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SAND2020-4934PE

Verification, Validation and Uncertainty Quantification Supporting Simulation and Analysis Development

SNL, NREL, PNNL

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May 5th, 2020

SAND2020 PE

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V&V/UQ Background and Context

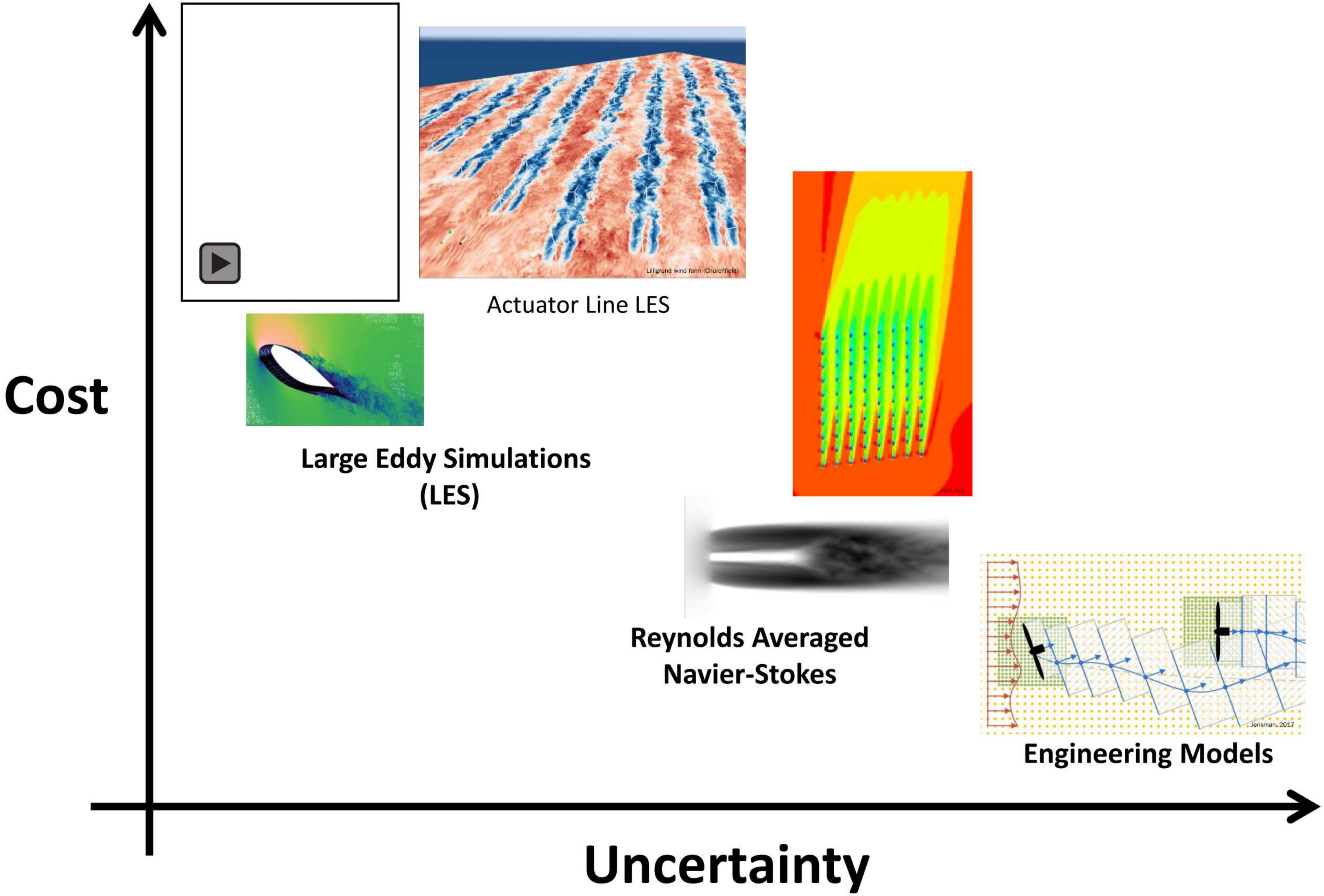
- Transform today's wind plant operating environment through advanced physics-based modeling, analysis, and simulation capabilities

- 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

- V&V started as a nascent effort in 2014
- UQ effort started in 2017 within HFM project
- V&V/UQ project started in FY20

Levels of Models

Models for wind plant performance



Project Overview and Objectives

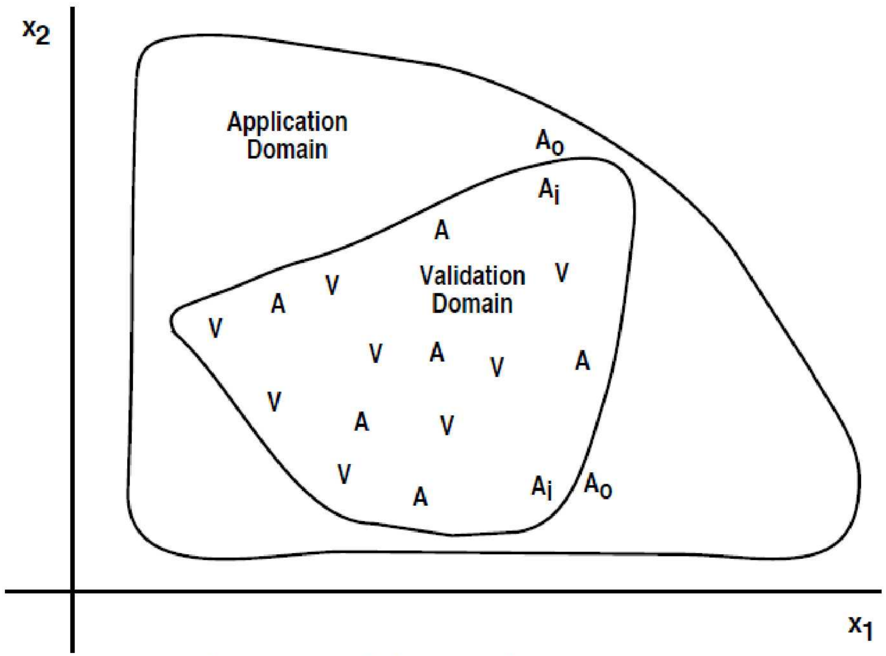
- **This project will ensure that the predictive capability of the suite of models being developed across A2e is established through formal V&V/UQ processes.**
  – Quantitatively establish where models are valid and where improvements are necessary

- **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

V&V Overview

- **Verification and Validation, and Uncertainty Quantification (V&V/UQ) are the processes by which we identify important physics and assess the level to which computational models capture them**

- **Validation is not a pass/fail exercise for a simulation**
  - Assesses the uncertainty of the predictive capability that the user can utilize to judge its suitability for a given application

