SAND2020-13038PE

Verification, Validation & Uncertainty Quantification

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FY21 A2e Kickoff Meeting

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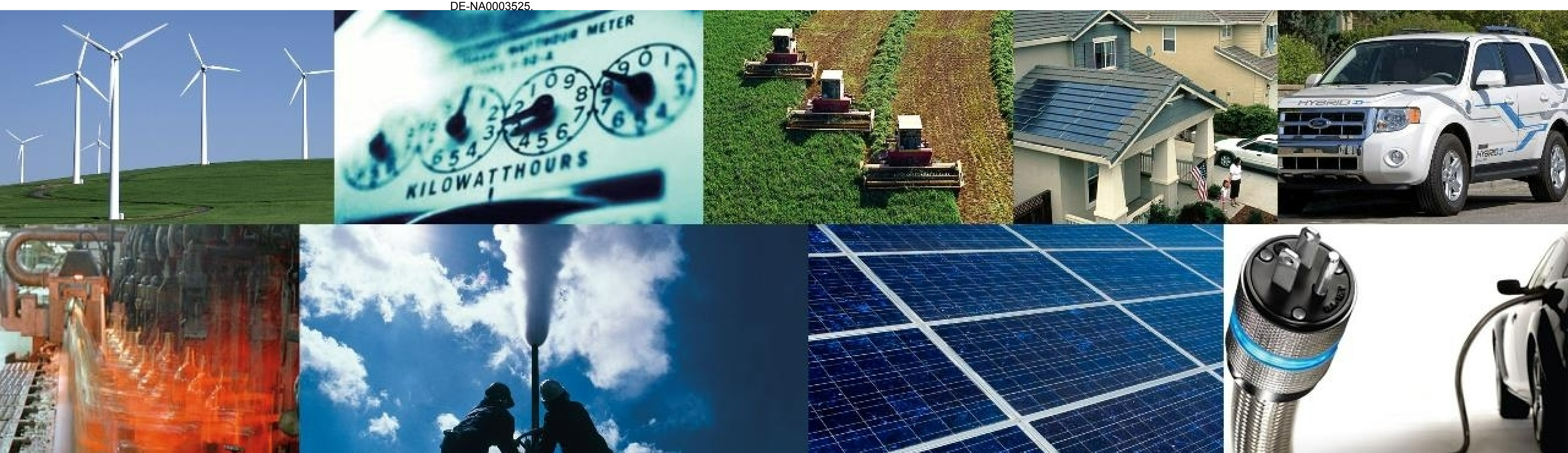


Verification, Validation, and Uncertainty Quantification of Wind Plant Models

The Verification, Validation, and Uncertainty Quantification (V&V/UQ) project will ensure that the predictive capability of the suite of models being developed across the Atmosphere to electrons (A2e) program is established through formal verification, validation, and uncertainty quantification processes. It will accomplish this goal by coordinating validation activities across A2e, developing and applying formal VV&UQ processes, and ensuring that any V&V gaps are addressed. Uncertainty Quantification (UQ) is critical for quantitative model validation focused on enabling predictive numerical simulations in research studies and advanced engineering design, as it codifies the assimilation of observational data; the characterization of errors, uncertainties, and model inadequacies; and forward predictions with confidence for untested / untestable regimes.   Activities under this area will also include the development of methods and processes required to quantify the uncertainty of measurements and computational models as required for associated validation campaigns.

Budget (SNL): FY20-22, $825k BA/FY

- Started in FY20 under a 3-4 year merit review proposal, built off HFM and Wake Dynamics projects

Key Program Goals & Objectives

- 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.

Current Program Status & Accomplishments

Task Structure:

1.0 Validation Coordination: Coordinate validation activities across A2e and disseminate V&V methods to stakeholders, in collaboration with the international wind community.

2.0 Uncertainty Quantification Development: Create the tools to quantify the predictive capability of mid- and high-fidelity computational models.

3.0 Validation and Uncertainty Quantification Application: Quantify the predictive capability of wind energy high-fidelity computational models and demonstrate V&V/UQ techniques for industry relevant applications.

Current Program Status & Accomplishments

1.0 Validation Coordination

1.1 A2e Validation Coordination.

1.2 Validation roadmap annual updates.

1.3 Development of a short-term validation campaign.

2.0 Uncertainty Quantification Development

2.1 Multilevel-Multifidelity UQ forward and inverse methods for wind plant applications.

2.2 Multilevel-Multifidelity Optimization under uncertainty methods for wind plant applications with Nalu-Wind(ExaWind) and WindSE.

