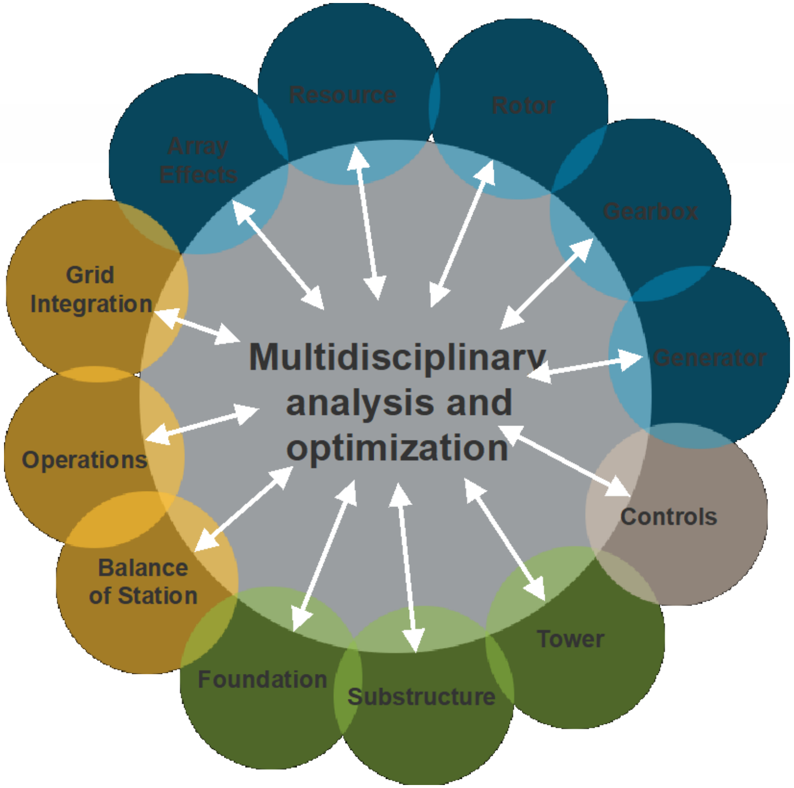
Integrated Systems Design & Analysis: Systems Engineering and Optimization (ISDA-SEO)

T9

Garrett Barter

NREL



FY17–FY18 Wind Office Project Organization

"Enabling Wind Energy Options Nationwide"

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

Analysis & Modeling (cross-cutting)

Project Overview

T9: Integrated Systems Design & Analysis: Systems Engineering and Optimization

Project Summary

- The Systems Engineering and Optimization initiative develops an analysis platform and research capability to capture full wind plant system interactions to achieve a better understanding of how to improve system-level performance and achieve system-level cost reductions
- The effort incorporates advances in computational algorithms, simulation methods, physics-based improvements, cost, and performance modules to assess new technology opportunities and advance the state-of-the-art and best practices in multidisciplinary design, analysis, and optimization.

Project Objective & Impact

Objectives:

- Integrate wind plant engineering performance and cost software modeling to enable full system analysis.
- Apply a variety of advanced analysis methods in multidisciplinary design analysis and optimization (MDAO) and related fields to the study of wind plant system performance and cost.
- Develop a common platform and toolset to promote collaborative research and analysis among national laboratories, industry, and academia.

Impact:

- Demonstration of LCOE reduction potential through MDAO
- Knowledge transfer of research capability; results and best practices to industry through publications, workshops, and tutorials.

Project Attributes

Project Principal Investigator(s)

Garrett Barter (formerly Katherine Dykes)
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DOE Lead

Michael Robinson (formerly Alana Duerr)

