

Verification, Validation & Uncertainty Quantification

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A2e Mid-Year Program Review

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V&V/UQ Background and Context

- Transform today's wind plant operating environment through advanced physics-based modeling, analysis, and simulation capabilities
- Approach
 - Support the development of credible high fidelity models and physics based engineering models
 - Collection of existing data and generation of new data through an experimental measurement campaign
 - Strategic linking of these efforts through a Validation Focused Program

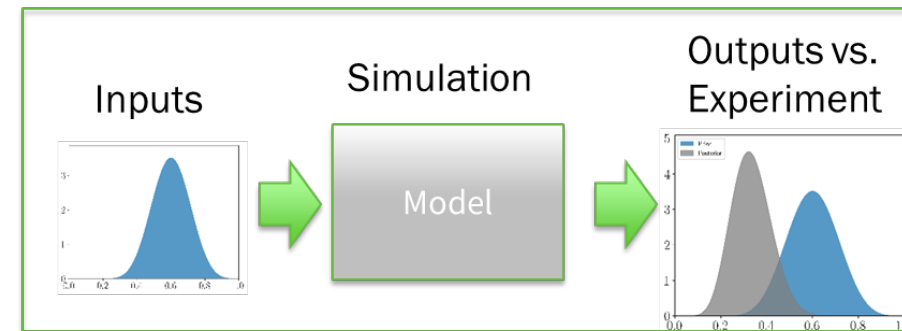
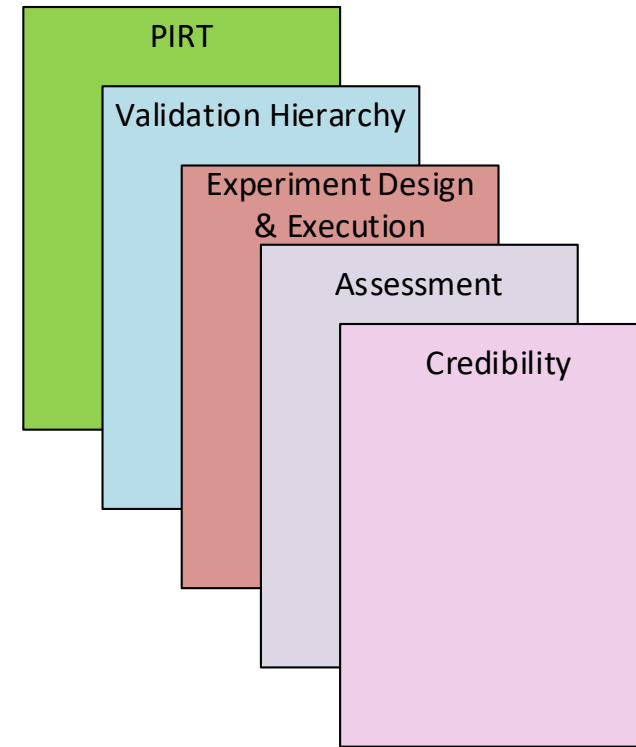


Project Overview and Objectives

- **This project will ensure that the predictive capability of the suite of models being developed across A2e is established through formal V&V/UQ processes.**
 - Quantitatively establish where models are valid and where improvements are necessary
- **The result will be established V&V/UQ techniques applied to computational modeling tools spanning a range of fidelities**
 - These tools will be adopted by the wind industry or used to improve in-house software

Importance of V&V/UQ

- The application of V&V/UQ processes mitigates the risk of using the data from computational models for making decisions for wind energy applications
- V&V/UQ thus allows us to quantify the uncertainty of a model for a specific application
 - Knowing the uncertainty allows for better planning
 - Reducing the uncertainty reduces risk

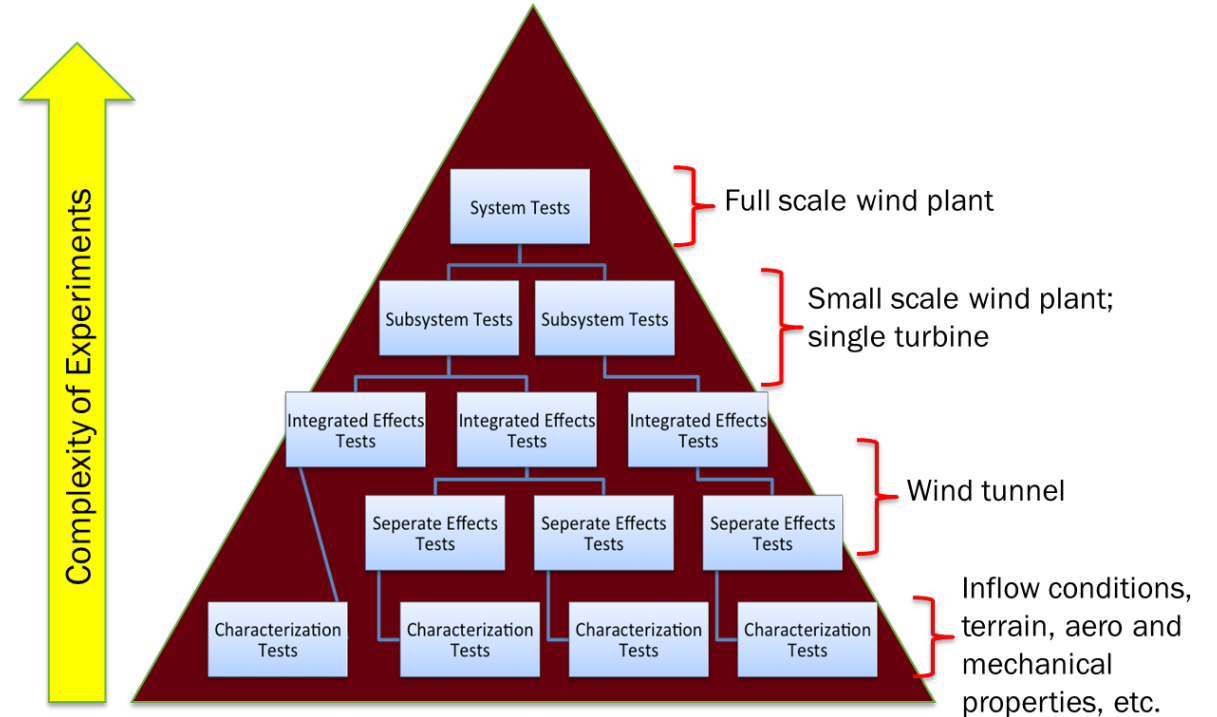


V&V Framework

PIRT: Phenomenon Identification Ranking Table

Phenomenon	Importance at Application Level	Model Adequacy		
		Physics	Code	Val
Inflow Turbulence/Wake Interaction				
Wind direction (shear/veer/asymmetry)	H	L	M	M
Turbulence characteristics (intensity, spectra, coherence, stability)	H	L	M	M
Coherent turbulence structure	H	L	M	L
Surface conditions (roughness, canopy, waves, surface heat flux, topography)	H	L	M	M
Momentum transport (horizontal and vertical fluxes)	H	L	L	L
Multi-Turbine Wake Effects				
Wake interaction, merging, meander	H	L	L	L
Plant flow control for optimum performance	H	M	M	L
Wake steering (yaw & tilt effects)	H	L	L	L
Wake dissipation	H	L	L	L
Wake Impingement (full, half, etc.)	H	L	L	L
Deep array effects (change in turbulence, etc.)	H	L	L	L
Other Effects				
Wind plant blockage effects and plant wake	M	M	M	L
Acoustic Propagation	H	L	L	L

Validation Hierarchy



Current Program Status & Accomplishments

Status:

- V&V started as a nascent effort in 2014
 - Focused on HFM, has been adopted across A2e
- UQ effort started in 2017 within HFM project
 - UQ efforts in MMC, ISDA, and Wake Dynamics grew in parallel
- V&V/UQ project started in FY20 under a 4 year merit review proposal
 - Proposed effort with 3 labs (SNL, NREL, PNNL) + UWYO
 - Funded at reduced level at 1 lab with startup funds from ‘donor’ projects
 - Three tasks: Validation Coordination, Uncertainty Quantification Development, and V&V/UQ Application

Current Program Status & Accomplishments

Accomplishments (Under past projects, HFM and Wake Dynamics):

- Publication of V&V Framework and V&V Integrated Program Planning for Wind Plant Performance
- Development of HFM Validation Roadmap
- Adoption of V&V processes by IEA Tasks 30, 31, 36 and across A2e
- Development of initial multilevel-multifidelity (MLMF) UQ forward propagation method to Nalu-Wind and OpenFAST/TurbSim
- Initial validation of Nalu-Wind for wake strength and deflection

Current Program Status & Accomplishments

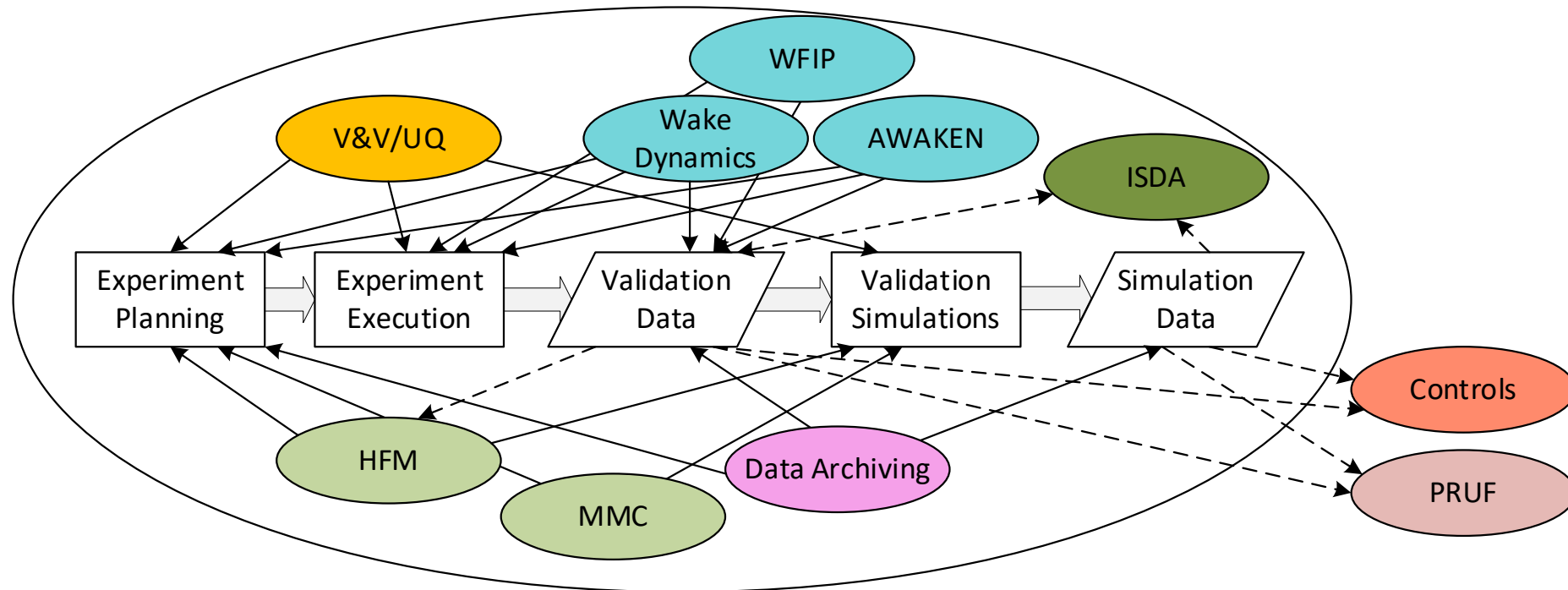
Accomplishments (Under V&V/UQ Project):

- Publication of HFM Validation Roadmap
 - Basis of AWAKEN instrumentation needs to meet validation objectives
- Organized joint Non-Deterministic Approaches and Wind Energy session at the AIAA SciTech 2020 conference, shared 4 papers summarizing UQ work
- Developed and demonstrated novel uncertainty quantification techniques to wind energy analyses using a range of computational models
 - Forward, inverse and optimization under uncertainty (OUU) using MLMF-UQ methods (WindSE, OpenFAST/TurbSim, Nalu-Wind)
- Initial validation of Nalu-Wind for wake strength and deflection

