U.S. DEPARTMENT OF ENERGY

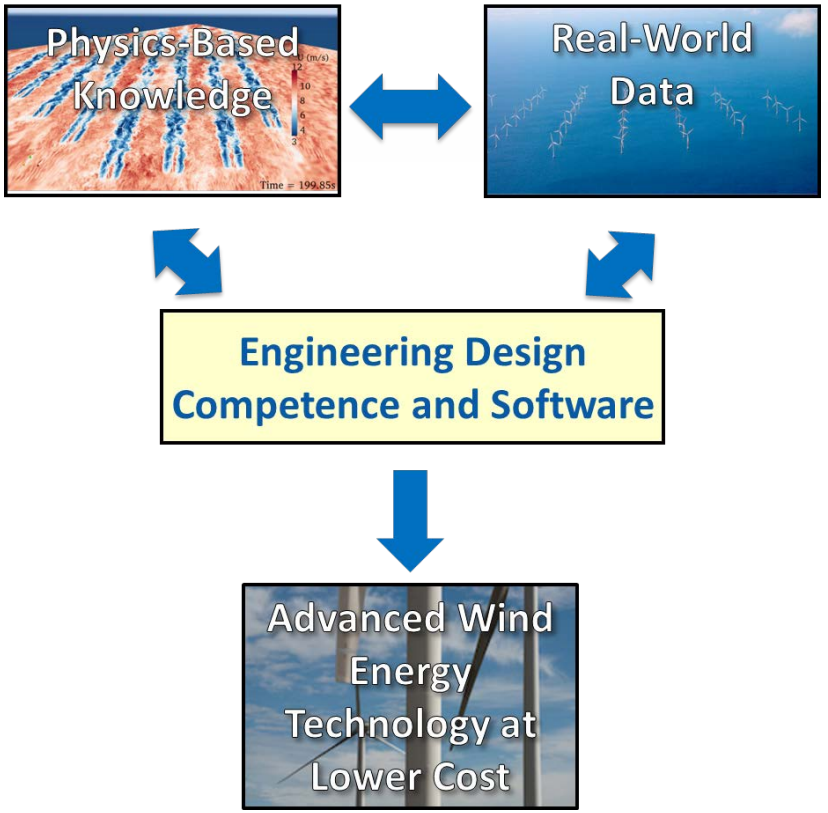
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Multi-Physics Model Validation and Uncertainty Quantification

Project ID #T28

Jason Jonkman

NREL



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

T28: Multi-Physics Model Validation and Uncertainty Quantification

Project Summary

- Enable the development of advanced wind-plant technology by leveraging knowledge, data, and high-fidelity modeling (HFM) results from the broader Atmosphere to Electrons (A2e) initiative to verify and validate (V&V) and improve physics-based engineering tools at both the turbine and plant levels

Project Objective and Impact

- Systematically V&V physics-based engineering tools by comparisons to HFM and experimental data to quantitively understand their applicability, accuracy, and uncertainties
- Improve the physics of engineering tools to expand the tools' applicability where limitations hinder technology advancement
- Engage in international V&V collaboratives among research laboratories, academia, and industry to further advance engineering models

Project Attributes

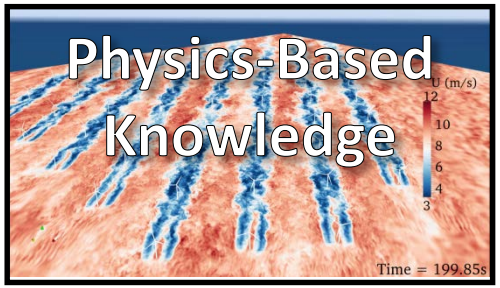
Project Principal Investigator(s)
PI (NREL): Jason Jonkman Other (NREL): Paula Doubrawa, Amy Robertson, Kelsey Shaler
DOE Lead
Alana Duerr
Project Partners/Subs
IEA Wind Task 29 Aerodynamics IEA Wind Task 31 WakeBench DNV GL JIP on "Validation of Turbulence Models"
Project Duration
October 2016–September 2018

Technical Merit and Relevance

Why?
Lower wind cost of energy requires technology advancement through improved engineering capability founded on physics.

What?
Improved physics-based engineering design competence and software needed to advance wind energy technology.

How?
Use the knowledge, data, and results from the broader A2e initiative to improve physics-based engineering design competence and software collaboratively with the wind energy community.