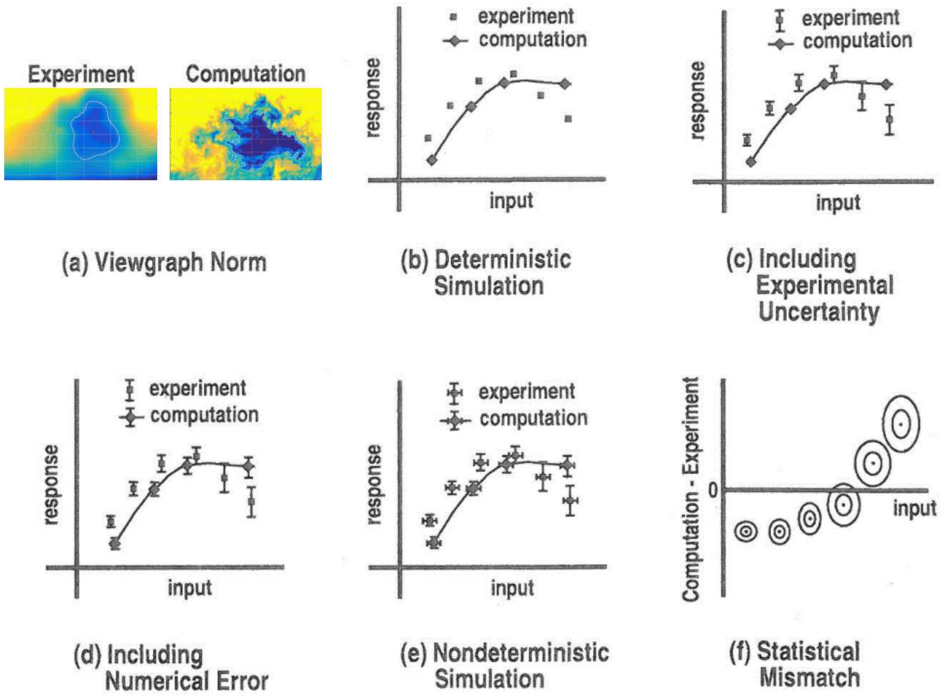


x_1 and x_2 are model parameters

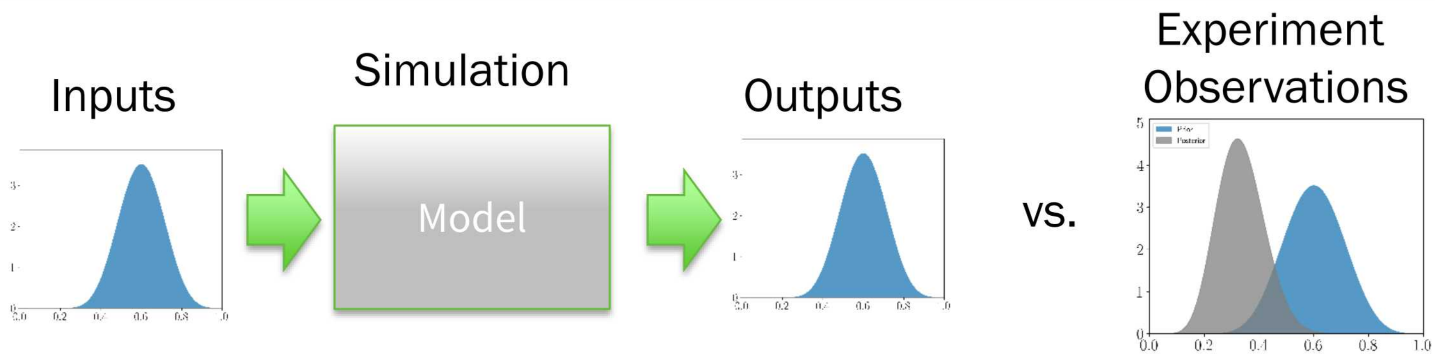
What is Uncertainty Quantification?

- Methods to codify the assimilation of observational data
- The characterization of errors, uncertainties, and model inadequacies
- Forward predictions with confidence for untested/unstable regimes

Levels of Precision

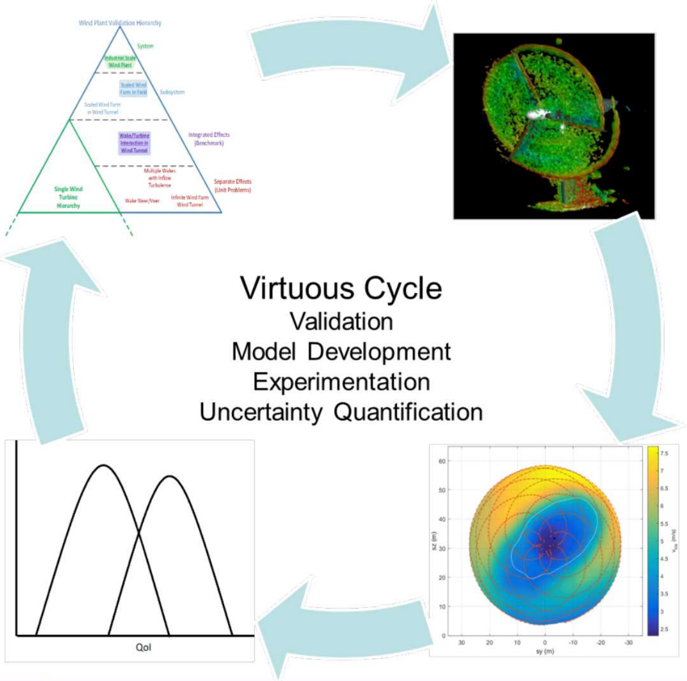


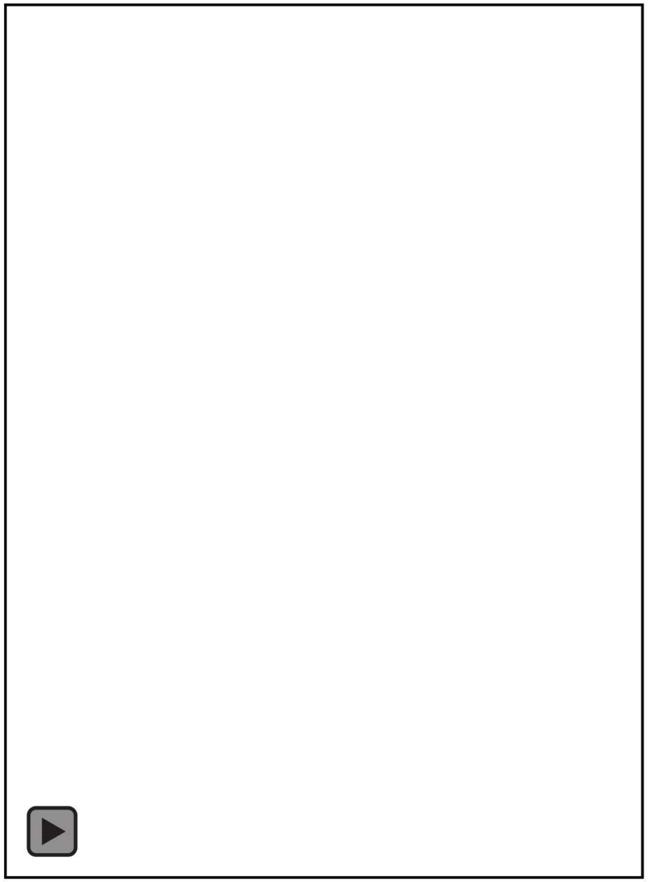
Stochastic Modeling



Model Development and V&V

- As wind turbine technology matures, the cost of testing and the required level of uncertainty demand a new approach
- High fidelity models enable reduced development risk through pre-prototype qualification and optimization
- Without a level of trust of our tools, the results are of limited value for impacting decisions
- The Verification and Validation Framework is the process to define the conditions where model predictions can be trusted





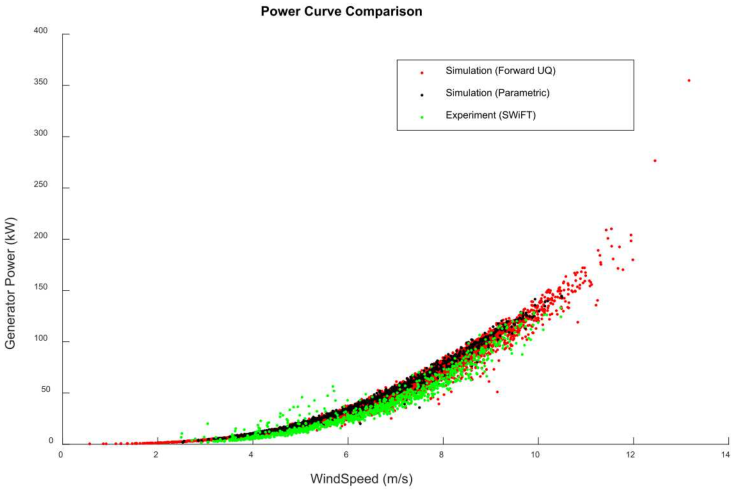
V-27 Nalu Simulation, M. Barone, S. Domino, and C. Bruner, 2017

