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SAND2019-9722PE

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Overview of the A2e Verification, Validation, and Uncertainty Quantification Program Area

DOE Wind Energy Technologies Office
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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

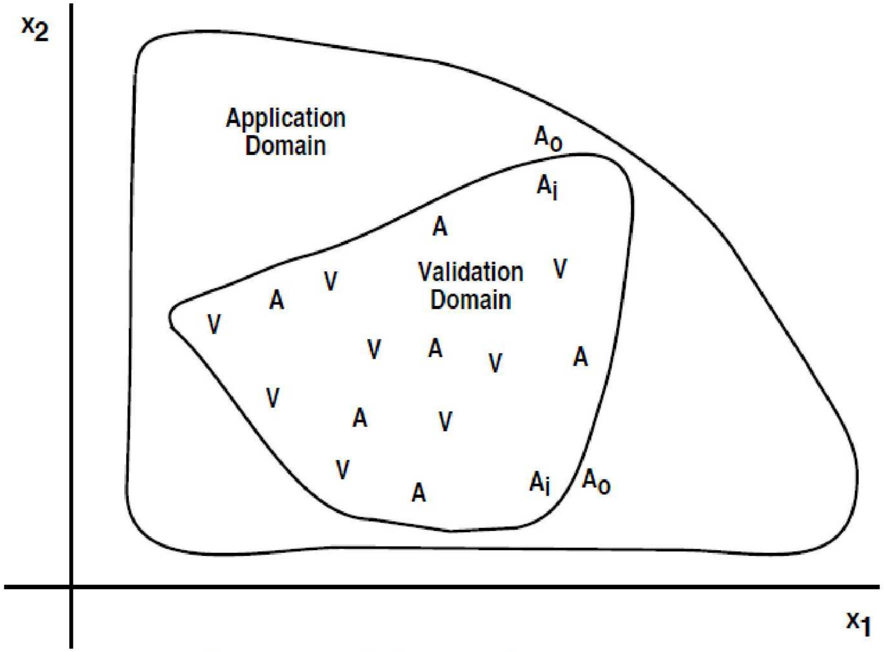
- Approach
  - Development of high fidelity models
  - Collection of existing data and generation of new data through an experimental measurement campaign
  - Strategic linking of these efforts through a Validation Focused Program

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

V&V Overview

- Verification and validation are integral parts of establishing a model's predictive capability for an intended application.
- 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.



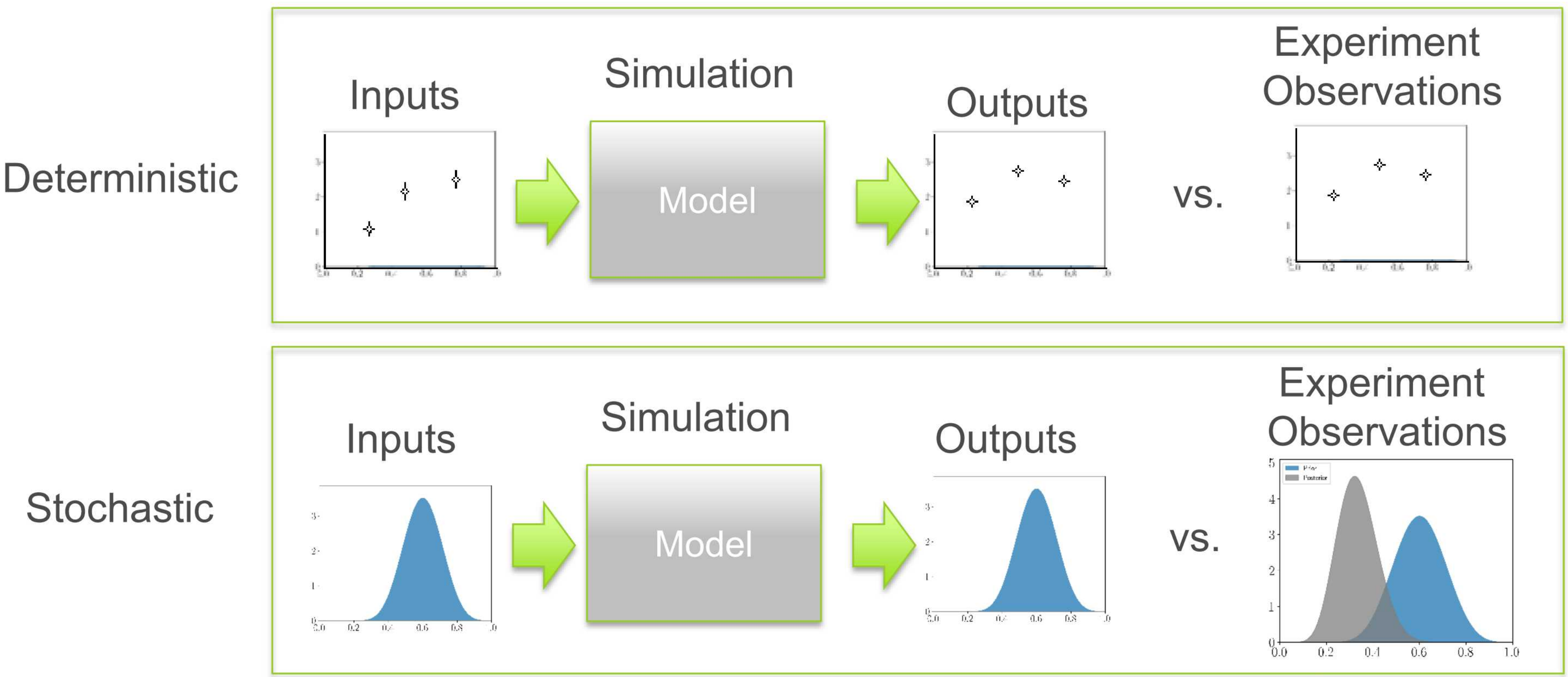
x_1 and x_2 are model parameters

What is V&V?

- **Validation**
  - The process of determining the degree to which a model is an accurate representation of the real world, from the perspective of the intended uses of the model
    - Note that validation is not an acceptance/ rejection/ endorsement of a model
- **Verification**
  - Code verification
    - Software errors or algorithm deficiencies that corrupt simulation results.
  - Solution verification
    - Human procedural errors or numerical solution errors that corrupt the simulation

What is Uncertainty Quantification?

- Methods to codify the assimilation of observational data
  - UQ methods are critical for quantitative model validation focused on enabling predictive numerical simulations in research and advanced design
- The characterization of errors, uncertainties, and model inadequacies
- Forward predictions with confidence for untested/unstable regimes



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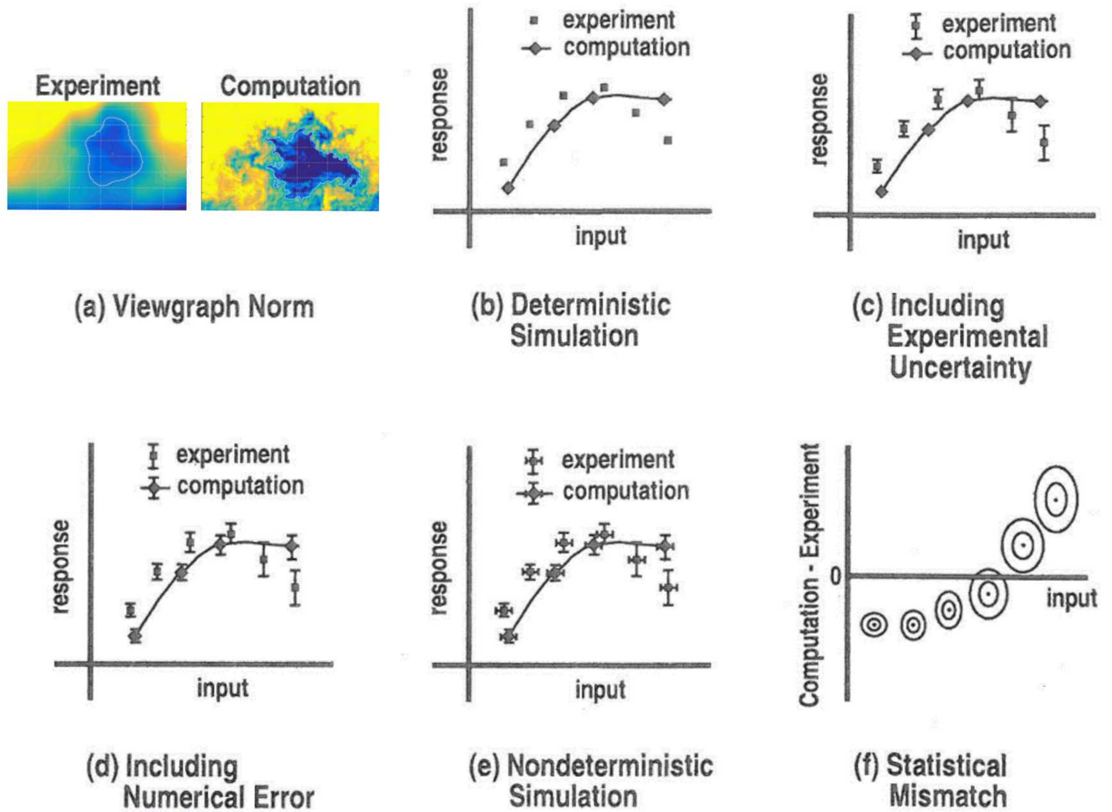
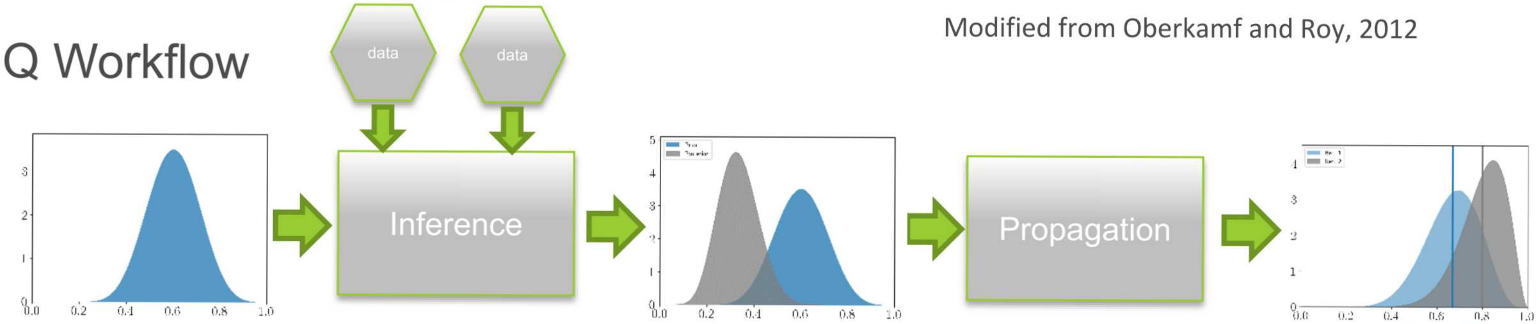
What is Uncertainty Quantification?