Engineering Design Competence and Software

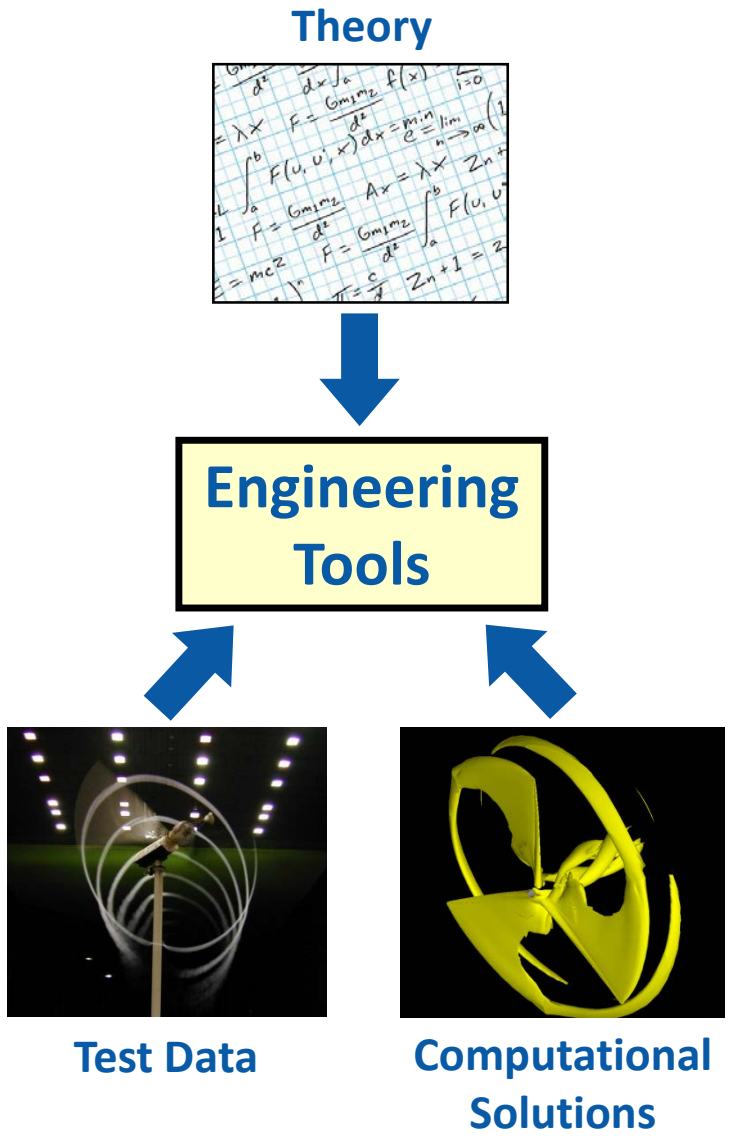
Approach and Methodology

Workshops: Host workshops to plan out how A2e can improve wind-industry capability and technology through international collaboration.

