U.S. DEPARTMENT OF
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Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Cost of Energy Reduction for Offshore Tension-Leg Platform (TLP) Wind Turbine Systems through Advanced Control Strategies for Energy Improvement

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(presented by Brad Ring and Gary Norton, DOE)

FY17-FY18 Wind Office Project Organization

"Enabling Wind Energy Options Nationwide"

Technology Development	Market Acceleration & Deployment
Atmosphere to Electrons	Stakeholder Engagement, Workforce Development, and Human Use Considerations
Offshore Wind	Environmental Research
Distributed Wind	Grid Integration
Testing Infrastructure	Regulatory and Siting
Standards Support and International Engagement	
Advanced Components, Reliability, and Manufacturing	

Analysis and Modeling (cross-cutting)

Project Overview

T25: Cost of Energy Reduction for Offshore Tension-Leg Platform (TLP) Wind Turbine Systems through Advanced Control Strategies for Energy Improvement

Technology Summary: Integration of advanced sensing, actuation, and control algorithms and techniques into floating offshore wind turbine systems to reduce overall structural loads and material requirements, and increase energy capture. Evaluated technologies included: LiDAR-assisted controls, advanced yaw controls, atmospheric characterization, specific control algorithms, structural dampers, and wave-forecasting-based controls.

Period of Performance: September 30, 2011 – April 30, 2018

Technology Impact: Lower Levelized Cost of Energy (LCOE) of floating turbine system by 5% compared to baseline levels

Project Goals:

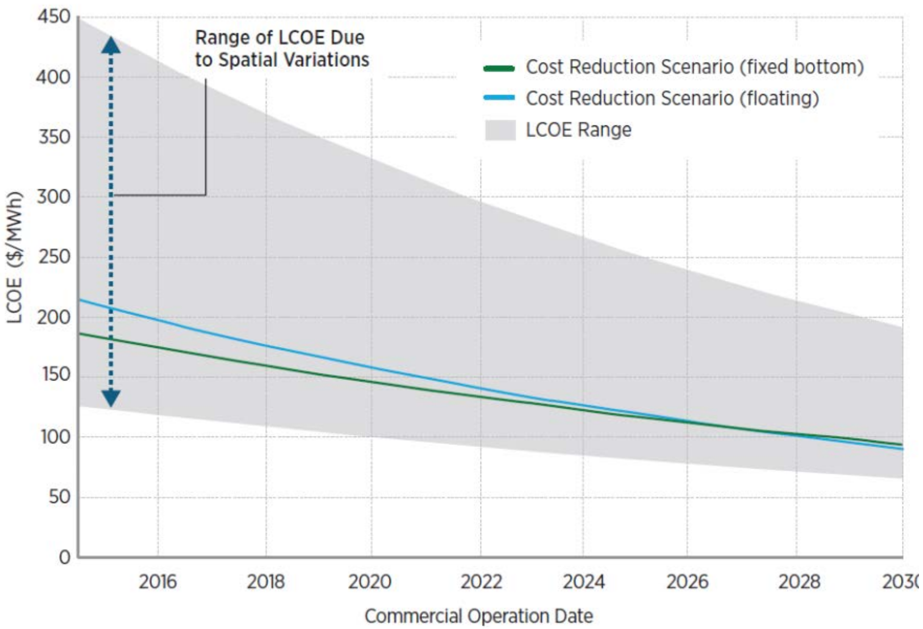
- **Overcome key technical barriers** to the deployment of deep water floating offshore wind turbines;
- **Improve energy generated** by wind turbines through advanced control strategies (e.g. Light Detection and Ranging (LiDAR)-based preview controls, advanced supervisory controls, etc.);
- **Lower the capital costs** for both wind turbines and floating foundations through advanced control strategies.