Levels of Precision



Modified from Oberkamf and Roy, 2012

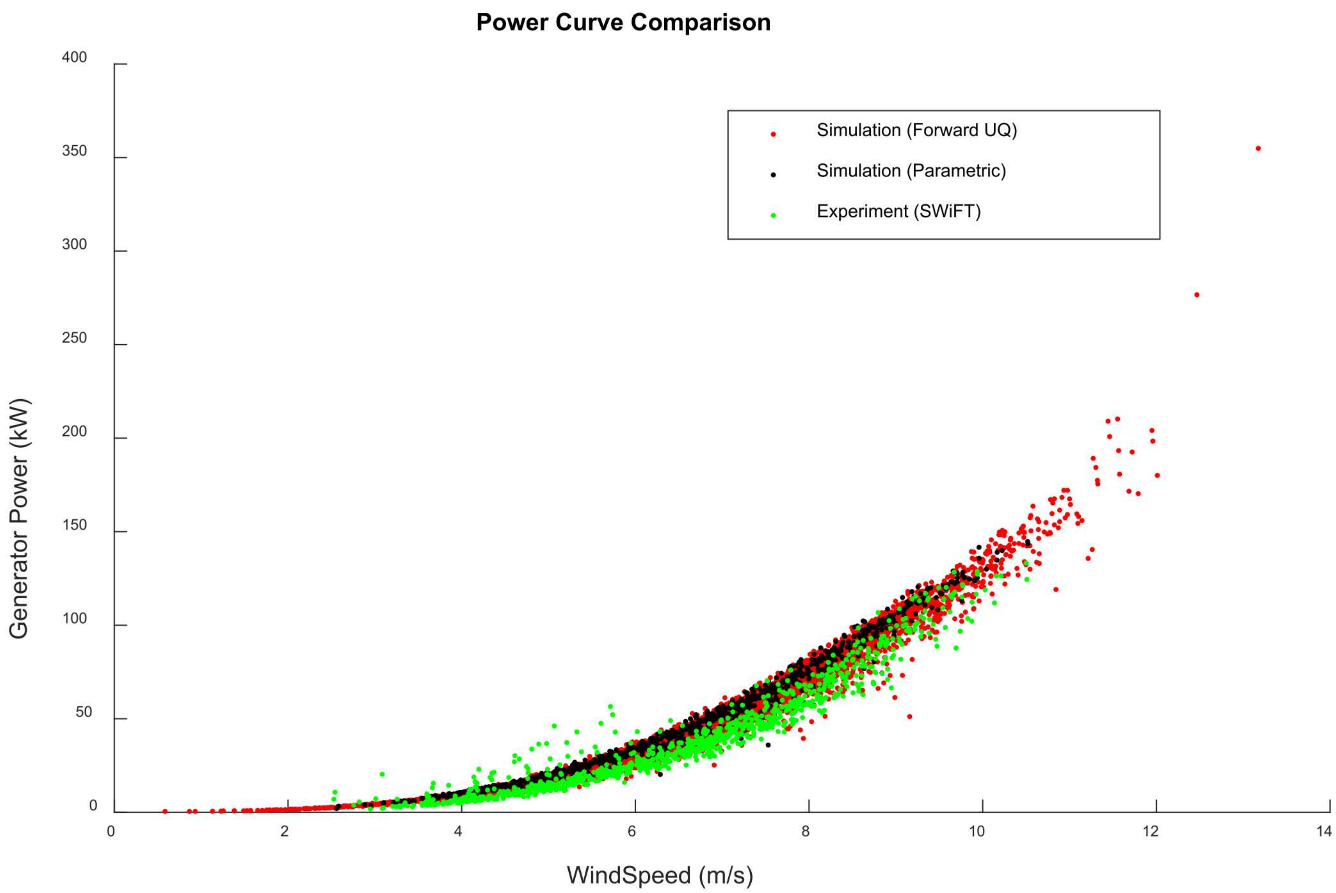
UQ Workflow



Modified from M. Eldred, 2019

Wind Turbine Power Curve Example

- Wind energy is non-deterministic, as wind is naturally stochastic.



A. Hsieh, WESC 2019

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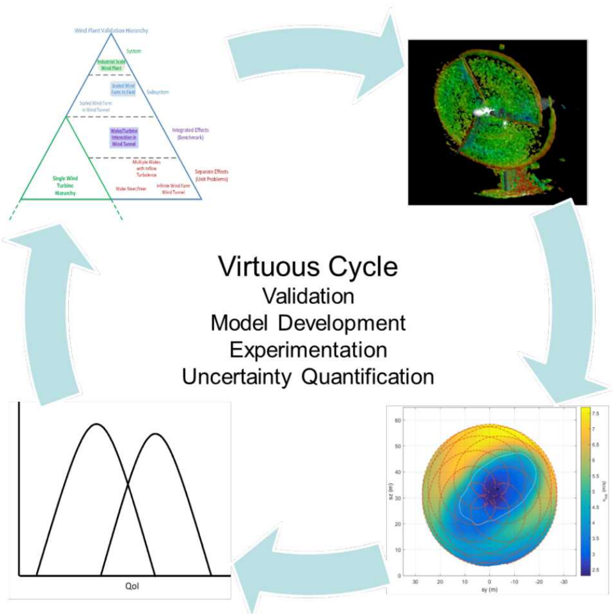
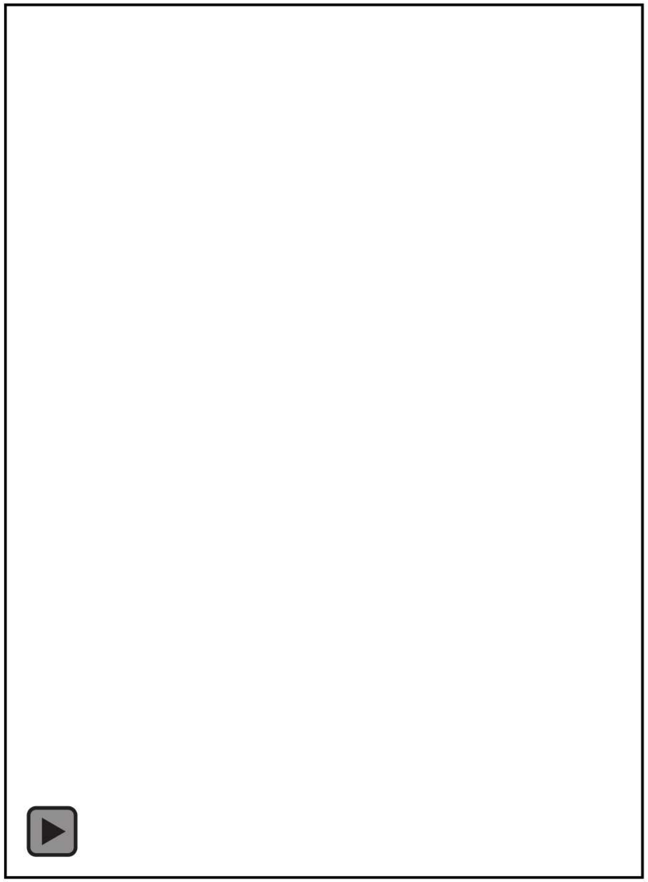
High Fidelity Modeling (HFM) and Verification & Validation (V&V)

- 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, there results are of limited value
- Recently, our ability to simulate wind turbine and wind farm simulations has outstripped our ability to know whether the results are meaningful
- 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

V&V Process Overview

- **V&V Framework**
  - Phenomena Identification and Ranking Table
  - Validation Hierarchy
  - Prioritization
  - Experiment Design, Execution & Analysis
  - Verification of Code
  - Validation Metric Determination
  - Assessment
  - Determination of level of credibility

SANDIA REPORT
SAND2015-7455
Unlimited Release
Printed September 2015

V&V Framework

Richard G. Hills, David C. Maniaci, Jonathan W. Naughton

Prepared by
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Albuquerque, New Mexico 87185 and Livermore, California 94550

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Approved for public release; further dissemination unlimited.

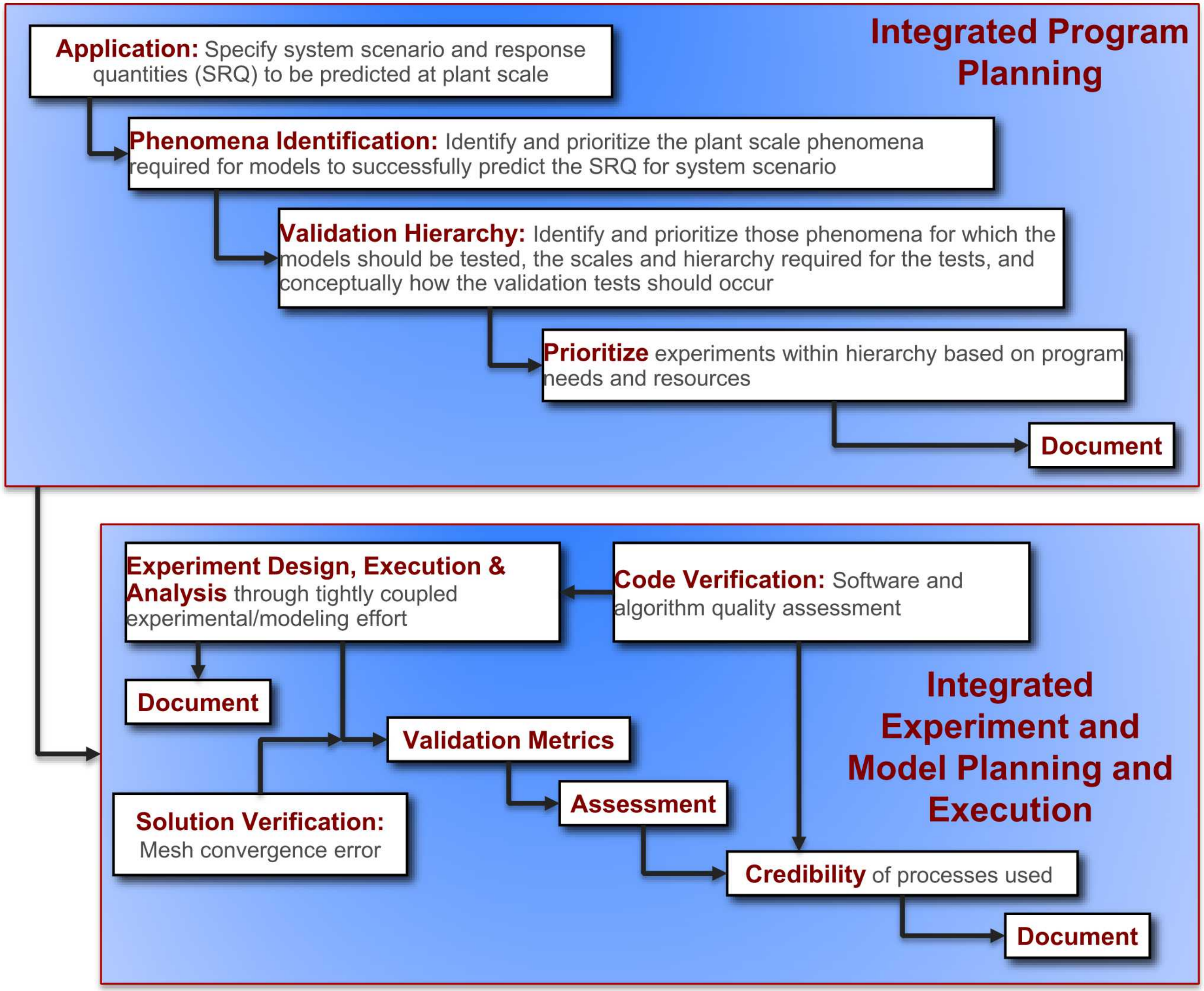
V&V Framework (2015 Hills, Maniaci, Naughton)

Integrated Planning

- Program leaders, modelers, software developers, experimentalists, V&V specialists

Validation Planning

- Domain specific program leaders, modelers, experimentalists, V&V specialists, data acquisition specialists



