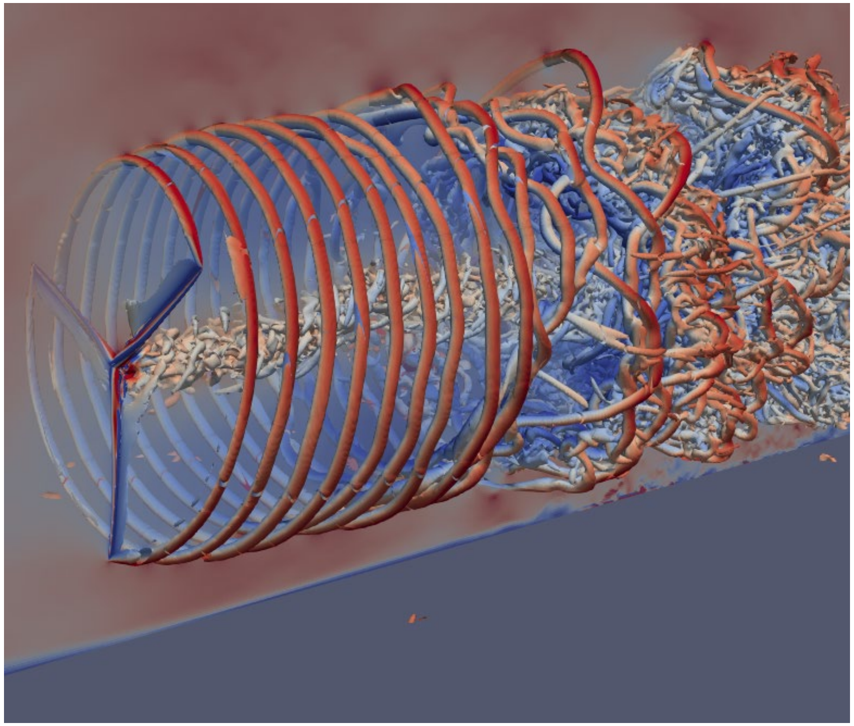
U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

2021 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY
WIND ENERGY TECHNOLOGIES OFFICE



T18 - High-Fidelity Modeling

Wind - Wind – Atmosphere to Electrons (A2e)

Michael A. Sprague
NREL

August 4, 2021

FY21 Peer Review - Project Overview

Project Summary:

- Creating an open-source, multi-fidelity modeling and simulation environment for wind energy called *ExaWind* (Nalu-Wind, AMR-Wind, OpenFAST)
  - Rigorous verification and validation
  - Modern software engineering and development best practices
  - Capable on running on laptops (low-fidelity) and on latest graphical-processing-unit (GPU) accelerated DOE supercomputers
- Executed in close collaboration with the “ExaWind” subproject of the DOE Exascale Computing Project (ECP)
- Performing simulations designed validate the codes and to create new understanding of complex flow physics and turbine dynamics
- Establishing new methods for reduced-order modeling and uncertainty quantification
- Focusing on land-based wind; initiated offshore development in FY20

Project Objective(s) 2019-2020:

- Implement and verify the multi-fidelity simulation capability in Nalu-Wind and expand that capability into the full ExaWind code suite (Nalu-Wind, AMR-Wind, OpenFAST)
- Hierarchical validation that quantifies predictive capability
- Initial high-fidelity-model development for offshore wind

Overall Project Objectives (life of project):

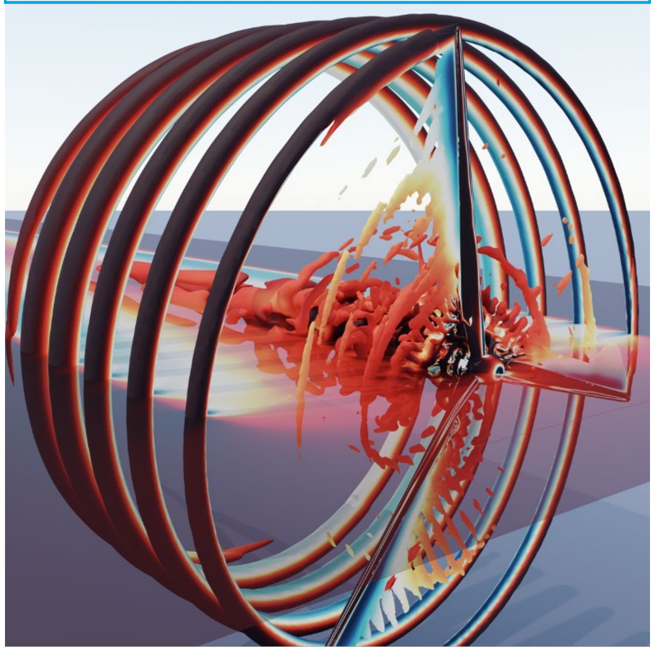
- A well-tested, robust, open-source code suite that provides multi-fidelity simulations of wind farms that can run on workstations and next-generation high-performance computers
- A new depth of understanding of wind turbine and wind plant dynamics