3.0 Validation and Uncertainty Quantification Application

3.1 Nalu-Wind turbine array validation assessment, including a complete range of atmospheric inflow conditions.

3.2 Quantification and propagation of experiment uncertainty quantification, including advanced wake analysis methods.

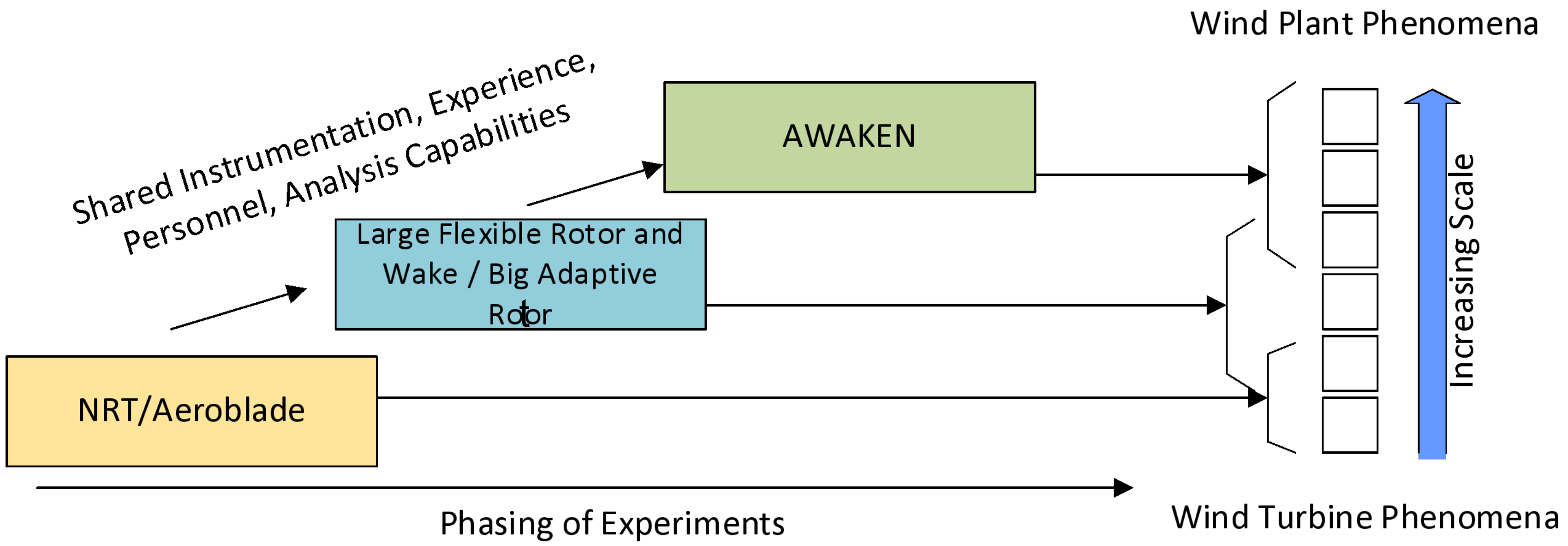
3.3 Demonstrate MLMF-UQ for validation of power and loads in waked conditions. Focused on ExaWind/Nalu-Wind, WindSE, OpenFAST, and FAST.Farm.

Current Program Status & Accomplishments

- Reports:
  - V&V Framework (2015)
  - V&V Integrated Program Planning for Wind Plant Performance (2019)
  - Wind Energy High-Fidelity Model Verification and Validation Roadmap (2020)
- International Collaboration and Standards:
  - Adoption of V&V processes by IEA Tasks 30, 31, 36 and IECRE-JWF
  - Member of AWER TR-1 on wind plant power uncertainty
  - Joint Non-Deterministic Approaches and Wind Energy session at the AIAA SciTech 2020 & 2021 conferences

Validation Coordination Status & Accomplishments

- Synergy Between V&V Focused Experimental Campaigns
- Careful planning can ensure maximum use of limited funds
- Experience gained in early campaigns can feed into later campaigns



Validation Coordination Status & Accomplishments

- **A2e validation experiment roadmap, laying out validation activities to meet multiple modeling applications. This report will be a living document, updated as validation activities advance.**

	FY 20			FY 2	
	Q2	Q3	Q4	Q1	Q2
	Jan-20	Apr-20	Jul-20	Oct-20	Jan-21
Wind Turbine					
SWiFT NRT			Execution		
SWiFT Aeroblade					
Wake Management		Planning			
Wake Steeting					

Timeline of Experiments for all A2e Efforts

		Month				
	Experiment Name	1	2	3	4	5
	A completed experiment					
	An ongoing experiment		Planning			
	An experiment being discussed					
	An experiment not yet being discussed					
	Wind Turbine					
Unit						
Benchmark	Dynamic Stall Experiment					
Subsystem	Wake Steeting					
	SWiFT NRT					
System	Large Flexible Rotor and wake					
	Offshore Large Flexible Rotor and Wake					

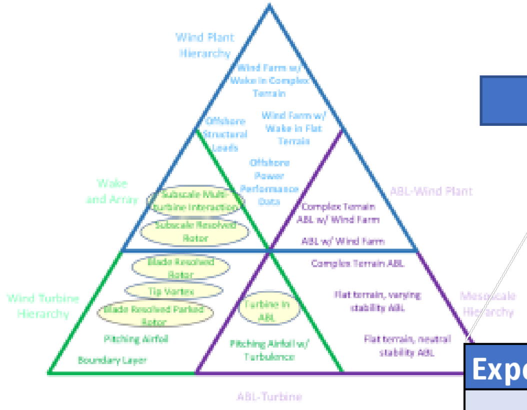
Mapping of Experiments to Validation Campaigns

Experiment Name:	
Type of Validation Experiment:	*(Separate Effects, Benchmark, Subsystem,or System) Where will this experiment have its primary impact on the validation hierarchy?*
Experiment Intent:	*What is the goal and intended impact of this experiment? In addition to validation goals, does it include scientific discovery or proving a new technology?*
Phenomena Targeted:	*List primary and secondary phenomna targeted by the experiment.*
Models targeted:	*List models used to design the experiment, and target for calibration or validation using the experiment data. This section can also describe required and desired quantities of interest for model validation and scale/geometry requirements if such information is available.*
Instrumentation Used:	
Data Gathered:	*List data channels that are planned to be part of the experiment. Resolution can be included if known. Priority of data can be added as well.*
Experiment Depend On:	
Future Work Depending on This Experiment:	
Publications Documenting Experiment:	
Publications Using Data for Validation:	

Description of Experiments and Validation Objectives

Validation Coordination Status & Accomplishments

Instrumentation Mapping



Validation Campaigns

Experiment	1.Mesoscale to ABL turbulence	2. Terrain ABL	3. Surface Model ABL	4. LES SGS static blade wake and loads	5. LES SGS and RANS blade loads and aero.	6. Rotor aero. and wake development	7. Wake evolution in a cluster	8. Wake evolution in a wind farm	9. Fluid structure interaction
Aeroblade-Wake	0	0	0	0.5	1	2	0.75	0	0.5
Large Flexible Rotor	0	0	0	0.25	1	0.25	0	0	2
AWAKEN	1	0	0	0	0.25	0.5	1	2	0