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

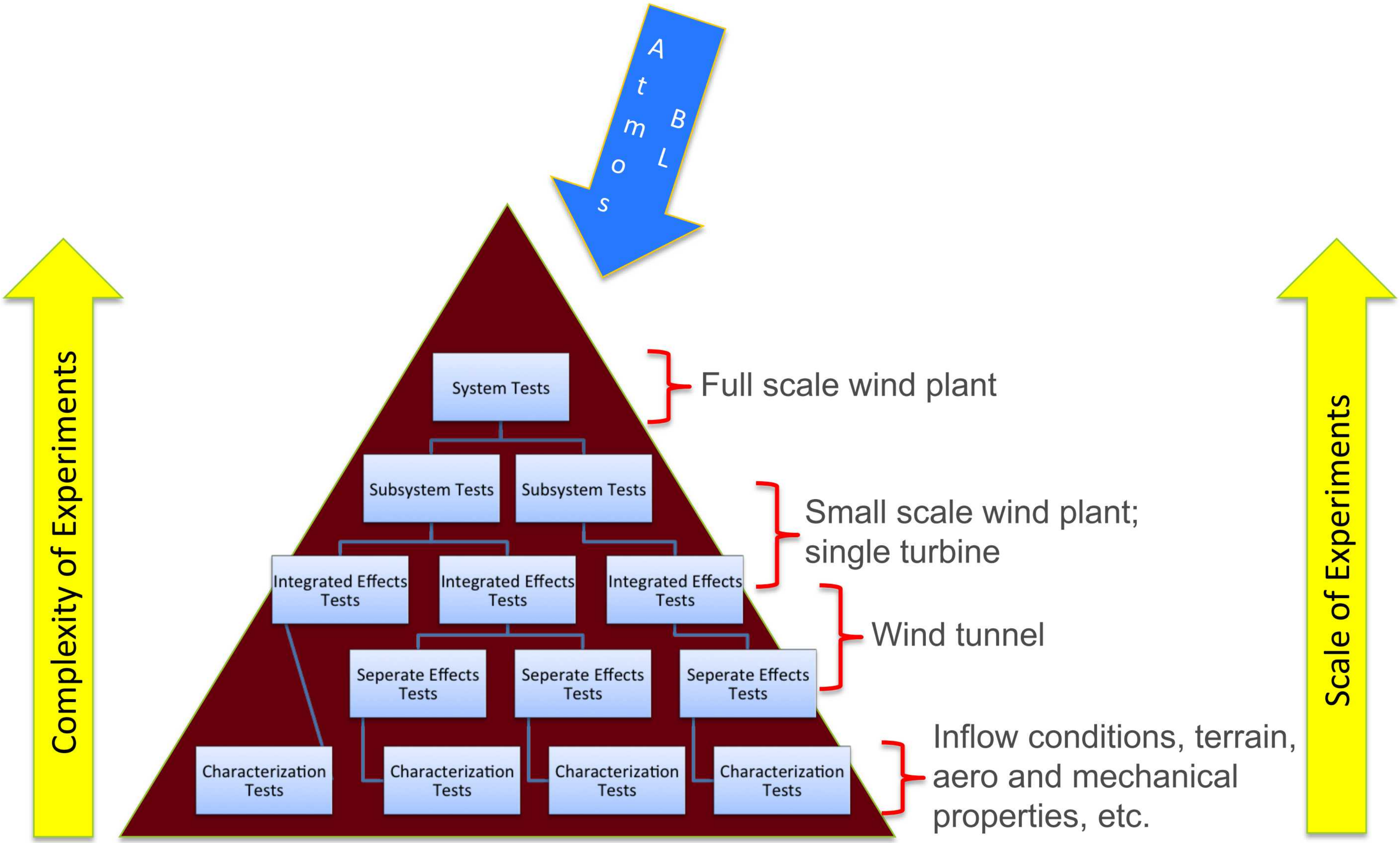
Backbone of Prioritization Process: PIRT

PIRT: Phenomenon Identification Ranking Table

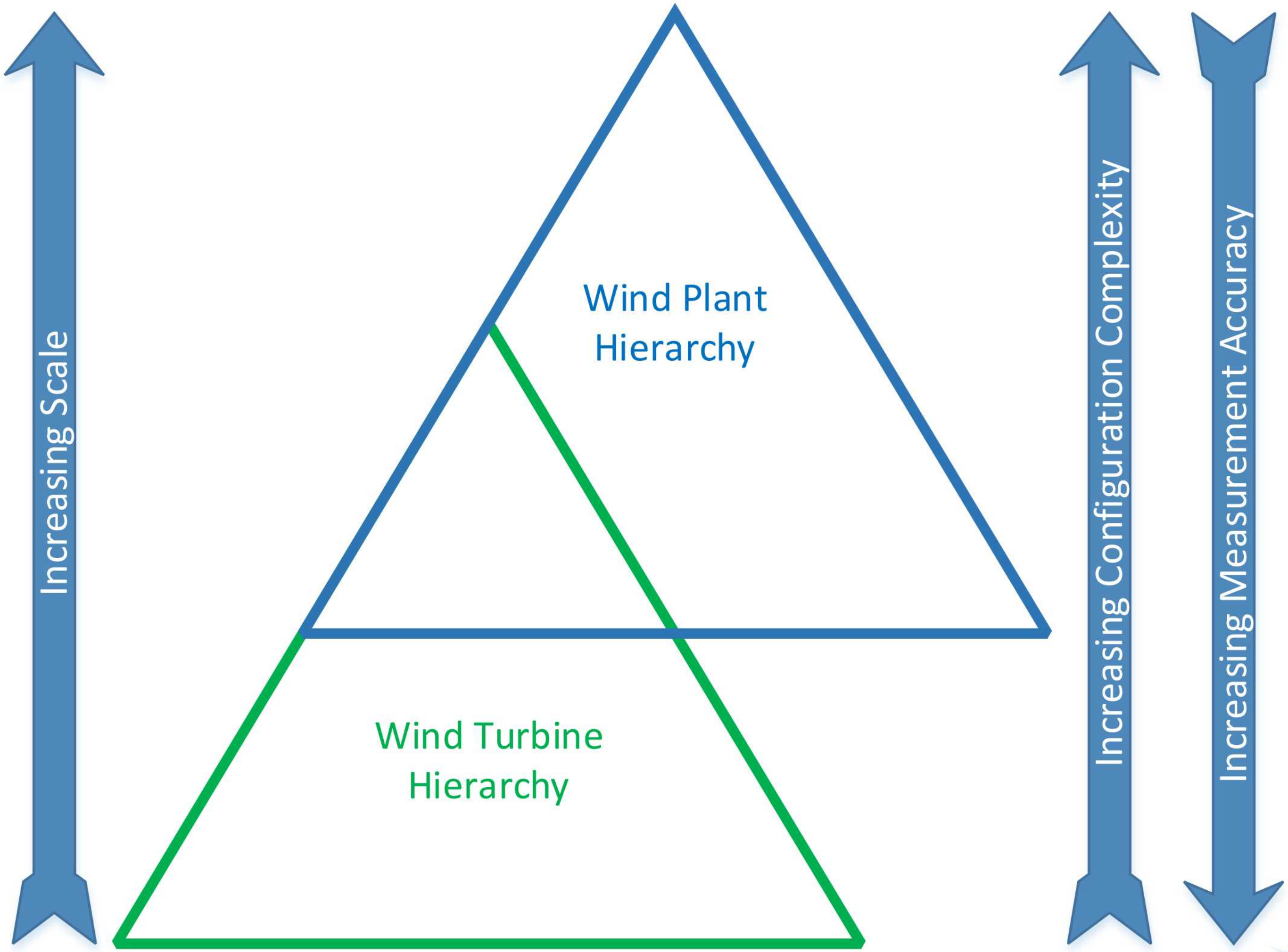
- Consensus based
- Provides gap analysis of ability to model phenomena
  - Physics gaps
  - Numerical gaps
  - Data gaps
  - Validation gaps
- Gap analysis used to prioritize planning, including experimental planning

Phenomenon	Importance at Application Level	Model Adequacy		
		Physics	Code	Val
Turbine scale flow phenomena				
Blade Aero / Wake Generation				
Blade load distribution effects and rotor thrust	H	M	L	L
Tip and root vortex development, and evolution and merging	H	M	L	L
Vortex sheet and rollup (in addition to tip/root vortex)	M	M	M	L
Blade generated turbulence characteristics (energetic scales)	H	L	L	L
Root flow acceleration effect ('hub jet')	Unknown	M	L	L
Boundary layer state on turbine performance (roughness, soiling, bugs, erosion)	H	L	L	L
Boundary layer state (Re)	L	M	L	L
BL details near TE and LE	H	M	L	L
Rotational augmentation	H	L	L	L
Dynamic stall	H	L	L	L
Unsteady inflow effect (turb. intensity, spectra, coherence; veer, shear)	H	L	L	L
Blade flow control	M	L	L	L
Tower/rotor/nacelle wake interactions	H	M	L	L
Icing	L	L	L	L