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

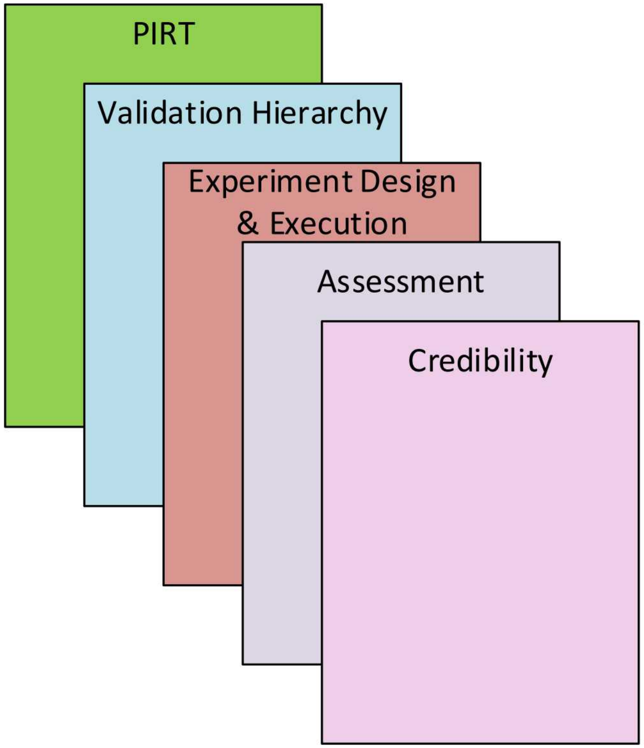
Horns Rev wind farm, DK; Photographer: Christian Steiness. 12 February 2008 at 13.00 (Hassager et al., 2013)

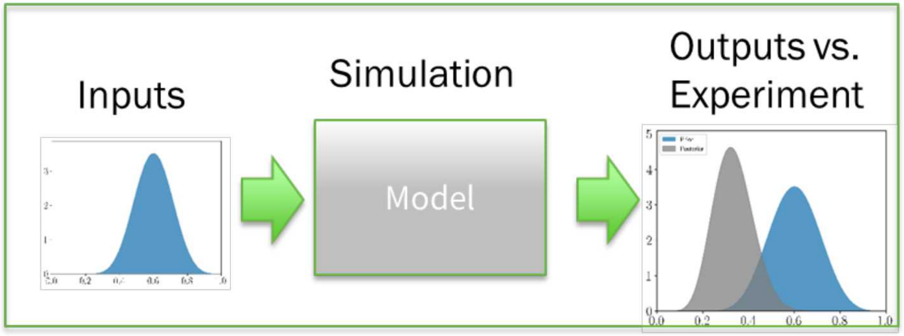


Importance of V&V/UQ

- **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



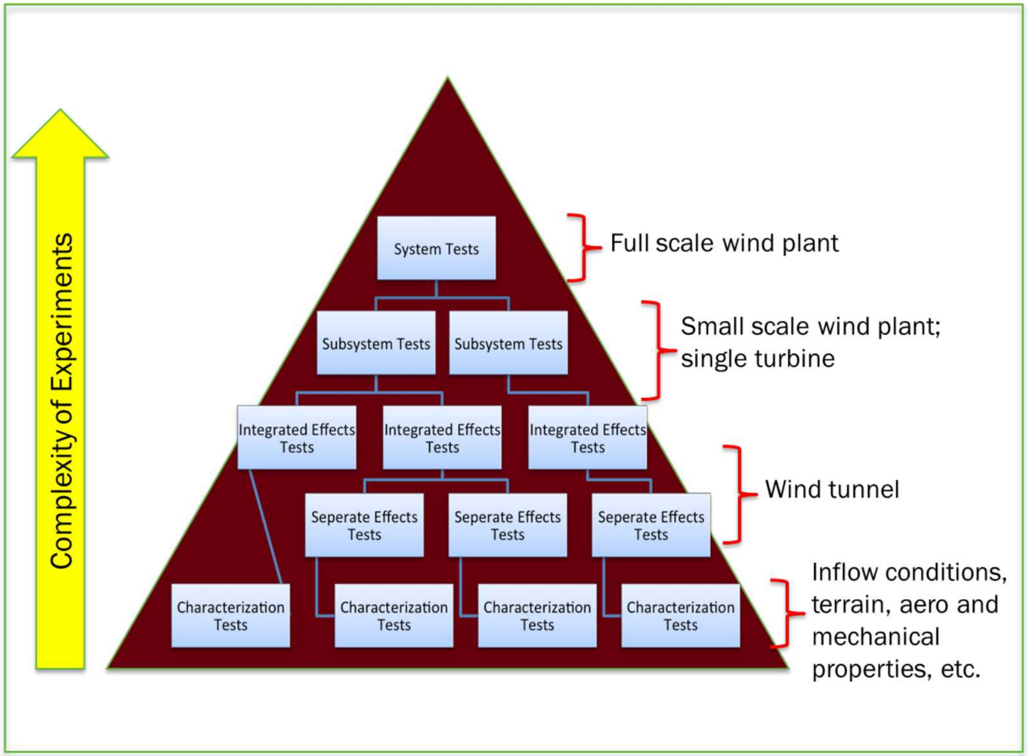


V&V Framework

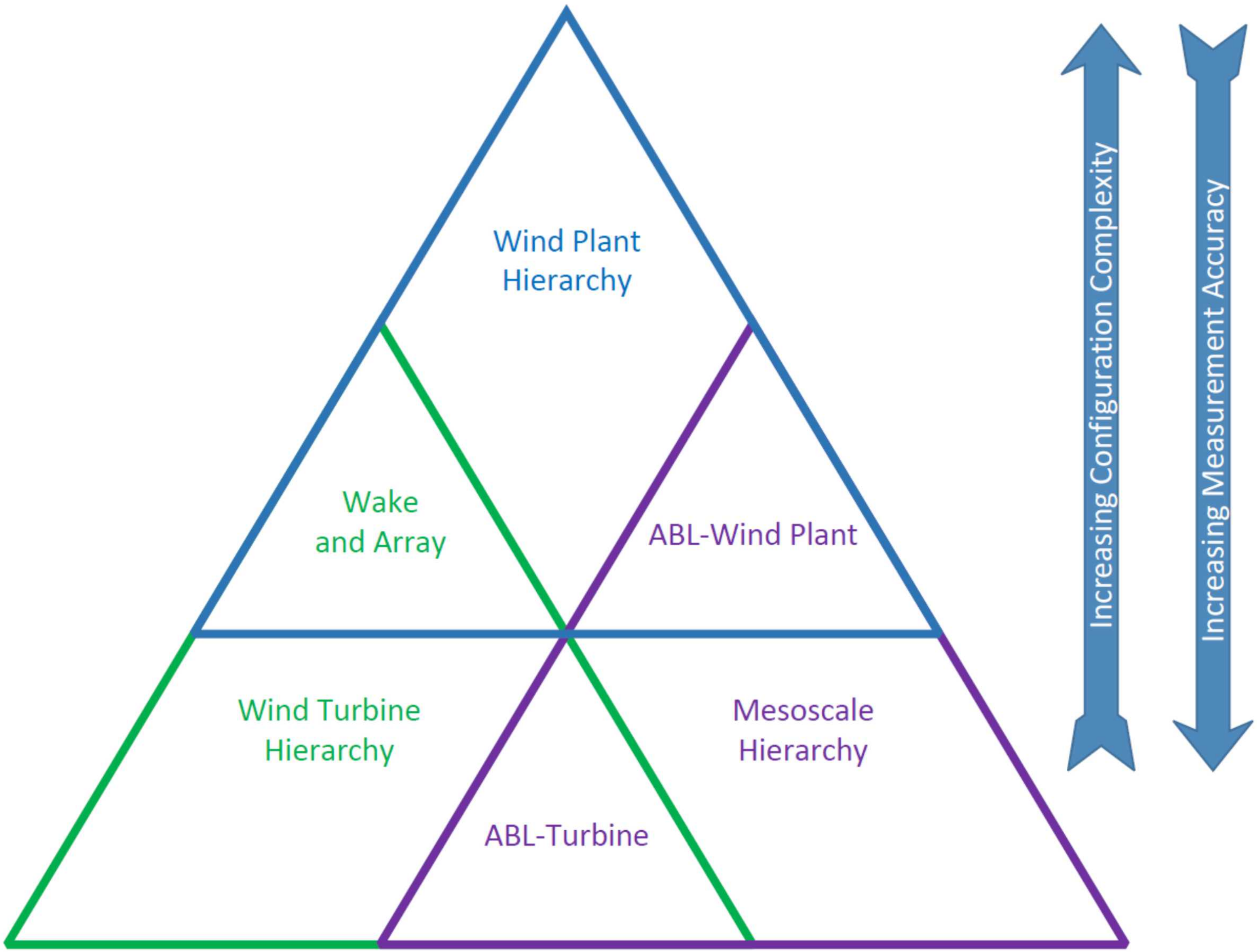
PIRT: Phenomenon Identification Ranking Table