Instrument Map

	Instruments for Aeroblade-Wake Experiment	Campaign 1	Campaign 2	Campaign 3	Campaign 4	Campaign 5	Campaign 6	Campaign 7	Campaign 8	Campaign 9	Total
1	Met Tower	2	2	6	0	0	5	9	9	2	17.75
2	Fast Response taps	0	0	0	4	4	4	1	0	2	15.75
3	Kulites	0	0	0	4	4	4	1	0	2	15.75
4	SpinnerLidar	0	0	0	1	1	4	6	9	1	14.5
5	Scanning Lidar/Radar	2	2	0	1	1	3	4	7	1	11
6	Distributed strain fiber	0	0	0	2	2	2	1	0	6	10.75
7	Profiling lidar	2	2	4	1	1	3	3	1	1	10.25
8	Wind Scanner	0	1	0	1	1	3	2	8	0	9
9	Foil	0	0	0	2	2	2	1	0	2	8.75
10	Fiber Bragg	0	0	0	2	2	2	1	0	2	8.75

Uncertainty Quantification Development Status & Accomplishments

Public Outreach/Industry Engagement:

- Organized joint Non-Deterministic Approaches and Wind Energy session at the AIAA SciTech 2020 conference, shared 4 papers summarizing UQ work

Papers presented at AIAA SciTech 2021 conference:

- "Multilevel Uncertainty Quantification Using CFD and OpenFAST Simulations of the SWiFT Facility", Alan Hsieh, David C. Maniaci, Thomas G. Herges, Gianluca Geraci, Daniel T. Seidl, Michael S. Eldred, Myra L. Blaylock, and Brent C. Houchens; AIAA Scitech 2020 Forum.
- "Multifidelity strategies for forward and inverse uncertainty quantification of wind energy applications," Daniel T. Seidl, Gianluca Geraci, Ryan King, Friedrich Menhorn, Andrew Glaws, and Michael S. Eldred; AIAA Scitech 2020 Forum.
- "Higher moment multilevel estimators for optimization under uncertainty applied to wind plant design," Friedrich Menhorn, Gianluca Geraci, Daniel T. Seidl, Michael S. Eldred, Ryan King, Hans-Joachim Bungartz, and Youssef Marzouk; AIAA Scitech 2020 Forum.
- "A Probabilistic Approach to Estimating Wind Farm Annual Energy Production with Bayesian Quadrature," Ryan King, Andrew Glaws, Gianluca Geraci, and Michael S. Eldred; AIAA Scitech 2020 Forum.

Multilevel Uncertainty Quantification Using CFD and OpenFAST Simulations of the SWiFT Facility

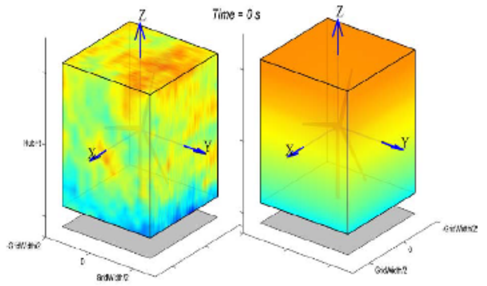
Research Scope: Evaluation of MLMF-UQ methods to improve predictive capabilities of computational models for wind farm applications

Motivation

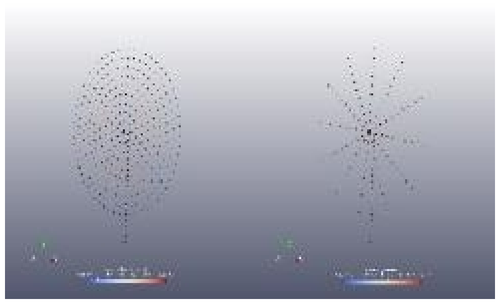
- UQ is necessary for predictive wind simulations but requires high numbers of simulations
- High-fidelity simulations are needed for accurate predictions but have high computational costs
- By leveraging lower-resolution, lower-fidelity simulations with high-fidelity simulations, Multilevel-Multifidelity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

Research Methodology

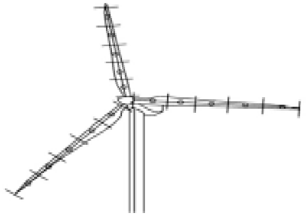
- Simulate V27 wind turbine at SWiFT in neutral atmospheric boundary layer
- Select hierarchy of model fidelities, uncertain turbine input parameters, and relevant QoIs (power, thrust, loads)
- Perform sampling study and apply Multilevel-Multifidelity (MLMF), Multilevel Monte Carlo (MLMC), and Monte Carlo (MC) sampling strategies