Project Partners/Subs

Professor Andrew Ning, BYU

Project Duration

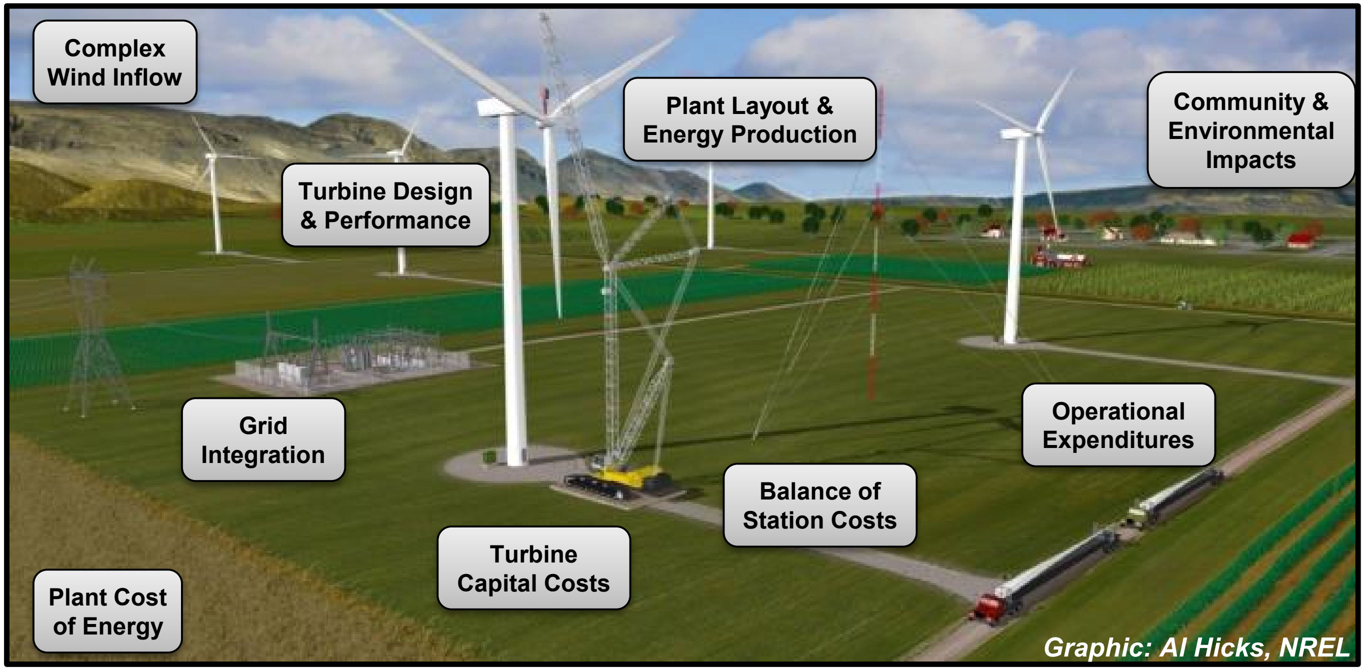
FY 2016–FY 2019

Technical Merit and Relevance

Motivation

- Wind plants are technically complex and highly coupled systems
- A full wind plant involves many stakeholders and considerable technical complexity
- Plant design, development, and operations are partitioned between subsectors in a large industry.

This results in suboptimal system-level performance as well as cost and risk aversion to the adoption of new innovations



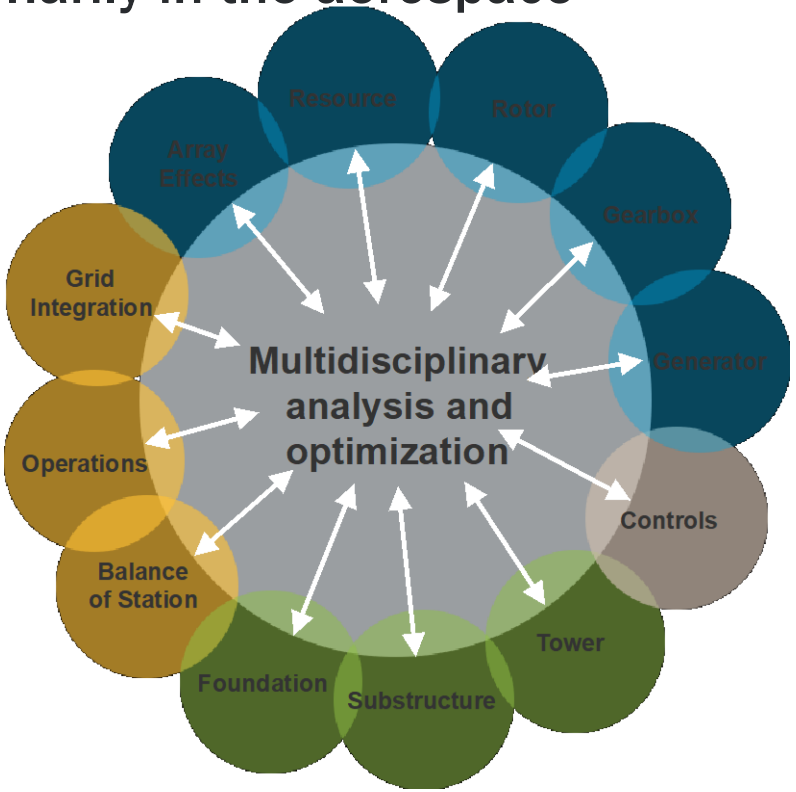
Approach and Methodology

- The ISDA-SEO project established a new pathway toward LCOE reduction by considering the entire wind plant life cycle as a single system that could be improved with optimization