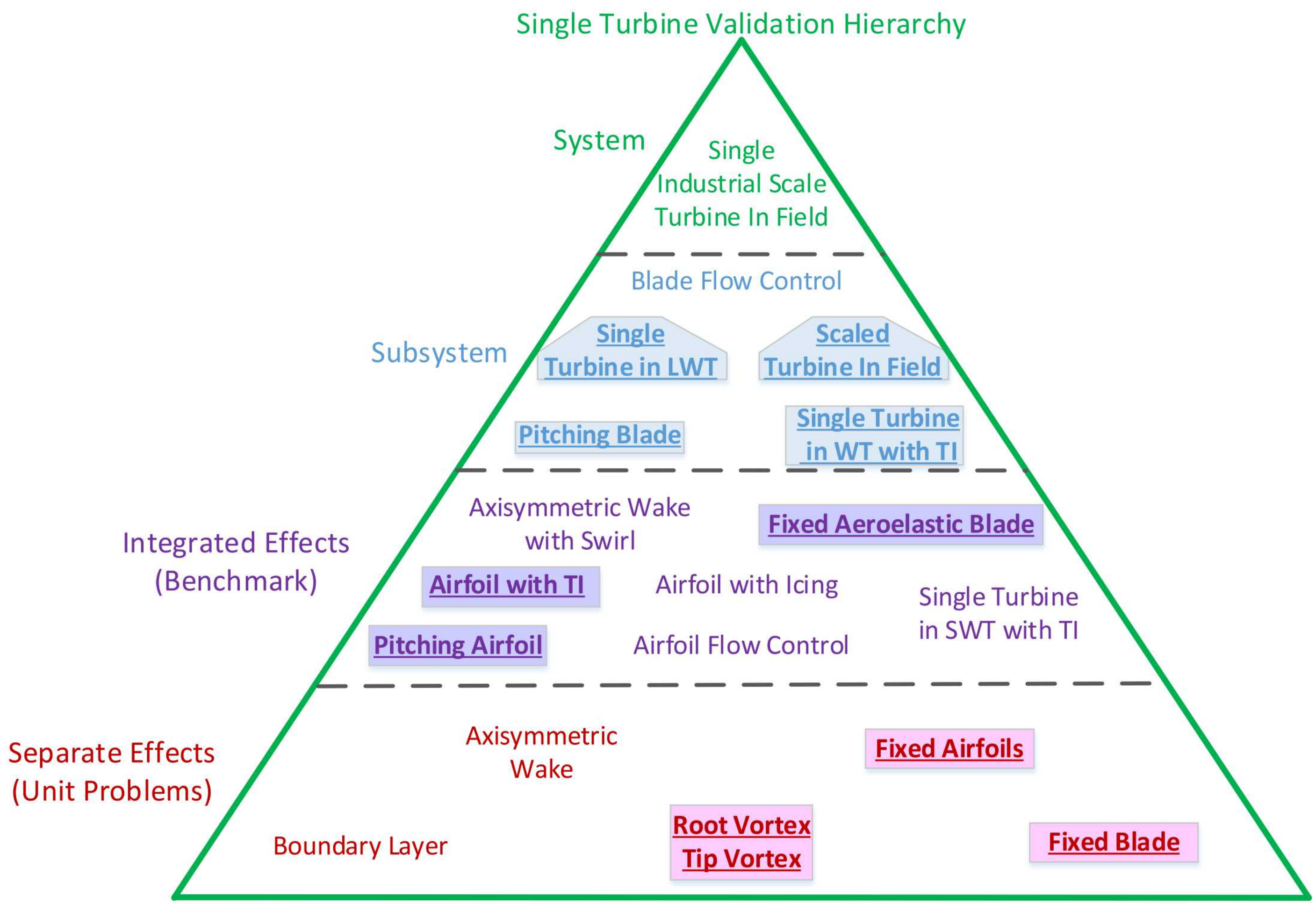
PIRT Leads to the Validation Hierarchy



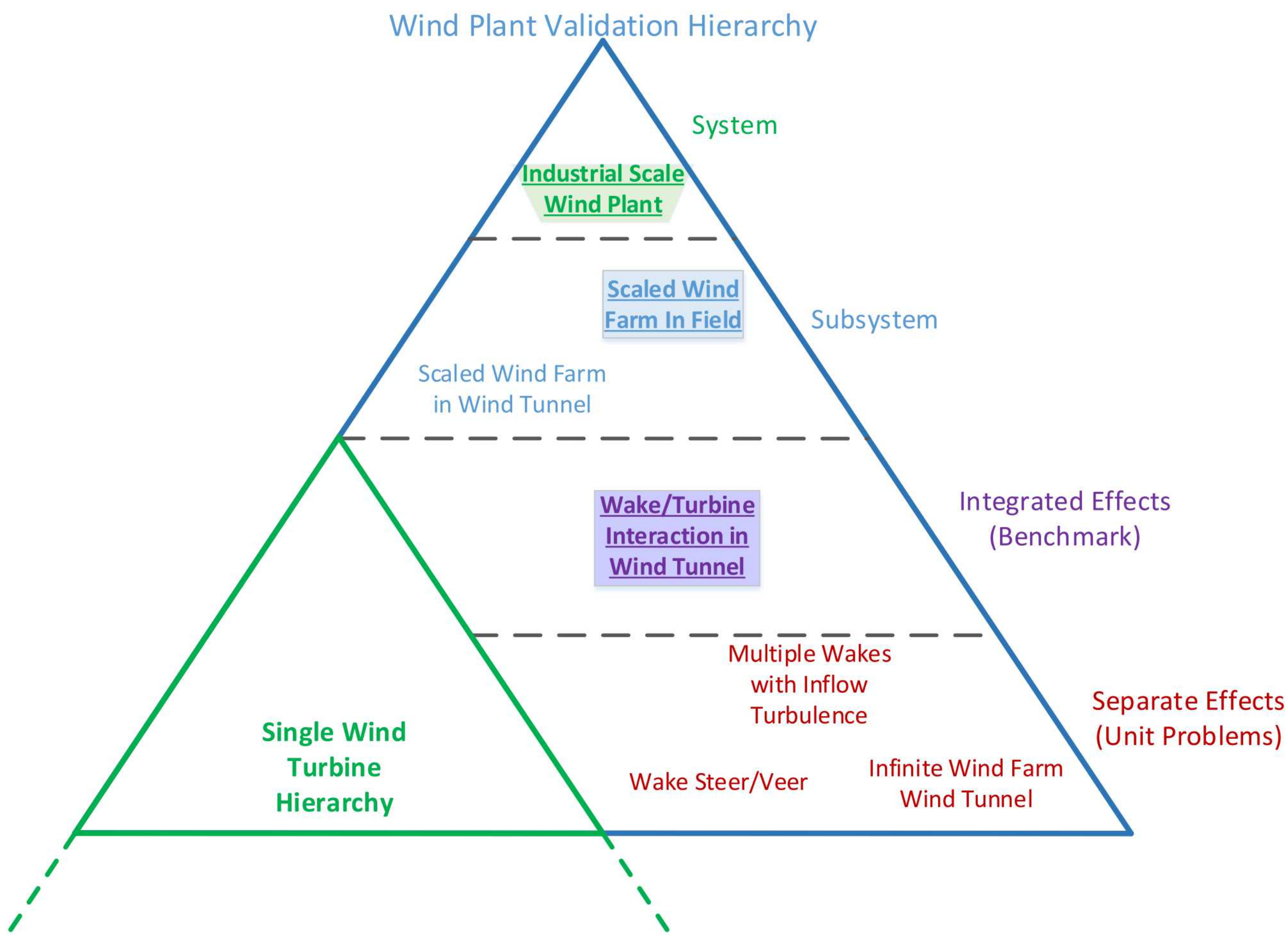
Validation Hierarchy

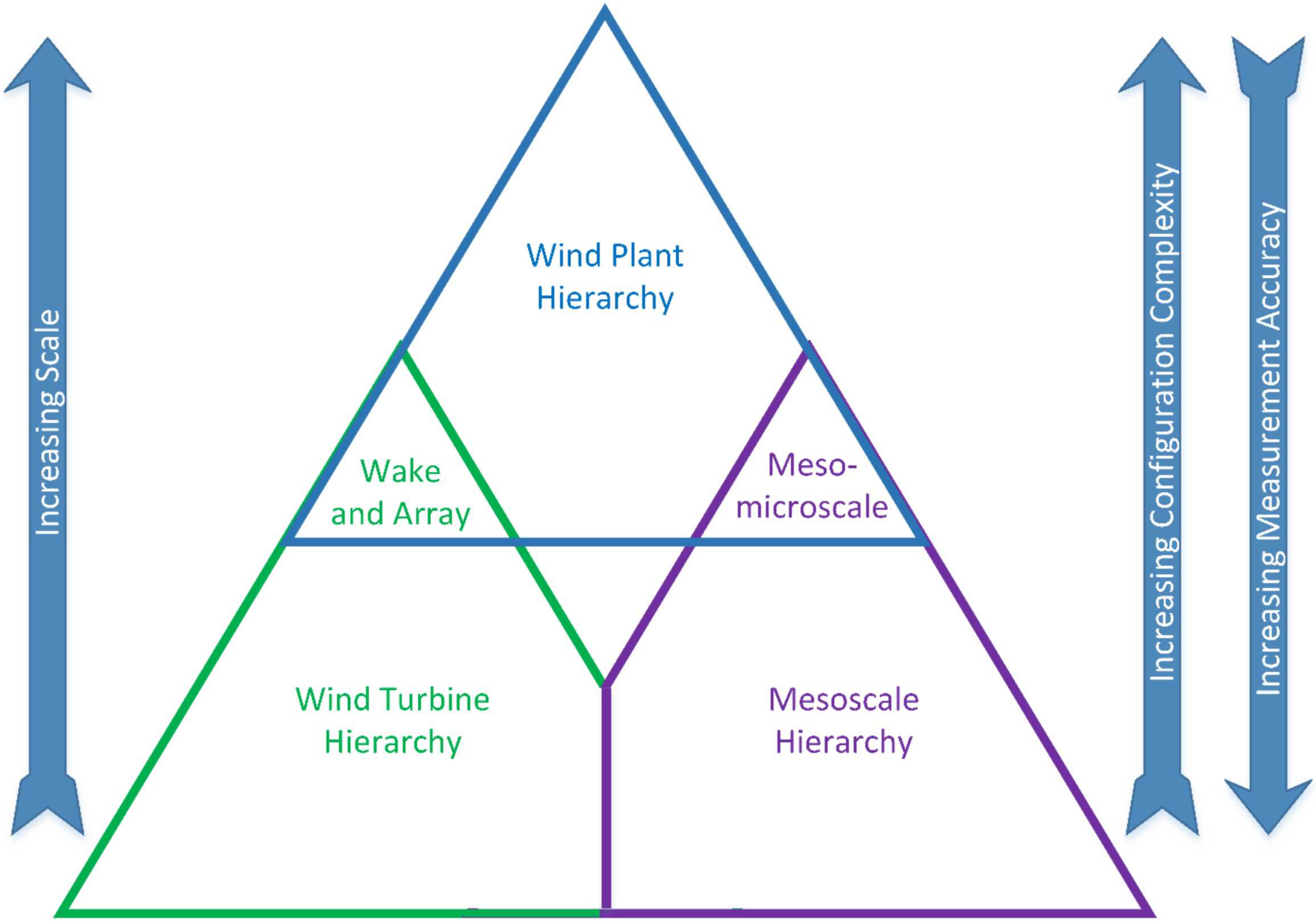


Wind Turbine Validation Hierarchy



Wind Plant Validation Hierarchy




Increasing Scale
Wind Plant
Hierarchy
Wake
and Array
Meso-
microscale
Wind Turbine
Hierarchy
Mesoscale
Hierarchy
Increasing Configuration Complexity
Increasing Measurement Accuracy

PPEM (Prioritized Phenomenon Experiment Mapping)

Wind Plant

Physics Present/Physics Measured

- Entirely
- Mostly
- Somewhat
- Limited
- Missing

	Multi-Turbine Wake Effects				**Inflow Turbulence Wake Interaction**			
	Interaction, Merging, Motion	Steering (Yaw/Tilt Effects)	Wake Dissipation	Wake Impingement (Full/Half/Near)	Wind Direction	Surface Conditions	Turbulence Statistics	Momentum Transport
Industrial Scale Wind Farm in (60 m rotor)								
Physics Present	Entirely	Entirely	Entirely	Entirely	Entirely	Entirely	Entirely	Entirely
Physics Capture by Measurements	Limited	Limited	Limited	Limited	Somewhat	Mostly	Limited	Limited
Scaled Wind Farm in Field (20 m rotor)								
Physics Present	Entirely	Entirely	Mostly	Entirely	Entirely	Mostly	Mostly	Mostly
Physics Capture by Measurements	Somewhat	Somewhat	Limited	Somewhat	Mostly	Mostly	Somewhat	Limited
Scaled Wind Farm in VL WT (2 m rotor)								
Physics Present	Mostly	Mostly	Somewhat	Mostly	Entirely	Somewhat	Somewhat	Somewhat
Physics Capture by Measurements	Mostly	Mostly	Mostly	Entirely	Entirely	Entirely	Mostly	Mostly
Wake/Turbine Interaction in WT (2 m rotor)								
Physics Present	Limited	Mostly	Limited	Mostly	Somewhat	Somewhat	Mostly	Mostly
Physics Capture by Measurements	Mostly	Mostly	Somewhat	Entirely	Entirely	Entirely	Mostly	Mostly

D. Maniaci and J. Naughton, 2017

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VV&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 VV&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

Project Team

SNL

- Mike Eldred
- Gianluca Geraci
- Myra Blaylock
- Brent Houchens
- Brian Naughton
- Thomas Herges
- Chris Kelley
- Robert Knaus
- Phil Sakievich
- David Maniaci
- Alan Hsieh
- Ken Brown

NREL

- Jason Jonkman
- Amy Robertson
- Patrick Moriarty
- Ryan King
- Matt Churchfield
- Mike Sprague
- Garrett Barter

PNNL

- Larry Berg
- Ben Kravitz
- Raj Rai

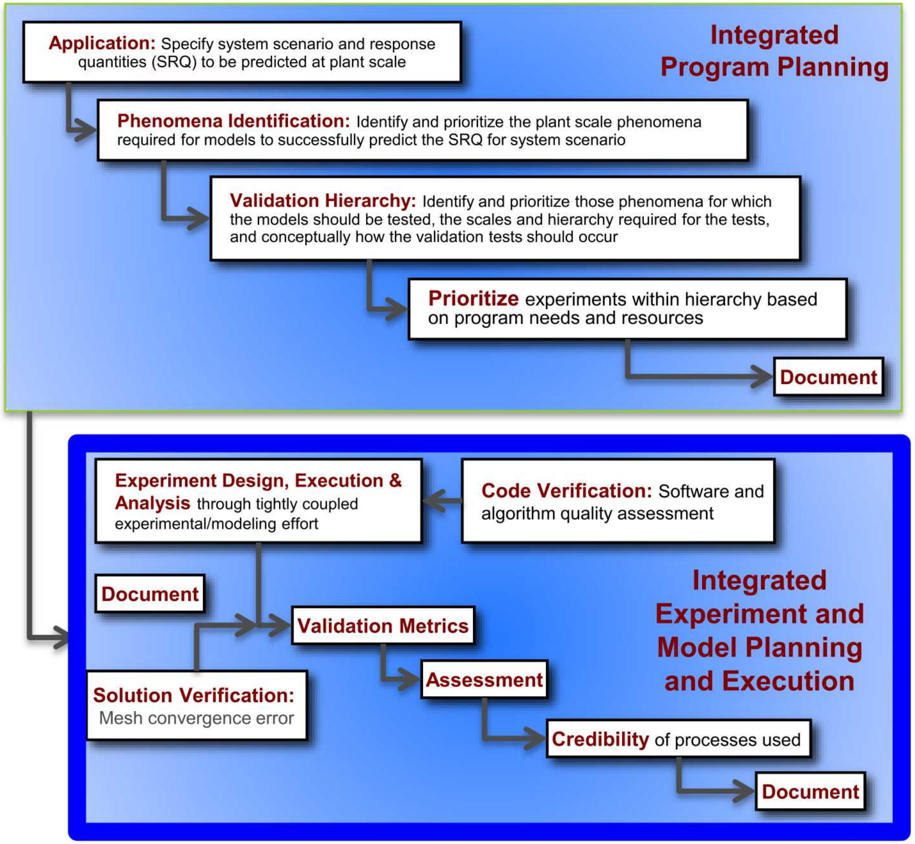
UWYO

- Jonathan Naughton

V&V Coordination (J. Naughton)

