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

ATMOSPHERE TO ELECTRONS
U.S. DEPARTMENT OF ENERGY

A2e Program Overview

Michael Robinson

2019 Wind Program Peer Review

Program/Activity *Area* Lead

April 30 – May 2, 2019

Wind Office Goals

Enabling Wind Options Nationwide

FY 2017–18 LCOE Targets

- The Office <u>exceeded</u> its Government Performance Reporting Act (GPRA) levelized cost of energy (LCOE) end of year targets for both land-based and offshore wind in Both FY 2017 and FY 2018.

<u>FY 17-18 GPRA Targets</u>

Land-Based Wind: Reduce the unsubsidized market LCOE for utility-scale land wind energy systems from a reference wind cost of $.074/kWh in 2012 to $.057/kWh by 2020 and $.042/kWh by 2030.

Offshore Wind: Reduce the unsubsidized market LCOE for offshore fixed-bottom wind energy systems from a reference of $.18/kWh in 2015 to $.15/kWh by 2020 and $.096/kWh by 2030.

Future Goals

- **LCOE targets:** The office works to achieve breakthroughs in reducing the LCOE for land-based wind by 50% from today's LCOE, to $.023/kWh without subsidies by 2030, and achieving a 50% reduction in offshore wind and distributed wind by 2030 from a 2015 benchmark.

- **Additional non-LCOE targets are under development by the office**

Wind Office Strategic Priorities

Clean, low-cost wind energy options nationwide

	Land-Based Wind	Offshore Wind	Distributed Wind
Technology Development & Scientific Research	Atmospheric Science & Wind Plant Systems Engineering	Atmospheric Science & Wind Plant Systems Engineering	Atmospheric Science
	Standards and Certification	Standards and Certification	Standards and Certification
	Technology Innovation	Technology Innovation	Technology Innovation
	World Class Testing Facilities	World Class Testing Facilities	
	Tech to Market Commercialization	Tech to Market Commercialization	
	Integrated Systems Design	Integrated Systems Design	
		Offshore Specific R&D	
		Advanced Technology Demo Projects	
Market Acceleration & Deployment	Advanced Grid Integration	Advanced Grid Integration	Advanced Grid Integration
	Workforce and Education Development	Workforce and Education Development	Workforce and Education Development
	Stakeholder Engagement	Stakeholder Engagement	Stakeholder Engagement
	Environmental Research	Environmental Research	
	Siting & Wind Radar Mitigation	Siting & Wind Radar Mitigation	
Analysis & Modeling	Evaluate and Prioritize R&D	Evaluate and Prioritize R&D	Evaluate and Prioritize R&D
	Model Development and Maintenance	Model Development and Maintenance	Model Development and Maintenance
	Techno-economic Analysis	Techno-economic Analysis	Techno-economic Analysis
	Electricity Sector Modeling	Electricity Sector Modeling	Electricity Sector Modeling

A2e – Science & Engineering in Wind Energy

“There is no such thing as a special category of science called applied science; there is science and its applications, which are related to one another as the fruit is related to the tree that has borne it.”

Louis Pasteur
Correspondence de Pasteur 1840-1895 (1940), Vol. 1, 315

“The Engineer is one who, in the world of physics and applied sciences, begets new things, or adapts old things to new and better uses; above all, one who, in that field, attains new results in the best way and at lowest cost.”

Henry R. Towne
Address on 'Industrial Engineering' at Purdue University (24 Feb 1905)

A2e Focus: Wind Plant Technology Innovation

Objective

Develop new wind turbine and plant technologies to reduce LCOE by 50% ($23 MWh).

Approach:

Provide a better physical understanding of the atmospheric boundary layer interaction with wind plants and develop new technologies that maximize energy capture and optimize cost performance through integrated plant systems analysis, design and operation.

Current State of Wind Energy Technology

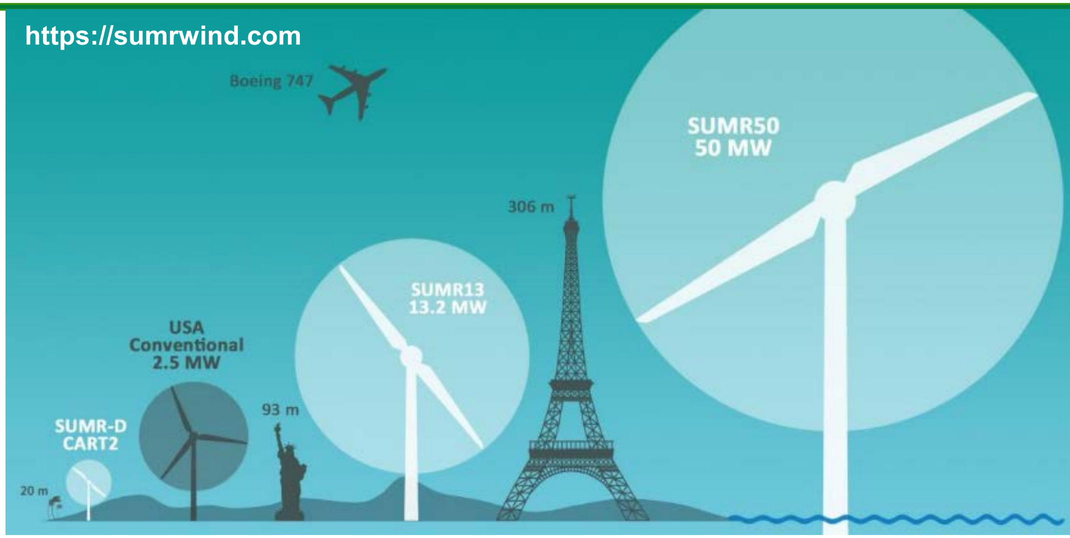
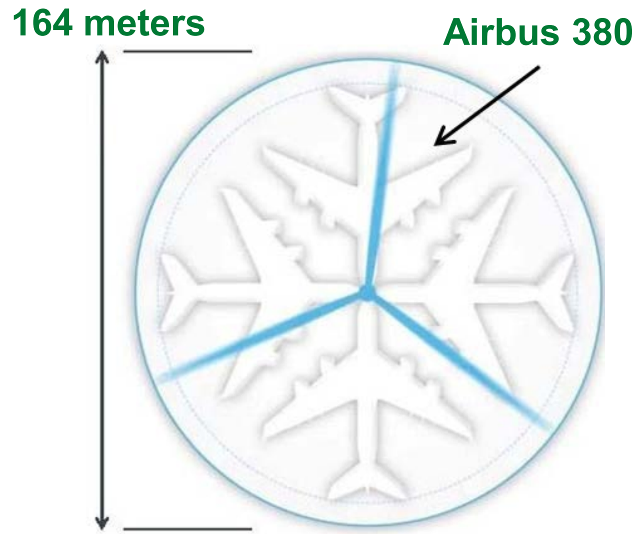
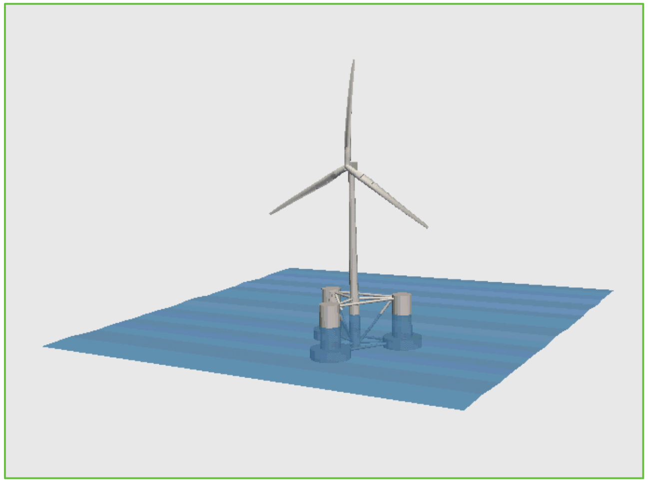


Image by Eric Loth et. al.