Phenomenon	Importance at Application Level	Model Adequacy Physics	Code	Val
Inflow Turbulence/Wake Interaction				
Wind direction (shear/veer/assymetry)	H	L	M	M
Turbulence characteristics (intensity, spectra, coherence, stability)	H	L	M	M
Coherent turblence 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

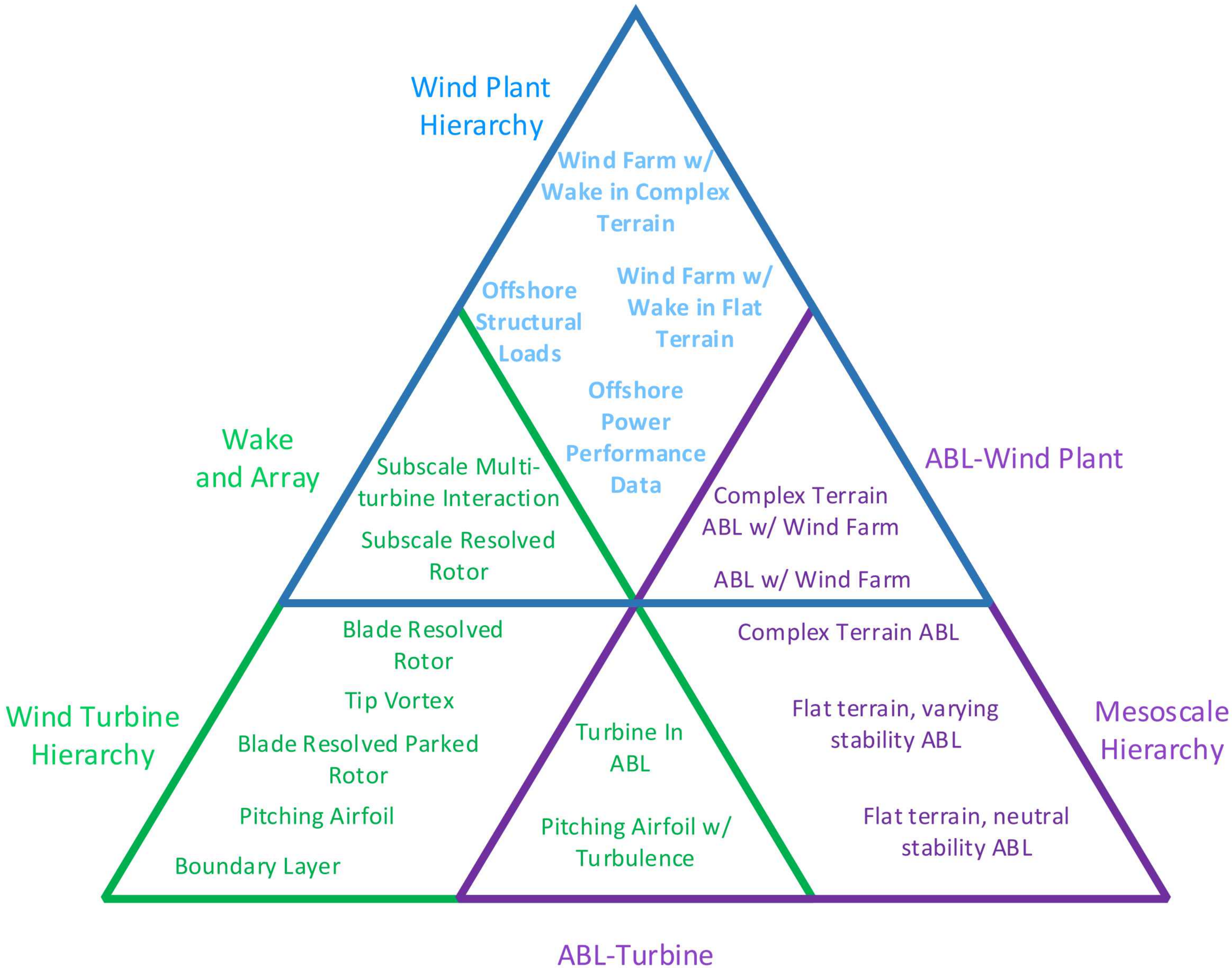
Validation Hierarchy



Wind Plant Validation Hierarchy



Wind Plant Validation Hierarchy



V&V/UQ Program Area Organization

Three main task areas:

1. **Verification, Validation, and Uncertainty Quantification Coordination across A2e**
   - Coordination of validation activities
   - Outreach and support for application of UQ methods
   - Common V&V/UQ methodology and terminology
2. **Uncertainty Quantification Method Development**
   - New UQ methods necessary for wind applications, based on gaps in task area 1
   - Customization of existing methods for the wind application space
3. **Validation and Uncertainty Quantification Application**
   - Test and example problems for UQ methods
   - Validation applications bridging across A2e areas

A2e Validation Coordination Working Group

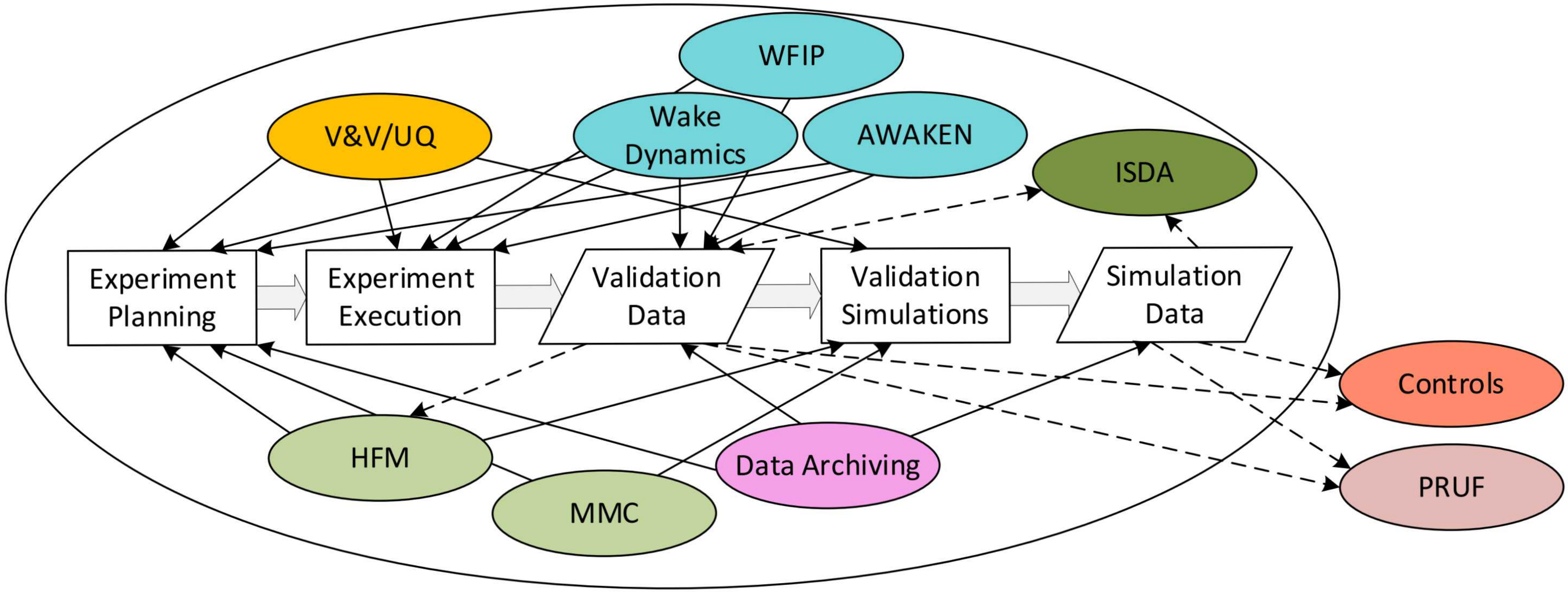
A2e Area	Validation Leads
A2e Validation Coordinator	Jonathan Naughton (UWYO)
VV&UQ PI	David Maniaci (SNL)
DAP	Matthew Macduff, Chitra Sivaraman (PNNL)
Offshore	Amy Robertson (NREL)
ISDA-Systems	Garrett Barter (NREL)
ISDA-Offshore	Amy Robertson, Jason Jonkman (NREL)
HFM	Mike Sprague(NREL), Shreyas Ananthan(NREL), 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