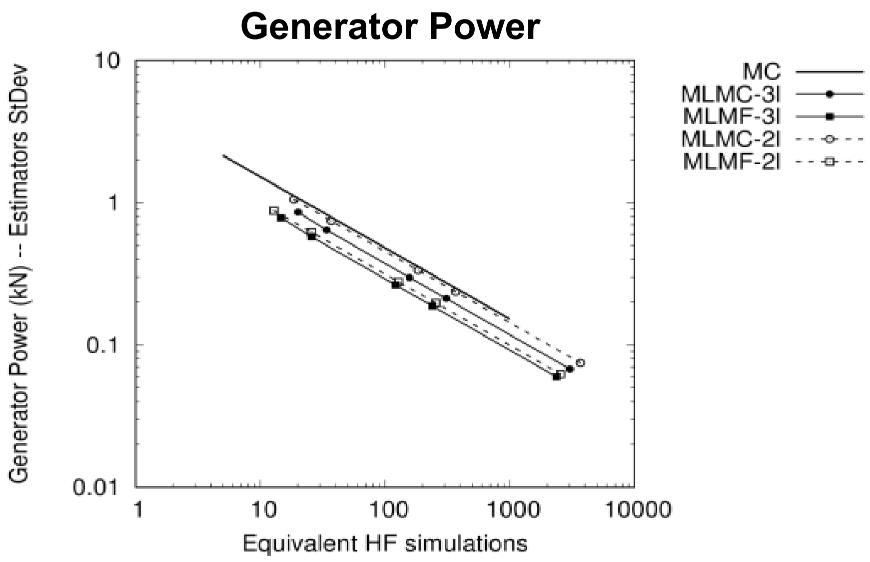
Low-fidelity model: TurbSim+OpenFAST



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



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

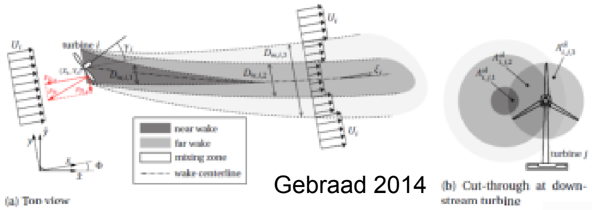


Conclusions

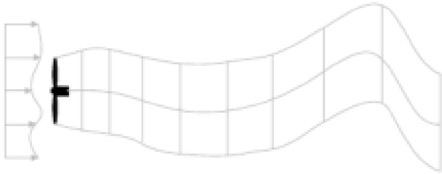
- Consistent performance trends from different sampling methods
  - MLMF methods showed higher efficiency compared to MLMC and MC methods
- Significant improvements have been made with Nalu-Wind simulation capabilities and integration with UQ workflow

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)** (>ExaWind)
- Vortex Method Free Wake
- **Nalu-Wind Actuator Disc** (>ExaWind)
- **Nalu-Wind Actuator Line** (>ExaWind)
- ExaWind Blade Resolved URANS w/ LES

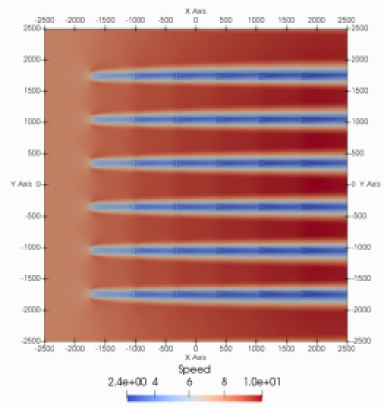


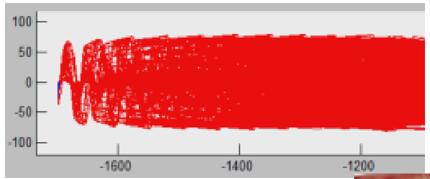
Gebraad 2014



Shaler 2019

WindSE





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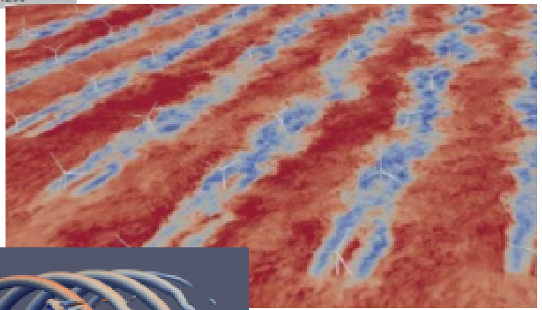
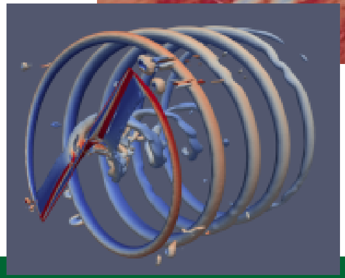




Nalu-Wind Blade Resolved

Multifidelity Strategies for Forward and Inverse Uncertainty Quantification of Wind Energy Applications

Wind plant challenges for UQ

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

Multifidelity strategies

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

Objectives of the study:

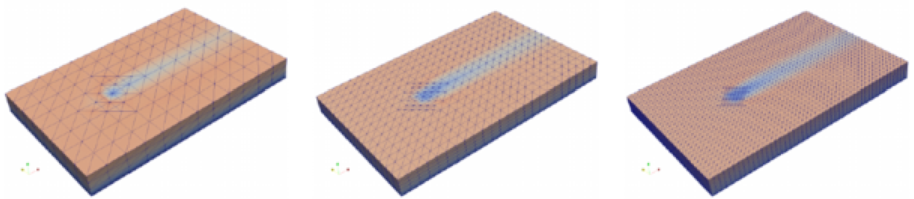
1 Demonstrate multifidelity (MF) surrogate efficiency for **efficient forward UQ**
→ Uncertainty's impact on wind plant performance

2 Leveraging MF strategies for **efficient inverse UQ**
→ Uncertainty characterization

3 Adaptation of MF sampling strategies for **Optimization Under Uncertainty** workflows
→ Wind plant's performance augmentation under uncertainty

Accomplishments:

- ► We exercised the full machinery that enabled us to go from building the ML surrogate to the inverse step
- ► ML surrogates demonstrated to be effective for a wind energy application
- ► Leveraging surrogates for Bayesian Calibration is effective (rejection rate was around 20%)
- ► We calibrated a RANS solver against LES data
- ► MLMC extended and adapted to OUU workflows