Vestas 9 MW

- Commercial Technology:
  - GE 4.8 MW Land Based Machine (158 meter) recently announced by GE
  - Offshore 9.0 MW Commercially Available in Europe (164 meter)
  - GE 12 MW Haliade-X Offshore Machine (214 meter)
  - 15 MW Offshore Machine Likely to be available by 2020
  - Rotor Energy Momentum Extraction and Mechanical to Electrical Conversion Systems are near Theoretical Max – Lower Specific Power Rotors
- Turbine Dynamic Stability and Non-Linear Behavior are Design Drivers Due to Material Strength, Stiffness and Total Mass Reduction
- Turbines Are Designed as Integrated Systems
- US Deployment Characterized by Large Multi-Array Wind Farms Containing Broad Spectrum Inflow Load Drivers From Turbulence
- Integrated System Design Requiring High Fidelity Coupled Models
- Large Turbine Development Programs Targeting Offshore Markets



Offshore Floating Platform Technology Remains "The Last Frontier"

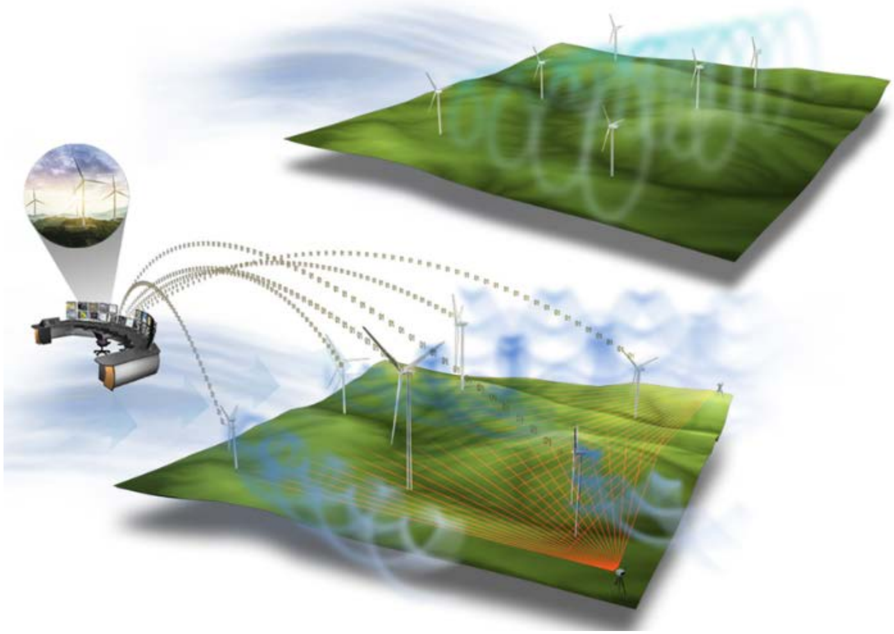
Drivers Impacting A2e R&D Direction

Wind Industry Technology Status:

- 90+ GW Deployed (6.3+ % of U.S. Electricity Generation 2017)
- Land-based wind: $46 MWh (unsubsidized)
- Excel's most recent proffers $18 MWh (subsidized)
- UK's most recent proffers $45 MWh Shallow Water Offshore
- Multi-Billion dollar industry dominated by multi-national corporations
- 15 MW Turbine from Design to Delivery (offshore) ≈ $500 - $750 Million
- NextERA: "Wind is the Cheapest Power Plant you can put on the grid"

Wind Industry R&D Direction:

- Advances in fundamental science needed to drive major innovation
- Moving toward HFM & HPC design and analysis methods to lower risk and uncertainty
- Fundamentals, tools and capabilities facilitating innovation & insight not new component development programs

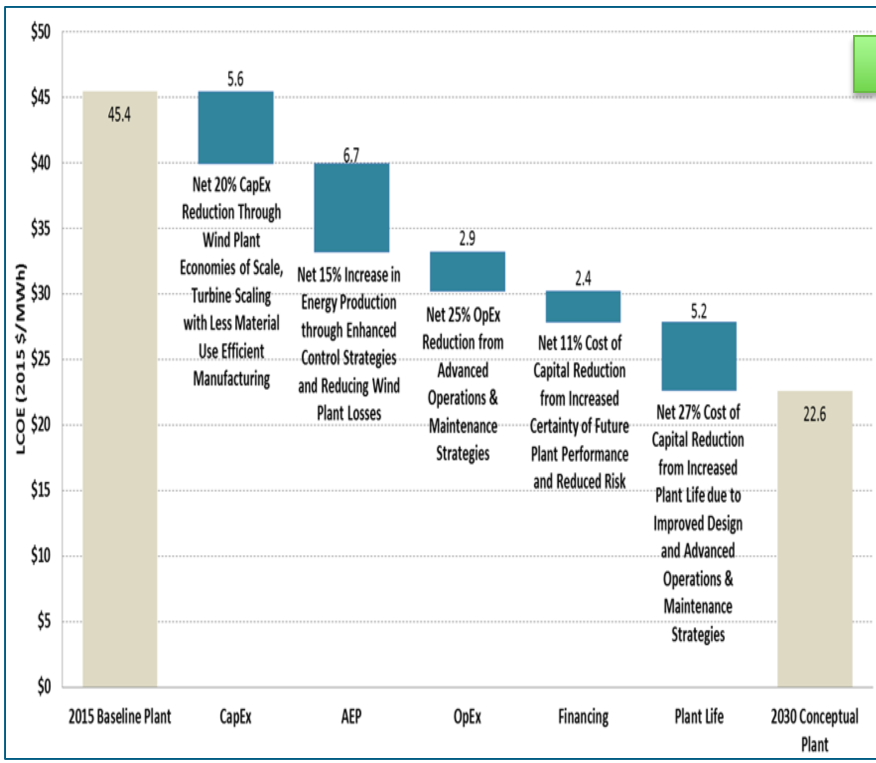


Wind Plant Optimization R&D

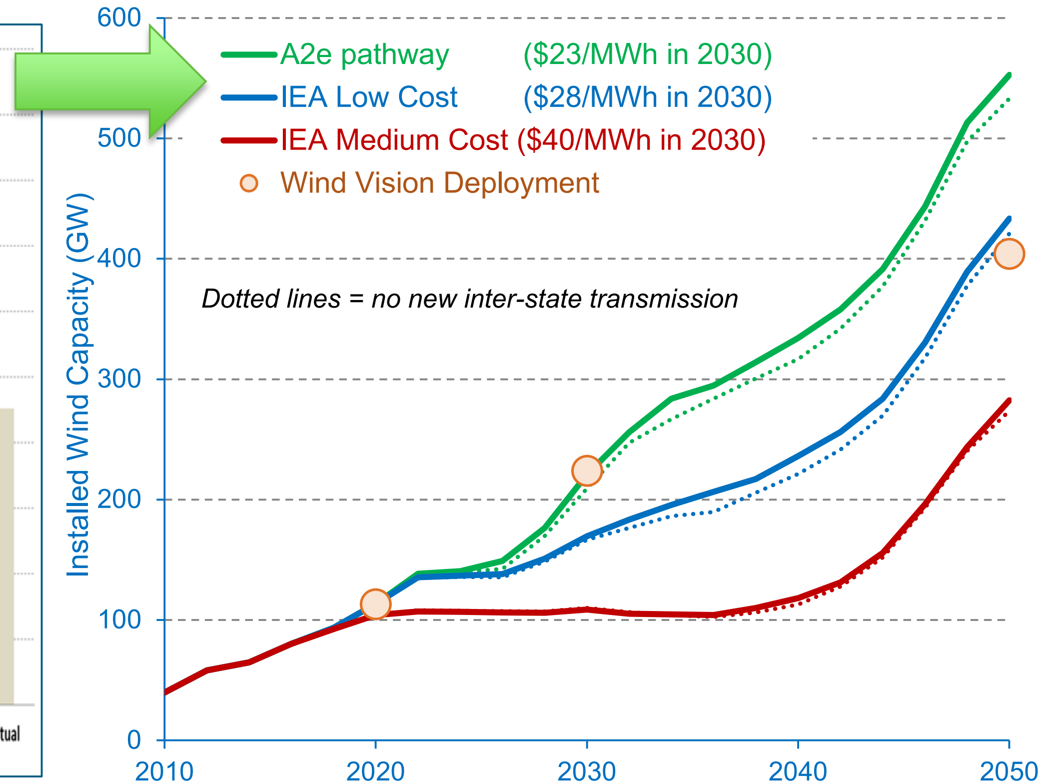
- Develop new technologies that exploit turbine interactions, resource, & complex operating environments
- Design for operation at optimal project profitability and Internal Rate of Return (IRR)
- Lower LCOE by 50% ($2.3 MWh)
- Wind plant physics & science challenges require new HPC & HFM core competencies