Project Start Year: 2016
Expected Completion Year: FY22
Total expected duration: 6.5 years

FY19 - FY20 Budget: $3,360,510

Key Project Personnel:
Mike Sprague, NREL
Paul Crozier, SNL

Key DOE Personnel:
Michael Derby, Ben Hallissy



Nalu-Wind simulation of the NREL 5-MW turbine

Project Impact

Why is the High-Fidelity Modeling (HFM) project important? HFM Provides:

- Pathways to understanding wind plant physics and reducing wind plant losses
- Simulation-data and knowledge foundations for the next-gen design tools
- The capability to explore disruptive technology innovations quickly and with confidence
- Close collaboration with the DOE Office of Science Exascale Computing Project (ECP) and access to the largest DOE supercomputers

What new opportunities have emerged due to the HFM project?

- Code base that is ready for expansion for floating offshore wind
- Partnership with ECP, which is funding ExaWind development with **$19.5M over FY17-23**
  - HFM and ECP have engagement from over 40 researchers across 5 institutions: NREL, SNL, Oak Ridge National Laboratory, Univ. of Texas at Austin, Univ. of Colorado-Boulder
- Partnership with General Electric:
  - National Offshore Wind Research and Development Consortium (NOWRDC) project; **$1.3M over 3 years**
  - DOE Technology Commercialization Fund (TCF) project; **$800k over 1 year**
  - DOE ASCR Leadership Computing Challenge (ALCC) computer-time award
  - GE is adopting the HFM codebase as their simulation platform
- Partnership with Continuum Dynamics, Inc. in SBIR Phase IIB project

Program Performance – Scope, Schedule, Execution

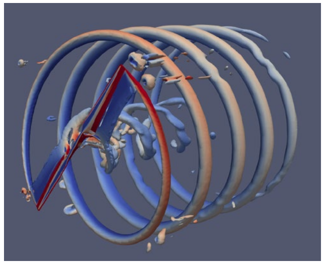
FY17 – FY18

- Establishment of principal codes and base algorithms for mid- and high-fidelity simulations: Nalu-Wind & OpenFAST
- Securement of additional funding through DOE Exascale Computing Project

Nalu-Wind blade-resolved large-eddy simulation (LES) of the NREL 5-MW turbine

FY19 - FY20

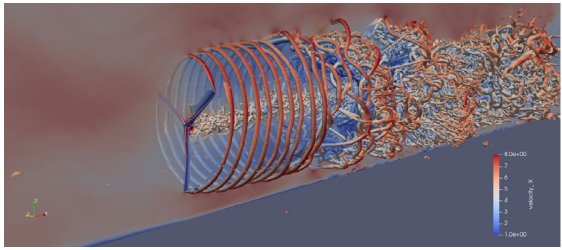
- Expansion/enhancement of codes & algorithms
- Completion of multi-fidelity blade-modeling capabilities
- Addition of AMR-Wind and “ExaWind” hybrid solver
- Verification, validation, uncertainty quantification, reduced-order modeling
- Preliminary development for offshore wind



Nalu-Wind blade-resolved Reynolds-Averaged Navier-Stokes (RANS) validation simulation of NREL Phase VI turbine

FY21 - FY22

- Offshore work split off into a new WETO project
- Completion of baseline hybrid-RANS/LES turbulence models and validation
- Completion of complex terrain models and validation
- Completion of fluid-structure interaction and validation