Integrated Program Planning transitions to Integrated Experiment and Model Planning and Execution

- Planning Stage Nearly Complete
  - Some work related to specific modeling efforts still needed
- Integrated Experiment and Model Planning and Execution Now Underway
  - Efforts underway
  - Better coordination and interaction among participants needed
    - Streamline process
    - Identification of roles
    - Ensure best outcomes



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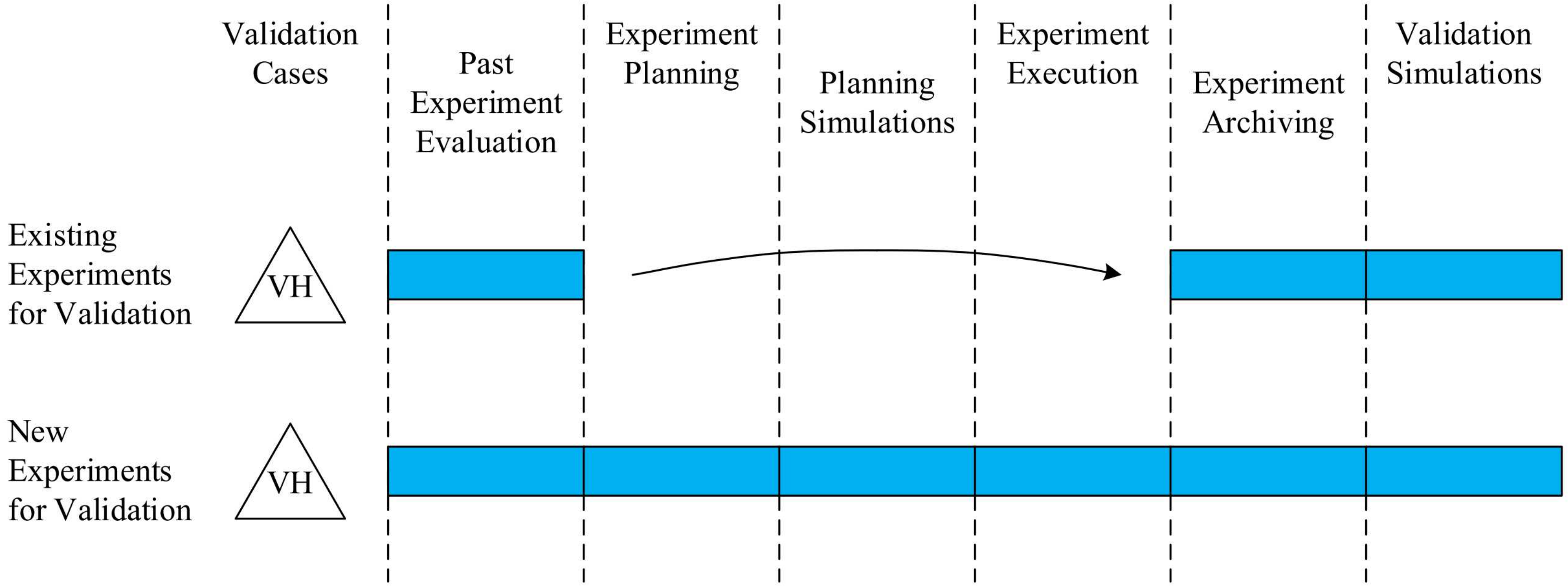
Integrated Experiment and Model Planning and Execution

- The Process

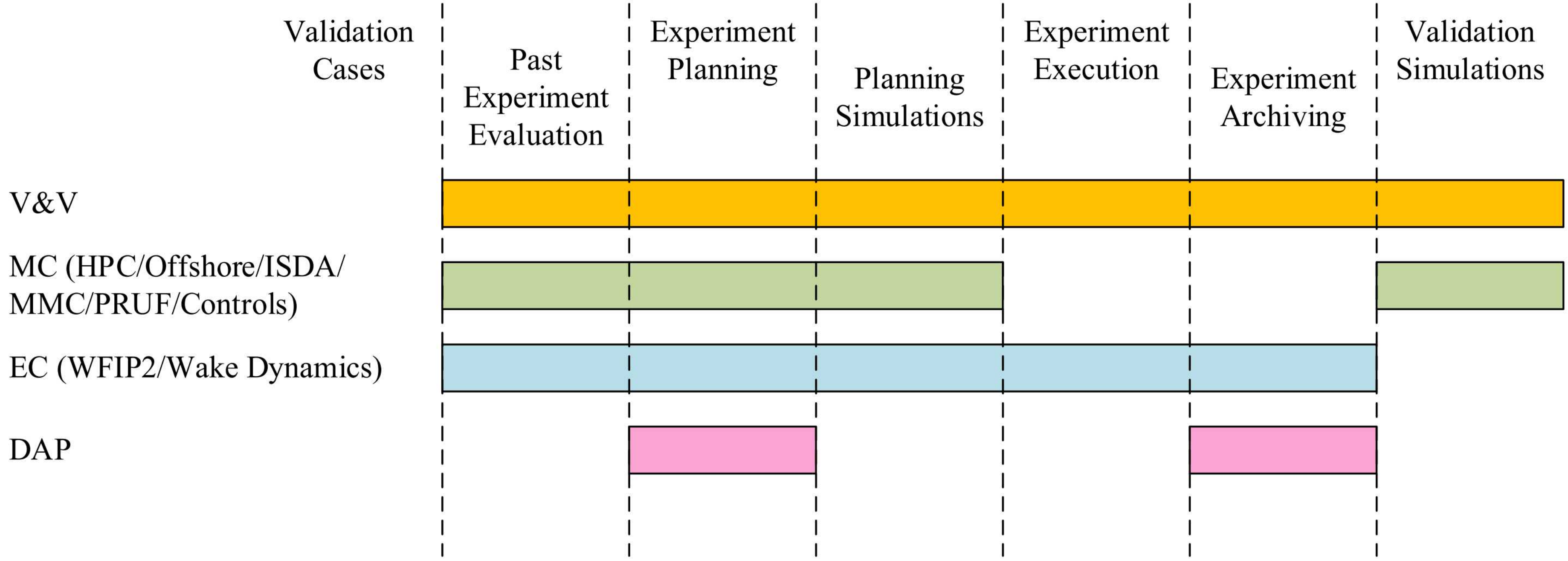


Integrated Experiment and Model Planning and Execution

- **Validation Cases**
  - Identified as part of the IPP
  - Pick specific cases
- **Past Experiment Evaluation**
  - Perform an evaluation of previous experiments that address the validation case of interest
  - Results in two outcomes
    - Past experiment fully meets validation requirements
    - Past experiment partially meets validation requirements
- **Experiment Planning**
  - Establish what are the Validation Metrics
  - Design experiment accordingly
- **Planning Simulations**
  - Part of Experiment Planning
  - Simulations support experiment design
  - Simulations identify issues early on in validation process
- **Experiment Execution**
  - Experiment is performed
  - Data is analyzed
  - Validation Metrics determined
- **Experiment Archiving**
  - Data documented and efficiently stored for use in validation efforts
- **Validation Simulations**
  - Assessment of simulations performed

Integrated Experiment and Model Planning and Execution
Put the "Integration" into IEMPE

- What roles do the different A2E efforts play



Integrated Experiment and Model Planning and Execution Roles

- Validation and Verification Team
  - Overall coordination and guidance for validation activities
  - Most often will not do experiments or simulations themselves
- Modeling Campaign Teams (HPC, Offshore, ISDA, MMC, PRUF, Controls)
  - Aid in identifying needs for validation experiments
  - Support development of validation experiments
  - Perform validation exercises
- Experiment Campaign Teams (Wake Dynamics, WFIP2, Offshore)
  - Aid in identifying needs for validation experiments
  - Develop validation experiments with support from other groups
  - Perform experiments and analyze data
  - Support data archiving effort
- Data Archive Portal Team
  - Support development of validation experiments
  - Lead data archiving effort

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-MV	Jason Jonkman (NREL)
HFM	Mike Sprague(NREL), Shreyas Ananthan(NREL), Paul Crozier (SNL)
Wake Dynamics	Pat Moriarty (NREL), Brian Naughton (SNL)
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**

Ongoing V&V Coordination Work

- **Coordinating Efforts within A2e**
  - Have met with nearly all groups with validation interest over the last 4 months
- **Documenting and Disseminating V&V Materials**
  - IPP Document Published
  - Interacting with Wind Community
    - IEA Tasks 29, 30, 31
    - Wind Energy Science Conference
- **Finalizing Validation Experiment Evaluation**
  - Applying to various previous experiments and ensuring all relevant issues addressed
- **Validation Roadmap**
  - Collecting input to develop roadmap(s)
- **Developing a short-term experiment as demonstration for V&V process**
  - Working with several possibilities suggested by A2e tasks
    - OC6 experiments
    - Unsteady aerodynamics experiments
    - Aero-elastic experiments
  - One or more may be chosen for demonstration purposes
  - Considering what methods to engage community
    - Workshops
- **Stakeholder Meetings**

V&V: Communication and Documentation

1. **IEA Task 31, Wakebench.** Working toward a collaborative validation process.
   1. WAKEBENCH Best Practice Guidelines for Wind Farm Flow Models First Edition (2015)
   2. WAKEBENCH Model Evaluation Protocol for Wind Farm Flow Models First Edition (2015)

2. **V&V Framework** (September 2015): the development and execution of coordinated modeling and experiential programs to assess the predictive capability of computational models of complex systems through focused, well structured, and formal processes.

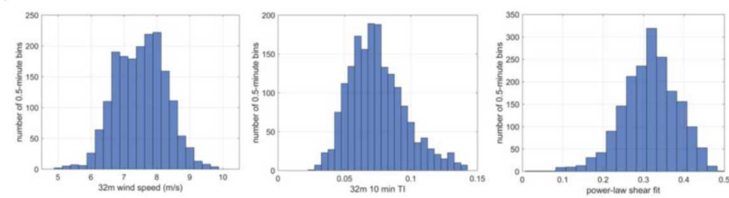
3. **A2e High Fidelity Modeling: Strategic Planning Meetings** (November 2015) : A report on the foundational planning for the A2e High Fidelity Modeling effort for predictive modeling of whole wind plant physics.