V&V/UQ Cross-project Collaboration

- V&V/UQ plays an integrating role across A2e projects

Validation-Directed Program

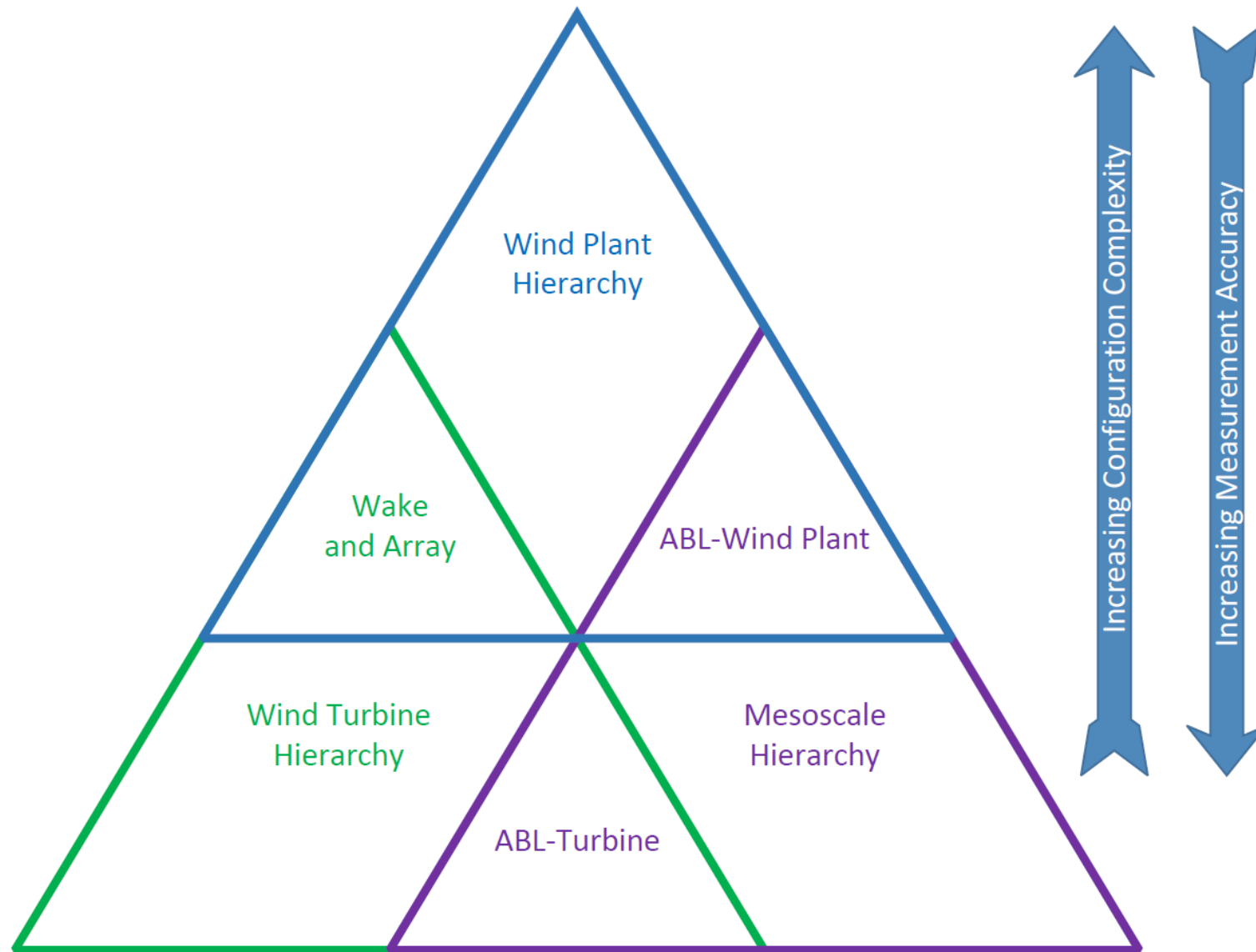


A2e Validation Coordination Working Group

A2e Area	Validation Leads
A2e Validation Coordinator	Jonathan Naughton (UWYO)
VV&UQ PI	David Maniaci (SNL)
DAP	Matthew Macduff, Chitra Sivaraman (PNNL)
Offshore	Amy Robertson (NREL)
ISDA-Systems	Garrett Barter (NREL)
ISDA-Offshore	Amy Robertson, Jason Jonkman (NREL)
HFM	Mike Sprague(NREL), Shreyas Ananthan(NREL), Paul Crozier (SNL)
Rotor Wake	Jonathan Naughton (UWYO)
AWAKEN	Pat Moriarty (NREL)
WFIP 2	Caroline Draxl (NREL)
MMC	Larry Berg (PNNL), Matt Churchfield (NREL), Sue Haupt (NCAR)
PRUF	Jason Fields (NREL)
Controls	Paul Fleming, Eric Simley (NREL)

- Bi-annual Meetings with smaller focus groups meeting more regularly
- Summary reports of A2e validation progress and plans
- Integration with IEA Task 31, 29, AWEA TR-1, and IEC V&V JWF

Wind Plant Validation Hierarchy



HFM Validation Roadmap

Proposed Validation Campaigns

Atmospheric boundary layer (ABL) observations

- Flat terrain, varying stability ABL
- Complex terrain ABL
- ABL with operating wind farm
- Complex terrain ABL with operating wind farm

Wind plant observations

- Offshore power performance data
- Offshore structural loads
- Full wind farm with wake detail in at terrain
- Subscale multiple turbine interactions
- Full wind farm in terrain with wake detail

Rotor and blade aerodynamics

- Non-rotating tip vortex
- Blade resolved parked rotor
- Subscale resolved rotor
- Rotating single turbine wake with resolved geometry



Multifidelity Strategies for Forward and Inverse Uncertainty Quantification

Wind plant challenges for UQ

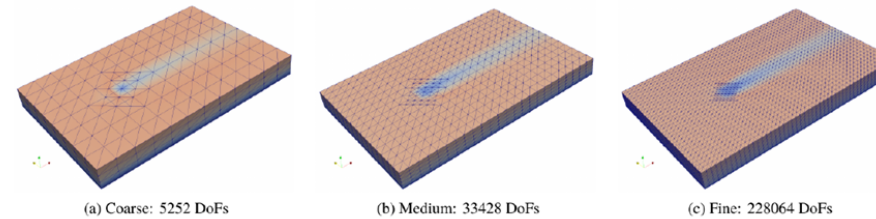
- **High-fidelity** state-of-the-art modeling and simulations with high performance computing
- **Severe** simulations **budget constraints**
- **Significant dimensionality** driven by model complexity

Multifidelity strategies

A **limited number of high-fidelity simulations** is fused with a much **larger set of low-fidelity simulations** to **reduce the overall computational burden** while keeping the overall error under control (*i.e.* deterministic + stochastic)

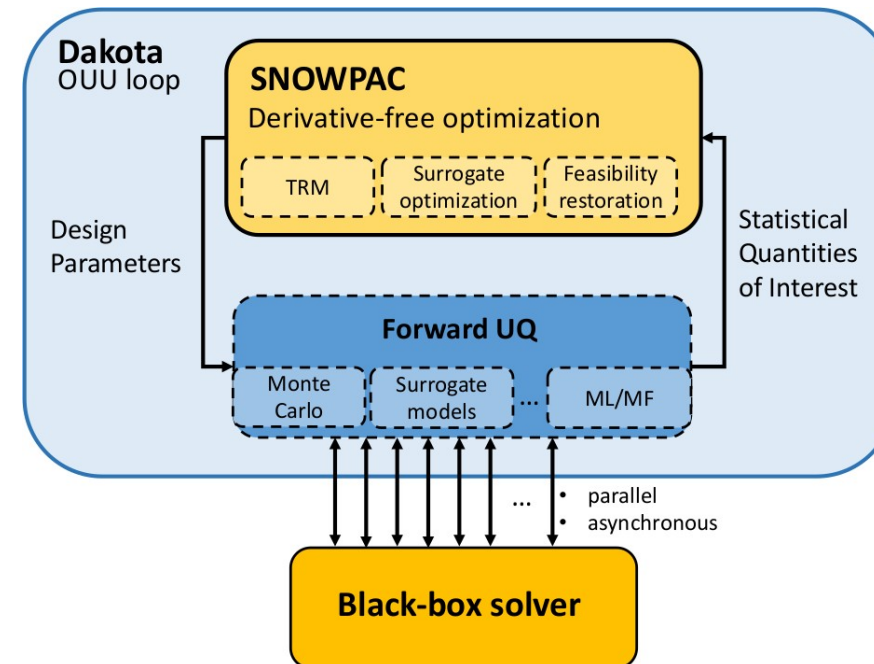
Objectives of the study:

- 1 Assess uncertainty's impact on wind plant performance via **efficient forward UQ**
- 2 Characterize uncertainty via **efficient inverse UQ**
- 3 Wind plant **Optimization Under Uncertainty** workflows using multi-fidelity sampling strategies



Model Resolution	N_x	$N_y = N_z$	Cost (s)
Coarse	12	8	8.51
Medium	24	16	60.4
Fine	48	32	1270

: Multilevel model hierarchy unrefined grid discretization and simulation cost.

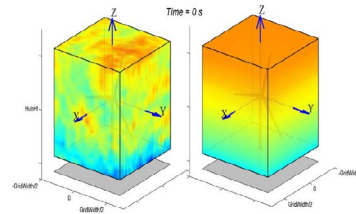


Multilevel Uncertainty Quantification

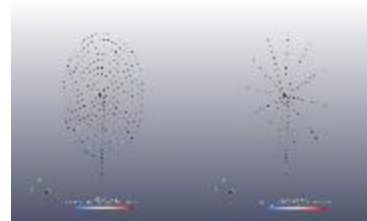
Research Scope: Evaluation of multilevel-multifidelity (MLMF) UQ methods to improve predictive capabilities of computational models for wind farm applications

Motivation

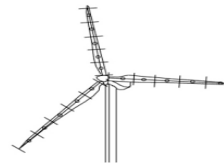
- UQ is necessary for predictive wind simulations but requires high numbers of simulations
- High-fidelity simulations are needed for accurate predictions but have high computational costs
- By leveraging lower-resolution, lower-fidelity simulations with high-fidelity simulations, multilevel-multifidelity-UQ can accelerate variance reduction and significantly reduce computational costs