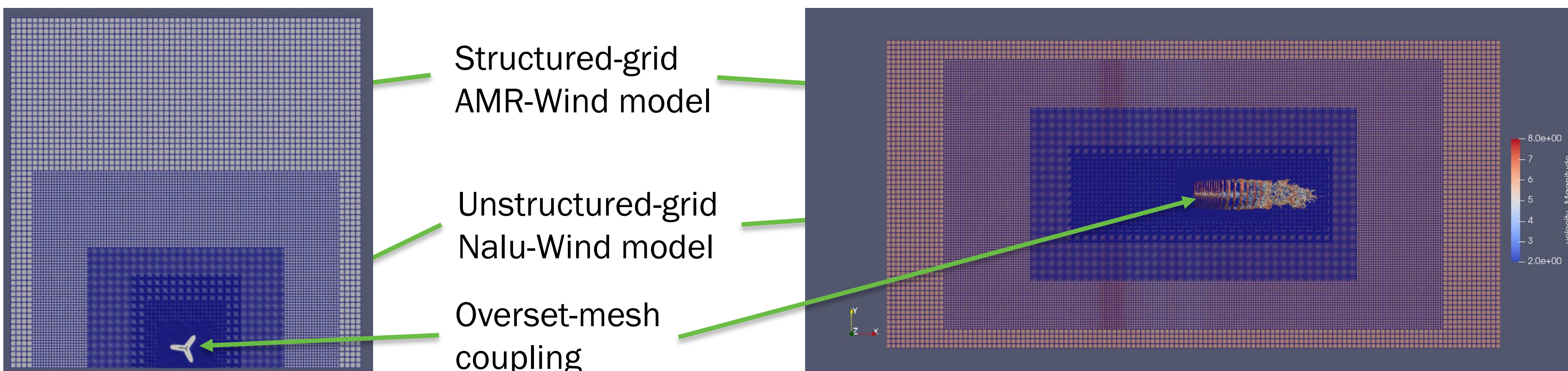
ExaWind blade-resolved hybrid-RANS/LES validation simulation of DanAero NM80 turbine

FY19 – FY20 were on budget and all ten milestones were completed with two being late

Program Performance – Accomplishments & Progress

- We are creating an open-source, multi-fidelity modeling and simulation environment for wind turbines and wind farms
  - Backed by rigorous verification and validation
  - Can run on laptops (lowest fidelity) and on latest graphical-processing-unit (GPU) accelerated DOE supercomputers (highest fidelity)
- Establishment of the hybrid-solver approach was a game changer
  - Exploits the best of the Nalu-Wind and AMR-Wind codes
  - Atmospheric boundary layer simulations in AMR-Wind are at least 5 times faster than those on Nalu-Wind

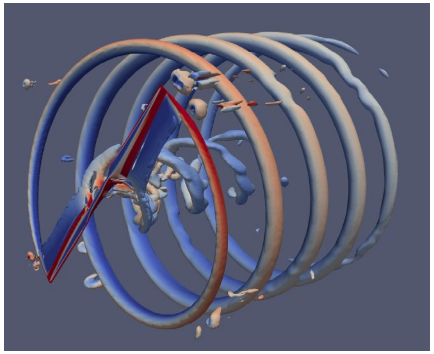
Example ExaWind hybrid simulation of the DanAero NM80 turbine



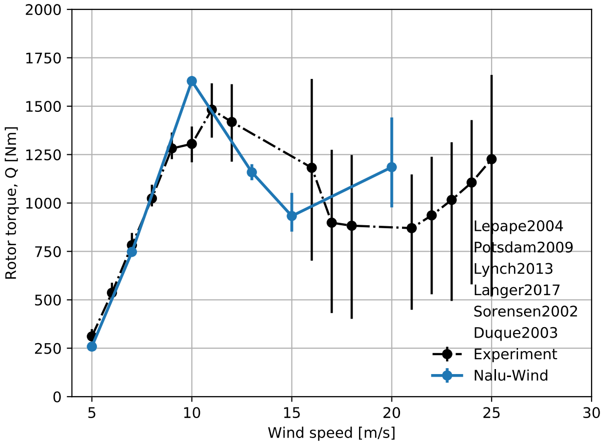
Model has 21M grid points; latest simulations take 1.3 hours per revolution at strong-scaling limit on the Eagle supercomputer

Program Performance – Accomplishments & Progress

NREL Phase-VI turbine validation; unsteady Reynolds-Averaged-Navier-Stokes (RANS) turbulence model