Partners:

- Glosten Associates
- Massachusetts Institute of Technology (MIT)
- National Renewable Energy Laboratory (NREL)
- Texas Tech University (TTU)
- University of Massachusetts – Amherst (U. Mass)

Technical Merit and Relevance

LCOE for Potential Offshore Wind Project in United States



Prioritization of Technical Barriers for Floating Wind

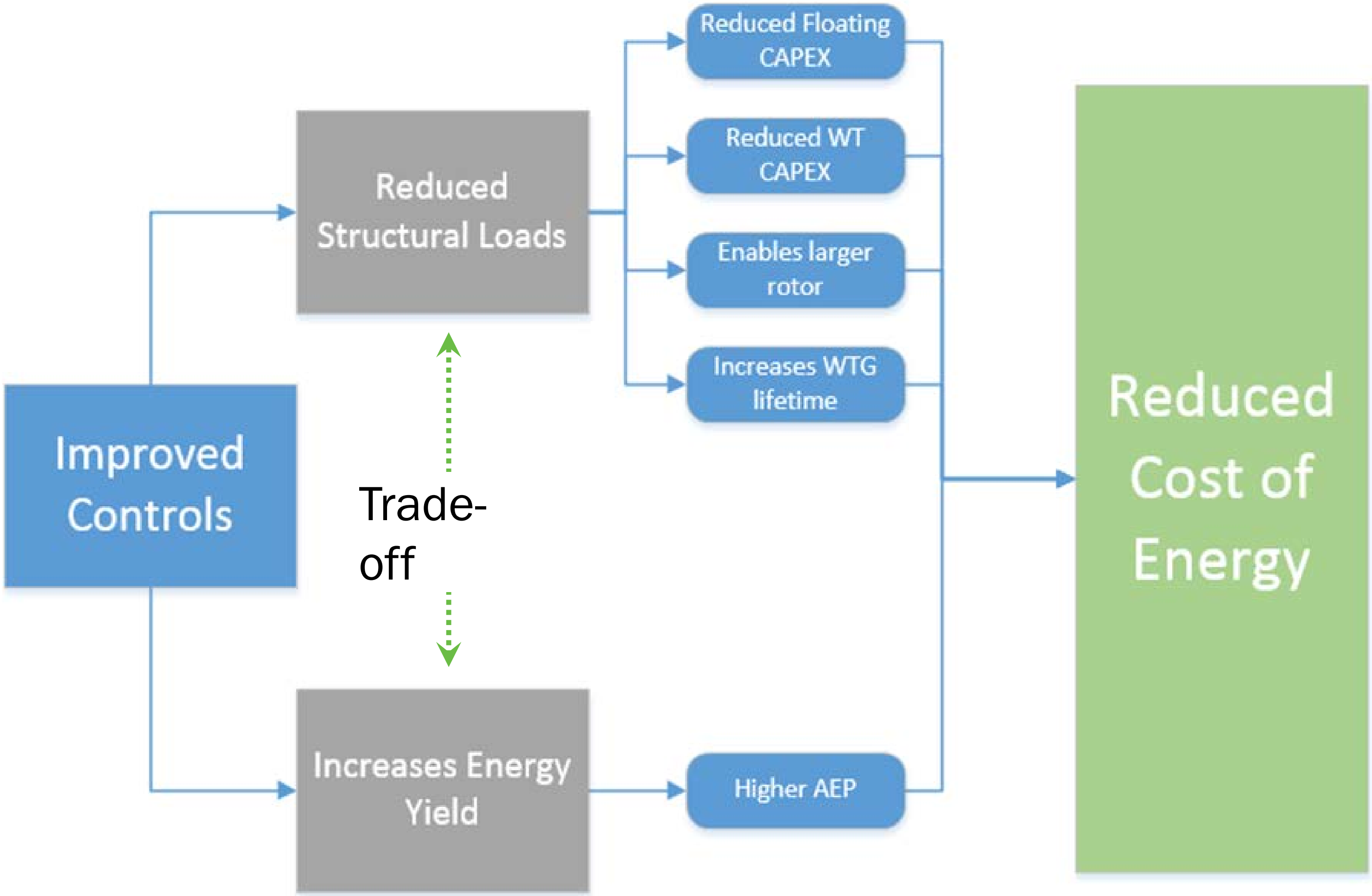
Technical challenge	Cost reduction potential	Urgency
Platform size & weight	2.7	2.4
Installation procedures	2.5	2.2
Port-side O&M (major repair procedures)	2.3	2.2
Floating substations/transformer modules	2.3	2.0
Advanced control systems for floating WTGs	2.2	2.2
Mooring design & installation	2.2	2.1
Anchor design & installation	2.1	2.1
Advanced tank testing facilities	2.0	2.1
Wind farm operation (wake effects, yield, AEP)	1.9	2.1
Advanced modelling tools	1.9	2.5
High voltage dynamic cables	1.8	2.1
Bespoke standards for floating wind	1.8	2.0
Environmental impact	1.4	2.1