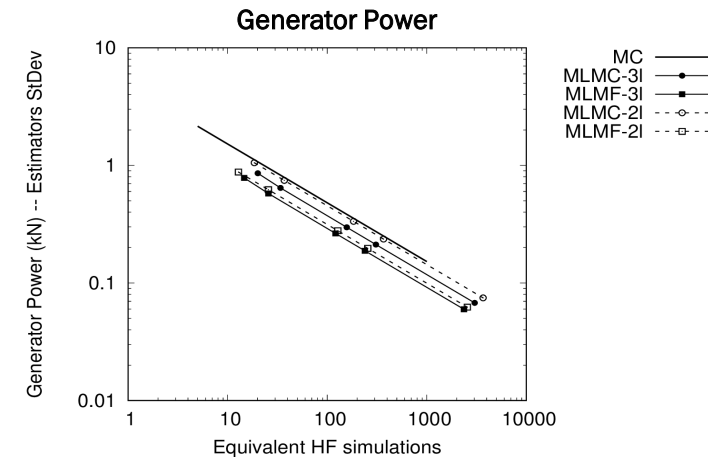
Low-fidelity model: TurbSim+OpenFAST



Mid-fidelity model:
Nalu-Wind Actuator Disk+OpenFAST



High-fidelity model:
Nalu-Wind Actuator Line+OpenFAST

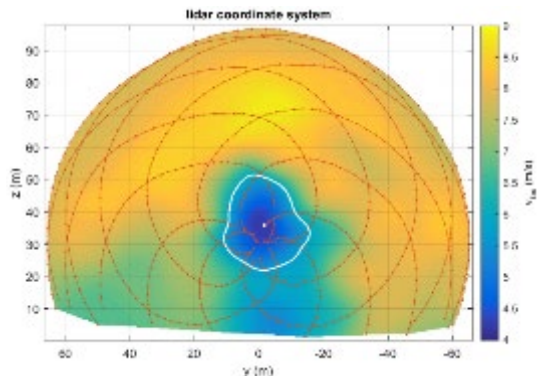


Conclusions

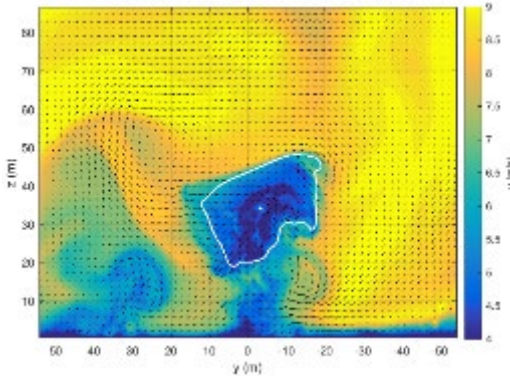
- Consistent performance trends from different sampling methods
 - MLMF methods showed higher efficiency compared to standard methods
- Significant improvements have been made with Nalu-Wind simulation capabilities and integration with UQ workflow

Nalu-Wind Wake Assessment, SWiFT

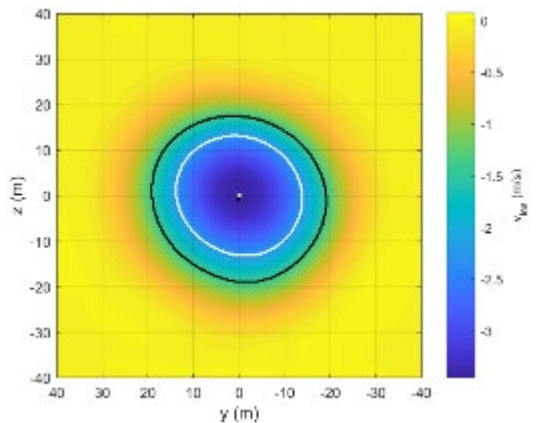
- Comparisons between neutral atmospheric boundary layer inflow experimental data were compared with Nalu-Wind simulations, including power, loads, and wake data.



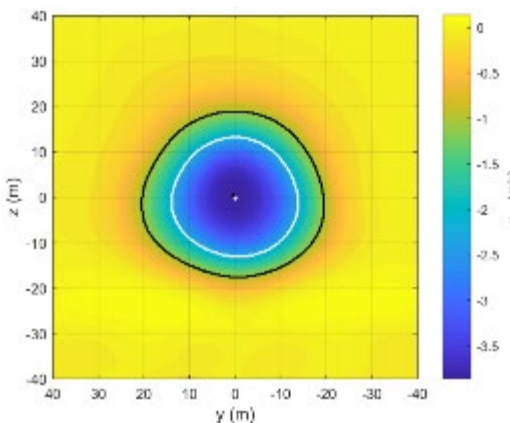
Sample of the wake data from the measured Spinnerlidar at the SWiFT facility.



Nalu-Wind Simulated wake data 5D downwind.



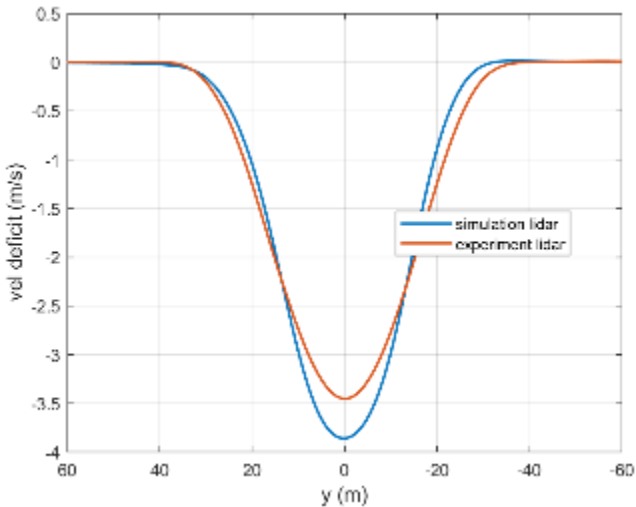
Average over 10 minutes of the wake data from the measured Spinnerlidar.



Average over 10 minutes for the simulated wake data 5D downwind, sampled to match the experimental lidar data.

	Simulation	Experiment
OOP Blade Bending (kN m)	37.0 ± 6.0	37.1 ± 6.2
Rel. Flapwise DEM (sim./exp.)	1.06	1.00
Generator Power (kW)	88.4 ± 17.3	81.2 ± 19.3

Upstream turbine (WTGa1) results of the 10-minute averages of the mean out-of-plane (OOP) blade-root bending moment for the three blades, relative flapwise DEM, and generator power for yaw = 0° case.



Comparison of wake velocity deficit for the experiment and the Nalu-Wind simulated lidar data.

Key Program Goals & Objectives By Completion

- Establish a validation framework with well-defined performance metrics, and apply it to benchmark wind-plant simulation cases.
- Coordinate validation activities across A2e, which will eliminate redundancies in process development and maximize the value from a limited number of facility experiments.
- Develop and demonstrate wind turbine and wind plant V&V/UQ techniques for industry relevant applications.
- Disseminate verification, validation, and uncertainty quantification methods and study results with stakeholders.
- Develop tools to define the most informative physical and high-fidelity computational experiments that best inform our predictive capability.