Cost Drives Deployment

- **Recent capacity expansion model runs suggest aggressive cost reductions (40-50% or more) could sustain recent high levels of wind deployment over the coming decades (blue and green lines, below right) and yield other benefits: jobs, emissions reductions, etc.**
- **Conversely, technology advancement leading to even moderate (10-20%) cost reductions could result in little or no net wind deployment over the same time period (red line, below right)**

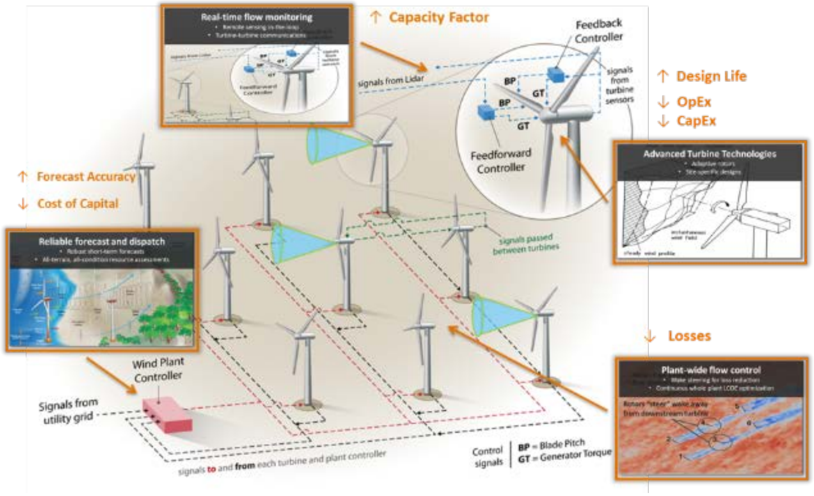


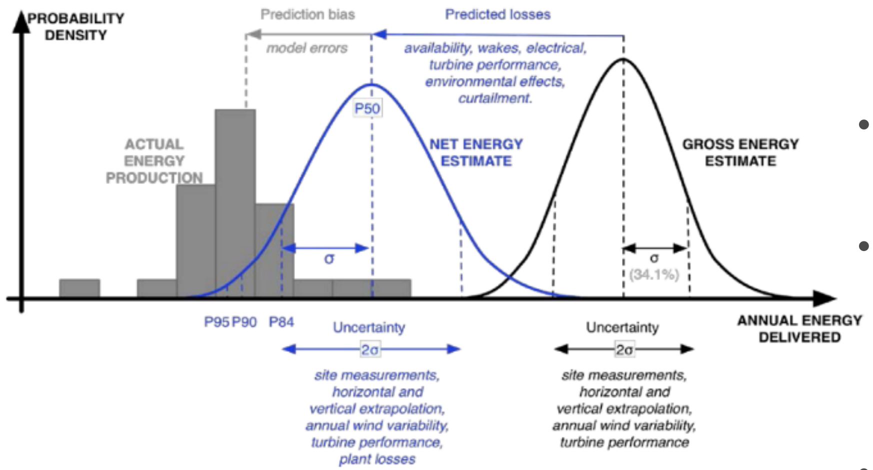
Dykes et al. 2017. "Enabling the SMART wind power plant of the future through science-based innovation." https://www.nrel.gov/docs/fy17osti/68123.pdf



Mai et al. 2017. "The value of wind technology innovation: implications for the U.S. power system, wind industry, electricity consumers, and environment." https://www.nrel.gov/docs/fy17osti/70032.pdf

Goal: Enabling SMART Wind Plant Technologies





SMART Plant Technology

Systems **M**anagement **of** **A**tmospheric **R**esources by **T**echnology

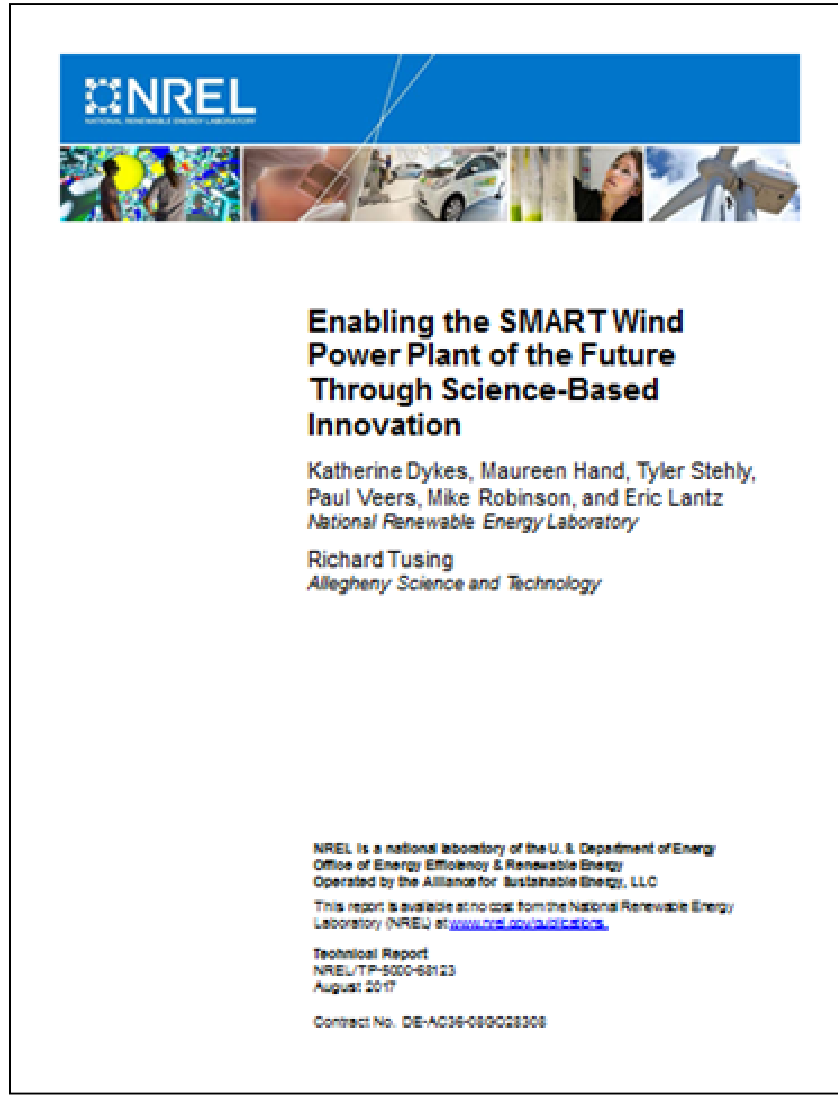
- ***Improve our understanding of the underlying physics driving wind plant performance through advanced computation and simulation;***
- ***Significantly improve industry's predictive capability of wind plant flow;***
- ***Enable next-generation wind plants and turbines that target significant improvements in cost and performance;***
- ***Extend operational life and improve wind plant reliability over 30-35 year lifetime;***
- ***Demonstrate real-time, plant flow control strategies capable of increased energy capture and loads mitigation in both existing and next-generation wind plants.***
- ***Achieve $23 MWh by 2030***

A2e Innovation & Impacts

“Enabling the SMART Wind Power Plant of the Future Through Science-Based Innovation”

http://www.nrel.gov/docs/fy17osti/68123.pdf

Systems **M**anagement **of A**tmospheric **R**esources by **T**echnology


NREL

Enabling the SMART Wind Power Plant of the Future Through Science-Based Innovation

Katherine Dykes, Maureen Hand, Tyler Stehly, Paul Veers, Mike Robinson, and Eric Lantz
National Renewable Energy Laboratory

Richard Tusing
Allegheny Science and Technology

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-5000-68123
August 2017

Contract No. DE-AC36-08GO28308

A2e Program Approach Elements

Physical Understanding of the ABL Characteristics Driving Wind Plant Performance:

- **WFIP Program** *Improving atmospheric theories and numerical weather prediction models to better represent driving physical processes with increased temporal and spatial wind prediction accuracy impacting wind energy forecasts.*
- **MMC Program** *Developing high performance computing based multiscale wind plant simulation tools that capture the complex atmospheric boundary layer flow characteristics required to optimize wind plant design and performance.*

Assessing Wind Plant / Atmospheric Boundary Layer Interaction Physics:

- **Wake Program** *Improve our physics based understanding of wake flow dynamics and turbine interactions driving wind plant performance utilizing advanced experimental methods in targeted field campaigns to validate and verify high-fidelity and engineering wind plant models.*
- **HFM Program** *Create the next generation of predictive and physics based computational simulation tools that scale on DOE Leadership Class HPC assets and are capable of fully resolving the 3-D turbine rotor interactions within the turbulent atmospheric and wake flow environment.*

Developing New Technologies That Optimize Wind Plant Cost & Performance:

- **ISDA Program** *Providing the mid-fidelity tools and methodology for the application of* ***integrated system modeling****, multi-design analysis and optimization, and multi- fidelity modeling to improve wind turbine and plant design, operation, and reduce LCOE (e.g. WISDEM, FAST, FASTFarm, OpenFAST).*
- **Controls** *Developing and demonstrating real-time, plant flow control strategies capable of increased energy capture and loads mitigation in both existing and next-generation wind plants.*

Impact Assessment & Results Dissemination Strategy:

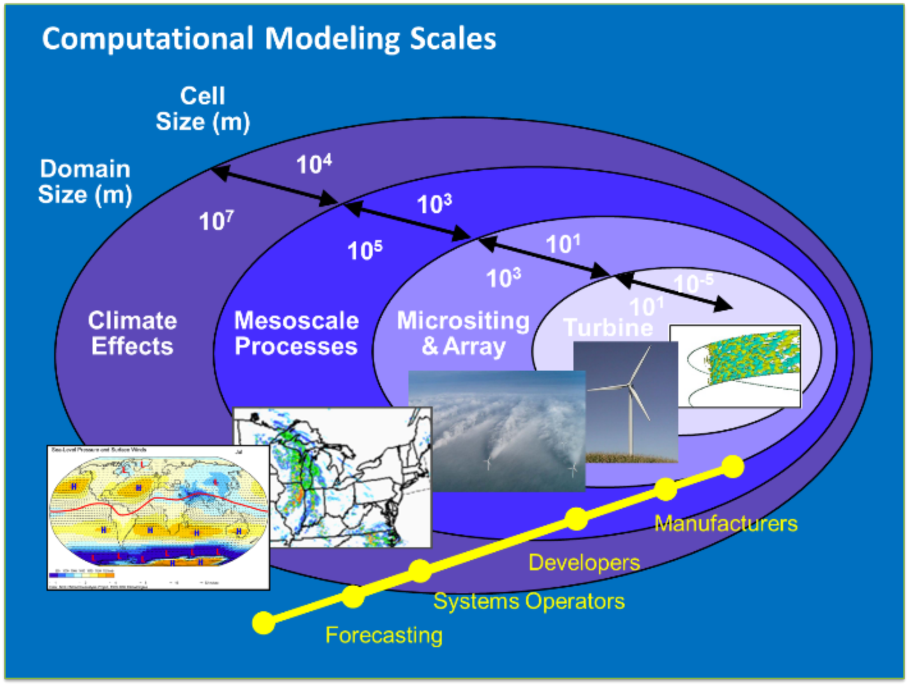
- **PRUF Program** *Improve understanding of financial and performance risks and uncertainties in the wind plant energy production and operational estimation process and identify the A2e R&D portfolio elements having the greatest potential to drive lower LCOE and increase deployment (IRR).*
- **DAP Program** *Collect, store, catalog, process, preserve, and disseminate all significant A2e data with state-of-the-art technology while conforming to or helping define industry data standards.*

Science ⬇ Modeling ⬇ Development ⬇ Reporting

HFM & HPC are Key to Resolving Physics

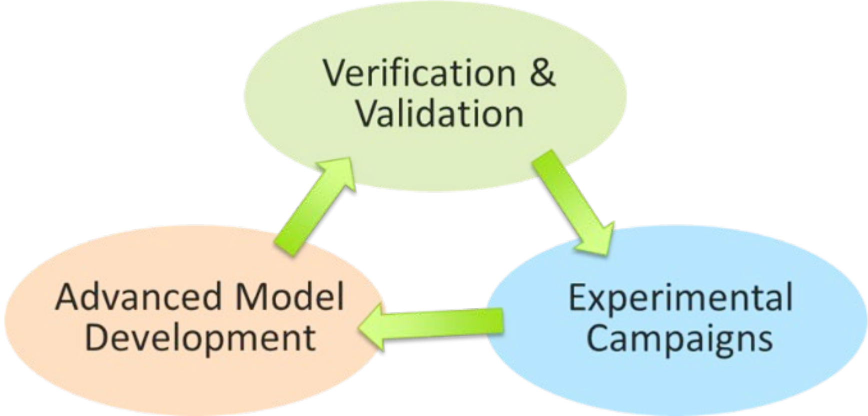
Energy Capture & Performance Driven by Multiple Scale Physical Processes

- Wind resource determined by weather driven phenomena at Mesoscale;
- Planetary Boundary Layer (PBL) is the wind plant energy resource;
- Turbine scale (e.g. rotor, blade) inflow characteristics directly impact production and turbine loading
- Blade scale sets the dynamic wake flow (meandering) & aeroacoustic characteristics
- Multiple turbine arrays and complex flow modify and alter the inflow, create energy loss, add turbulence and adversely impact turbine & plant performance



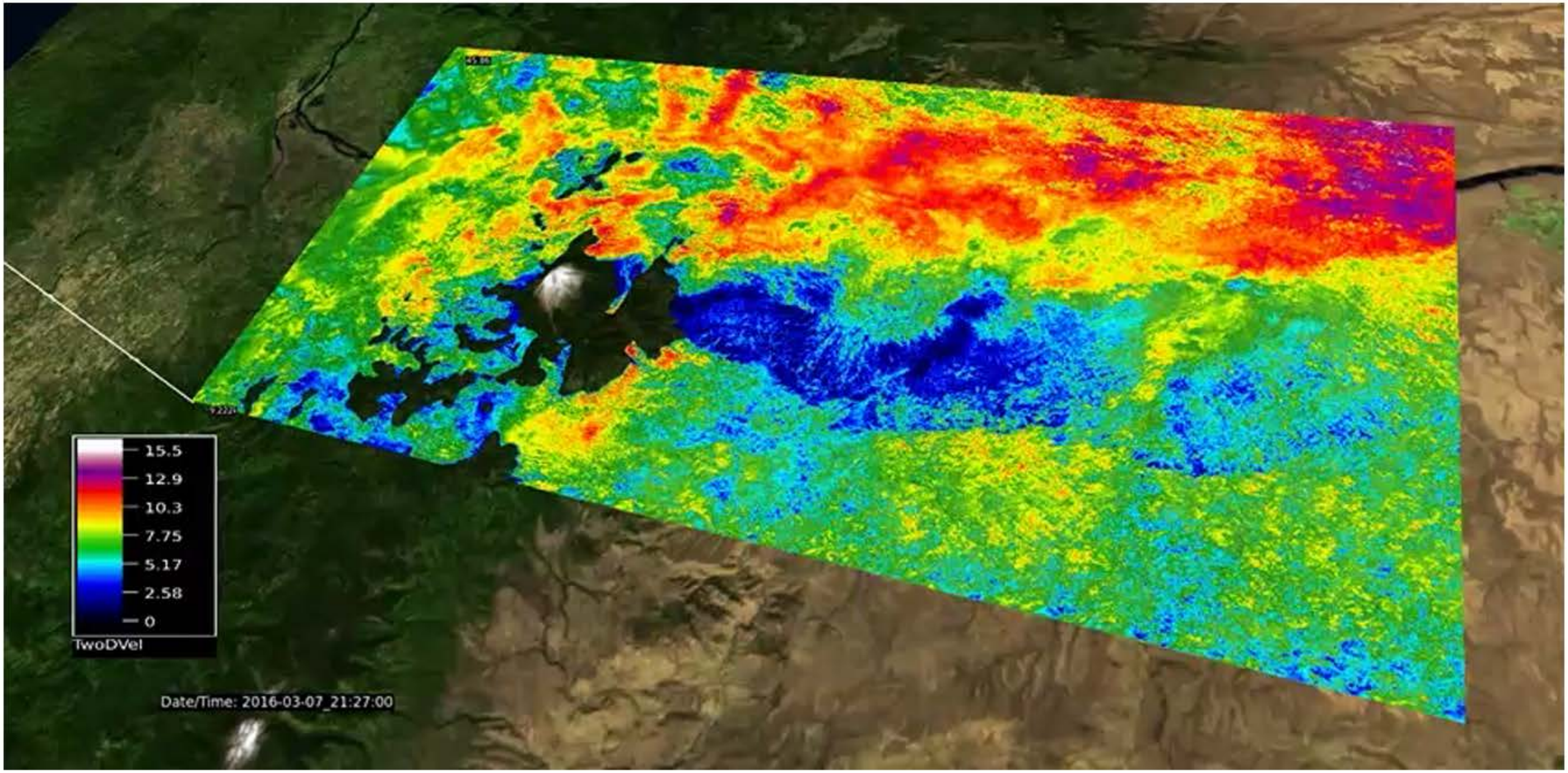
Wind Plant Physics Challenge:

- Multiple physics at multiple scales drive wind plant performance
- Physics resolved through loosely or uncoupled modeling and simulation approaches
- Quantifying uncertainty is the critical factor to industry in order to quantify risk.
- HPC capability to assess the temporally and spatially complex PBL/wind plant interaction driving wind plant performance



HFM & HPC Capturing Resource Drivers (WFIP & MMC)

Courtesy of NCAR; simulation by Pedro Jimenez Munoz, visualization Scott Pearse



Topographic Wake Simulation Around Mt. Hood (WFIP 2)

Wind Forecast Improvement Program

Project Objective:

To improve the physical understanding of atmospheric processes that directly affect wind industry forecasts and incorporate new physics and parametrizations into the foundational weather forecasting models that improve wind energy production estimates

"WFIP 2 was the way complex terrain studies should be done"

Prof Chris Bretherton, National Academies Workshop on The Future of Boundary Layer Observations

Executed major four-year field and modeling study involving DOE labs, NOAA, and industry in Columbia Basin of Pacific Northwest resulting in:

- **Development of comprehensive data set on telescoping scales for validation of nested forecast models**
- **Developed improved mixing algorithms now included in National Weather Service forecast models**
- **Demonstrated improved timing of cold pool erosion and associated wind up-ramps**

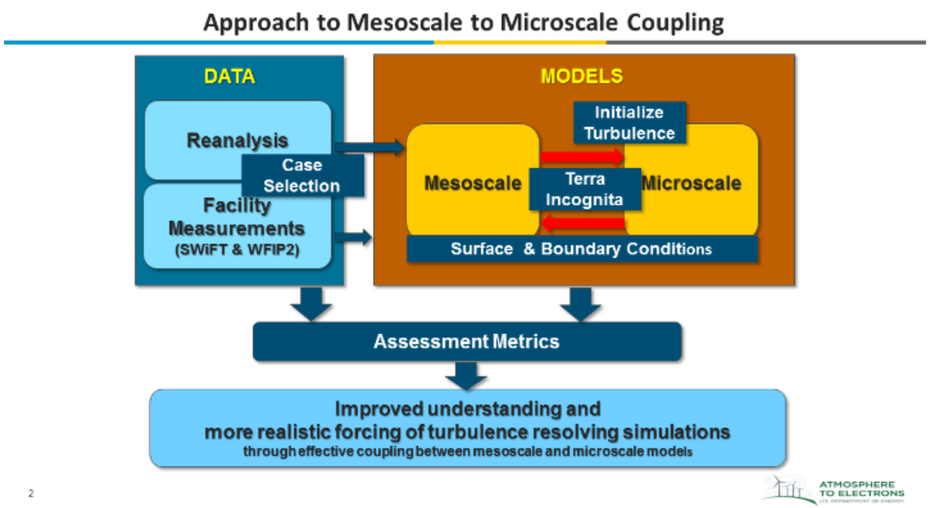
Wind turbines in complex terrain along the Columbia River

Meso- to Micro- Scale Coupling Program

Project Objective:

To create a new predictive numerical simulation capability that can efficiently use high-performance computing to accurately represent the full range of atmospheric flow conditions needed to optimize wind plant performance

- **Evaluated mesoscale and microscale models to identify candidates for numerical coupling and explored promise of multiple coupling approaches**
- **Assessed coupling techniques with respect to transferring necessary atmospheric structure to the microscale and to rapid generation of turbulence at model boundaries**
- **Developed recommendations for most promising directions for appropriately developing turbulence on microscale domain boundaries**



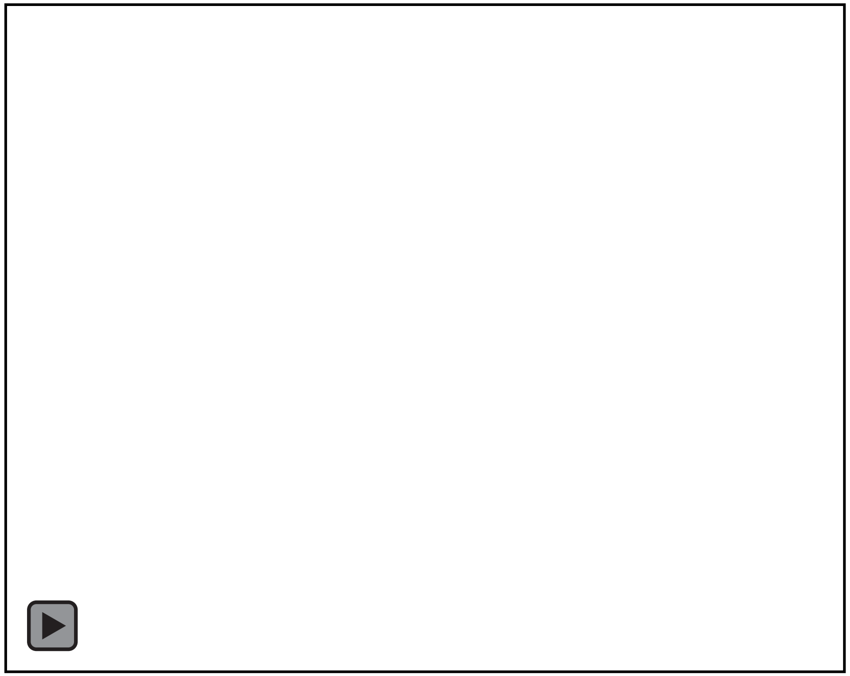
Wake Dynamics

Project Objective:

To make high fidelity measurements of wind turbines and plants operating in representative atmospheric conditions and to use the data to advance the understanding of wind plant physics. To validate advanced A2e-developed simulation tools using gathered data.

Two major field campaigns at SWiFT and NWTC to understand steered wake steering behavior and turbine response:

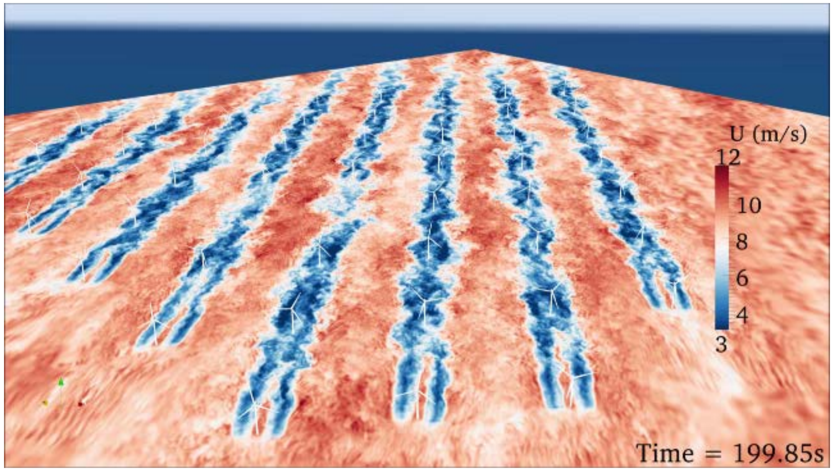
- Wake steering fundamentally changes wake behavior and entrainment of energy behind turbines. Observed curled wake behavior introduced into models.
- Fatigue loading behavior of steered turbines is not greatly increased within yaw offset range important for wake steering. Enabled access to NextEra Peetz Table wind farm for full scale tests in FY18.
- Wake behavior between two turbines different due to different aerodynamic loading distribution and ground proximity. Further observations of NRT rotor blades at SWiFT to provide more accurate basis for comparison.