V&V/UQ Cross-project Collaboration

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

Validation-Directed Program



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

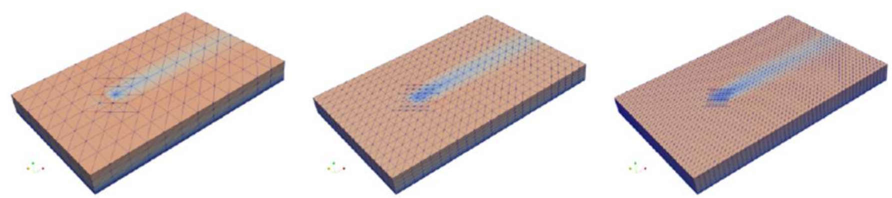
A **limited number of high-fidelity simulations** is fused with a much **larger set of low-fidelity simulations** to **reduce the overall computational burden** while keeping the overall error under control (*i.e.* deterministic + stochastic)

Objectives of the study:

1 Assess uncertainty's impact on wind plant performance via **efficient forward UQ**

2 Characterize uncertainty via **efficient inverse UQ**

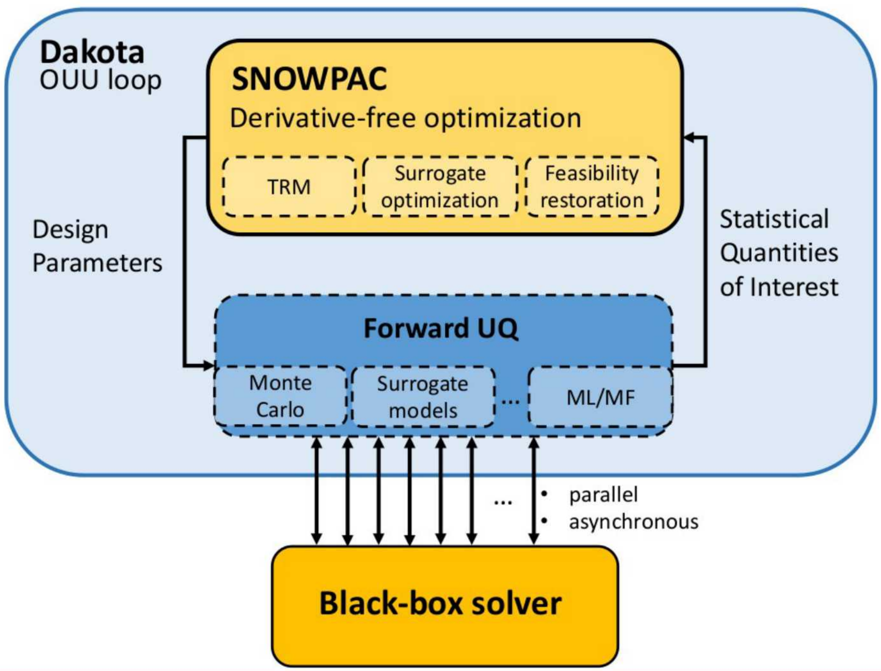
3 Wind plant O**ptimization Under Uncertainty** workflows using multi-fidelity sampling strategies



(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

: Multilevel model hierarchy unrefined grid discretization and simulation cost.

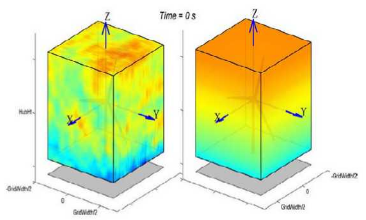


Multilevel Uncertainty Quantification

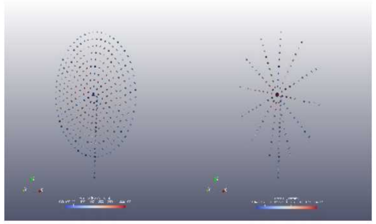
Research Scope: Evaluation of multilevel-multifidelity (MLMF) UQ methods to improve predictive capabilities of computational models for wind farm applications

Motivation

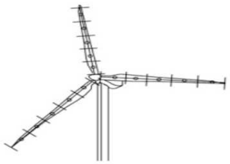
- UQ is necessary for predictive wind simulations but requires high numbers of simulations
- High-fidelity simulations are needed for accurate predictions but have high computational costs
- By leveraging lower-resolution, lower-fidelity simulations with high-fidelity simulations, multilevel-multifidelity-UQ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



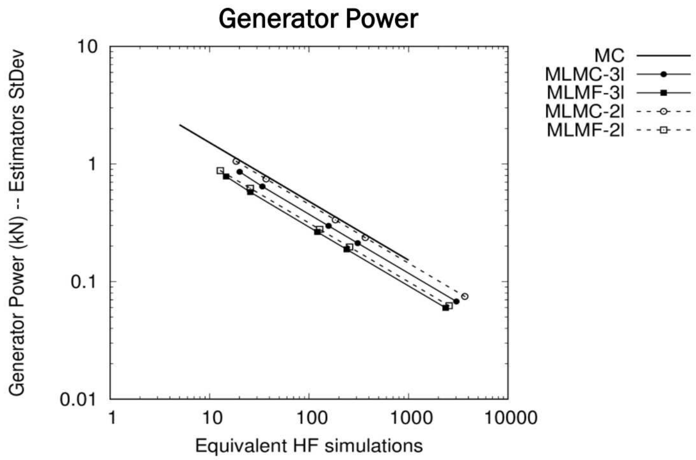
Low-fidelity model: TurbSim+OpenFAST



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



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

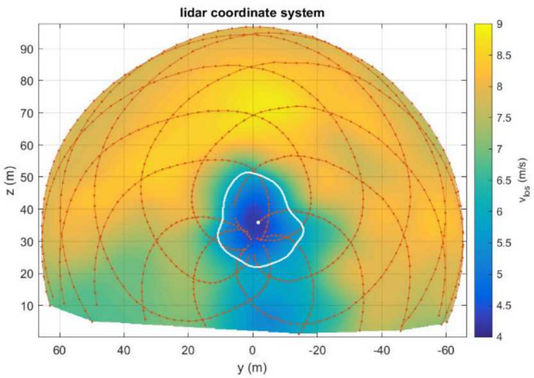


Conclusions

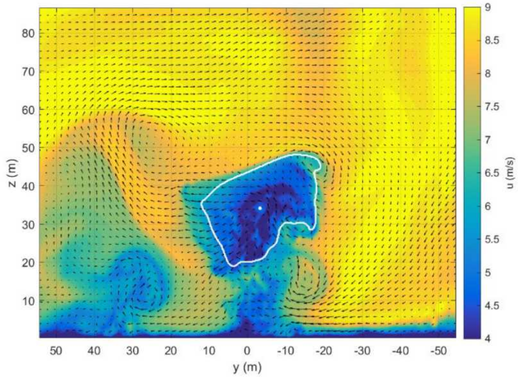
- Consistent performance trends from different sampling methods
  - MLMF methods showed higher efficiency compared to standard methods
- Significant improvements have been made with Nalu-Wind simulation capabilities and integration with UQ workflow

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.



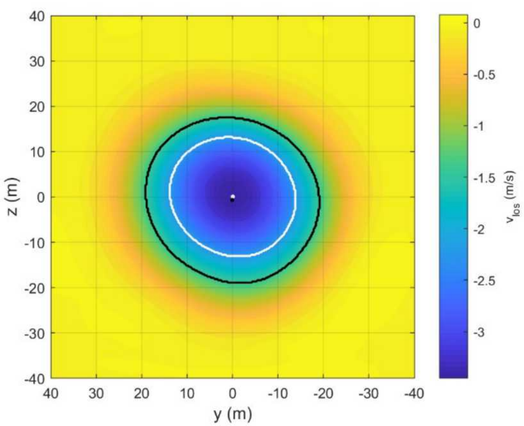
Sample of the wake date from the measured Spinnerlidar at the SWiFT facility.



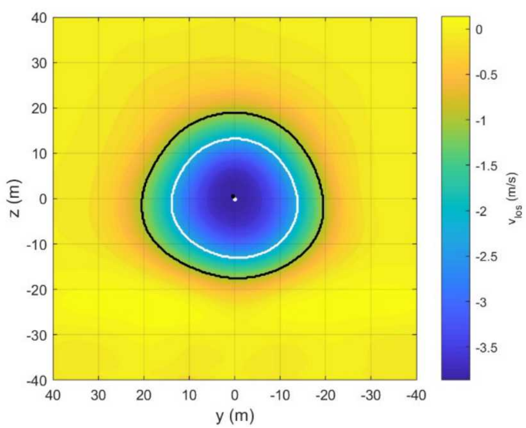
Nalu-Wind Simulated wake data 5D downwind.

