handling, and storage of records and data.
  - All NWTC IEC testing is accredited by the American Association of Laboratory Accreditation. A2LA is an independent organization that audits and monitors NWTC testing to ensure that sufficient quality-control procedures and processes are followed to produce reliable test results. A2LA accreditation ensures that NWTC test results are accepted by international wind turbine certifying agencies.

Technical Approach

Ensure Compliance with All Overarching DOE and NREL:

- Government-owned equipment and facility requirements
  - Qualified operation, maintenance, inspection, and repair of cranes, forklifts, aerial lifts, boom trucks, generators, hydraulics, tools, mobile hoists, trucks, trailers, test apparatus in accordance with DOE, NREL, OSHA, and Colorado Dept. of Highway requirements
  - Qualified inspections after major extreme events (e.g., wind storms, test failures, lightning strikes)
  - Managing, tracking, and disposing in accordance with DOE/NREL Property requirements (e.g., supporting annual property inventory audits, inventory location tracking/storage, proper excessing or recycling of expended, obsolete, or unsafe items)
  - Providing qualified technical interaction in development of agreements to interface NWTC test-specific project requirements with government-owned facilities and infrastructure (e.g., electrical, telecommunications network, facility space, fire protection)
- Activities essential to maintaining strong testing capabilities
  - Proficiency testing (as a member of the international Measuring Network of Wind Energy Institutes (MEASNET) field-test proficiency and procedures development committee
  - Advanced sensor development and calibration, maintenance and improvement of overarching instrumentation and data acquisition systems, testing and analysis to support specification of testing standards and accreditation
- National Environmental Policy Act requirements
  - NWTC staff and management support periodic DOE NEPA-required activities and ensure adherence to U.S. migratory bird act regulations including NWTC bird and bat surveys and other wildlife studies
  - Prep for NWTC site-wide NEPA Environmental Assessment in FY14

Accomplishments and Progress

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- Maintained exemplary safety record
  - Consistently exceeds DOE safety metrics (DART, TRC)
  - Only NREL Center found to be in compliance with DOE safety requirements after lab-wide investigations of safety incidents
    - "Extent of Condition Reviews to address Enforcement Letters from DOE Office of Health, Safety, and Security's Office of Enforcement and Oversight
      - Electrical Safety—inadequate PPE and training
      - Electrostatic Discharge and Flammable Mixtures—explosion
- Received annual letters of reaffirmation from the American Association of Laboratory Accreditation (A2LA) signifying successful renewal of all NWTC-accredited testing processes
- Supported lab-wide ISO 9001/14001 (QA) and OHSAS 18001 (safety) surveillance audits

Project Plan & Schedule

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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: NWTC Test Facilities – Field: DOE Turbine Facilities & Test Sites O&M												
Q1 Milestone: Complete annual simulated NWTC disaster response												
Q2 Milestone: Complete audit to ensure A2LA accreditation renewal												
Q3 Milestone: Provide documentation to DOE for NWTC Environmental Assessment												
Q4 Milestone: Satisfy all DOE/ NREL/ OSHA compliance requirements												
Q1 Milestone: Complete annual simulated NWTC disaster response												
Q2 Milestone: Complete audit to ensure A2LA accreditation renewal												
Q3 Milestone: Ensure all safety equipment in compliance, especially fall protection												
Q4 Milestone: Excess obsolete, unsafe, and end-of-life equipment items in compliance with DOE Government Property regulations												

Comments

- All milestones completed on time and within budget

Research Integration & Collaboration

Partners, Subcontractors, and Collaborators

- NWTC currently has 90 testing facilities partnerships
  - AOP, CRADA, WFO, FOA
  - Industry, university, other labs
  - As defined in NREL Facility Partnership Metrics reported to DOE quarterly
- Subcontracts supporting this project
  - Windward Engineering—mechanical engineering, technicians

Communications and Technology Transfer

- This project keeps the facilities safe and operational
- Results are communicated by researchers and other facility users

Next Steps and Future Activities

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FY14/Current activities

- Support DOE process to update NWTC Environmental Assessment
- Update NWTC Hazard Awareness Training (required training for all who have NWTC access)
- Update NWTC Test Equipment Design and Verification Process
- Implement new barcode and RFID equipment tagging and inventory system

Proposed future activities

- Continue to evolve NWTC safety procedures in response to:
  - Partnership and weekly meetings with DOE Golden safety enforcement staff
  - Lab-wide safety process changes resulting from Extent of Condition reviews
  - Partnership and weekly meeting with Facility Management Team at NREL Energy Science Integration Facility (ESIF)
  - Partnerships with industry and lessons learned
- Support NWTC A2LA audits
- Support lab-wide ISO 9001/14001 (QA) & OHSAS 18001 (safety) surveillance audits