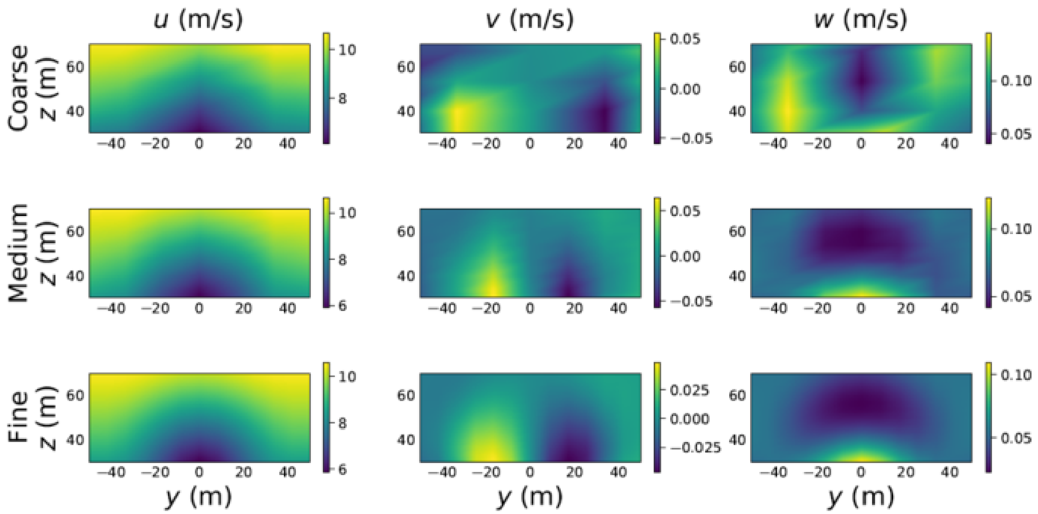


(a) Coarse: 5252 DoFs (b) Medium: 33428 DoFs (c) Fine: 228064 DoFs

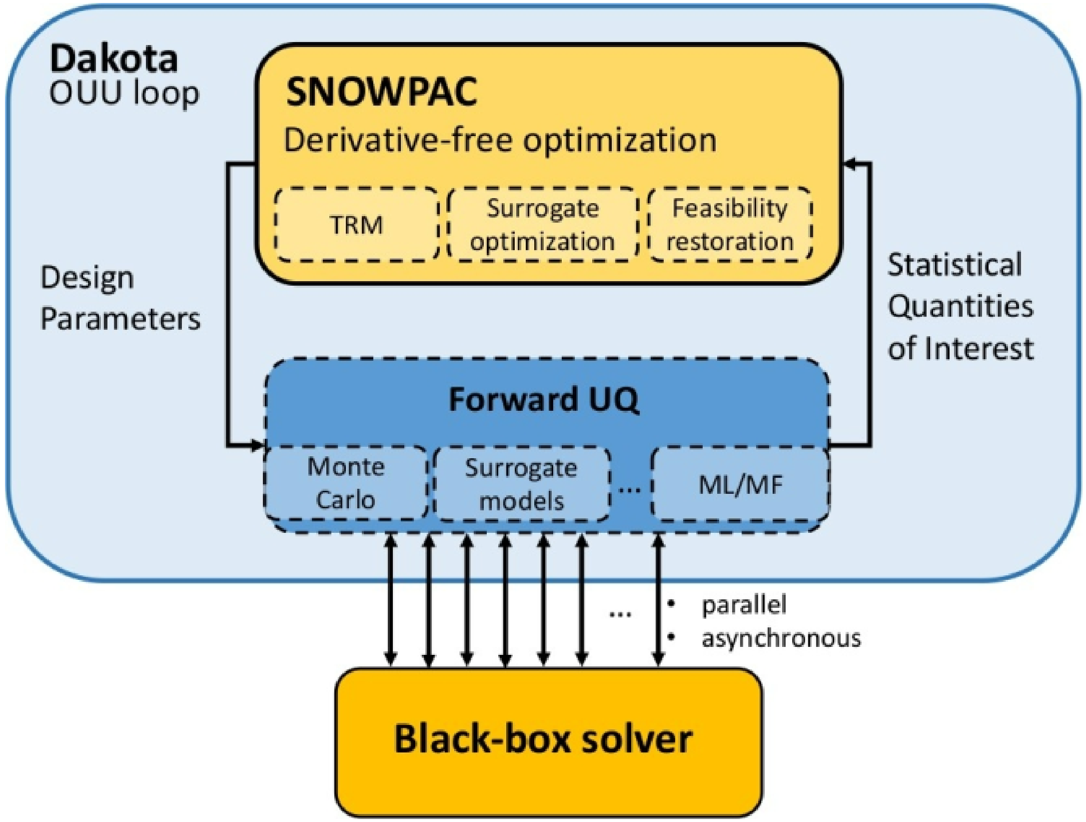
Model Resolution	N_x	$N_y = N_z$	Cost (s)
Coarse	12	8	8.51
Medium	24	16	60.4
Fine	48	32	1270

Table: Multilevel model hierarchy unrefined grid discretization and simulation cost.

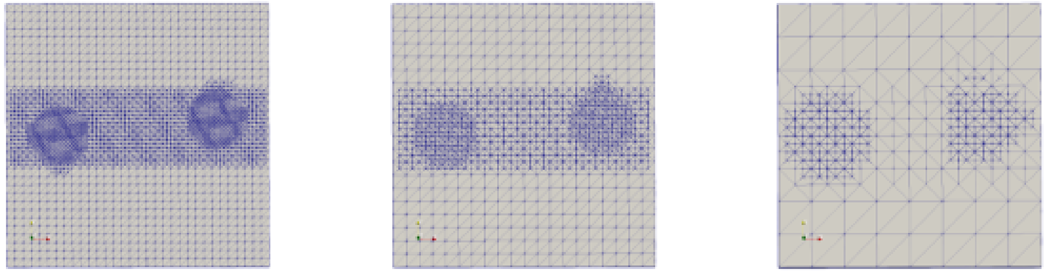
Flow Fields over the Slice for all Model Levels



Optimization Under Uncertainty with SNOWPAC and DAKOTA

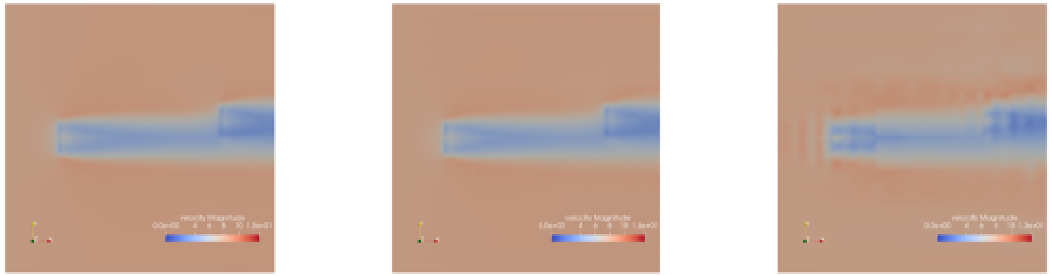


Meshes:



(a) FINE (DoF 242788) (b) MEDIUM (DoF 86364) (c) COARSE (DoF 12548)

Reference solutions:



(a) FINE (DoF 242788) (b) MEDIUM (DoF 86364) (c) COARSE (DoF 12548)

Sample allocation (for each design point!):