Key Program Goals & Objectives By Completion

Near-term (FY20-21) activities:

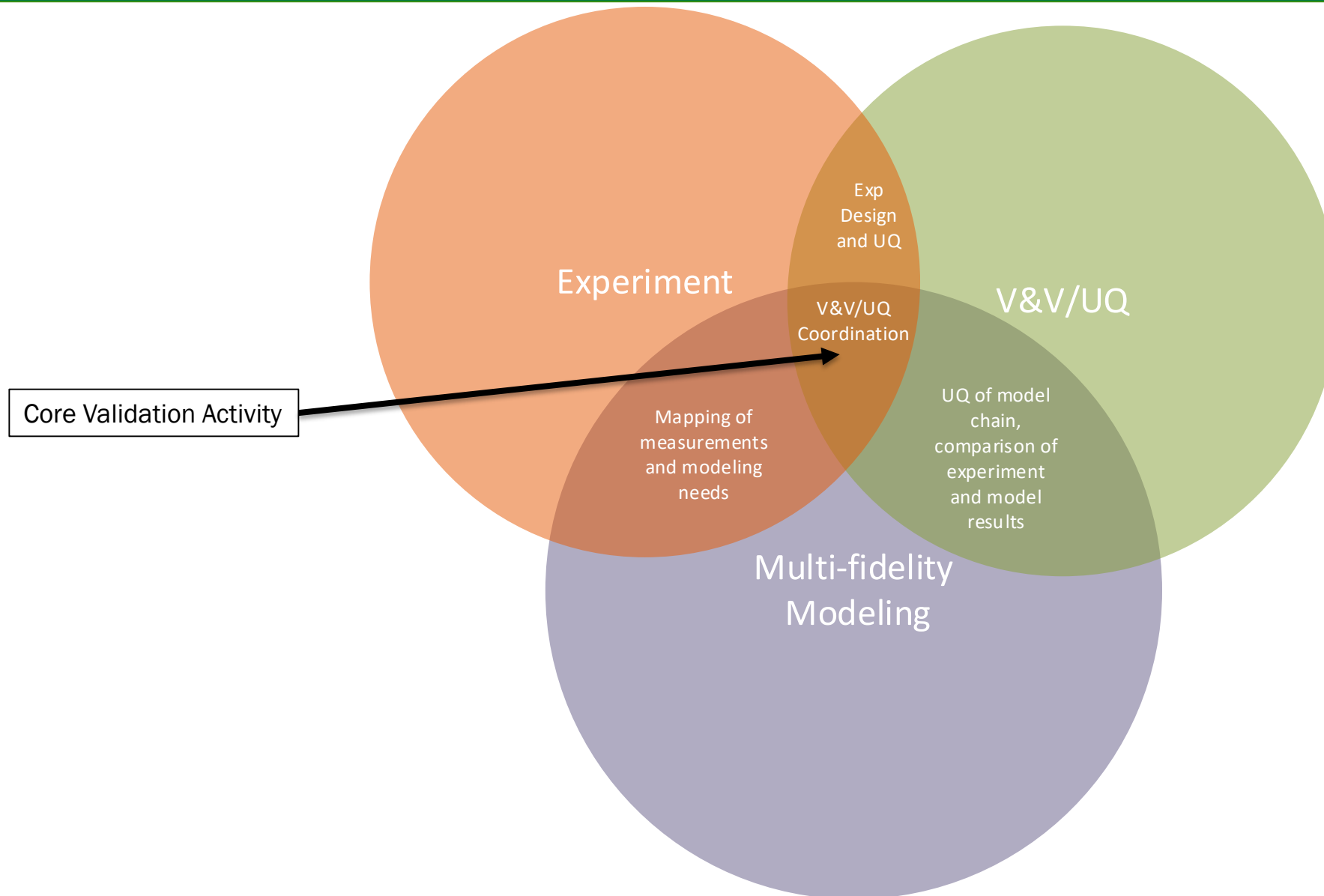
- Validation Roadmap: bridge between long term validation objectives and experiment development
 - Supports instrumentation prioritization (AWAKEN and Rotor Wake projects)
- Wind plant UQ framework and demonstrations
 - Multilevel-Multifidelity UQ Forward, Inverse, OUU
 - Deploy for new Nalu-Wind capabilities
 - Incorporate demonstrations with engineering models to link with industry
 - Power performance and wakes: WindSE + Nalu-Wind AL/AD (OpenFAST for ST)
 - Wake induced loads: FAST.Farm + Nalu-Wind AL/AD

Key Program Goals & Objectives By Completion

Near-term (FY20-21) activities (continued):

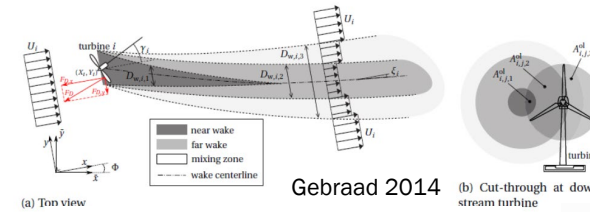
- Enhanced validation techniques, linking of experiment and model UQ
 - Lidar uncertainty development, presenting at Torque 2020
 - Wake assessment through proper orthogonal decomposition (POD) and machine learning
 - Estimating rotor thrust through wake momentum deficit measurements
- Validation of HFM capabilities
 - AD/AL/AAL validation and parameter optimization for ABL simulations
 - Stable ABL validation for inflow, loads, and wake deficit
 - Identify best practices and quantify the sensitivity to model input parameters for both the ABL and the turbine
- New V&V/UQ Standards Activities:
 - IEC Joint Working Forum on V&V, AWEA TR-1: Wind Plant Rev. Uncertainty

Project Organization



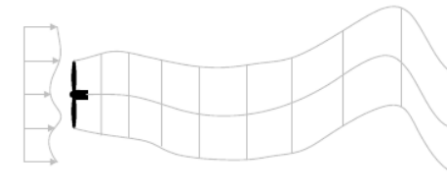
Wind Turbine Array Model Hierarchy

- Empirical Wake Model
- FAST-AeroDyn+TurbSim
- FAST.Farm w/o ABL
- Vortex Method Prescribed Wake*
- WindSE (RANS 2D)*
- WindSE (RANS 3D)*
- Vortex Method Free Wake*
- Nalu-Wind Actuator Disc
- Nalu-Wind Actuator Line
- Nalu-Wind Blade Resolved URANS w/ LES

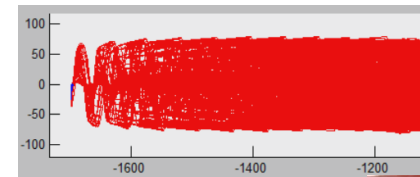


Gebraad 2014

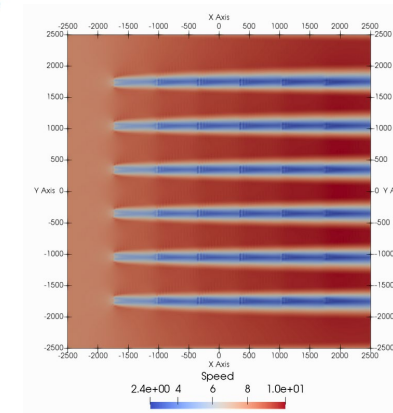
(b) Cut-through at downstream turbine



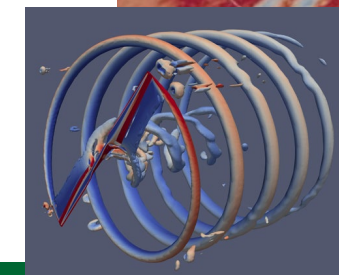
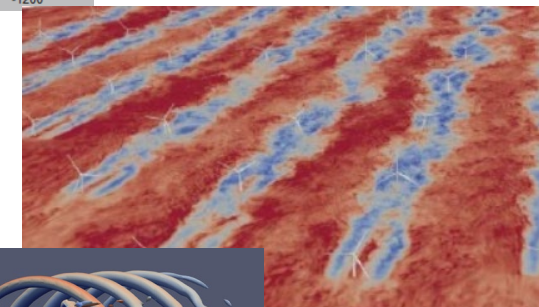
Shaler 2019