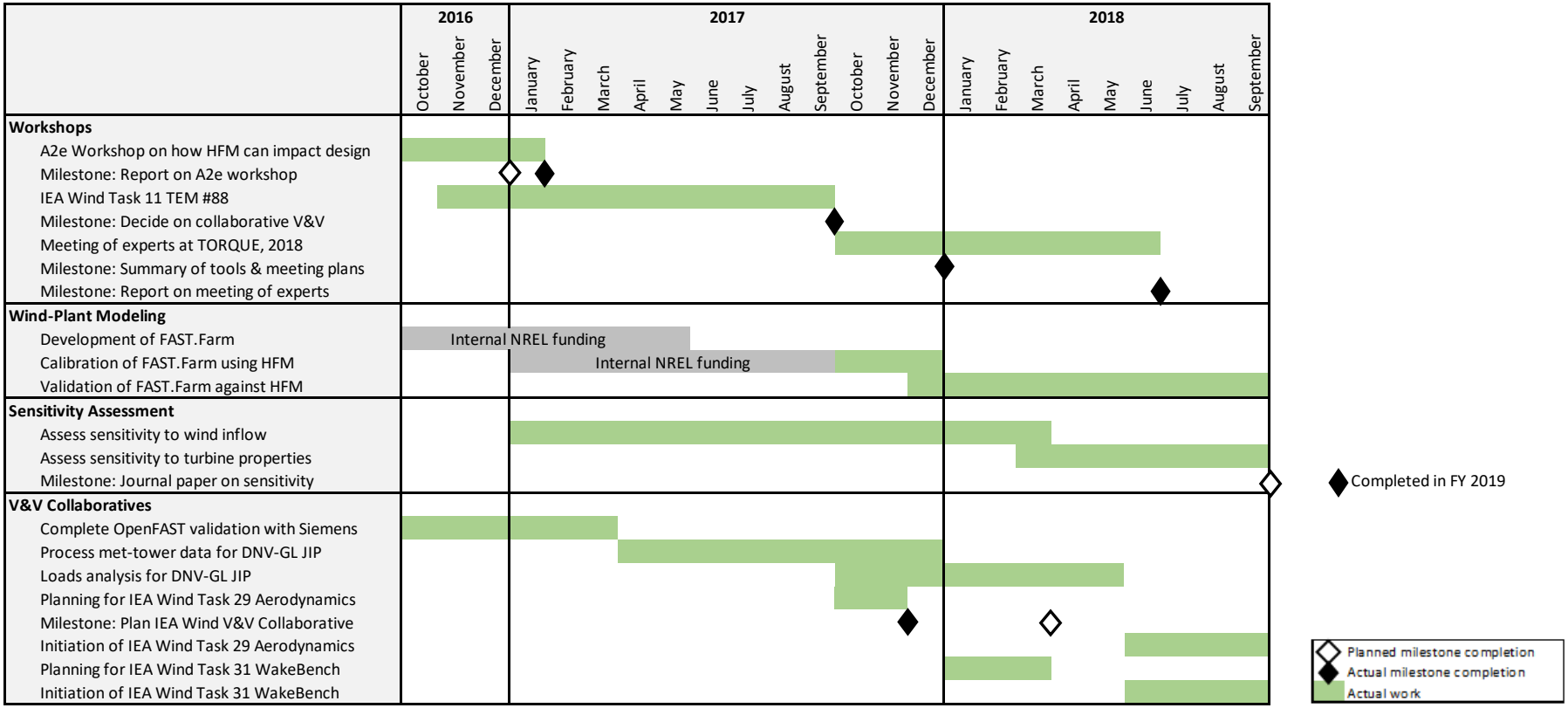
Wind-Plant Modeling: Support the development and V&V of the next generation of mid-fidelity wind-plant engineering tools that have the ability to model the relevant physics of wind plants and are needed to develop next generation wind-plant technologies.

Sensitivity Assessment: Understand the effect of uncertainty in input parameters to engineering models of wind turbines and wind plants on modeling results.

V&V Collaboratives: Engage in V&V collaboratives—to not only validate and improve A2e-developed tools—but to improve other tools used within the wind industry.



Accomplishments and Progress



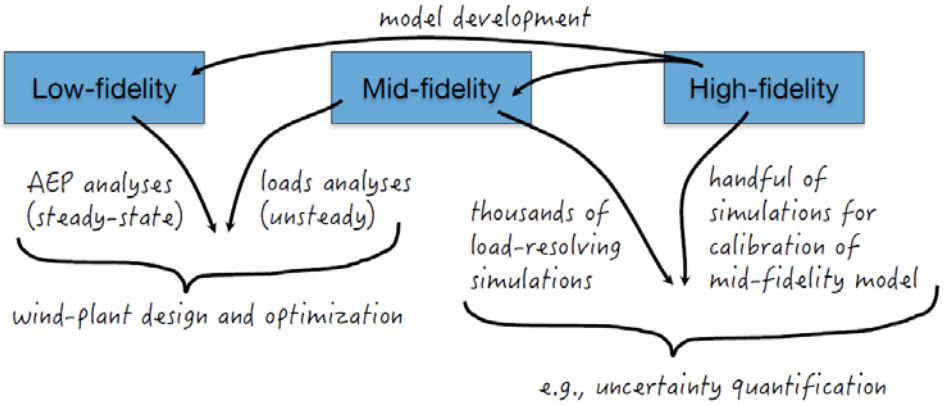
IEA = International Energy Agency | JIP = joint industry project | NREL = National Renewable Energy Laboratory | TEM = topical experts meeting

- **Milestones**
  - All but two milestones were completed on time or ahead of schedule
  - Fiscal Year (FY) 2017 Q1 milestone completed one-month late to ensure proper participation at A2e workshop
  - FY 2018 Q4 milestone completed one-quarter late due to the project complexity
- **Go/No-Go Decision Points**
  - FY 2017: Should an IEA Wind V&V Collaborative on rotor aero-elastics move forward? Go