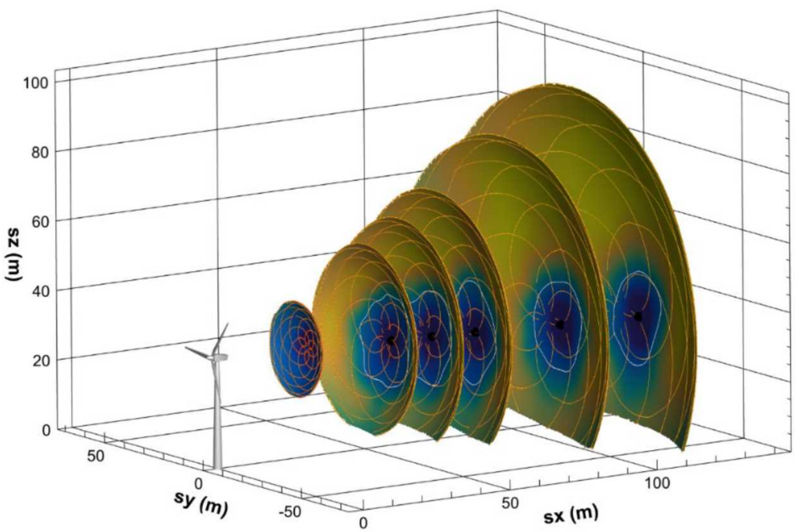
4. **V&V Integrated Program Planning for Wind Plant Performance** (June 2019): This document outlines the integrated program planning (IPP) process and applies it to wind plant performance prediction.

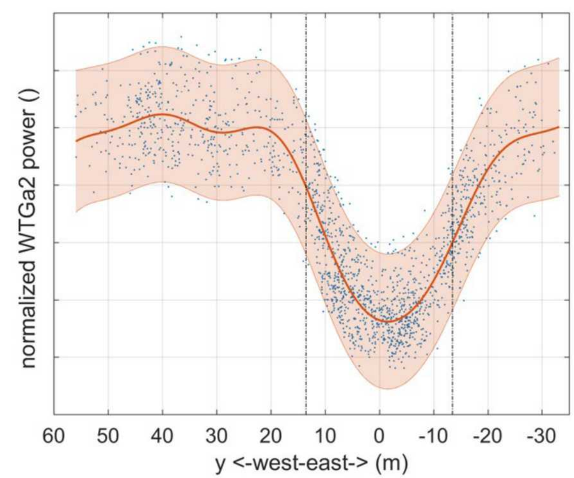
5. **A2e High Fidelity Modeling Validation Roadmap** (August 2019): This document outlines a comprehensive validation program for high fidelity wind plant models.

Uncertainty Quantification and High Fidelity Modeling

- Uncertainty Quantification (UQ) is critical to enable predictive numerical simulation for scientific discoveries and advanced engineering design.
- Complex high fidelity models (HFM) and large numbers of uncertain parameters lead to prohibitive computational cost for conventional UQ methods
- Multifidelity UQ aggregates several low accuracy models with a handful of high fidelity simulations







Uncertainty Quantification Workflow (M. Eldred)

Characterization of input uncertainties 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

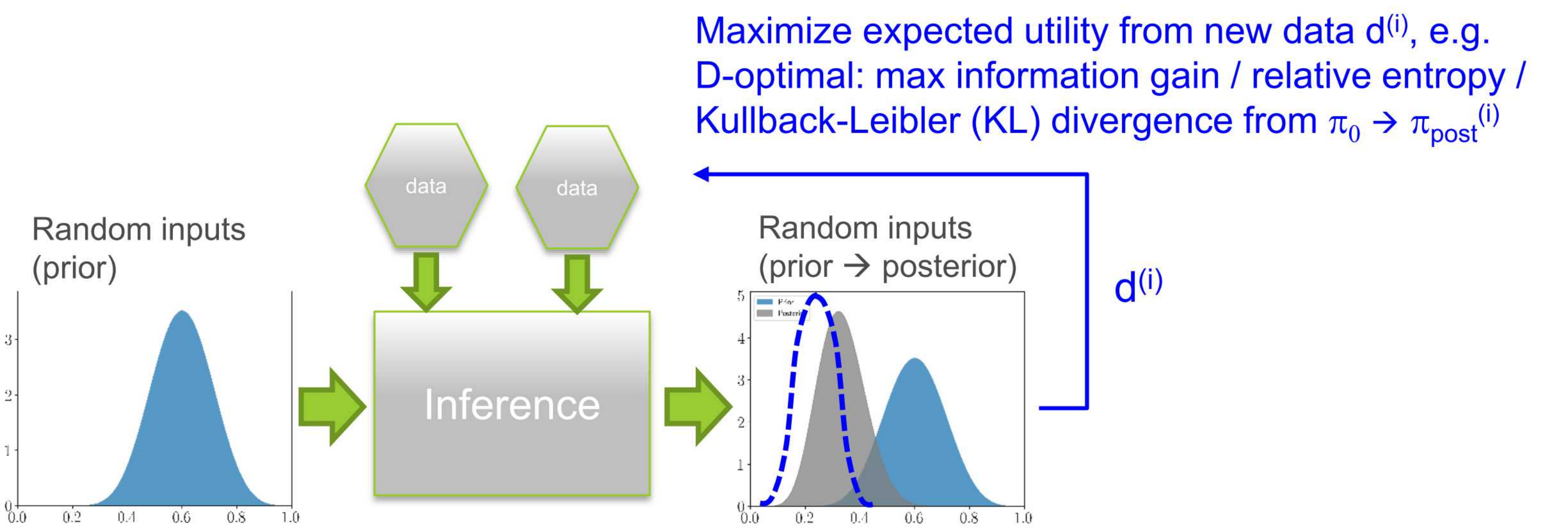
Propagation of input uncertainties to response QoI

- Push forward of posterior distributions
- Compute statistics that reflect goals of OUU process (i.e., moments, failure probabilities)

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



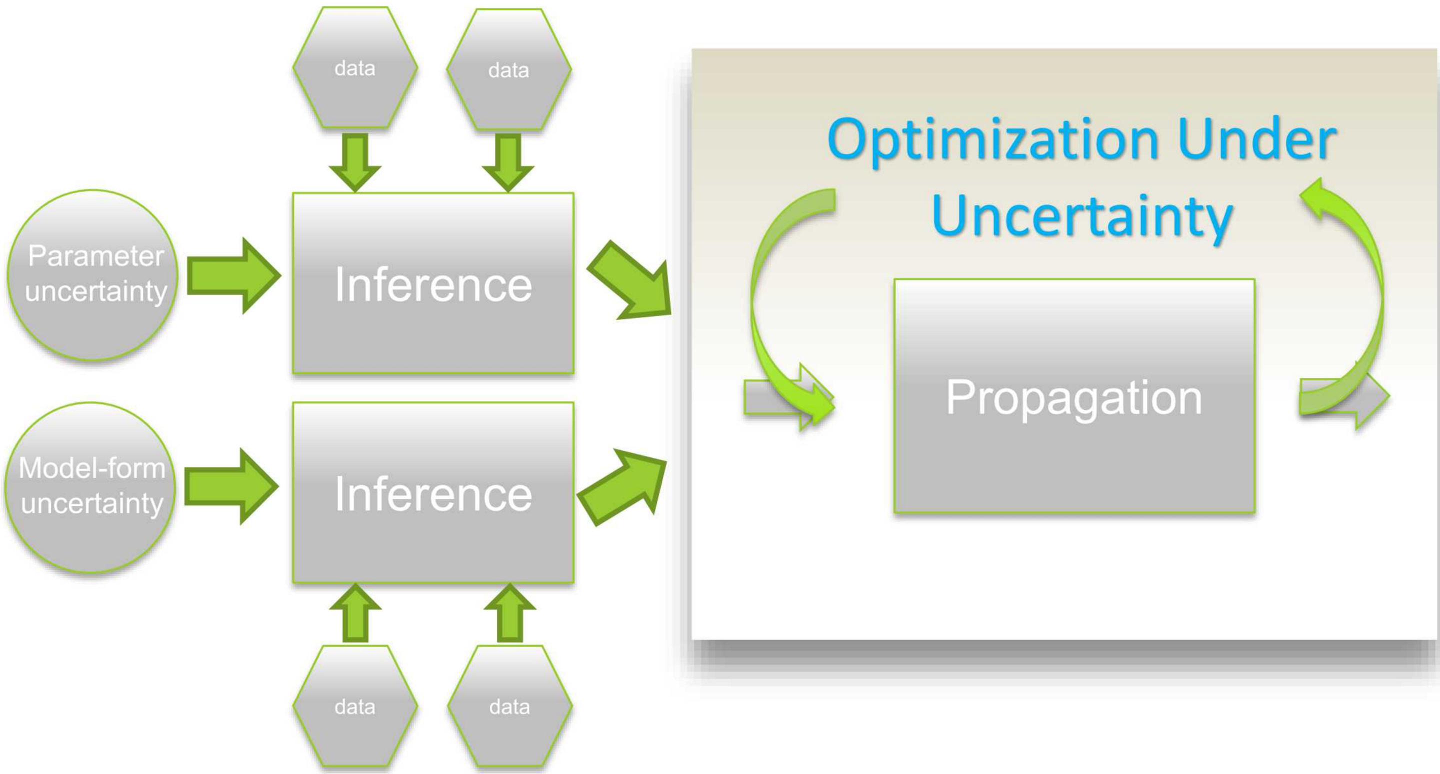
Optimization Under Uncertainty (OUU) Workflow

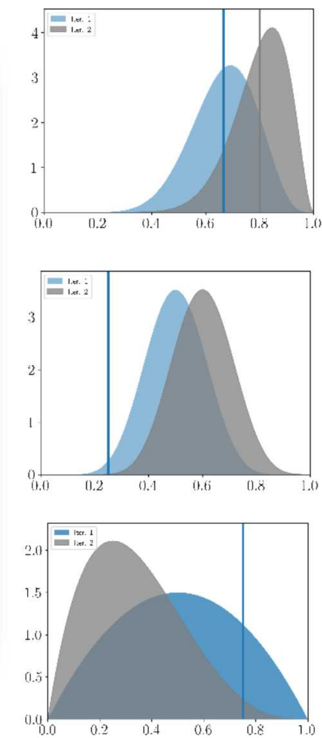
Roll up of capabilities

- 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





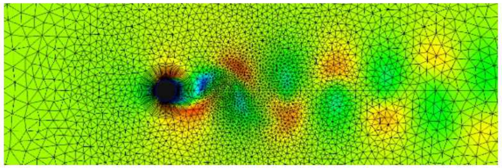
Summary of Wind UQ Studies under A2e

Previous: Forward UQ
- Cylinder wake in Nalu (initial demo at right)
- SWiFT Site with Nalu + OpenFAST

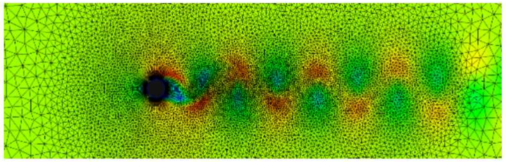
Current: Inverse UQ
- Infer upstream conditions from SwiFT data sets
  - OpenFAST + WindSE (+ Nalu)

Future: OED / OUU
- Determine best configurations (locations in random parameter space) to collect more data
- Design of wind plants for an uncertain operational environment

Coarse Mesh: 10 minute time to soln.

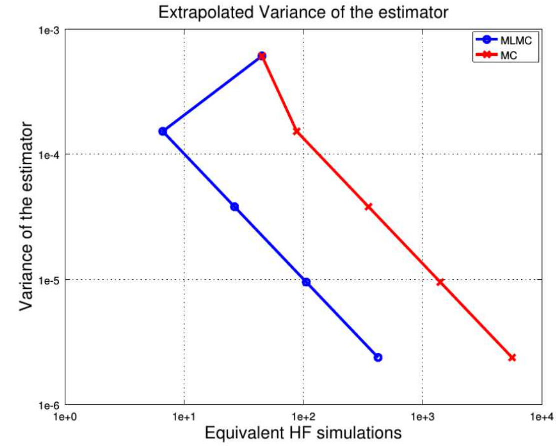


Medium Mesh: 4 hours time to soln.