X =	MC	$\mathbb{E}$	$\mathbb{V}$
N^X_{FINE}	150	5	20
N^X_{MEDIUM}	0	7	46
N^X_{COARSE}	0	223	396
Cost	**4650**	**481**	**1590**

Main novel contribution:

- We **extended the 'classical' MLMC sample allocation** to target higher-order moments: in this case **variance** to compute the standard deviation for the optimization metric

Public Outreach/Industry Engagement:

Papers presented at the Torque 2020 conference:

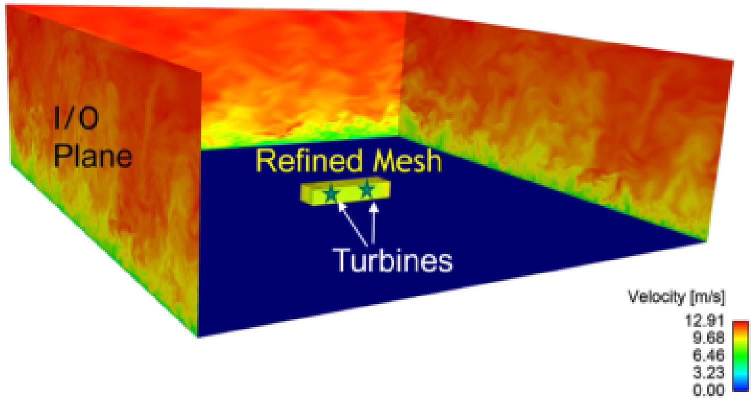
- "Residual uncertainty in processed line-of-sight returns from nacelle-mounted lidar due to spectral artifacts," Ken Brown and Tommy Herges.
- "Representation of coherent structures and turbulence spectra from a virtual SpinnerLidar for future LES wake validation," Kenneth Brown, Alan Hsieh, Thomas Herges and David Maniaci.
- "Quantification of rotor thrust and momentum deficit evolution in the wake using Nalu-Wind simulations," Thomas Herges, Christopher Kelley, Alan Hsieh, Kenneth Brown, David Maniaci and Jonathan Naughton.
- "Large-eddy simulations of the Northeastern US coastal marine boundary layer," Lawrence Cheung, Colleen Kaul, Alan Hsieh, Myra Blaylock and Matthew Churchfield. (Primarily under HFM)
- "Uncertainty Quantification of Leading Edge Erosion Impacts on Wind Turbine Performance," David C. Maniaci, Carsten Westergaard, Alan Hsieh and Joshua Paquette. (Primarily under BRC)

Journal paper submission: "High-Fidelity Wind Farm Simulation Methodology with Experimental Validation and Application to Wake Steering" Alan Hsieh, Kenneth Brown, Nate deVelder, Thomas Herges, Robert Knaus, Phil Sakievich, Lawrence Cheung, Brent Houchens, Myra Blaylock, and David Maniaci

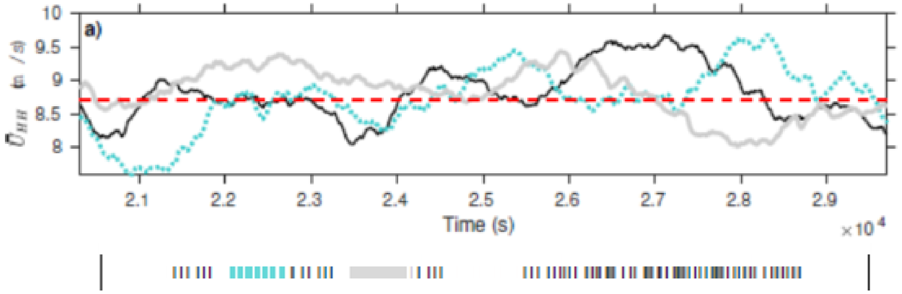
High-Fidelity Wind Farm Simulation Methodology with Experimental Validation and Application to Wake Steering

- **Verification and validation of Nalu-Wind for wake deficit strength and deflection in neutral atmospheric inflow, including a novel method for atmospheric inflow selection.**

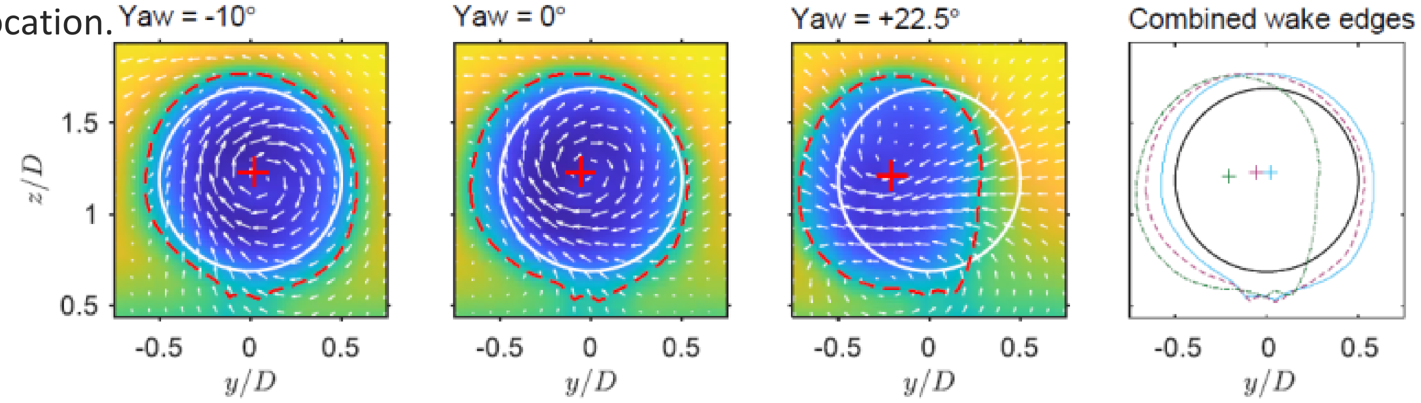
Location of refinement regions and turbines in the Nalu-Wind simulation domain.