Accomplishments and Progress

- **Hosted three workshops to plan out how A2e can improve wind-industry capability and technology through international collaboration:**
  - A2e workshop on how investment in HFM and their V&V can connect to improvement of wind-industry-wide design capability and technology
  - IEA Wind Task 11 Topical Experts Meeting (TEM) #88 on three-way V&V between data, HFM, and engineering tools in areas of wind-plant aerodynamics, rotor aero-elastics, and offshore support structures
  - Meeting of experts on "Mid-Fidelity Wind-Plant Models" at TORQUE, 2018

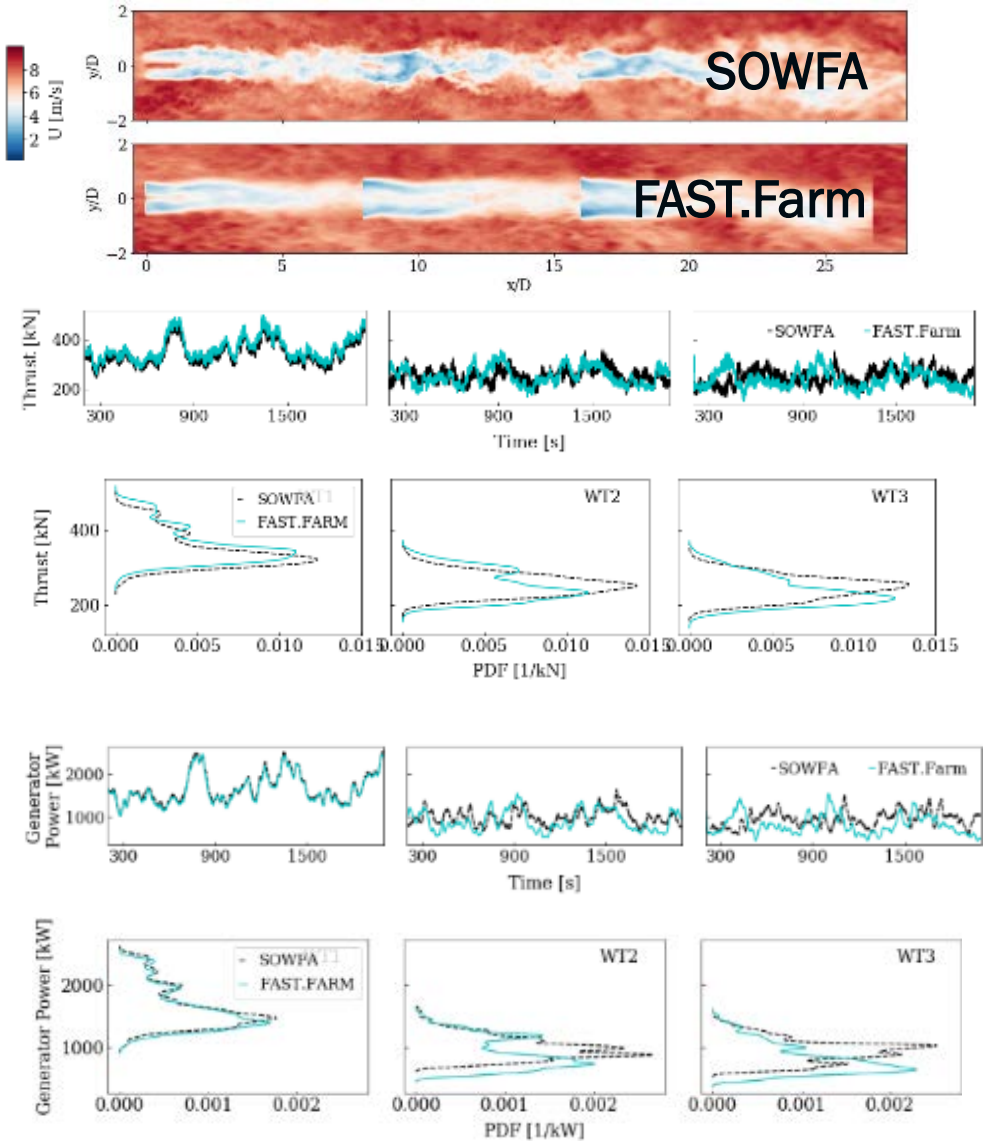
Photo from IEA Wind Task 11 TEM #88



Accomplishments and Progress

- **Completed development, calibration, and validation of FAST.Farm:**
  - Originated under internal NREL funding
  - New multi-physics engineering tool captures relevant physics for accurate prediction of power performance and loads, but maintains computational speed to enable loads analysis
  - Developed calibration procedure to adjust tunable model parameters of **FAST.Farm** to match results of HFM Simulator fOr Wind Farm Applications (**SOWFA**)
  - Validated **FAST.Farm** against the **SOWFA** to highlight where **FAST.Farm** functions well and where potential improvements could be needed