HFM & HPC Resolving Complex Inflow/Turbine Interactions (Wake Dynamics & HPC)

HPC/HFM Predictive Plant & Turbine Modeling

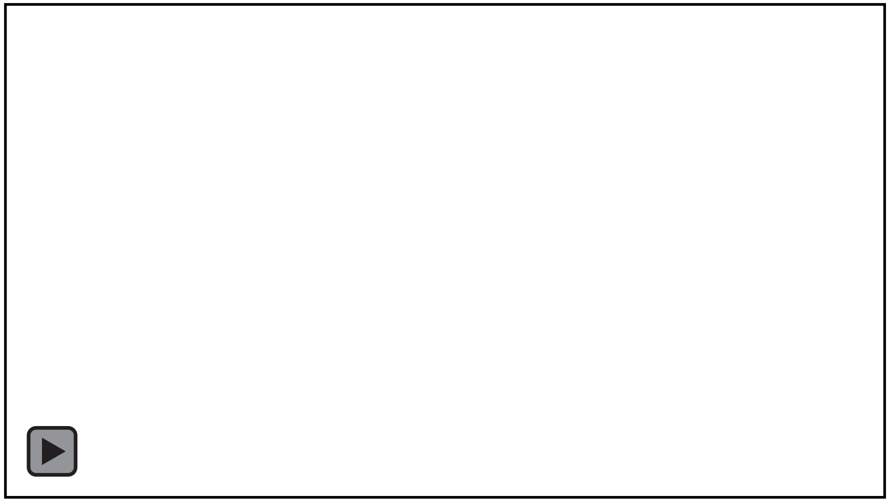
Where Are We Today?



SOWFA simulation of Lillgrund

- SOWFA led by Matt Churchfield (NREL)
- Turbines modeled as “actuator lines”; forcing tied to 2-D aerodynamic look-up tables
- Demonstrated the potential of high-fidelity simulation to understand wind-plant fluid dynamics
- Not suitable for the extreme-scales required for predictive simulations

Predictive Modeling at Exascale is the Next Step



Nalu-Wind:

- Unstructured-grid, low-Mach-number computational fluid dynamics
- Built on Trilinos leveraging NNSA
- Demonstrated scaling up to 500,000 cores
- Development collaboration:
  - NREL, SNL, ORNL, UT-Austin
- Expected Accomplishments:
  - Fully Resolved FSI Rotor & Atmospheric Turbulence

HFM & HPC Developing Advanced Controls (Controls)

Objective:

- A high-fidelity wind-plant aerodynamics tool to study wind plant flow phenomena and performance
- Must be flexible and modular enough that it can be applied to a wide variety of wind-plant applications ranging from basic flow physics understanding to advanced controls and optimization

Approach:

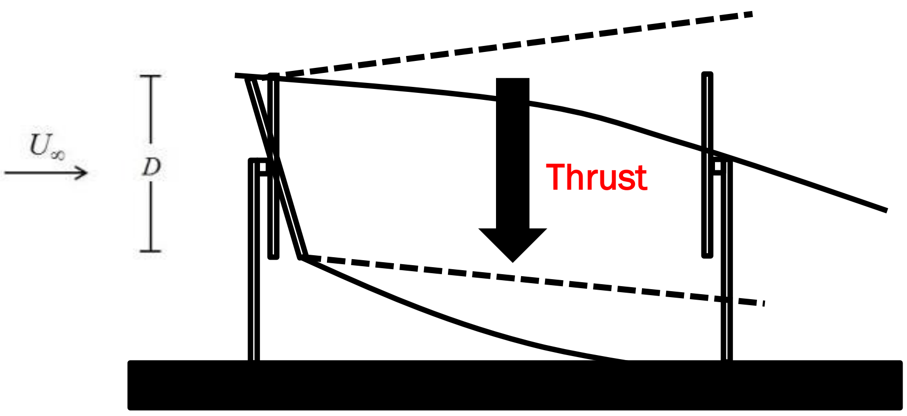
- Atmospheric large-eddy simulation combined with actuator turbines (ranging from low-resolution actuator disks to high-resolution advanced actuator lines)
- Built from the OpenFOAM open-source CFD toolbox
- Unstructured, finite-volume, incompressible with Boussinesq buoyancy

A wind-plant controls application of SOWFA: Intentional yaw misalignment can be used to direct and shape wakes in a more desirable way during waking conditions in which wind plant performance is decreased. Left is baseline normal control (every turbine optimizing itself); right is yaw-based control optimizing full plant performance.

Wind Plant Controls Program

Develop integrated wind plant control methods such as wake steering, axial control, tilt and other techniques with advanced algorithms and design tools to demonstrate increased AEP and reduced turbine loading for optimized cost and performance

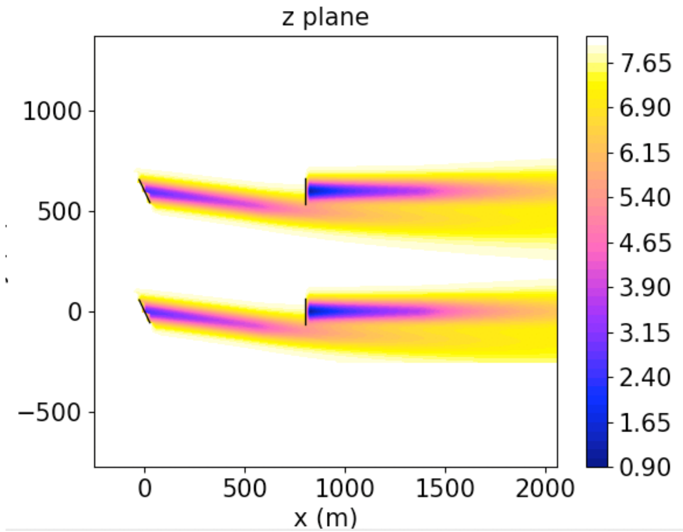
- Demonstrated capability of wake steering, tilt-based actuation, axial control using detailed SOWFA simulation studies
- Used HFM to understand physics and guide design of control-oriented models of wind farm control
- Used HFM to design field-test campaigns



Wind Plant Power Production Increases up to 13%

FLORIS, a control-oriented model for wind farm control,

- FLORIS has been used to design wind farm controllers applied in HFM studies and also in field-trials
- FLORIS has also been coupled to system-engineering tools to investigate AEP benefit of wind farm controls
- Open-source and highly optimized for performance