WindSE

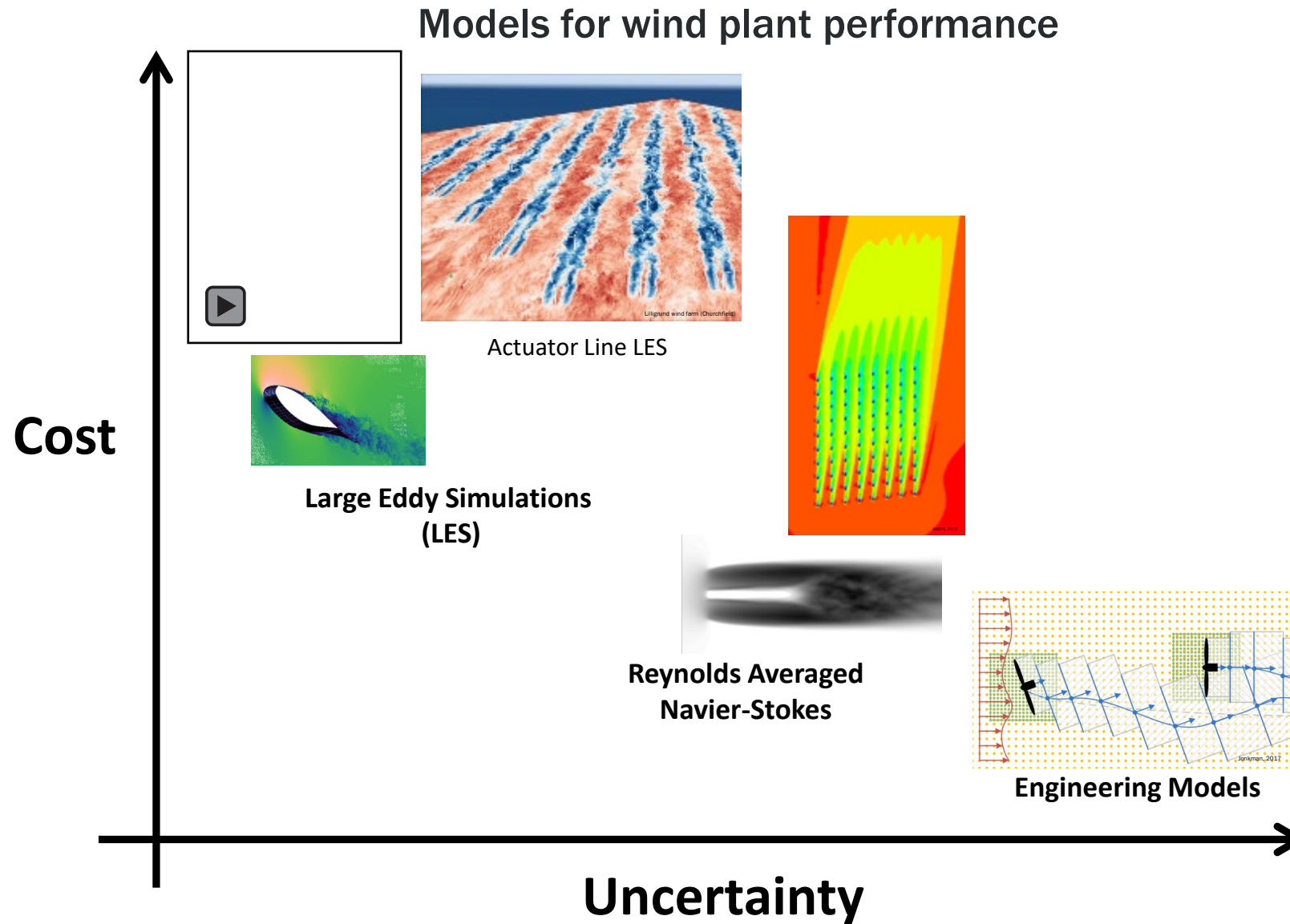


SOWFA AL-LES



Nalu-Wind Blade Resolved

Levels of Models



New Projects & Activities Supporting WETO Program

- International Wind Energy Validation Roadmap: bridge to long term validation objectives that can only be met by the international community
 - Build off V&V collaboration work in IEA Task 31 Wakebench
- Develop Offshore PIRT for **multi-fidelity modeling** with the international wind research community
- Integrate blade resolved simulation capability in to V&V/UQ application
- Adoption of V&V/UQ Processes in international wind community
 - Wind plant and turbine UQ framework development and demonstration
- Machine learning algorithms for data science applications
 - Power curve uncertainty, wind plant power production uncertainty
 - Real-time prediction of reliability and long-term robust revenue optimization

New Projects & Activities Supporting WETO Program

- **Big data and AI transition**
 - Demonstrate AI / machine learning improvement of wind plant performance and reliability
 - Apply massive and fused sensor arrays for damage/anomaly detection and performance enhancement
 - Apply and combine AI, ‘Digital Twin’, or probabilistic models with massive sensors to predict life performance and remaining useful life
 - Apply machine learning towards advanced instrumentation, sensor fusion with CFD
 - Infer previously unavailable QoI’s – full unfiltered turbulence content from lidar returns

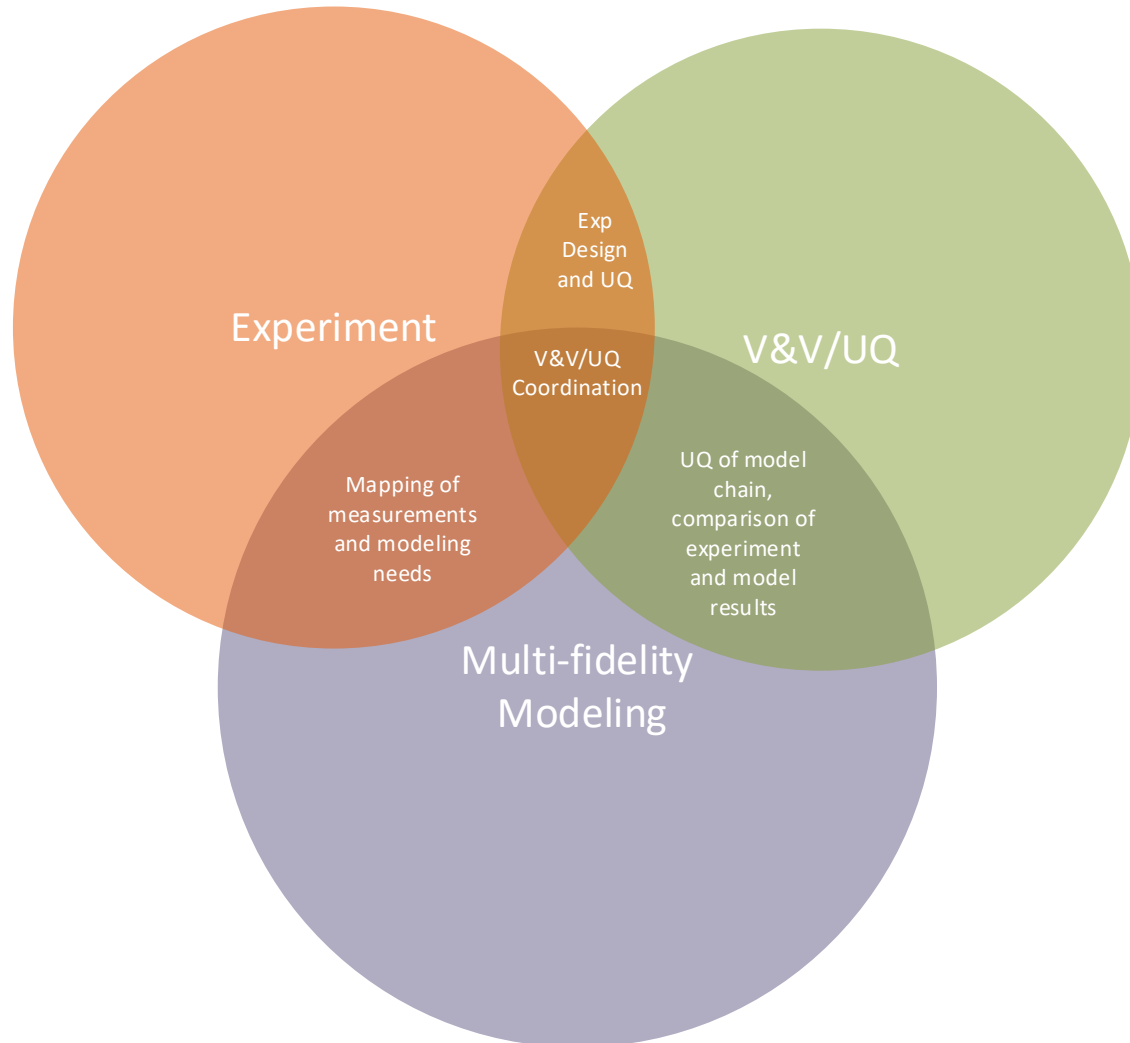
New Projects & Activities Supporting WETO Program