Flow Visualizations and Results

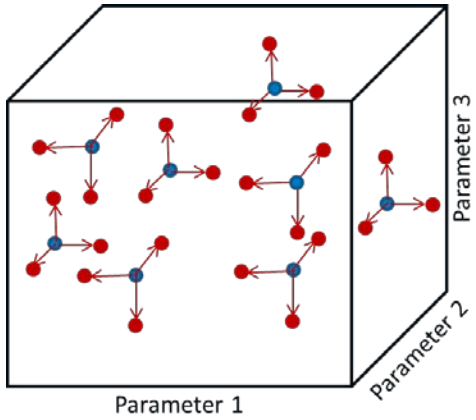


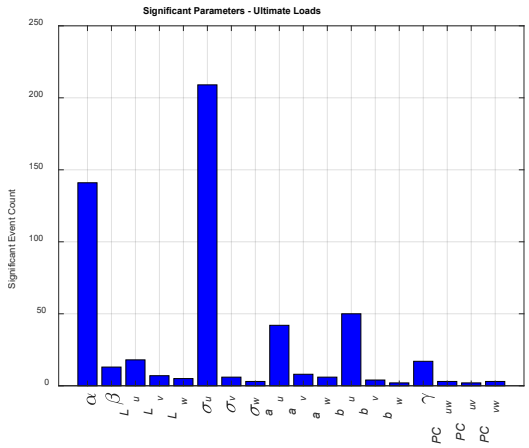
Accomplishments and Progress

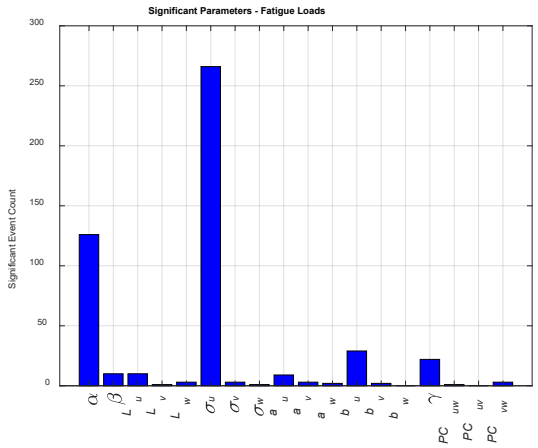
- **Assessed sensitivity of aero-elastic modeling to identify inputs with high variability/uncertainty that are most influential on loads and power:**
  - Sensitivity to wind inflow (profile, spectra, coherence, correlations)
  - Sensitivity to turbine properties (aerodynamic coefficients, mass, stiffness, damping, control)
- **Understanding effects of input uncertainty is critical to help establish error bars on model predictions in validation efforts and to inform future probabilistic design processes and site-suitability analyses**

Elementary Effects:

$$\mathrm{EE} = \frac{\partial Y}{\partial U}\Delta U$$

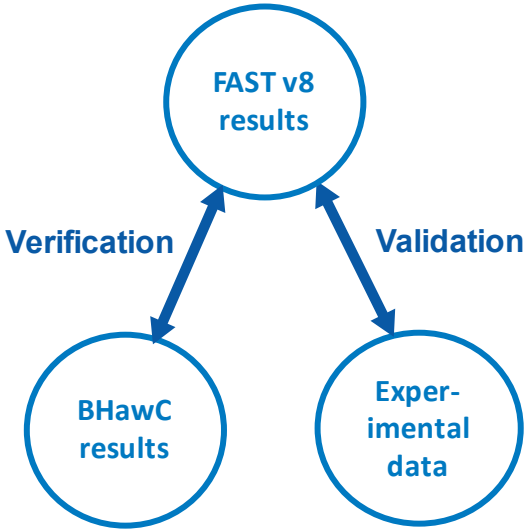


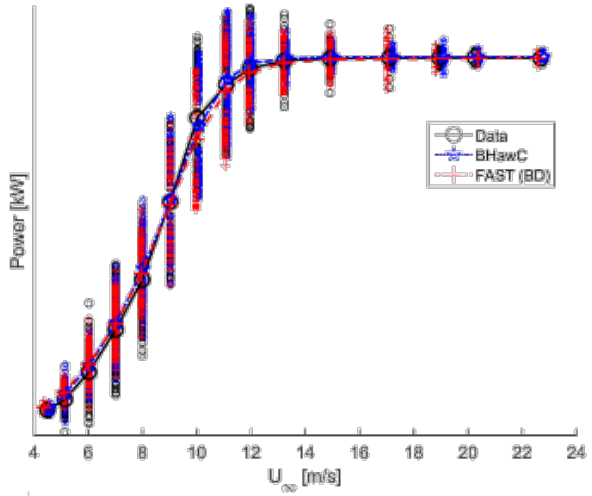


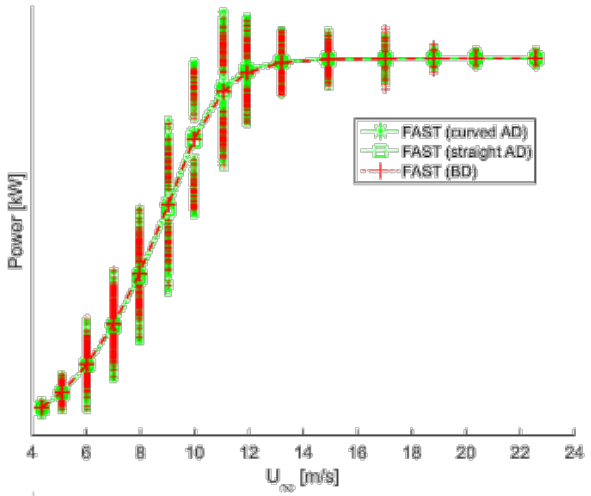


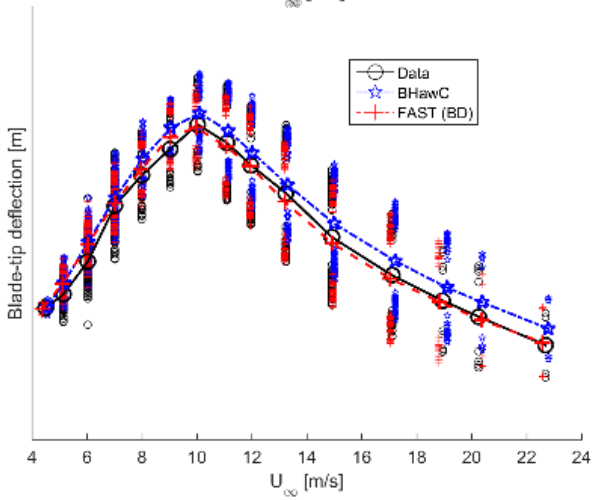
Accomplishments and Progress

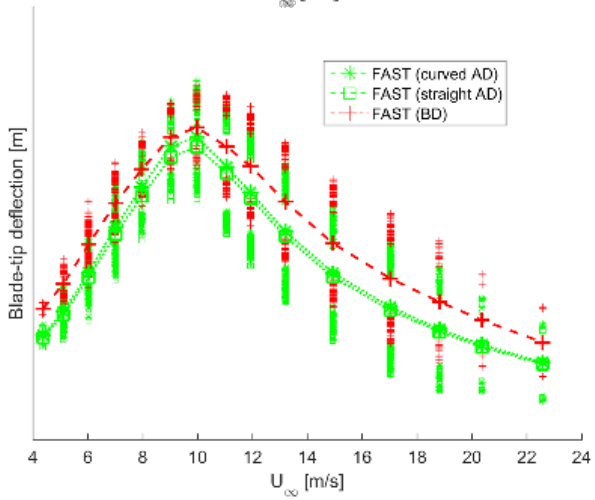
- Completed V&V of **OpenFAST** (previously known as **FAST**) against experimental data and modeling results from the Siemens 2.3-MW turbine