- Brought to bear multidisciplinary optimization thinking and techniques that were developed primarily in the aerospace industry

- Achieving a base level of multidisciplinary and system functionality was the featured achievement during the previous ISDA-SEO peer review

- FY 2017–FY 2018 project focused on real-world relevant plant optimization and design methodologies.

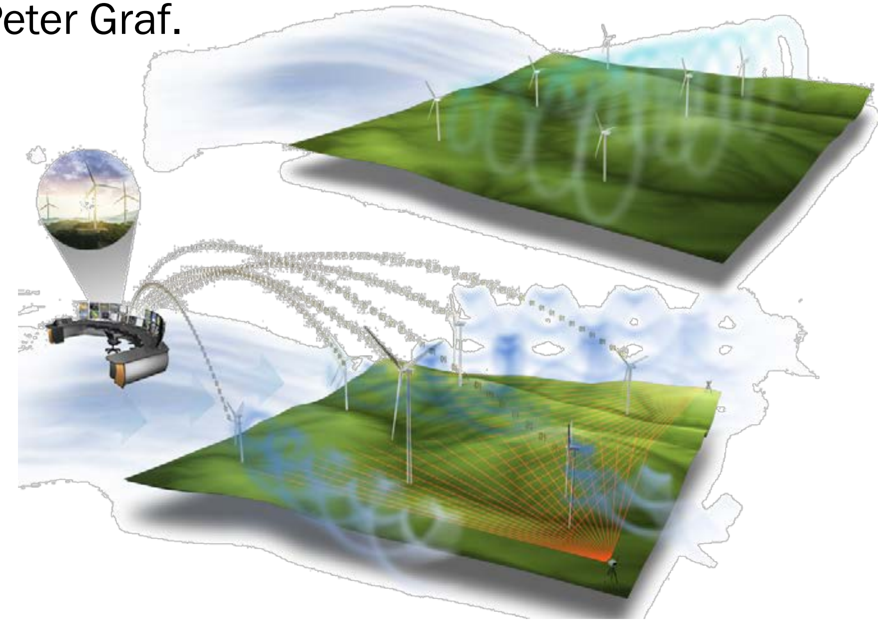


Approach and Methodology

- **Focus on plant-level modeling, optimization, and control**
  - Optimization: Improve the ability to optimally place turbines in an array and open up the possibilities of heterogenous wind plants. Led by Professor Andrew Ning, BYU
  - Control: Continue to focus on studies that advance the technology readiness of plant-level control via wake steering. Led by Jennifer (Annoni) King.
  - Modeling: Develop engineering-fidelity wind plant flow modeling that is well suited to optimization and control problems. Led by Ryan King.

- **Build up cross-cutting capability that enables optimal solutions to engineering problems that are otherwise difficult and time-intensive**
  - Use importance sampling to arrive at estimates extreme loads more quickly and rigorously than current methods. Led by Peter Graf.

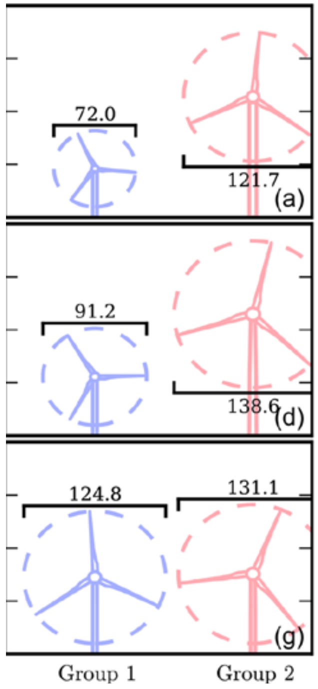
- **Continuation of International leadership activities**
  - IEA Wind Task 37
  - Workshops for MDAO practitioners
  - Conference symposia for a wider audience
  - Led by Katherine Dykes.
- **Continue to enhance the capability and international recognition of WISDEM (Wind-Plant Integrated System Design & Engineering Model).**