Flowfield visualization of the Nalu-Wind simulation

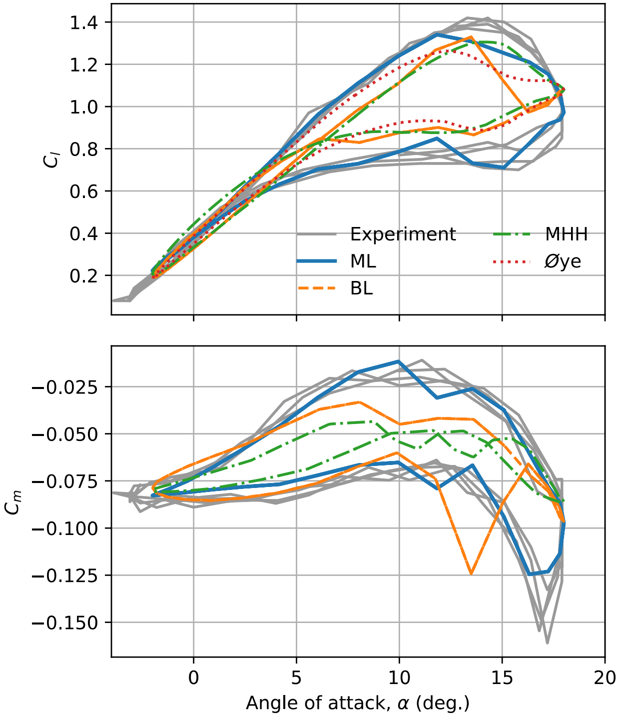


Experimental and simulated average rotor torque of the NREL Phase VI turbine, including Nalu-Wind results

Sprague, et al., 2020, ExaWind: A multifidelity modeling and simulation environment for wind energy, *J. Phys.: Conf. Ser.* 1452

New machine-learning (ML) unsteady aerodynamics (UA) model performs much better than state-of-the-art UA models; shows how ML can be trained with HFM results

Comparison of the new ML unsteady-aerodynamics model, three state-of-the-art UA models, and experimental data for coefficient of lift and moment (C_l and C_m) of a pitching N4415 airfoil (BL – Beddoes-Leishman; MHH – Hansen et al.; Øye – Øye dynamic stall)

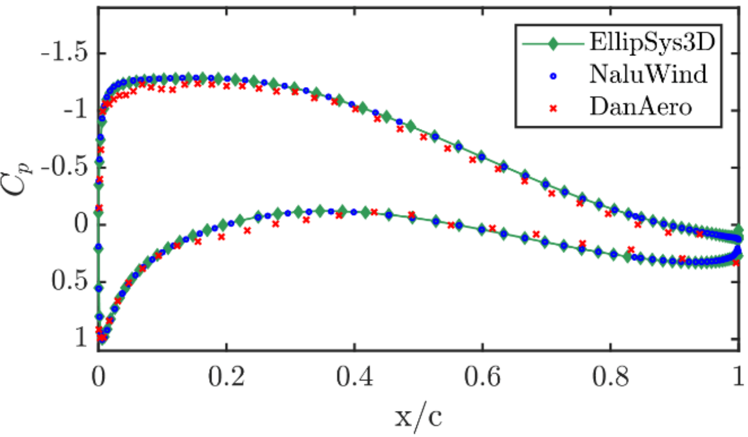


Ananthan, et al., 2020, A DNN surrogate unsteady aerodynamic model for wind turbine loads calculations, *J. Phys.: Conf. Ser. 1618*

Program Performance – Accomplishments & Progress

Nalu-Wind validation of MW-scale turbine in sheared flow

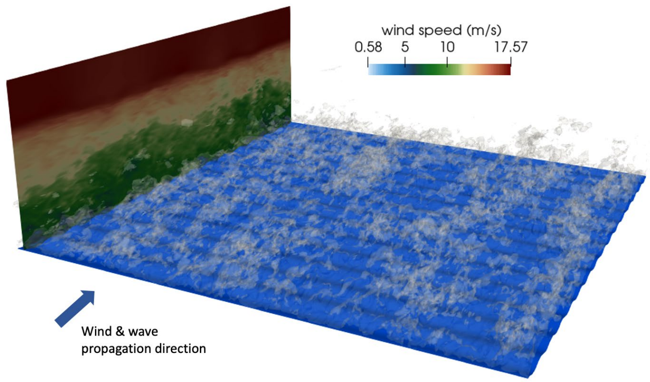
- Validation performed as part of IEA Wind Task 29; DanAero turbine
- Collaboration with Denmark Technical University and their code EllipSys3D



Pressure distributions at 33% 76% blade length for axisymmetric flow.