	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

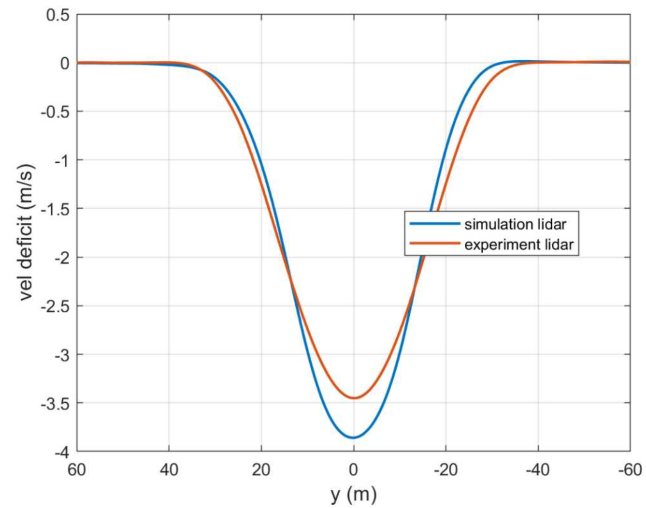
Upstream turbine (WTGa1) results of the 10-minute averages of the mean out-of-plane (OOP) blade-root bending moment for the three blades, relative flapwise DEM, and generator power for yaw = 0° case.



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.



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

V&V/UQ – SNL Publications

Publications at AIAA SciTech 2020 joint session between Wind Energy and Non Deterministic Approaches :

- "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. January
- "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. January
- "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. January
- "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. January

Publications planned for Torque 2020:

- *"Inference of uncertainty in line-of-sight velocity returns from wind turbine nacelle-mounted lidar,"* Ken Brown
- *"Towards validation of LES near-wake physics for scaled wind turbines in a neutral atmosphere,"* Ken Brown
- *"Momentum deficit from wake measurements,"* Tommy Herges
- *"LES of the Northeastern US coastal marine boundary layer,"* Lawrence Cheung
- *"Uncertainty of leading edge erosion performance impacts,"* David Maniaci

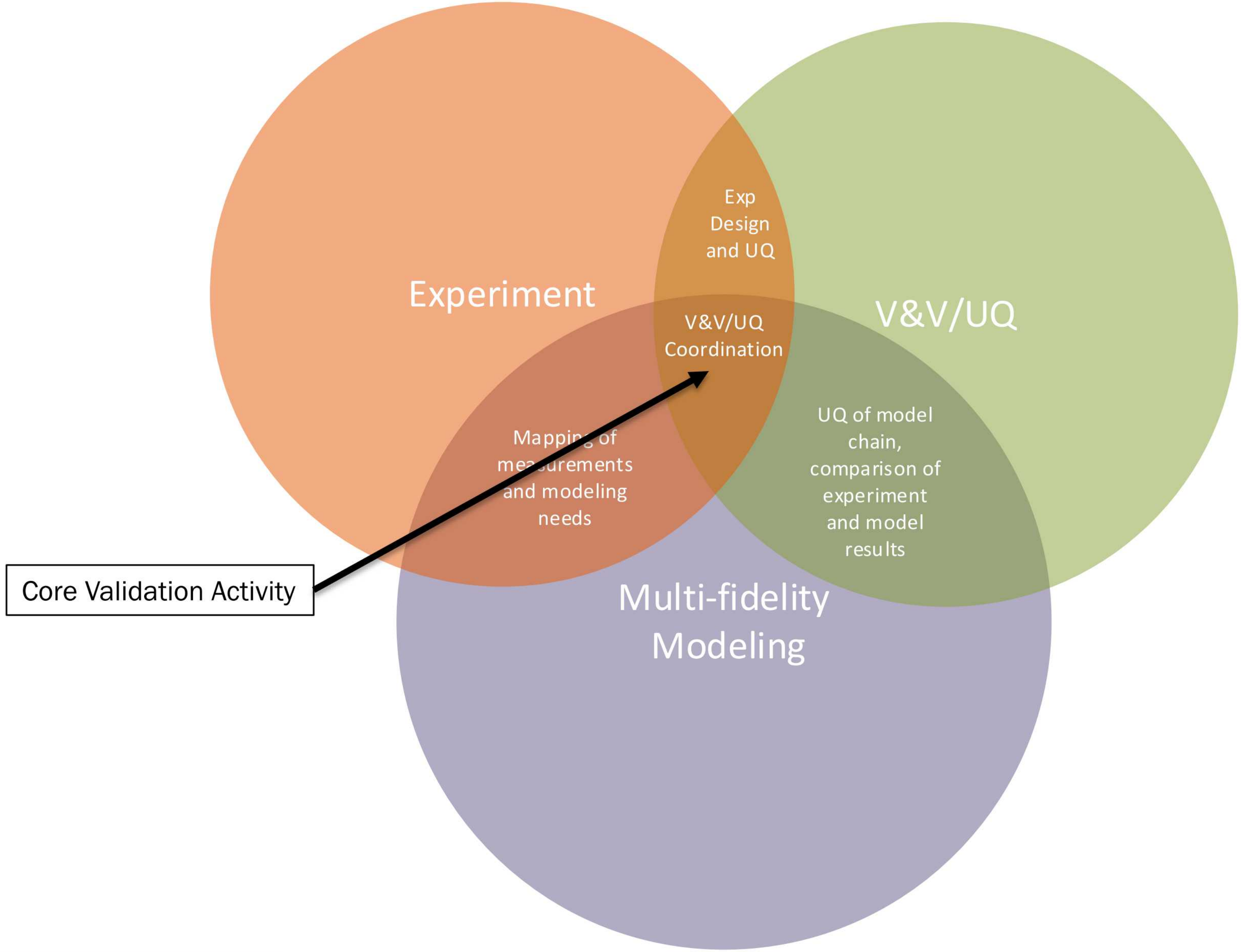
Journal publications planned for FY20:

- *ASME paper on Nalu-Wind wake V&V*
- *Paper on MLMF-UQ methods for wind*

V&V/UQ Multi-year Goals

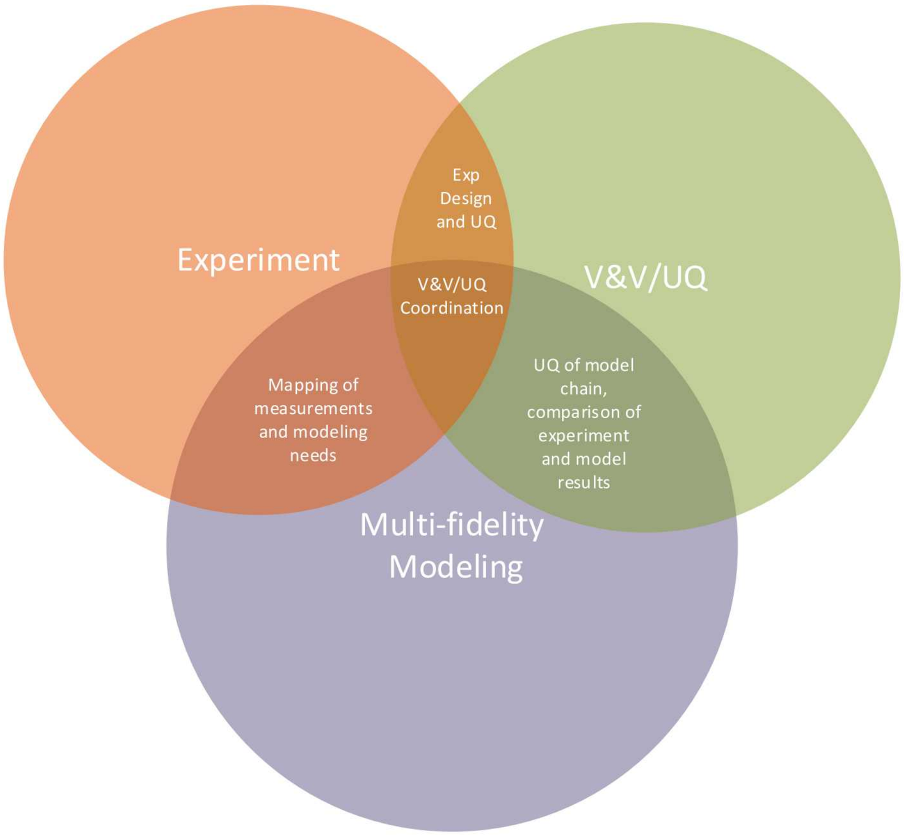
- **Enable simulation and design of optimized wind plants**
- **Execute model validation campaigns across A2e to:**
  1. Improve the research community's physical understanding of wake dynamics and turbine interaction
  2. Quantify model prediction uncertainty of wake flow dynamics and turbine interaction as a function of inflow conditions
- **Develop and demonstrate uncertainty quantification tools and processes for wind energy applications**
- **Engage with the public to disseminate results and progress on a regular basis**