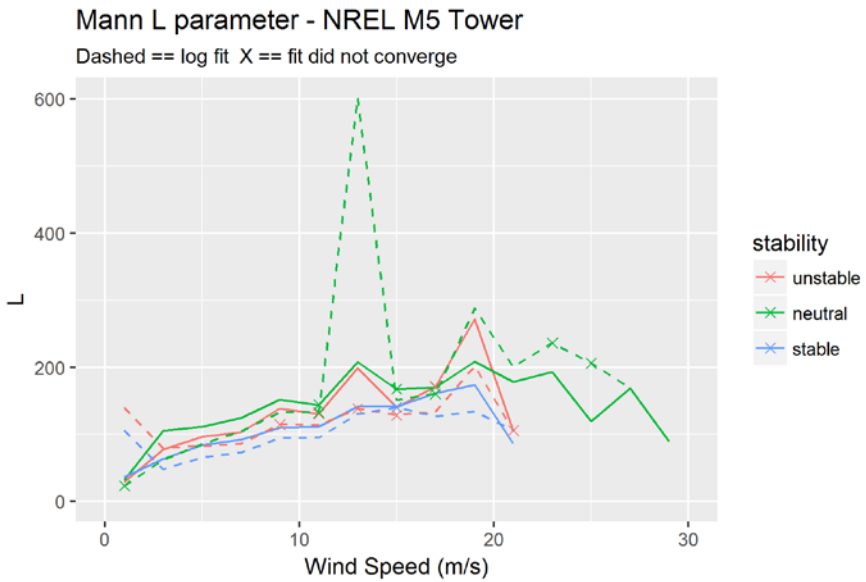


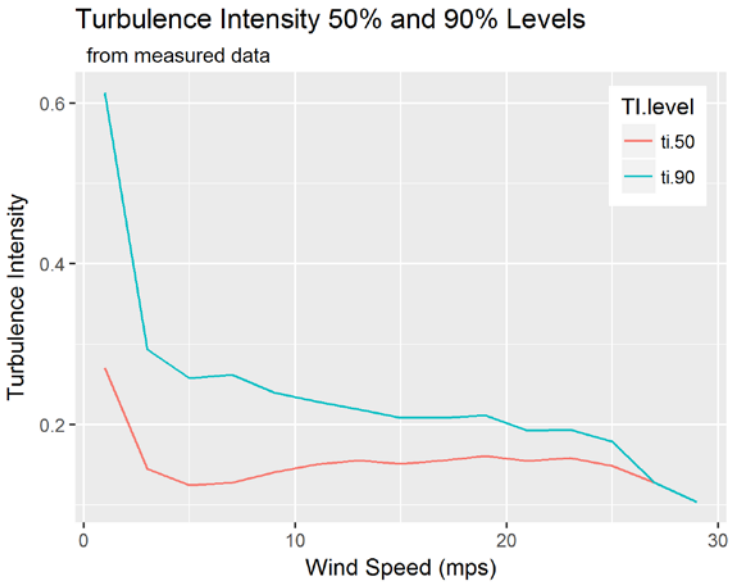
Accomplishments and Progress

- Completed DNV-GL Joint Industry Project (JIP) on "validation of turbulence models"

- **Objective:** Quantify turbulence properties at the heights and scales of modern utility-scale turbines and evaluate how various atmospheric turbulence properties impact turbine design

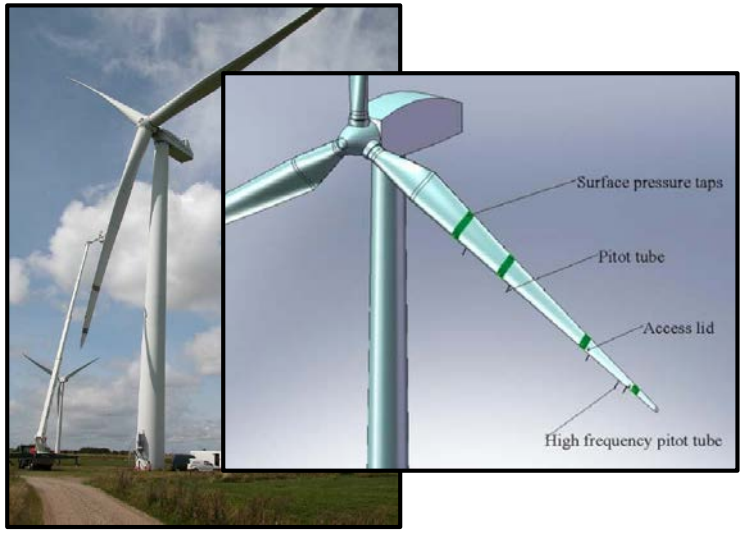
- **Activities:**
  - Processed met-tower data to quantify turbulence properties from a suite of datasets
  - Investigated sensitivity of turbine loads to turbulence model parameters