N.B. Scoring from 1-3; High = 3, Med = 2, Low = 1.

Source: Carbon Trust 2015

- A significant portion of potential offshore sites have depths of more than 60m
- Floating LCOE likely to reach parity with fixed-bottom market by 2030 (*NREL, 2016*)
- Key technical challenges: a) platform weight and associated cost, b) turbine controls to ensure stability, c) adequacy of modeling tools, and d) testing
- Industry is banking on technology innovation + volume to drive 50% LCOE reduction

Approach and Methodology



Advanced Controls for Improved Performance and Reduced LCOE

Approach and Methodology

1. Innovative technologies were evaluated: LiDAR-assisted feedforward controls, advanced yaw controls, model-based control algorithms, structural dampers, and wave forecasting-based control
2. Baseline systems were considered for simulations and analysis: GE's 6-Megawatt (MW) Haliade on a) the PelaStarTM Tension Leg Platform (TLP) and b) a semi-submersible floating platform using current state-of-practice controls.
3. Advanced controls for both configurations were developed, simulated, and assessed using industry-standard modeling platforms such as Fatigue, Aerodynamics, Structures, and Turbulence (FAST) [2] and BLADED [3].
4. FAST simulation models were verified against higher-fidelity simulation models including OrcaFlex [4] and ANSYS [5].
5. A subset of promising technologies was field tested on full-scale land-based wind turbines.

Approach and Methodology

Summary of Technology Evaluation

Technology	Simulation Evaluation	Field Testing/Evaluation
LiDAR-assisted controls	FAST modeling: 3-MW onshore and 6-MW offshore GE turbines	3-MW land-based GE turbine
Advanced yaw controls	FAST modeling: 3-MW: land-based and 6-MW offshore GE turbines	3-MW land-basedGE turbine 1.6-MW land-based GE turbine
Offshore atmospheric characterization	FAST modeling: 5-MW National Renewable Energy Laboratory (NREL) reference turbine [Ref]	Wind energy areas of Virginia, Great Lakes, and the North Sea (Europe)
Controls algorithms for floating turbines	a) FAST models of 6-MW offshore GE turbine on PelaStarTM TLP b) Bladed models of 6-MW offshore GE turbine on a semi-submersible.	NA
Structural dampers	FAST modeling: 3-MW land-based and 6-MW offshore GE turbines	3-MW land-based GE turbine
Wave-forecasting-based controls	FAST modeling: 6-MW offshore GE turbines on PelaStarTM TLP	Wave-tank data

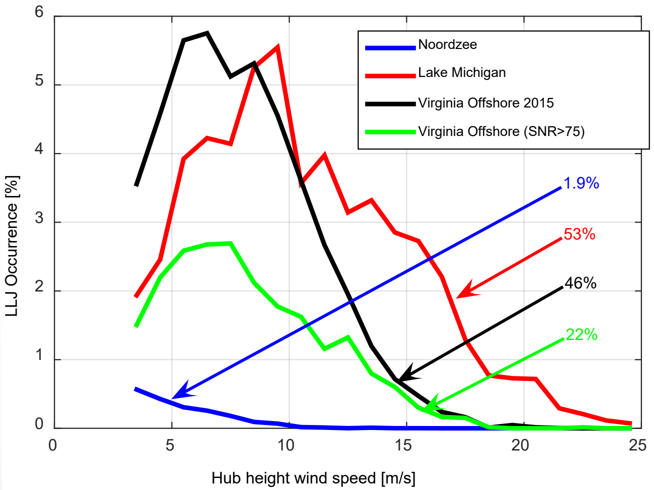
The impact of candidate technologies on Key Performance Indicators (KPIs), including fatigue and extreme loads, Annual Energy Production (AEP), rotor speed regulation, and actuator usage, was evaluated. Wind and wave conditions representative of the Gulf of Maine and the North Sea were considered to assess these KPIs.