Accuracy	Multilevel simulations				Equivalent Cost	
	Coarsest	Coarser	Coarse	Medium	MLMC	MC
6.08e-05	28	20	4	1	18	221
6.08e-06	2796	194	37	3	167	2202
6.08e-07	27952	1935	364	25	1657	22140
6.08e-08	279520	19345	3640	242	16551	220130

TABLE: Optimal MLMC samples allocation Vs MC allocation



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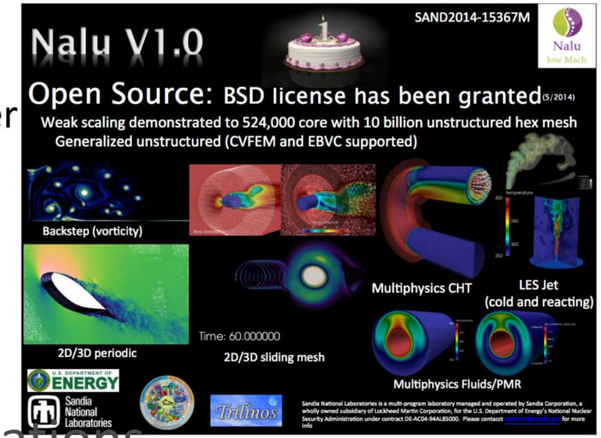
Computational Approach

- Low Fidelity: **OpenFAST-AeroDyn-Turbsim** (https://github.com/OpenFAST)
  - Turbsim generates turbulent atmospheric boundary layer flow field, semi-empirical
  - AereoDyn models the aerodynamic forces on the rotor
  - OpenFAST models the structural and controls response of the rotor (same for Nalu)

- High Fidelity: **Nalu** (https://github.com/NaluCFD)
  - LES, Solves the Navier-Stokes equations in the low-Mach number approximation with the one-equation, constant coefficient, TKE model for SGS, unstructured massively parallel.
  - Actuator Line model of the rotor
  - Single, uniform mesh (no nesting)



- Cost estimates for Nalu and OpenFAST simulations.

Case	Mesh size	Simulation time (seconds)	CPUs	Cost (CPU-hours)	Cost (relative)
OpenFAST		500	1	0.42	1
Coarse	100x50x50	2000	80	240	576
Medium	200x100x100	2000	160	960	2304
Fine	400x200x200	2000	400	6860	16500
Reference	800x200x200	2000	400	38400	91400

Domino, S. "Sierra Low Mach Module: Nalu Theory Manual 1.0", SAND2015-3107W, Sandia National Laboratories Unclassified Unlimited Release (UUR), 2015. https://github.com/NaluCFD/NaluDoc

Wind Turbine Sensitivity Analysis (Jonkman et al.)

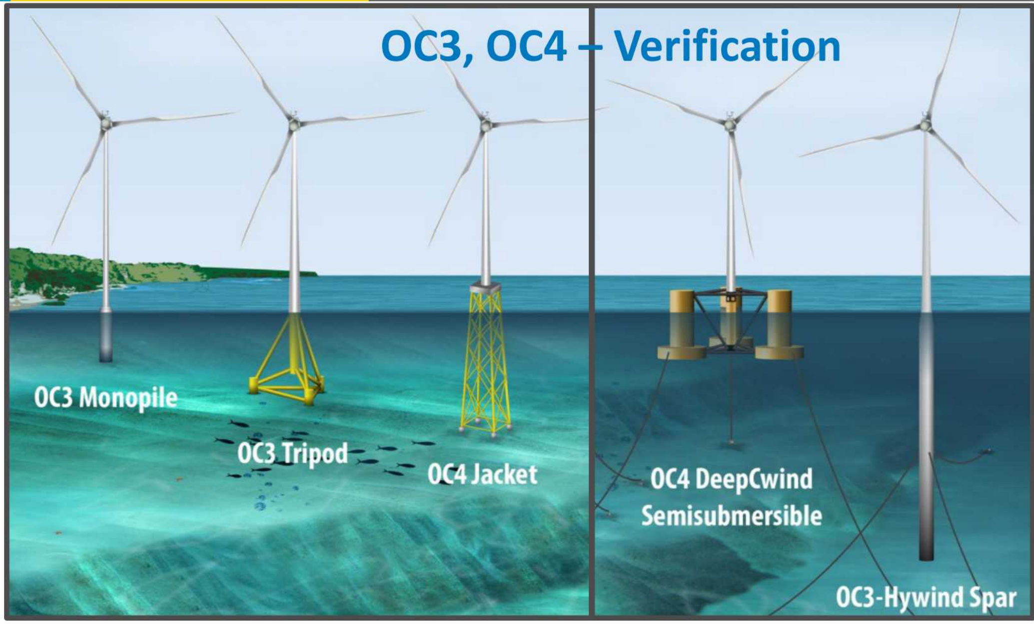
Project Objective: *Identify input parameters with high uncertainty / variability that are most influential to ultimate & fatigue loads during normal operation*

- Related work:
  - Sensitivity assessment of inflow turbulence (profile, spectrum coherence, correlations) – Paper / presentation @ *AIAA SciTech 2018*; updated in publication submitted to *Wind Energy Science*
  - Sensitivity assessment of aerodynamic subset of turbine properties – Paper / presentation @ *AIAA SciTech 2019*

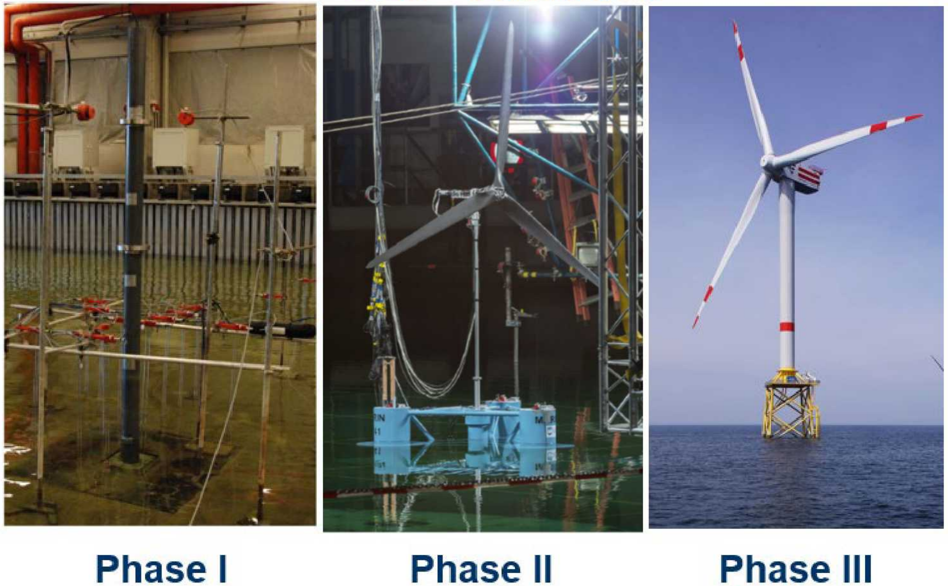
- This work:
  - Overview of sensitivity assessment of inflow & full turbine properties (aerodynamic, structural, control) – Publication submitted to *Wind Energy Science*
- Outcome of this research could inform:
  - Probabilistic design approaches
  - Better site-suitability analyses
  - Development of surrogate models
  - Propagation of uncertainty to support model validation

IEA Wind Task 30 – V+V of Offshore Wind Modeling Tools (Robertson)

- Offshore Code Comparison Collaboration (OC3) – run under IEA Wind Task 30
- ***Verify and validate the engineering-level tools used to design offshore wind systems*** to advance the overall accuracy of offshore wind computer modeling tools, to improve their predictive capability for estimating structural loads.
  - Project running since 2010 (OC3/OC4/OC5)
  - Coupled tools (aero-hydro-servo-elastic) used to predict motions/global loads in a system, ensuring the design meets IEC standards
  - Example tools: FAST, Bladed, HAWC2, FLEX
- Group models benchmark problems, and compares solutions between codes and to measurement data from scaled testing and full-scale prototypes
  - Identify errors, examine differences in modeling theories/approaches, improve tools, train analysts, identify R+D needs

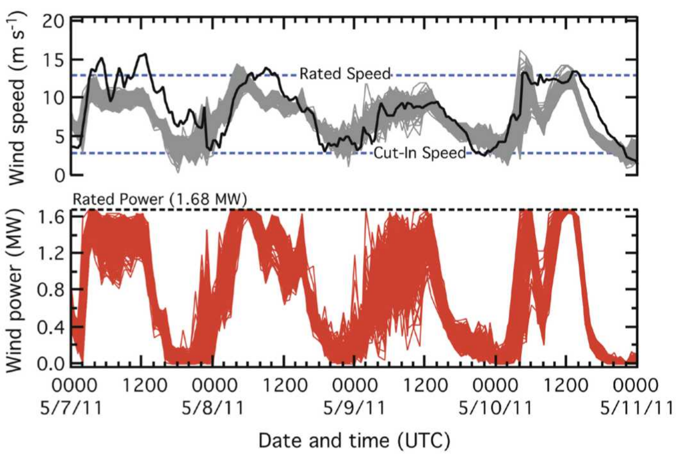


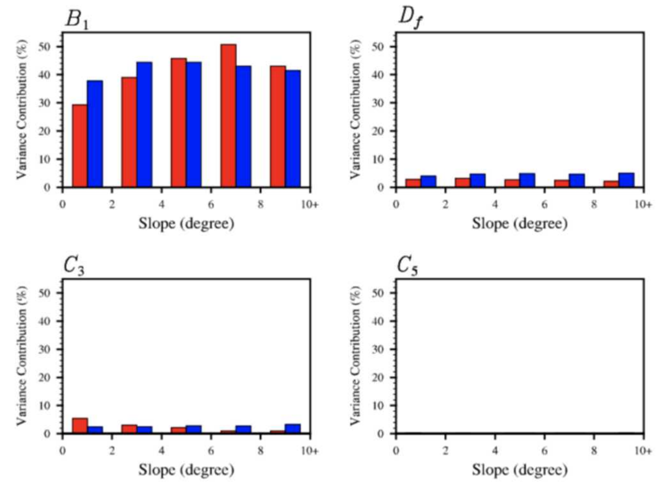
OC5 - Validation



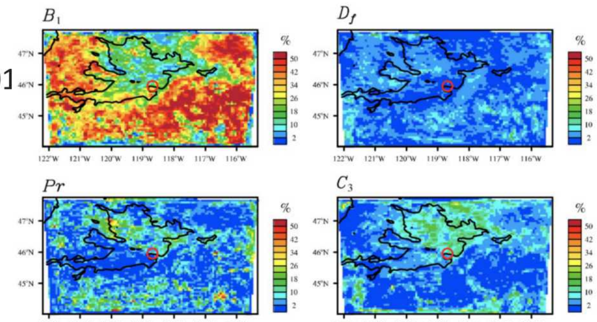
Mesoscale Uncertainty Quantification
(Berg, Kravitz, et al.)

- Bottom line: If you get the inflow wrong, you get everything wrong.
- How “right” do we need to be? What are the key controls on uncertainty in modeling the mesoscale flow?