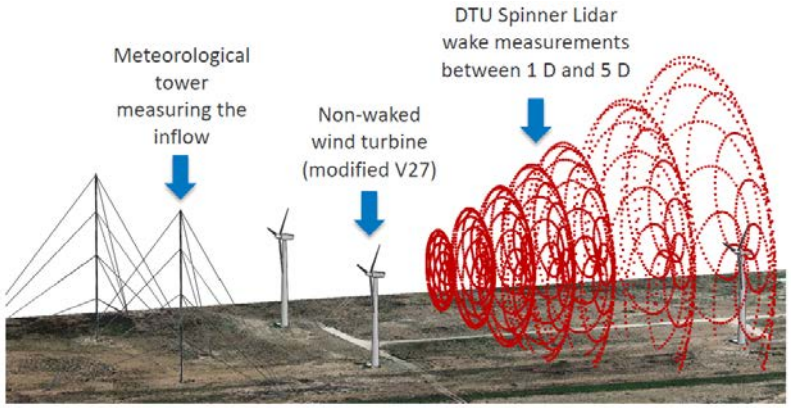




Accomplishments and Progress

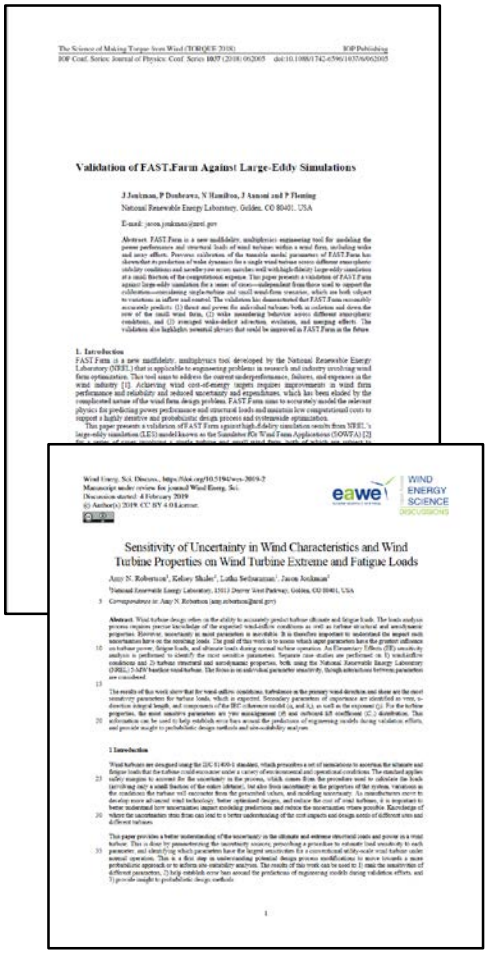
- **Initiated IEA Wind Task 29 Aerodynamics:**
  - Led by ECN part of TNO (G. Schepers) and Technical University of Denmark (DTU) (H. Madsen)
  - **Objective:** Exploit data from the Danish DanAero field experiment of NM80 2-MW wind turbine at Tjaereborg to validate and improve turbine aero-elastic models (both engineering and HFM)
  - Participating using **OpenFAST**
- **Initiated IEA Wind Task 31 WakeBench Phase 3:**
  - Led by NREL and Sandia National Laboratory (SNL)
  - **Objective:** Exploit data from the Scaled Wind Farm Technology (SWiFT) facility field experiment to validate and improve simulations of wind-turbine wakes (both engineering and HFM) under different atmospheric conditions (neutral, unstable, stable)
  - Participating using **FAST.Farm**





Communication, Coordination, and Commercialization

- **Deliverables:**
  - Wind turbine and wind plant engineering tools
  - V&V results published in conferences and journals
- **Customers:**
  - U.S. Department of Energy projects involving HFM V&V and design applications
  - External research laboratories, academia, and industry who apply the tools directly or use to V&V internal tools
- **Workshops and V&V Collaboratives:**
  - Active engagement with wind-energy designers, consultants, developers, and certification bodies
  - IEA Wind Tasks 29 and 31
  - DNV-GL JIP
- **Several related externally funded industry projects:**
  - Envision Energy, Equinor, Vestas, Google X / Makani, etc.



Software Downloads	Workshops	Journal Articles	Conference Papers	Other Reports
10,000+ per year	3	4	5	5

Upcoming Project Activities

- Continue to advance engineering design capabilities needed to design larger and more flexible wind turbines and innovative concepts in the wind-plant context
- Wind-Plant Modeling:
  - Assess the sensitivity of **FAST.Farm** to inflow generation technique and discretization
  - Validate **FAST.Farm** against HFM and data from Lillgrund
  - Publicly release **FAST.Farm**
- Sensitivity Assessment:
  - Complete the turbine property assessment
  - Inform A2e-HFM regarding most sensitive parameters
  - Assess sensitivity to wind inflow on loads of downstream turbines in a wind plant
- V&V Collaboratives:
  - V&V using DanAero data in IEA Wind Task 29
  - V&V using SWiFT data in IEA Wind Task 31
  - Initiate new DNV-JL JIP on deriving wind data for simulation from measurements