Accomplishments and Progress

I Feed Forward Controls and LIDAR

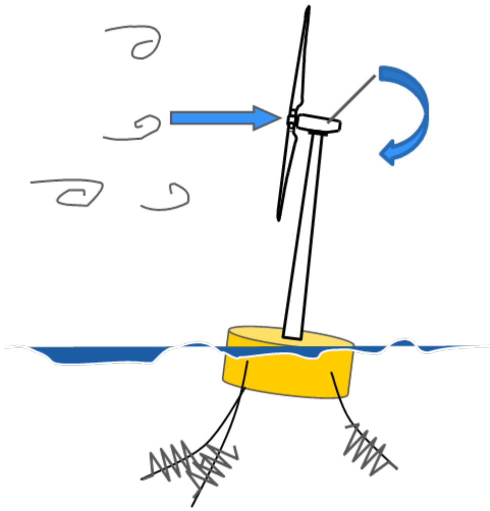
- Significant generator speed and tower base load improvements
- Positive loads/AEP trade-off

II Atmospheric Characterization



- Frequent Low level jet events observed
  - 5% to 10%
- LLJs significantly affect power performance
  - ~1.5 %
- Need for further investigation

III Floating Controls



- Rotor collective pitch control very effective at reducing tower/platform fore-aft bending loads
- Independent blade pitch effective in stabilizing the tower side-side mode and reducing side-side bending loads.

IV Dampers and Control Algorithms

- Field tested at NREL
- Out-rigger dampers effective at extreme loads reduction
- Efficient Finite Element models showed reasonable correlation to field measurements