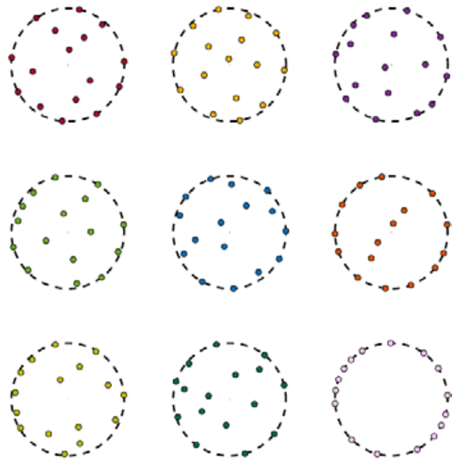
Advancing wind plant layout optimization capability with BYU

- Plant layout optimization is difficult because of the number of possible configurations and the numerical difficulties in finding truly optimal solutions
- Developed new methodologies that combine multifidelity wake physics and advanced optimization techniques to show significant benefit over other approaches
- Also shown that wind plants can produce more power if heterogeneous turbines are used within a plant
  - Ex: multiple hub heights/rotor diameters, etc.

"Coupled wind turbine design and layout optimization with nonhomogeneous wind turbines" **(Stanley and Ning, Wind Energy Science)**



At tight turbine spacing, the turbines alternate between larger and smaller rotor diameters (and different hub heights) for minimal wake impact. As turbine spacing increases, the two turbines approach the same diameter and hub height.

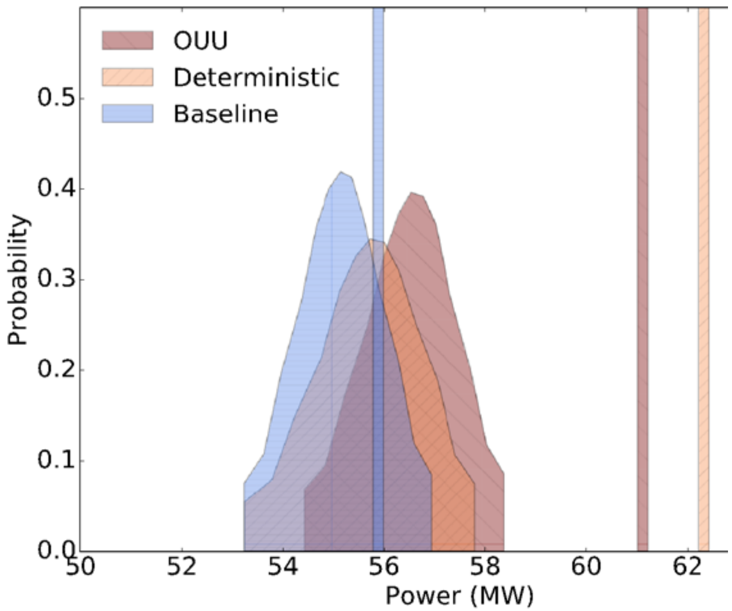


"Best Practices for Wake Model and Optimization Algorithm Selection in Wind Farm Layout Optimization" **(Baker et al., AIAA SciTech 2019)**

Round robin comparison of 9 optimization methods on the same problem to gain deeper insights into the problem and the algorithms

Plant control via wake steering and its impact on plant layout

- **Wake steering via yaw control significantly reduces plant wake losses**
  - Actual implementation requires good knowledge of the incoming flow to each turbine, which is difficult.
- **Developed methodologies to deal with the real-world limitations of measurement uncertainty and sparse measurement locations**
  - Wind field measurement sensors are not 100% accurate
  - Can only sparsely sample the wind field at a few locations.
- **How can wind field be reconstructed and wake steering strategies be robust to errors and uncertainty?**



Optimization Under Uncertainty for Wake Steering Strategies (Quick et al., TORQUE 2018)