Grinderslev et al., 2020, Validation of blade-resolved computational fluid dynamics for a MW-scale turbine rotor in atmospheric flow, *J. Phys.: Conf. Ser. 1618*

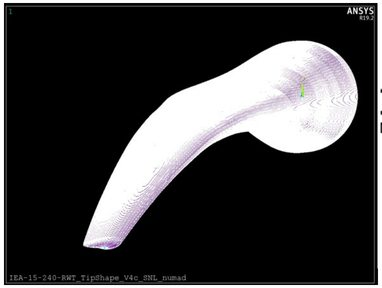
New marine atmospheric boundary layer simulation capability in Nalu-Wind



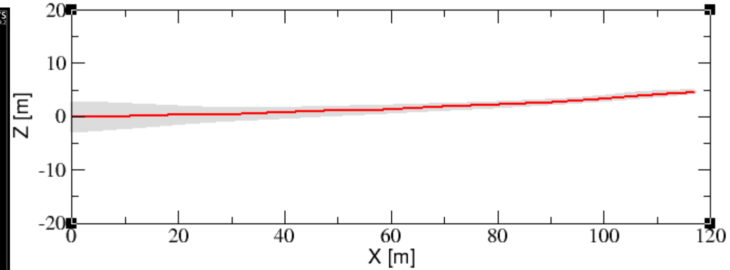
Snapshot of the velocity and vorticity atmospheric fields over a swell

Deskos, et al., 2021, Review of wind-wave coupling models for large-eddy simulation of the marine atmospheric boundary layer, *J. Atm. Sci.,* accepted.

Validation of nonlinear beam blade model

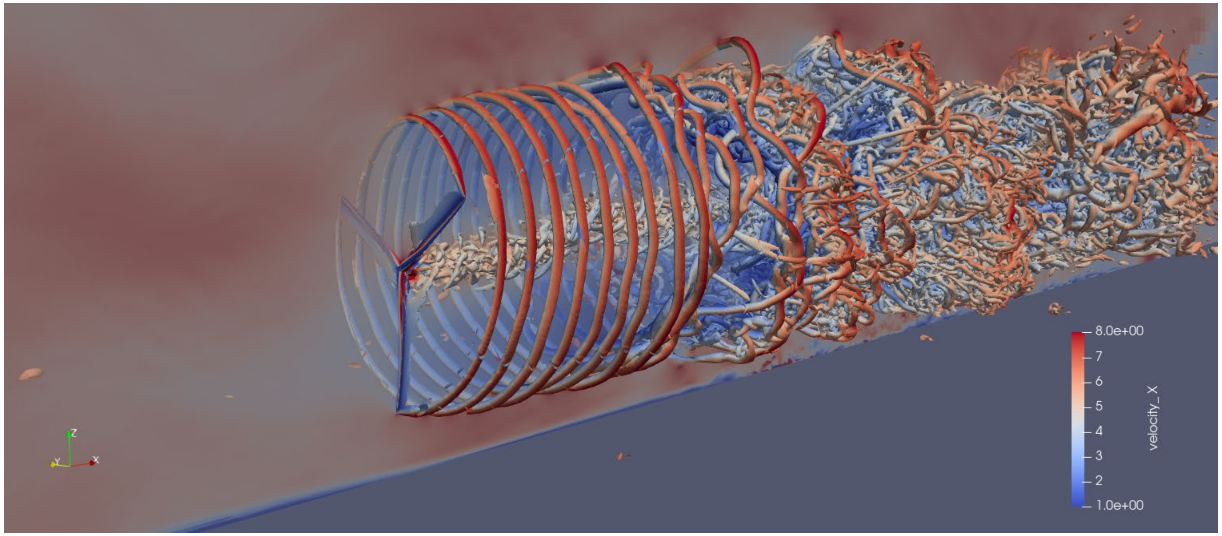


ANSYS model (68,445 Shell281 elements) of the IEA 15-MW reference turbines



ANSYS (gray) and BeamDyn (red) solutions for the IEA 15-MW turbine in deformed configuration under uniform force.