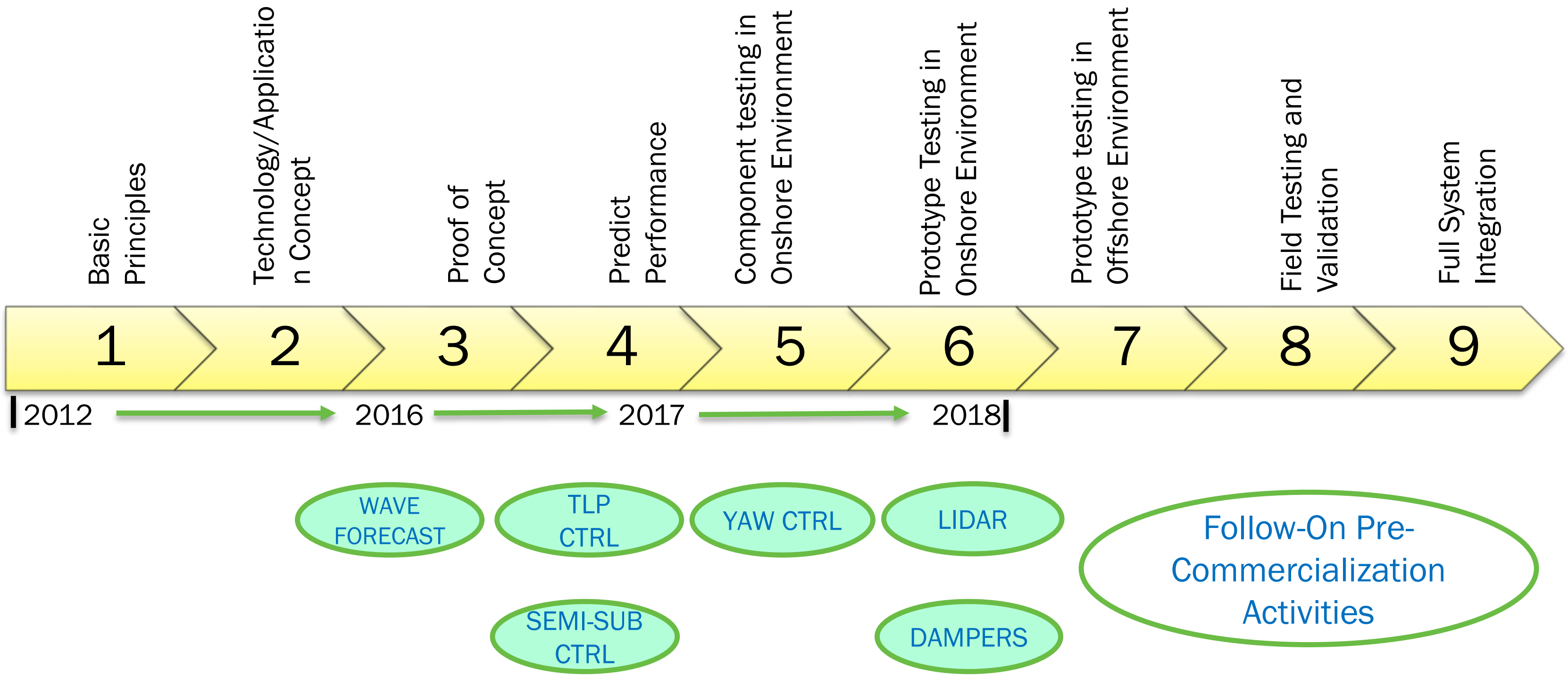
Accomplishments and Progress

Topic	Technology	Loads/RMS Reduction		Estimated AEP Increase
		KPI	% Reduction	
Feedforward controls	LiDAR + control algorithms	¨ Rotor speed (RMS) ¨ Tower base (Fatigue)	35% 7%	2%
Yaw correction	Spinner anemometer + control algorithms	NA	~0%	0.75%
Control of TLP System	Dampers + control algorithms	¨ Tower base fatigue ¨ Tendon tension fatigue	71% 25%	~0%
Control of Semisubmersible System	Control algorithms	¨ Tower base fatigue	4%	5%

AEP Enhancements and Structural Load Reduction → 4-5% LCOE

Accomplishments and Progress

Technical Readiness Evolution



All milestones were completed on time with the exception of the damper test, which was completed 1 quarter later and required a no-cost time extension

Communication, Coordination, and Commercialization

Publications	Event	Author	Type	Date
Development, Field Testing, and Evaluation of LIDAR –Assisted Controls	AWEA Onshore 2015	Ehrmann	Poster	5/20/2015
Turbine-mounted LIDAR Validation	NAWEA 2015 Symposium	Ehrmann	Presentation	6/9/2015
Floating Offshore WTC Integrated Load Analysis & Optimization Employing a Tuned Mass Damper	AWEA Offshore 2015	Rodriguez	Poster	9/30/2015
Smart Novel Semi-Active Tuned Mass Damper for Fixed-Bottom and Floating Offshore Wind	OTC 2016 Conference	Rodriguez	Paper	5/2/2016
An Investigation of Passive and Semi-Active TMD for a TLP Floating Offshore Wind Turbine in ULS Conditions	OMAE2016	Park	Paper	7/19/2016
Atmospheric Characterizations of the US Offshore Sites and Impact to Turbine Performance	AWEA Offshore 2016	Arora	Poster	10/25/2016
Advanced Controls Next Generation Offshore Wind Turbines Developments	AWEA Windpower	Arora	Poster	5/22/2017
An Investigation of Passive and Semi-Active structural Control of a fixed bottom and a Floating Offshore Wind Turbine (manuscript number WE-17-0107)	Wind Energy Journal	Park	Full Technical Paper	2nd Qtr 2017
Load Mitigation on Loading Offshore Wind Turbines with Advanced Controls and Tuned Mass Dampers	IOWTC	Arora Cross-Whiter	Full Technical Paper	11/4/2018

Shared Advancements at Numerous Industry Engagements