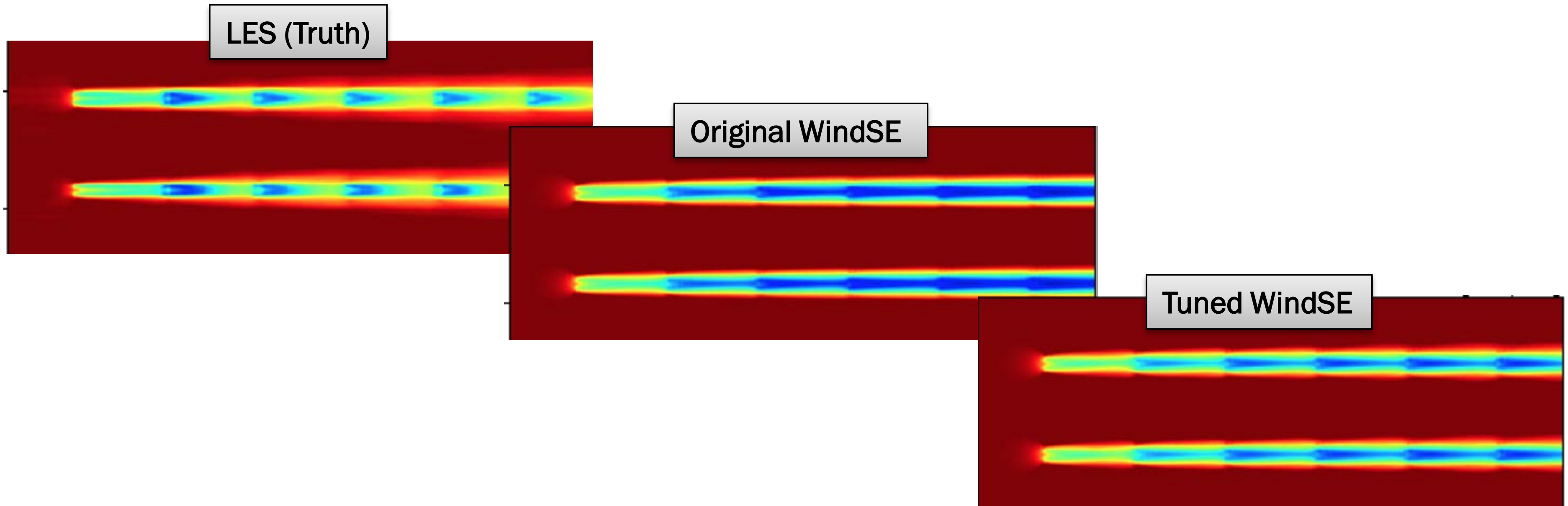
- Deterministic solution performs better if there is perfect knowledge of the inflow
- Under uncertainty, the OUU solution has less risk
- Generally uses less aggressive wake steering plan to avoid cases of over-steering

Sparse-Sensor Placement for Wind Farm Control (Annoni, TORQUE 2018)

- Develop an algorithm that uses atmospheric structures to reconstruct the flow field from limited point measurements
- Can then determine optimal placement of sensors for the best reconstruction.

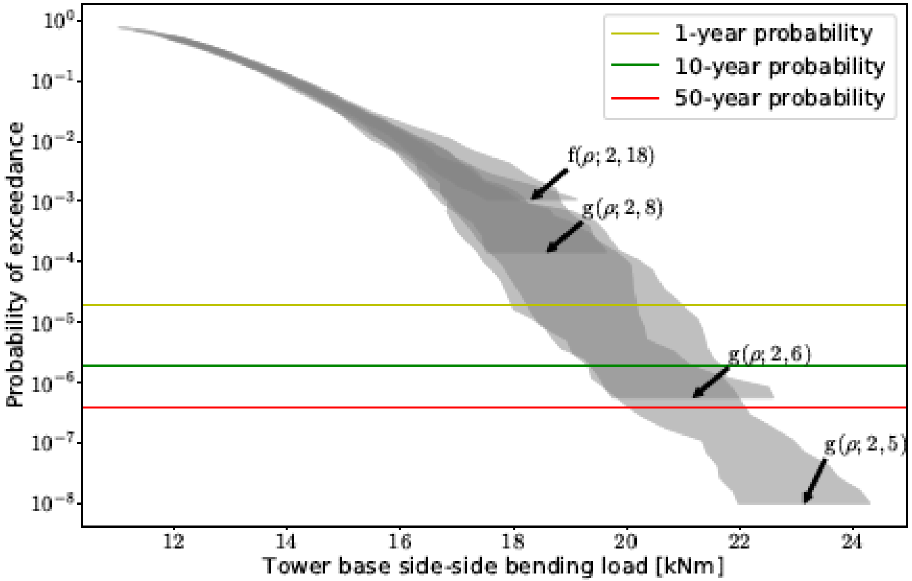
WindSE: High-fidelity flow model with turbulence physics and gradients for optimization