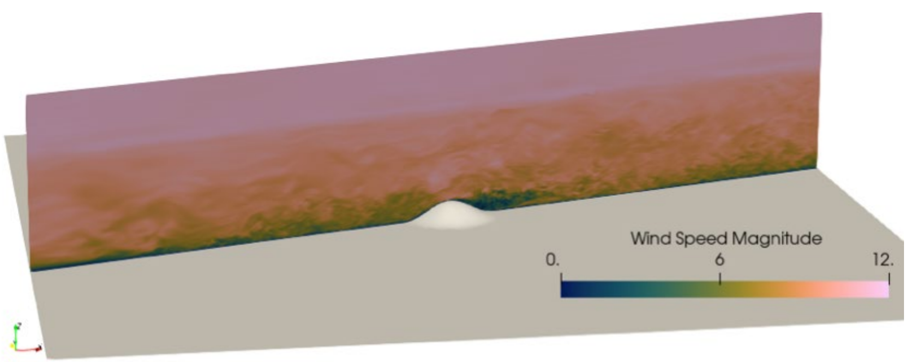
Project Performance - Upcoming Activities



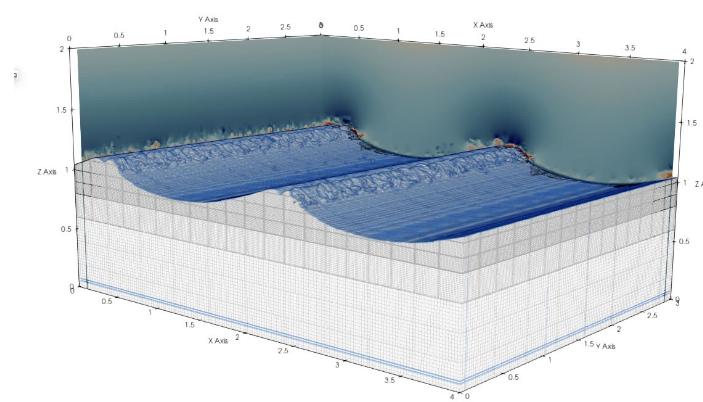
ExaWind validation of MW-scale turbine in turbulent atmospheric flow

- DanAero NM80 turbine
- IEA Wind Task 29; without fluid-structure interaction (FSI)
- IEA Wind Task 47; with FSI and coupled to OpenFAST
- Working with RAAW project for flexible-rotor validation

Complex terrain modeling and validation in AMR-Wind and Nalu-Wind



Multi-phase flow for floating offshore wind in AMR-Wind *(Floating Offshore Wind project)*



Stakeholder Engagement & Information Sharing

- **Overall strategy**
  - Creating open-source, robust, performance-portable software to accelerate adoption and use; provide support in open domain
  - Documenting model validation to establish user confidence; coordinate through our benchmark working group and International Energy Agency
  - Actively publishing and presenting modeling advances; organized user workshops
  - Maintaining active coordination with the DOE Exascale Computing project, which is supporting performance portability of ExaWind and provides access to DOE Leadership Computing Facilities and collaboration with Intel, AMD, and NVIDIA
- **Presentations, publications, & workshops (FY19-FY20)**
  - 8 papers/book-chapters published; 4 papers submitted
  - 14 presentations
  - 2 software-user workshops at the *2019 NAWEA/WindTech Conference*
- **Partnerships with universities (Univ. of Texas; Univ. of Colorado)**
- **Partnership with International Energy Agency Wind Tasks 29 and 47**
- **Partnerships with industry**
  - Partnerships with GE
  - Partnership with Continuum Dynamics, Inc
  - Exploring opportunities with multiple other potential industry partners

Key Takeaways and Closing Remarks

Project Impact:

We have created a state-of-the-art open-source multi-fidelity simulation capability that is backed by rigorous verification and validation and modern performance-portable software engineering

Project Performance:

Ten milestones were completed and on budget, with all but two milestones being completed on schedule; delays were actively managed to minimize delays and negative impacts

Stakeholder Engagement:

- *Numerous publications, presentations, and workshops*
- *Industry partnerships*
- *Partnership with IEA Wind through Tasks 29 and 47*
- *Partnership with the DOE Office of Science*