- Apply V&V/UQ to new areas
 - Grid and storage design relies completely on systems models now. \$1billion decisions rely on modeling.
 - Blade structure design and certification will increasingly rely on computational modeling, requiring formal V&V/UQ. How can we help industry push down this path ?
 - Integrate cost models with wind farm models, kind of like what we discussed with the LEE research, which would allow development of control strategies to optimize decision-making for operators

V&V/UQ Activities Summary

Core Validation Activity

-Links Rotor Wake, HFM, ISDA, and V&V/UQ



1. Validation Coordination

- Validation roadmap and meetings
- Support applying methods to offshore and grid research
- Share V&V Framework and drive its application in the wind international community

2. UQ Development

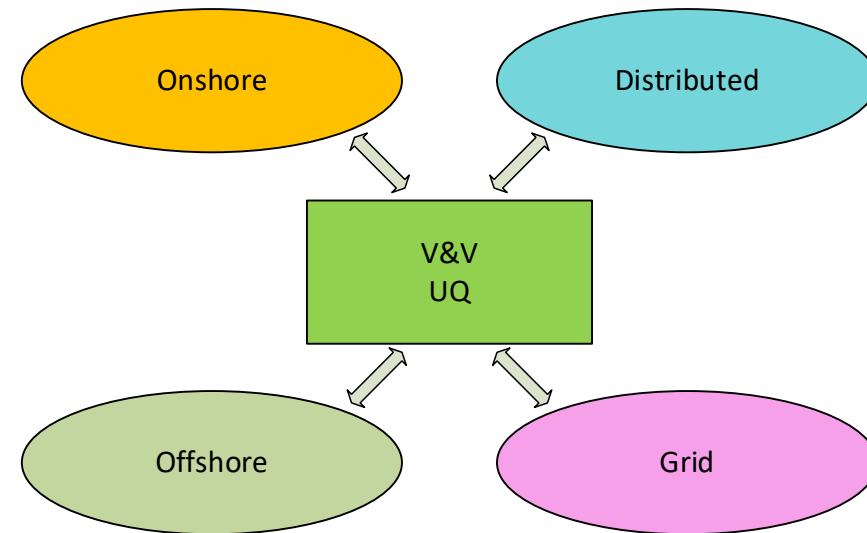
- MLMF-UQ of dynamic models for power and loads
- Experiment as reference rather than CFD
- Expand MLMF-UQ application to optimization
- OED: Optimal experimental design to support instrumentation development

3. Validation and UQ Application

- Expand UQ applications
- Advanced line/disk V&V+UQ (*onshore/offshore*)
- Wake induced loads via MLMF for stable ABL (*onshore/offshore/grid*)
- Power performance: support JWF (*onshore/offshore*)
- Leading edge erosion UQ support: (*offshore/onshore*)
- Sensitivity analysis to support experiment design

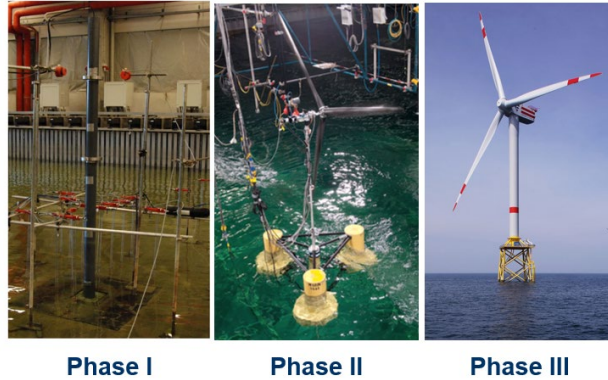
Role for V&V/UQ Across Wind Energy Technologies

- As A2e transforms, V&V/UQ will continue to play an important role
 - All wind subprograms will continue to require validation and uncertainty quantification
 - The tools we develop will be more valuable as a result of undertaking a validation-directed approach

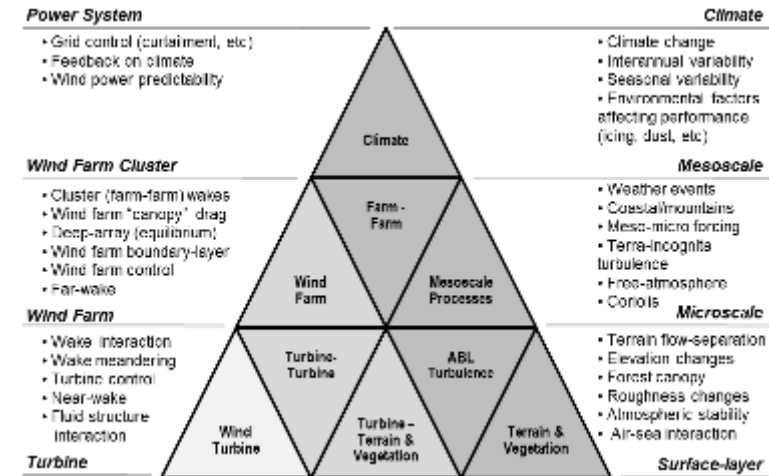


Adoption of V&V in Wind Energy Community

IEA Wind Task 30: Offshore Code Comparison Collaborative



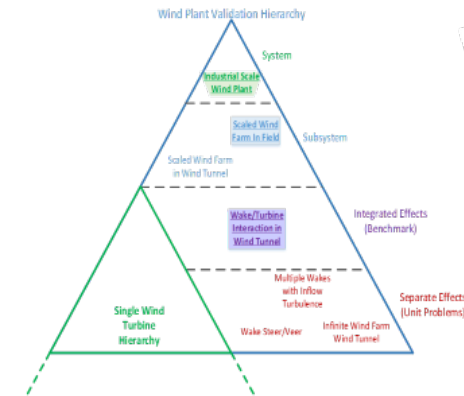
IEA Wind Task 31: Wakebench



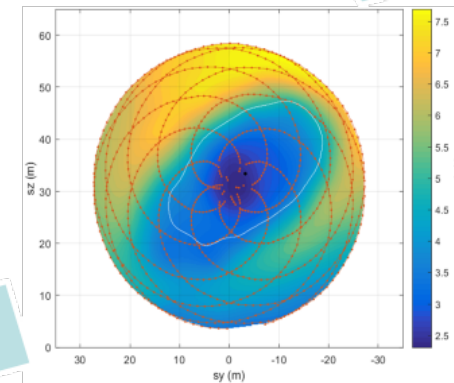
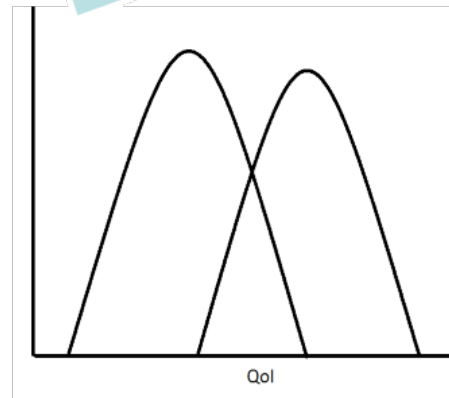
IEA Wind Task 36: Forecasting for Wind Energy