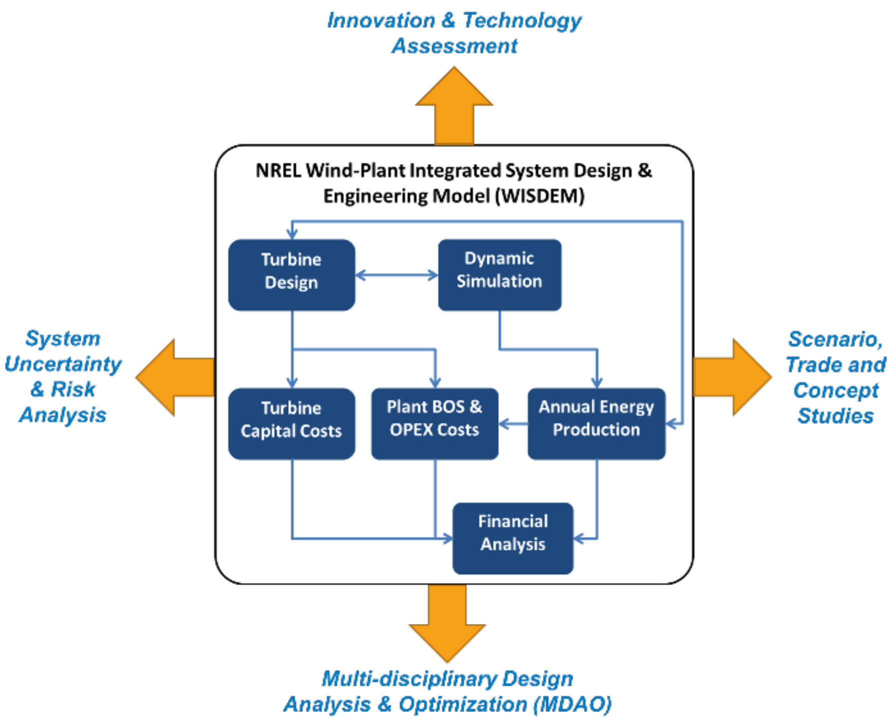
Field-testing of wind farm control

- Preliminary lidar-based tests of wake steering verified predictions of SOWFA and FLORIS
- Full utility scale plant testing now underway in partnership with industry to validate technology development

Integrated Systems Design & Analysis – Systems Engineering (ISDA-SE)

WISDEM is a multi-disciplinary design, optimization and analysis (MDAO) for full wind plant performance and cost analysis

- Built on NASA OpenMDAO software environment
- Open source, modular, extensible
- Cost and engineering models for all wind turbine and plant components
- Built in analytic or exact gradients for supporting advanced optimization and uncertainty analysis work



WISDEM has been applied to a broad range of wind turbine and plant analysis and optimization problems. Examples include:

- Evaluation of novel drivetrain technologies
- Full turbine optimization for different configuration options (orientation, tip speed, etc)
- Site-specific offshore support structure design
- Wind plant controls optimization and co-design of plant controls and layout

Fig. 1 Borssele wind energy areas III and IV are the site of the RWP.

Offshore wind park (SINTEF & TU Delft)

- 74 IEA10MW – 740 MW
- 30-40 meter water depth
- One transformer station 66 kV
- Transmission 220 kV – 40 km to shore

Integrated Systems Design and Analysis – Multi-Scale Validation (ISDA-MV)

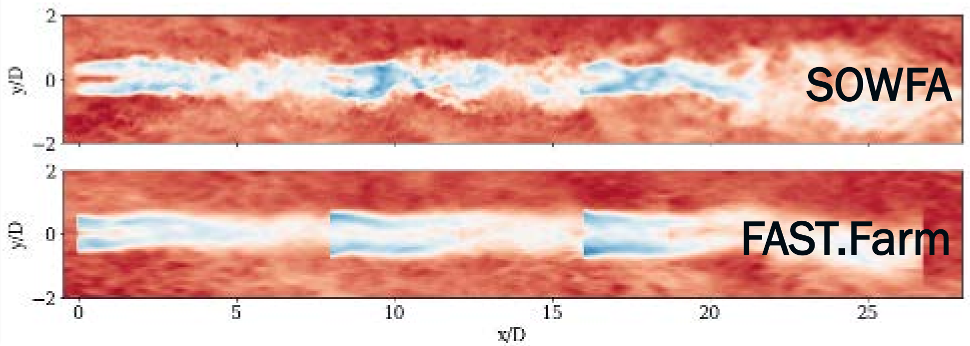
OpenFAST - multi-physics engineering tool for land-based and offshore fixed and floating wind turbine simulation

- Modular source-code implementation
  - Aero: BEM + corrections
  - Hydro: Potential flow + strip theory
  - Servo: Industrial controllers
  - Elastic: Nonlinear beam theory
- Open-source code-development community
- Computational efficiency to support an iterative & probabilistic design process & optimization (1,000's of simulations can be run overnight)
- V&V key to understand where models are suitable and where they are not

FAST.Farm - multi-physics engineering tool for wind-plant simulation and loads analysis:

- Modular source-code implementation, including parallelization (extension of OpenFAST)
  - Turbines: OpenFAST
  - Inflow: LES precursor or synthetic
  - Wakes: Dynamic Wake Meandering (DWM)
  - Super controller
- Computational efficiency to support an iterative & probabilistic design process & optimization (1,000's of simulations can be run overnight)
- V&V key to understand where models are suitable and where they are not

- Systematically V&V physics-based wind-turbine & wind-plant engineering tools by comparisons to HFM & experimental data to quantitatively understand their applicability, accuracy, & uncertainties
- Improve physics of wind-turbine & wind-plant engineering tools based on both the V&V outcome & requirements driven by technology innovations to expand the tools' applicability where limitations hinder technology advancement
- Engage in international V&V collaboratives among research laboratories, academia, & industry involving comparisons between data, HFM, & engineering tools to achieve the A2e V&V goals & scope, including:
  - Broadening the source of data & models that can be used for V&V
  - Ensuring A2e investment in HFM & V&V drives the development of the next-generation of wind-industry-wide design capabilities



Integrated Systems Design and Analysis – Offshore Wind (ISDA-OSW)

Overarching goal is to verify and validate the coupled (aero-hydro-servo-elastic) modeling tools used to design offshore wind systems

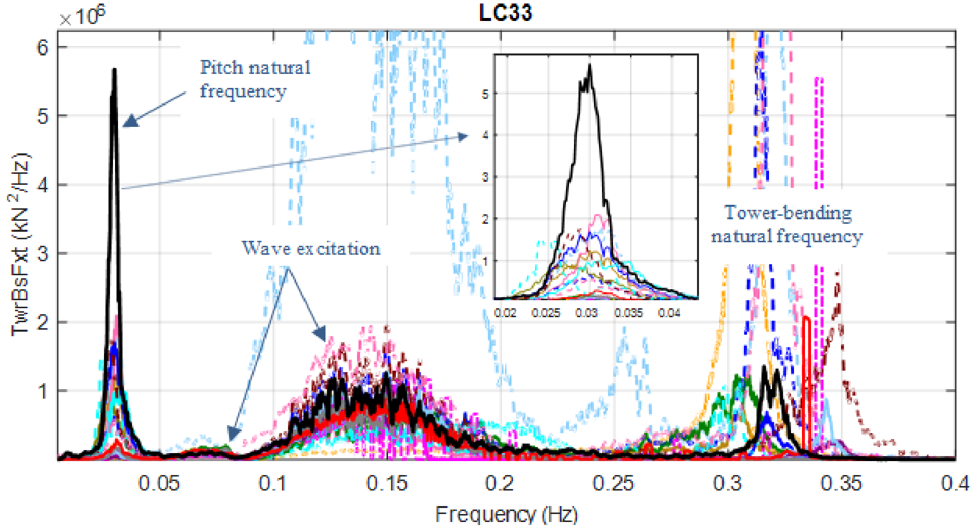
- Needed for floating systems
- Achieve better optimization of fixed-bottom systems

The main work in this project is centered on IEA Wind Task 30.

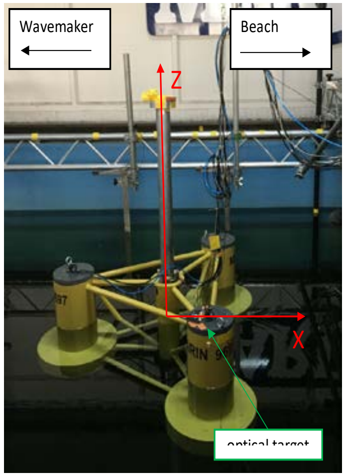
- An international research collaborative run under IEA Wind focused on the verification and validation of offshore wind design tools.
- NREL is the leader of this task, and also a participant.

Future OC6: Component-Level Hydrodynamics Validation Campaign

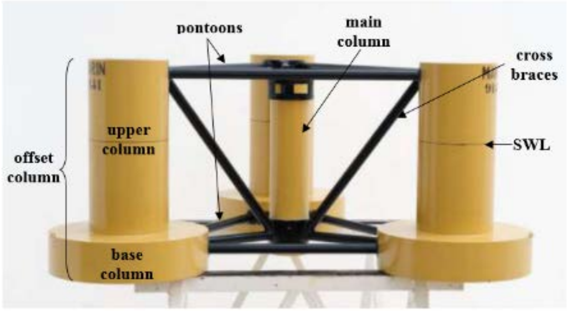
- Develop, model, and perform component-level validation test campaign in the U.S., to be used in OC6.