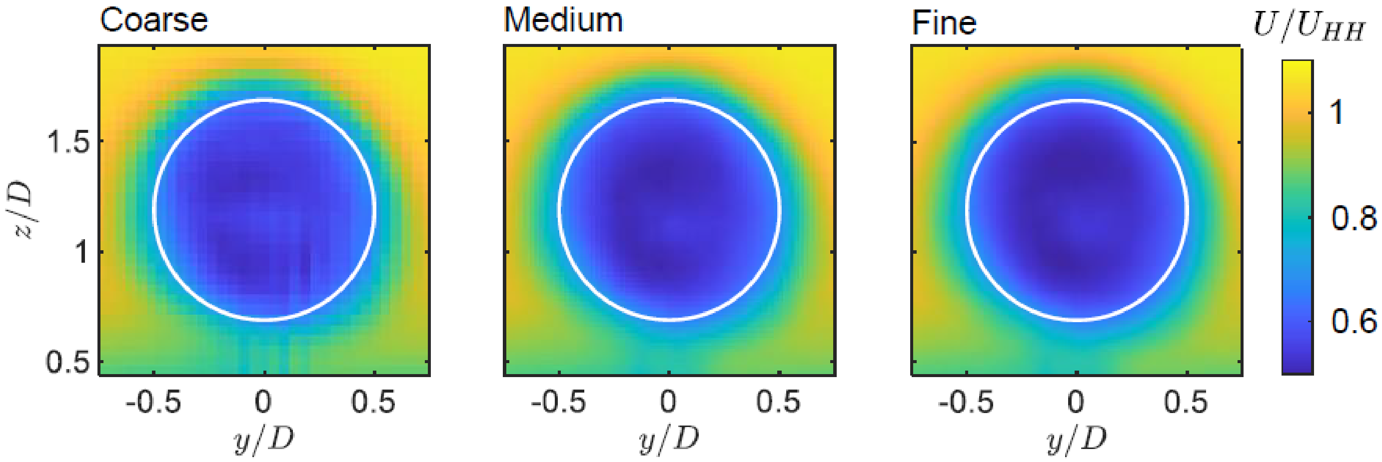
Effect of mesh resolution on simulated atmospheric inflow.



Effect of yaw on wake deflection 2D downstream. The white circle indicates the rotor location.



Effect of mesh resolution on simulated wake velocity contours 2D downstream .



Milestones & Deliverables

Milestones	Deliverables
Q1: Add currently planned A2e efforts to the *Validation Experiment Roadmap*, which lays out a coordinated path of experimental validation campaigns to address the range of model validation needs across the A2e program.	• A2e program validation experiment activities through the validation experiment roadmap.
Q2: Deploy multilevel uncertainty quantity method to the optimization under uncertainty workflow for wind turbine wake applications. Organize and chair a joint Non-Deterministic Approaches and Wind Energy session at the AIAA SciTech conference, which will include a presentation on this work.	AIAA 2021 SciTech, joint NDA-WE session: • Deployment of ML/MF forward UQ workflows for LES Nalu-Wind configurations. • OUU analyses will be based on ML hierarchies built upon the industrial state-of-the-art RANS based WindSE tools. (support w/ NREL)
Q3: Explore the use of state-of-the-art algorithms for the large-scale, multilevel-multifidelity forward uncertainty quantification propagation of Nalu-Wind and efficient low-fidelity auxiliary models.	Wakes Conference: • Enhanced forward UQ workflow by integrating wake analysis capabilities into the ML/MF UQ methods for high fidelity models. (support w/ NREL) • Higher-order physics analysis of Nalu-Wind wake predictions using POD for stable atmospheric conditions. Wind Energy Science Conference: • Verify and validate the new actuator disc and actuator line capabilities in Nalu-Wind for wake development related quantities of interest. (w/ NREL)
Q4: Develop a method for the high-fidelity processing of nacelle -mounted lidar data, leveraging machine learning for reduced uncertainty.	Journal Article: • High-fidelity processing for nacelle-mounted lidar leveraging machine learning for reduced uncertainty.

Looking Forward to FY-22 Goals & Objectives

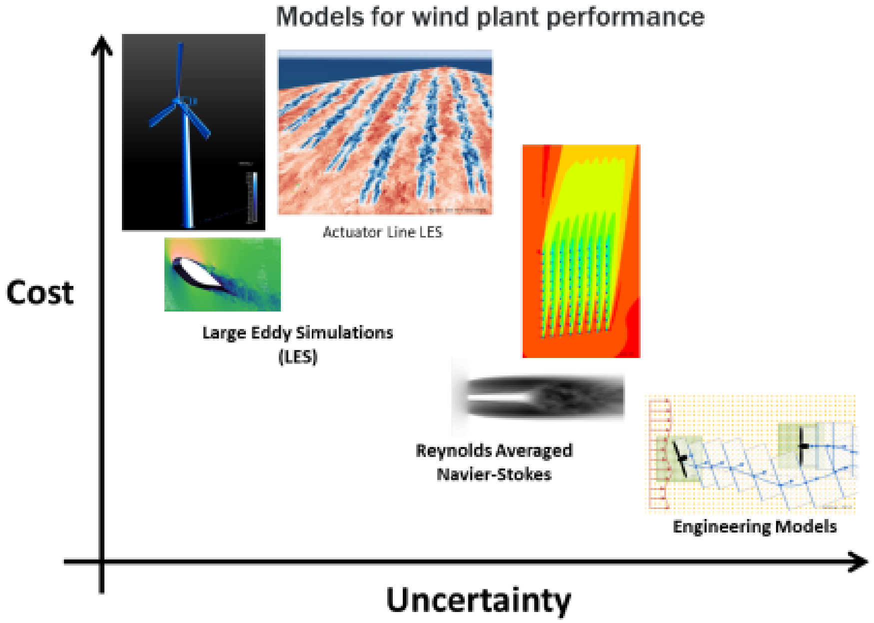
- Validation Experiment Roadmap development, move from a static report to an online format.
- Release updated PIRT for high and mid-fidelity models for Offshore wind energy design and analysis.
- Demonstrate V&V process through a short-term validation experiment.
- Publish journal article on the application of the MLMF-UQ methods for the wind plant optimization applications with uncertain input parameters.
- Validation and uncertainty quantification of ExaWind (Nalu-Wind AD/AL) for wind turbine wake phenomenon under multiple inflow conditions.
- Summary report on multi-fidelity methods for wind plant power and loads analysis.