New V&V/UQ Standards Activities:
 AWEA TR-1: Wind Plant Uncertainty
 IEC Joint Working Forum on V&V

Thank you



Virtuous Cycle
Validation
Model Development
Experimentation
Uncertainty Quantification

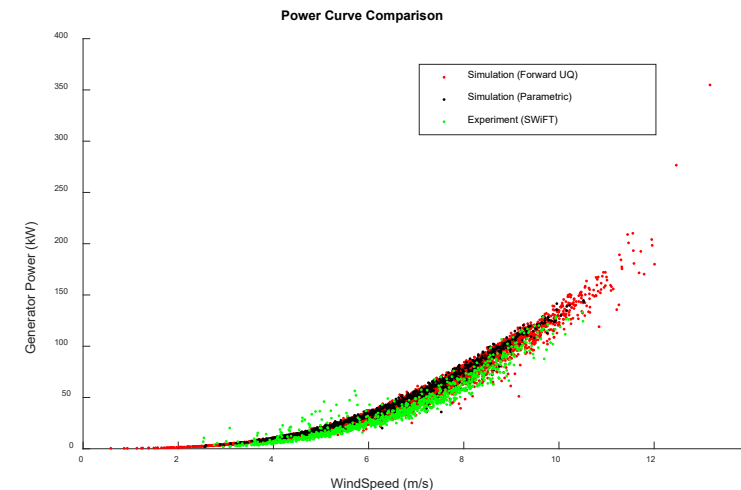


Importance of V&V/UQ

- Recent reports indicate underperformance of large wind farms due to blockage effects
 - Lower rate of return
- The underperformance stems from inadequacy of the models used to predict such effects
 - Models fail to capture relevant physics
 - New physics requirements are being introduced by larger turbines























































































































































Horns Rev wind farm, DK; Photographer: Christian Steiness. 12 February 2008 at 13.00 (Hassager et al., 2013)



PPEM (Prioritized Phenomenon Experiment Mapping)

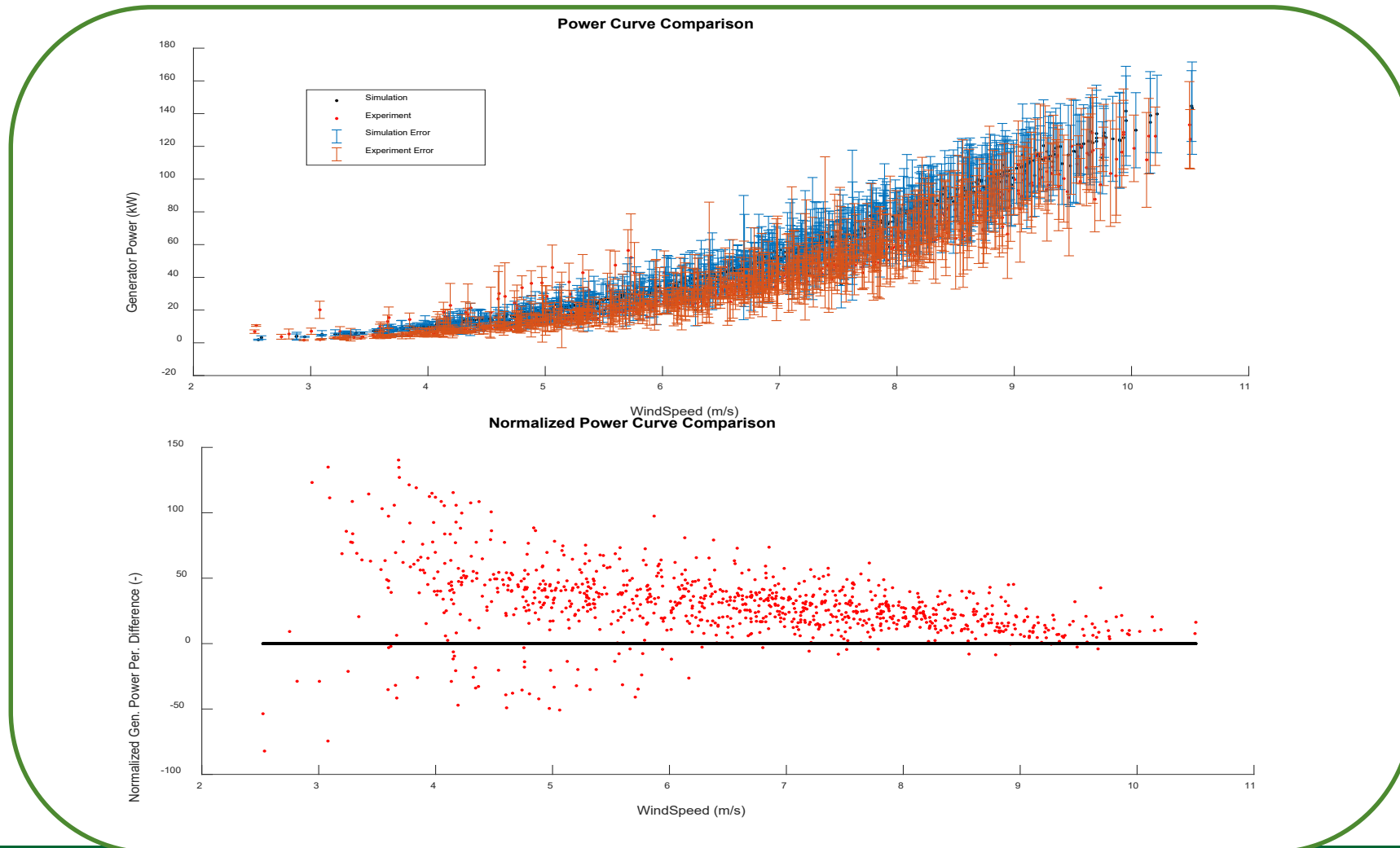
Physics Present/Physics Measured

-  Entirely
-  Mostly
-  Somewhat
-  Limited
-  Missing

	Blade Aero/Wake Generation	Blade Load Distribution Effects	Tip & Root Vortex Evolution	Vortex Sheet Evolution	Blade Generated Turbulence	Root Flow Acceleration	Boundary Layer Development	Surface Roughness Effects	Boundary Layer Near LE and TE	Rotational Augmentation	Dynamic Stall	Unsteady Inflow Effects	Blade Flow Control	Icing	Testing Issues	Boundary Conditions	Scale Effects
Pitching Blade (with Flow Control)																	
Physics Present																	
Physics Captured by Measurements																	
Turbine in WT (~1 m rotor), Turbulent Inflow																	
Physics Present																	
Physics Captured by Measurements																	
Turbine in VL WT (~5m rotor)																	
Physics Present																	
Physics Captured by Measurements																	
Scaled Turbine in Field (~30m rotor)																	
Physics Present																	
Physics Captured by Measurements																	
Industrial Scale Turbine in Field (~120m rotor)																	
Physics Present																	
Physics Captured by Measurements																	

Multilevel-Multifidelity Uncertainty Quantification

- Power curve comparison of 973 10-minute bin cases between SWiFT experimental results and OpenFAST-TurbSim simulations and normalization of the simulation/experiment power difference



Next Steps:

- Experiment UQ expansion for turbine loads and wake measurements – need identified during SWiFT benchmark
- Nalu-Wind Validation with SWiFT:
 - mesh convergence study for Neutral case
 - Stable ABL capability validation for inflow
 - Stable ABL validation for loads and wake deficit
 - MLMF Fwd propagation for power and loads (FAST-AD+TurbSim, FAST.Farm, WindSE)
 - MLMF wake-inflow inverse study

Expected Outcome: Assessment of Nalu for Power, Loads, and Wake QoI's for a range of relevant inflow conditions, including experimental and modeling uncertainty.

Future Application: Use of Nalu to assess wake steering design cases.