Example from OC5: Tower Base Shear Force under Wave Excitation

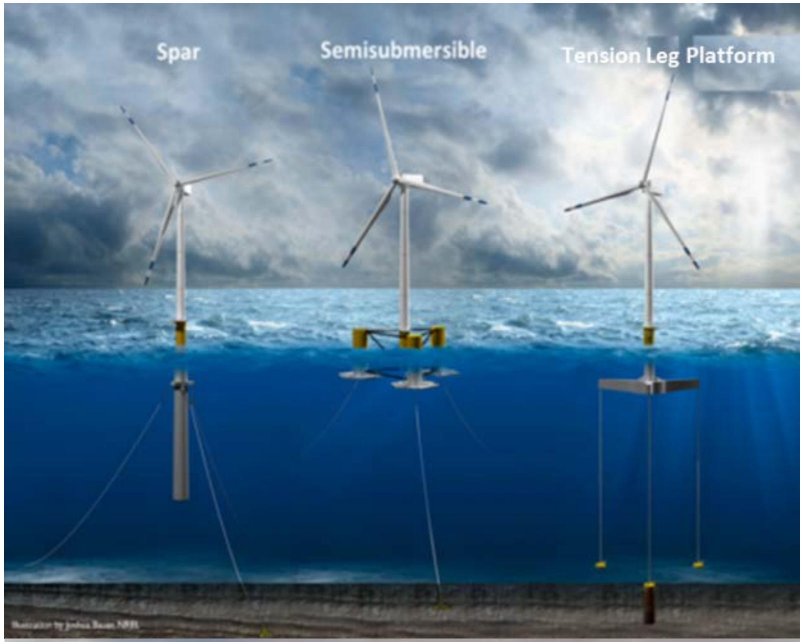


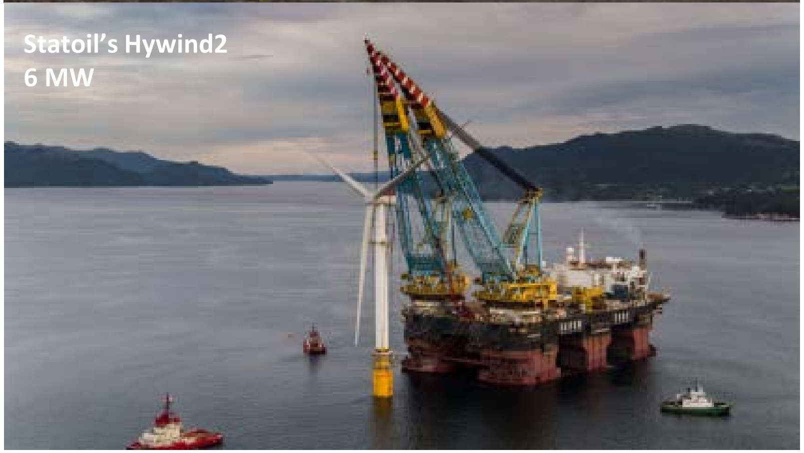
OC6: Break apart components of OC5 semi and test them individually



Future A2e Focus: Offshore Floating Wind Technology

Floating Wind Turbine Substructure Types

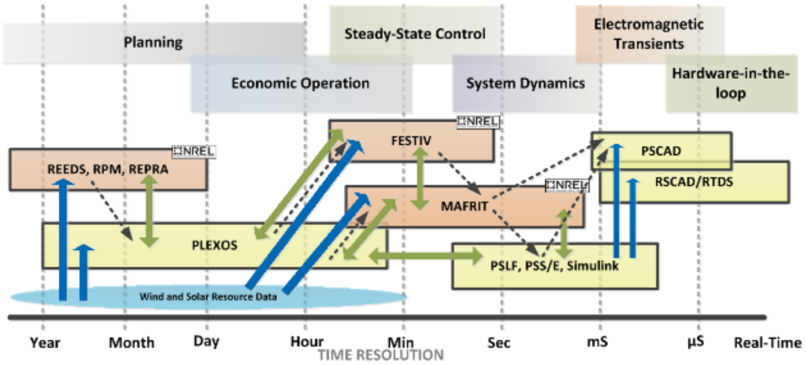


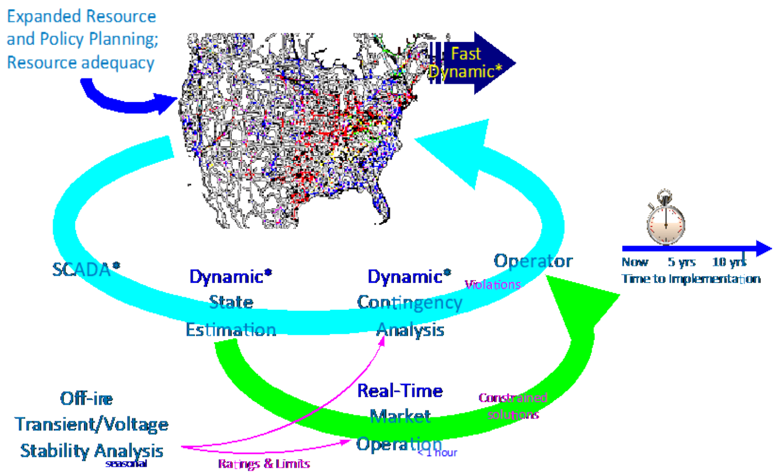


Floating Offshore Wind Research Opportunities

- *Leverage the ongoing research and development activities in HPC and HFM to fully assess the underlying physical phenomenology driving floating technology*
- *Develop better techniques to accurately characterize the Marine Boundary Layer (MBL) conditions encountered by offshore wind systems for site assessment, system design, and model validation*
- *Develop a suite of design tools capable of analyzing the next generation floating wind plant systems*
- *Validate design tools against data and higher-fidelity models to ensure accuracy and instill confidence in their use*
- *Develop control algorithms for platform stability, load management, and farm performance*
- *Test and validate deployed systems as part of a formal V&V and UQ analysis effort*
- *Lay the framework for a multi-year open development and public / private collaborations*
- *Help develop the next generation of offshore wind computational scientists*

Future A2e Focus: Seamless Wind Plant Grid Integration





Atmosphere to Grid

- **Integrated wind/energy storage**

  "Dispatchable" plants that enable grid services and ramp smoothing and enhance system reliability

- **Real-time wind power inertia estimation and forecast**

  Real time inertia equivalence, estimation and forecast by wind power plants for wide-area reliability operators resulting in a real time dynamic stability margin assessment

- **Co-optimized aerodynamic and electric loss control of wind power plants for increased annual energy production**

  Active loss management for different turbine power control modes integrating wake management, real-time measurements, short-term forecasts and power system state estimation

- **Optimized reserve strategies for large wind power plants**

  Dynamic and optimized curtailment based on forecasts, wake impacts and loads reduction for provision of primary and secondary reserves to the grid

- **Accurate methods for available power estimation**

  Accurate estimation of available wind plant headroom that operates off peak power point (curtailed mode) for active power reserve provisions

Summary

- *Our New Programmatic Goal Requires a 50% Reduction in LCOE to Achieve $23 MW/HR*
- *The R&D Focus has Transitioned from Individual Turbines to Optimized Wind Plant Performance*
- *Transition Reflects a Maturing Industry With Highly Advanced Turbine Development Capabilities*
- *A2e Addresses the Fundamental Science Challenges Required for the Next Generation of Technology*
- *Technology Innovation Requires Advances in Atmospheric Sciences and Wind Plant Interaction*
- *HPC & HFM are Cornerstones in Achieving Lower Cost & Seamless High Wind Penetration*
- *Floating Wind Turbine Technology and Seamless Grid Integration is the Next Focus*

Questions?

Michael Robinson

DOE/WETO
Mike.Robinson@ee.doe.gov
303-669-1098