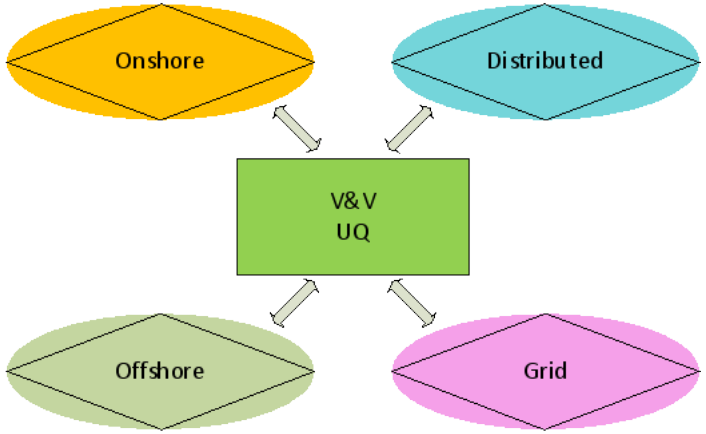
Issues & Concerns

- Path for application of the methods, algorithms, and tools developed under this project toward the fully deployed ExaWind code suite in FY23+
- Growing industry interest in machine learning tools and methods, but lack of formal V&V processes or understanding of UQ for this application area

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





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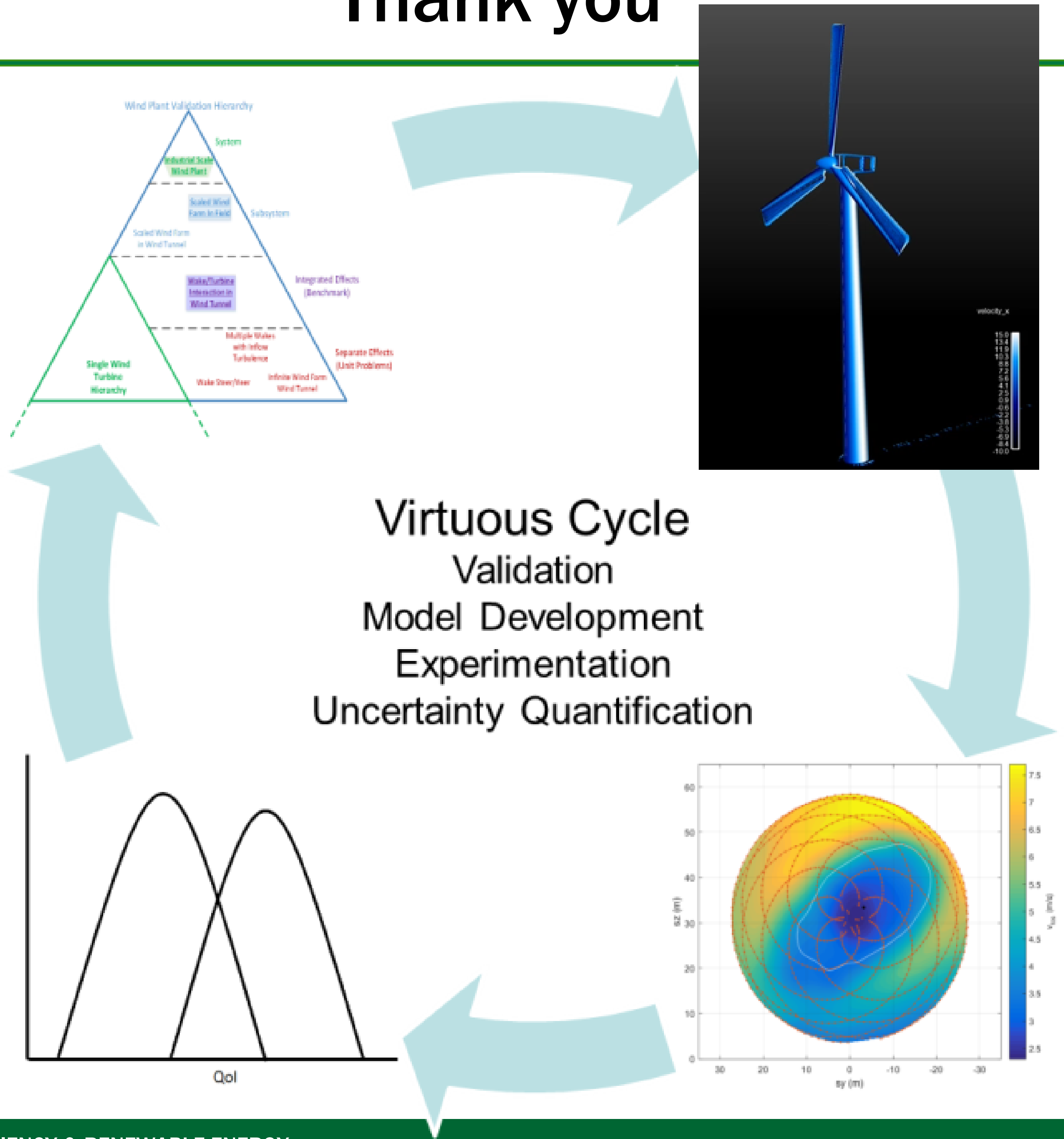

Wind Plant Validation Hierarchy
System
Industrial Scale Wind Plant
Scaled Wind Farm in Field
Subsystem
Scaled Wind Farm in Wind Tunnel
Integrated Effects (Benchmark)
Wake/Turbine Interaction in Wind Tunnel
Multiple Wakes with Inflow Turbulence
Separate Effects (Unit Problems)
Single Wind Turbine Hierarchy
Wake Steer/Veer
Infinite Wind Farm Wind Tunnel
velocity_x
Virtuous Cycle
Validation
Model Development
Experimentation
Uncertainty Quantification
QoI
sy (m)
sz (m)