Project Organization



V&V/UQ Vision

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

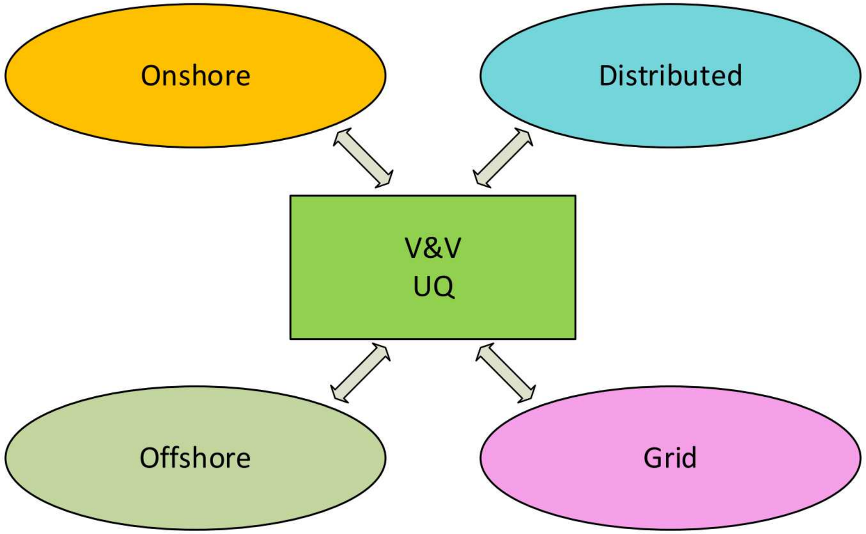


-Wake induced loads
-Rotor influence on wakes
-Wake/inflow/grid interaction

1. Validation Coordination
   - Validation roadmap and meetings
   - Support applying methods to offshore and grid research
   - Present V&V Framework and support its application in wind
2. UQ Development
   - MLMF-UQ for dynamic models
   - Experiment as reference rather than CFD
   - OED: Optimal experimental design
   - Expand MLMF-UQ application for optimization
3. Validation and UQ Application
   - Expand UQ applications
   - Advanced line/disk V&V+UQ (*onshore/offshore*)
   - Wake induced loads via MLMF, DEL (*onshore/offshore/grid*)
   - Power performance: support JWF (*onshore/offshore*)
   - Leading edge erosion: (*offshore/onshore*)
   - Sensitivity analysis to support experiment design

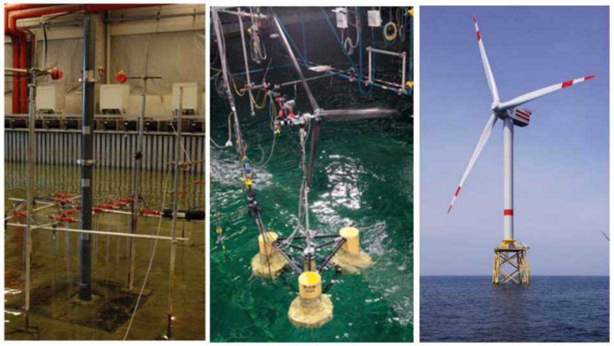
Role for V&V Moving Forward

- **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

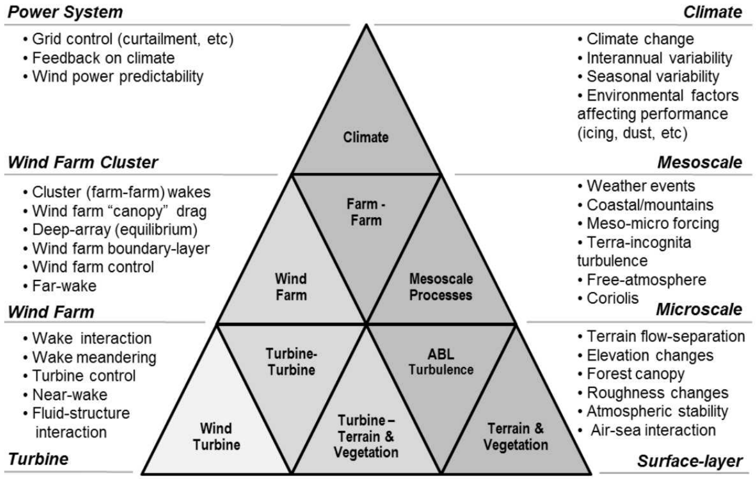


Adoption of V&V in Wind Energy Community

IEA Wind Task 30: Offshore Code Comparison Collaborative



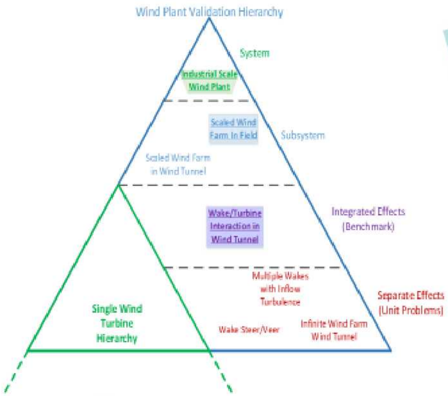
IEA Wind Task 31: Wakebench

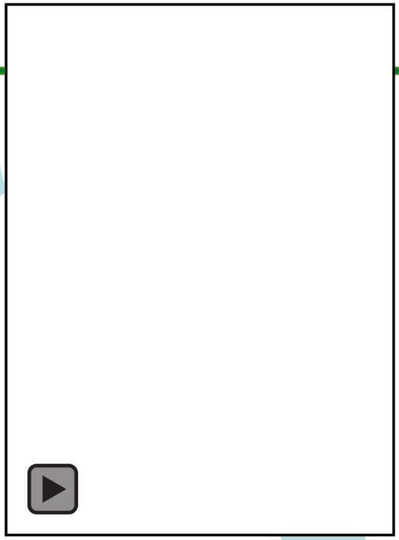


IEA Wind Task 36: Forecasting for Wind Energy

IEC Joint Working Forum on V&V

Thank you





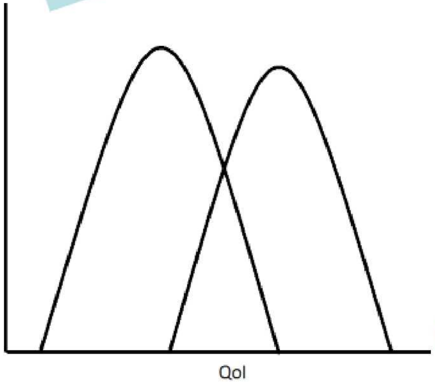
Virtuous Cycle

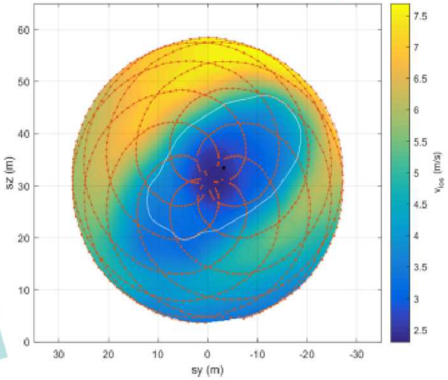
Validation

Model Development

Experimentation

Uncertainty Quantification





Primary Stakeholders

- **A2e Research Areas:** HFM, Wake Dynamics, ISDA, Control Science, MMC, WFIP, and offshore wind
- **International Community:** IEA Tasks 29, 31, 36
- **DOE Wind Energy Technologies Office**: improve understanding of wind plant complex flow, exploration of novel wind technology advances and validation of lower-fidelity models
- **Manufacturers**: improved energy capture and reliability of wind turbines through technology development and environment definition
- **Developers**: design optimized wind plants, quantify and reduce uncertainties in energy estimates
- **Owners/Operators**: maximize energy capture and reliability of existing farms, improved day-ahead and hourly forecasting