- **Layout optimization and plant control studies generally use idealistic assumptions of the terrain and atmospheric structures**
  - Accounting for these features would otherwise require high-fidelity modeling.
- **WindSE offers high-fidelity resolution with a much reduced computational cost, allowing it to be used with optimization**
- **FY 2017–FY 2018: significant developments in the usability and accuracy of WindSE**
  - Reduced-order model development (Active Subspaces for Wind Plant Surrogate Modeling, King et al., AIAA SciTech 2018)
  - Tuning of turbulence models with data and machine learning for more accurate wake and atmospheric behavior (Data-Driven Machine Learning for Wind Plant Flow Modeling King et al., TORQUE 2018)



Using importance sampling (targeting distribution tails) to estimate extreme loads

- Predicting 50-year extreme loads from turbulence is difficult because otherwise equivalent environmental conditions can lead to very different turbine loads
- 50-year prediction is typically done using either:
  - Extrapolation: Unsatisfying because predicting beyond data
  - Monte Carlo: Takes many simulations to converge to an estimate.
- Cast problem as stochastic optimization problem and use elements of both approaches
- Arrive at an extreme loads prediction more quickly and rigorously
- By further targeting the elements of turbulence that create extreme gusts, the simulation can converge even more efficiently



- Adaptive stratified importance sampling: hybridization of extrapolation and importance sampling Monte Carlo methods for estimation of wind turbine extreme loads (Graf et al., Wind Energy Science 2018)
- Temporal Coherence Importance Sampling for Wind Turbine Extreme Loads Estimation (Graf et al., AIAA SciTech 2019)

Accomplishments and Progress

	FY17 Q1	FY17 Q2	FY17 Q3	FY17 Q4	FY18 Q1	FY18 Q2	FY18 Q3	FY18 Q4
Plant layout optimization	AIAA SciTech, TORQUE papers			Journal submission	AIAA SciTech paper			
Plant control	AIAA SciTech, TORQUE papers		Wakes Conference paper	**Journal submission**			2 TORQUE papers	
Plant flow modeling					AIAA SciTech paper	ACC paper	TORQUE paper	
Importance sampling	AIAA SciTech paper		Journal submission					AIAA SciTech paper
International leadership	IEA Annual meeting, 2016 report	Draft reference turbines	Framework guidelines, WESC symposia, Task meeting	Co-organized SE workshop, IEA Annual Meeting	IEA Annual report, AIAA SciTech paper	Framework guidelines?	Annual meeting, TORQUE paper, Draft report	AIAA SciTech paper
WISDEM			Version 2	NAWEA workshop				

Legend: **Satisfied deliverable/milestone** **Slipped deliverable/milestone**

- Impressive research productivity from diverse team across 3 NREL centers, universities, and international collaborators
- Milestones that relied on international institutions (IEA Wind Task 37 related) slipped
  - Scope of work too aggressive and too much disconnect between NREL/DOE priorities and those of others.

Communication, Coordination, and Commercialization

- **Conferences presentations of FY 2017–FY 2018 work at**
  - TORQUE 2016, 2018
  - AIAA SciTech 2017, 2018, 2019
  - Wind Energy Science Conference 2017.

- **Collaboration with other researchers**
  - BYU (direct subcontract)
  - DTU, TUM, TUDelft, Sintef (Task 37 leadership)
  - Many others through workshops.

- **MDAO evangelism**
  - System Engineering workshop at DTU 2017: focus on other researchers and industry practitioners (summary report provided to DOE)
  - Conference sessions (AIAA, TORQUE) and symposia (WESC) to bring MDAO to the broader wind audience.

- **Industry collaboration**
  - Active agreements for collaborative studies with Envision, Goldwind, Vestas
  - Active conversations with General Electric, Oersted, Equinor, WEG, others
  - WISDEM commercialization possibility through Ystrategies.

Upcoming Project Activities

FY 2019 (current merit review covers FY 2017–FY 2019)

- Continue current focus areas.

FY 2020–FY 2023: New merit review proposal with theme, "Bringing A2e contributions into the turbine/plant system design"

- Enabling real-world wind plant layouts with wake steering
- Site-customized, robust turbines and plants
- Floating offshore systems solutions
- System assessment of component technology innovations
- Continuing international leadership.