Application Use Cases

- **Predict**
  - Wind plant power performance and loads
  - Power production of a wind plant in at terrain, with blade-root loads
  - Diurnal flow field in complex terrain (pre-wind plant installation)
  - Loads and wakes of a next-generation turbine (qualification)
  - Forensics analyses with data assimilation to understand extreme or unusual load events
- **Discover**
  - Dominant phenomena governing wake evolution
  - New modeling approaches for wind energy
- **Innovate**
  - Explore the design space of next generation innovations to improve turbine and plant performance
  - Optimize new technology prior to demonstration testing

PPEM (Prioritized Phenomenon Experiment Mapping)

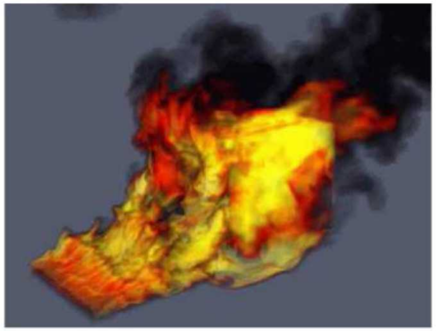
Physics Present/Physics Measured

- Entirely
- Mostly
- Somewhat
- Limited
- Missing

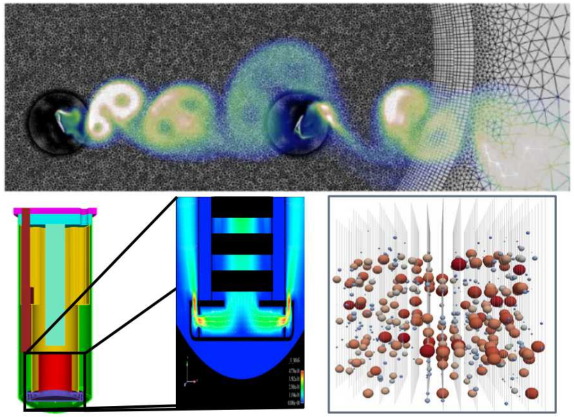
	Blade Load Distribution Effects	Tip & Root Vortex Evolution	Vortex Sheet Evolution	Blade Generated Turbulence	Root Flow Acceleration	Boundary Layer Development	Surface Roughness Effects	Boundary Layer Near LE and TE	Rotational Augmentation	Dynamic Stall	Unsteady Inflow Effects	Blade Flow Control	Icing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

UQ & Optimization: DOE/DOD Mission Deployment

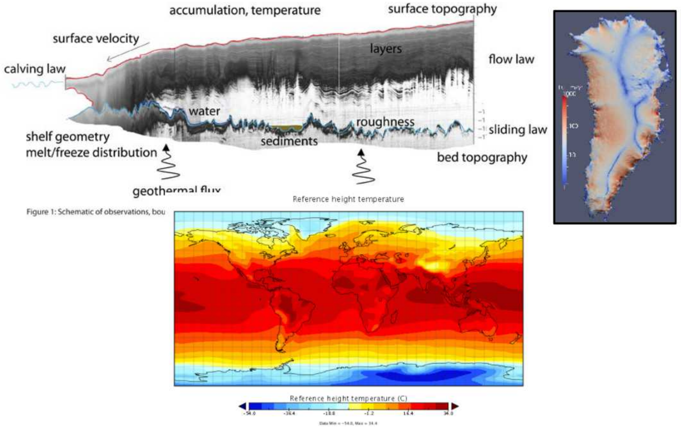
Stewardship (NNSA ASC)
Safety in abnormal environments



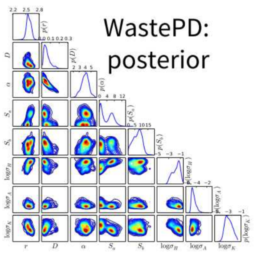
Energy (ASCR, EERE, NE)
Wind turbines, nuclear reactors

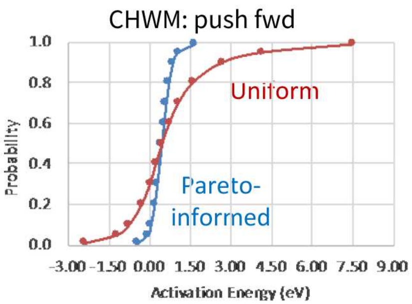


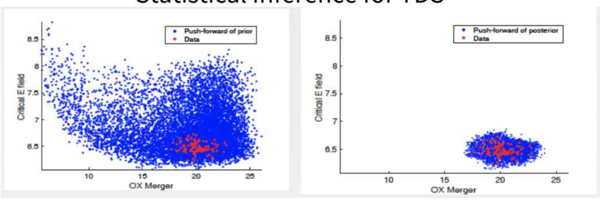
Climate (SciDAC, CSSEF, ACME)
Ice sheets, CISM, CESM, ISSM, CSDMS



Addtnl. Office of Science:
(SciDAC, EFRC)
Comp. Matls: waste forms / hazardous matls (WastePD, CHWM)
MHD: Tokamak disruption (TDS)







Common theme across these applications:

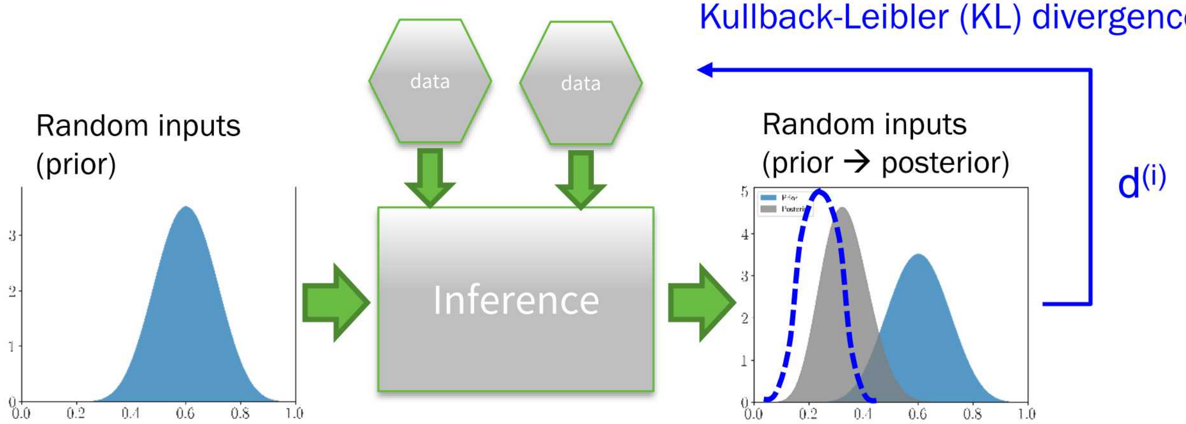
- High-fidelity simulation models: push forward SOA in computational M&S w/ HPC
  → Severe simulation budget **constraints** (e.g., a handful of runs)
  → Significant dimensionality, driven by model complexity (multi-physics, multiscale)

Optimal Experimental Design (OED) Workflow

<u>Characterization of input uncertainties</u> through assimilation of data

- Prior distributions based on *a priori* knowledge
- Observational data (experiments, reference solns.) → infer posterior distributions via Bayes rule
  - Use of data can reduce uncertainty in obj./constraints (priors are constrained)
  - Design using prior uncertainties can be overly conservative
  - Reduced uncertainty of data-informed UQ can produce designs with greater performance

Maximize expected utility from new data $d^{(i)}$, e.g. D-optimal: max information gain / relative entropy / Kullback-Leibler (KL) divergence from $\pi_0 \rightarrow \pi_{post}^{(i)}$



Optimization Under Uncertainty (OUU) Workflow

Roll up of capabilities

- Inference for parametric + model form uncertainties
- Scalable forward propagation
- Leverage surrogates: Active SS, ML-MF, ROM

Achieve desired statistical performance

- Common OUU goals:
  - Robustness → minimize QoI variance
  - Reliability → constrain failure probability