Yang et al. (201



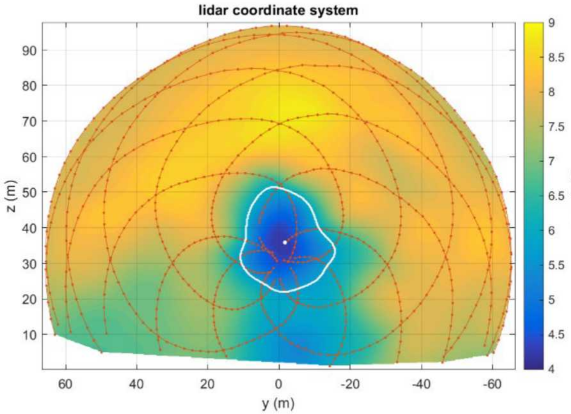
When calculating sensitivities, we can’t just average over the entire domain

Experimental Uncertainty Assessment and Propagation

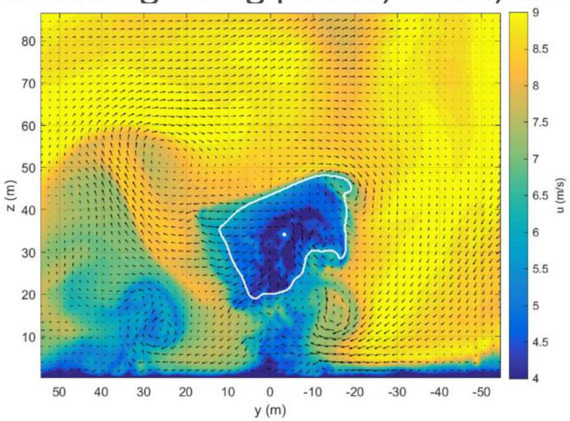
Wake comparison, Measured and Simulated Lidar

Nalu-Wind Wake Assessment, SWiFT

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



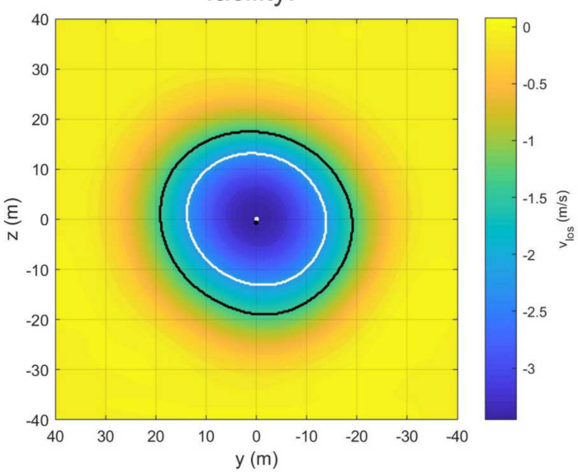
Sample of the wake date from the measured Spinnerlidar at the SWiFT facility.



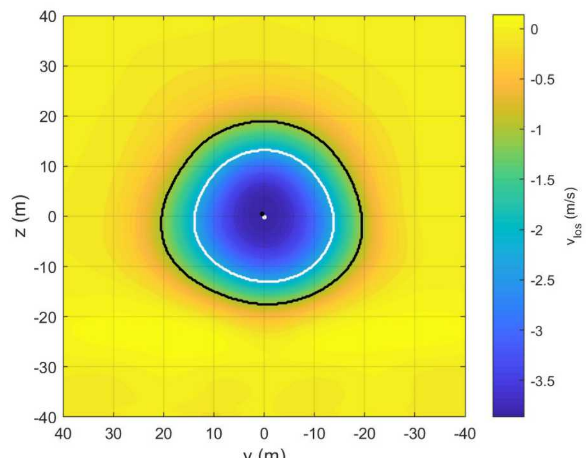
Nalu-Wind Simulated wake data 5D downwind.

	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

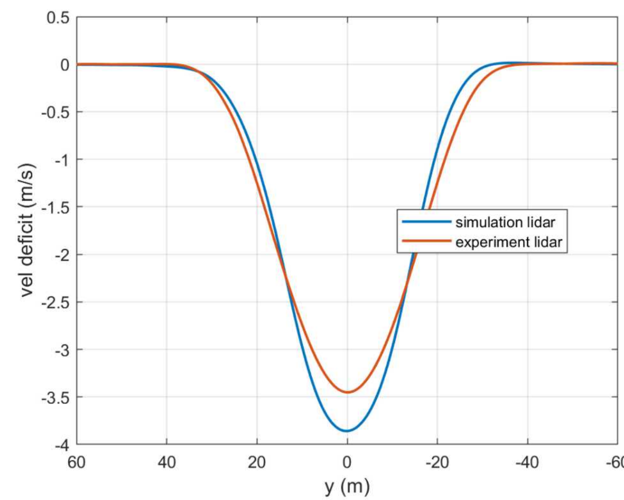
Upstream turbine (WTGa1) comparison between experimental and simulation results of the 10-minute averages of the mean out-of-plane (OOP) blade-root bending moment for the three blades (kN m), relative flapwise DEM (simulation/experiment) and generator power (kW) for yaw = 0° case.



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.

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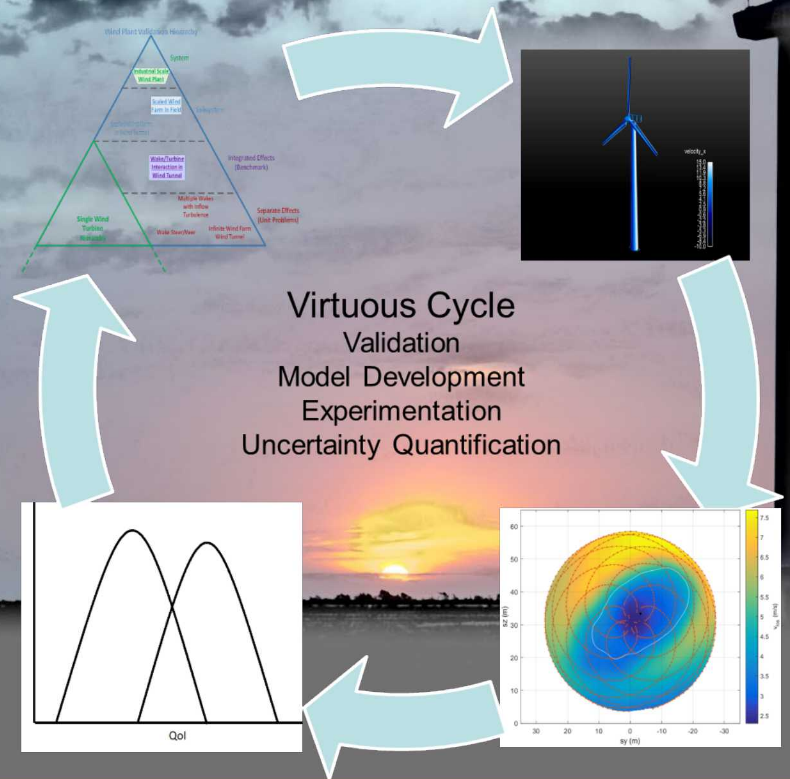
VV&UQ Multi-year Goals

- 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
- 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.

Thank you

"If a man will begin with certainties, he shall end in doubts; but if he will be content to begin with doubts, he shall end in certainties." - F. Bacon - 1605.



A2e Project Dependencies

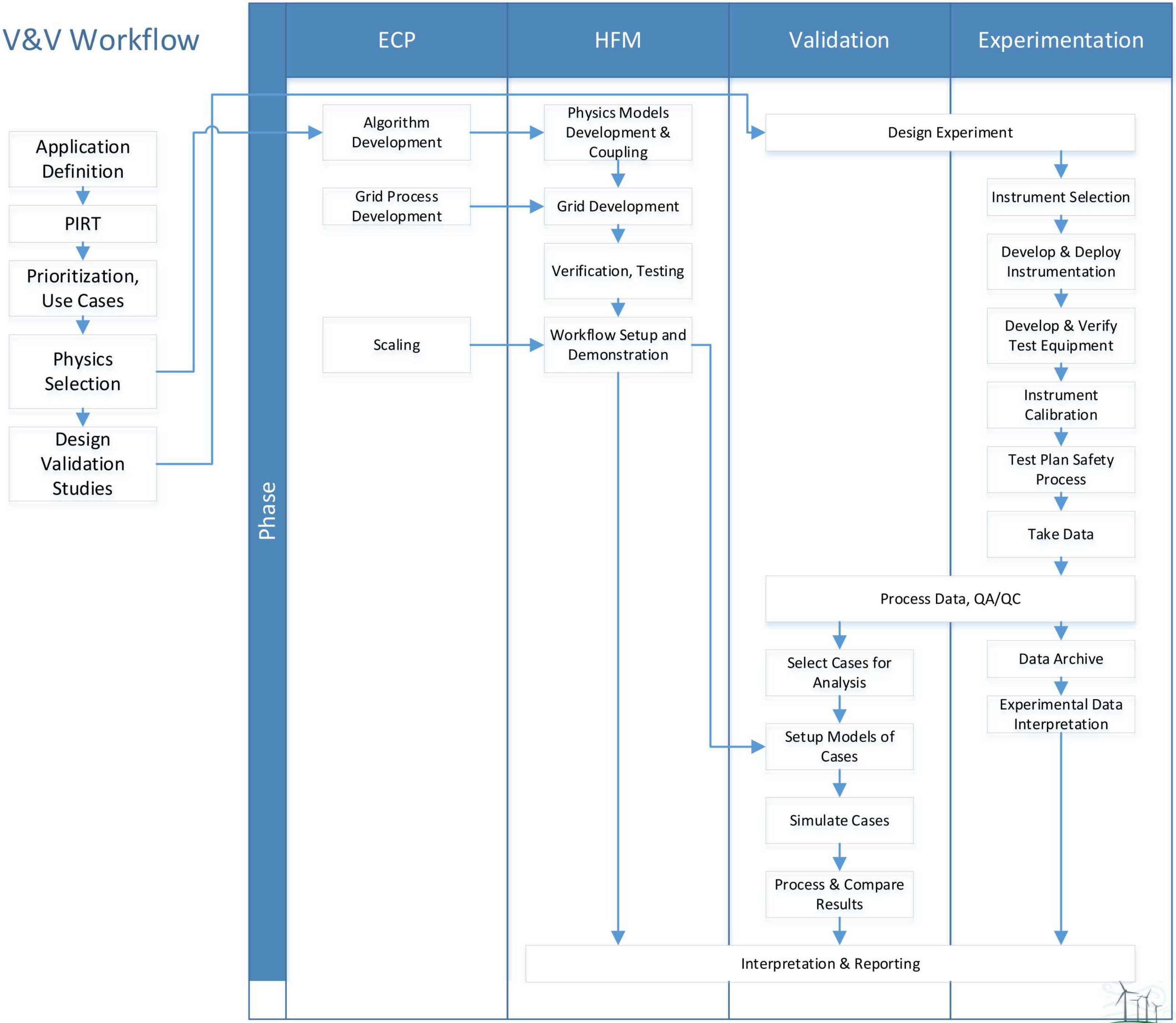
- V&V/UQ Project Dependencies:
  - Models with verified and demonstrated capabilities req'd for validation campaigns
  - Support for model deployment, including complete workflow
  - Experimental data of validation quality, with QA/QC, UQ, and with instrumentation that can be directly mapped to model QoI's and application SRQ's
  - A2e validation leads engaged on coordination activities
  - PRUF for QoI for uncertainty propagation and validation prioritization and impact

- Projects that depend on V&V/UQ:
  - HFM, Wake Dynamics, ISDA, Control Science, MMC, WFIP, PRUF, and offshore wind
  - Coordination of validation activities across A2e
  - Definition of validation framework, terminology, and methodology
  - Development and demonstration of UQ processes
  - Methods to prioritize parameters, estimate variance, and propagate to SRQ's

Uncertain Quantification Problems

- Turbine UQ:
  - Quantify uncertainty of field measurements (inflow, blade root loads, tower loads, generator power)
  - Propagation of measurement uncertainty to quantities of interest (power, thrust, root bending moment) and system response quantities (AEP, DEL).
  - Inverse: given a set of turbine load measurements, what are the most likely inflow and turbine model parameters?
- Wake UQ:
  - Quantify uncertainty in wake Lidar measurements and tracking algorithms
  - Propagate wake measurement uncertainty to deficit strength, movement, and downstream turbine loads and power
  - Inverse: given a set of wake measurements, what are the most likely inflow, turbine loading, and model parameters?
- Wind Plant UQ:
  - Uncertainty of measurements given limited information
  - Inverse: Given set of limited and highly uncertain measurements, what are most likely inflow, ABL, and turbine parameters

V&V Workflow



Application Definition
PIRT
Prioritization, Use Cases
Physics Selection
Design Validation Studies
Phase
ECP
HFM
Validation
Experimentation
Algorithm Development
Grid Process Development
Scaling
Physics Models Development & Coupling
Grid Development
Verification, Testing
Workflow Setup and Demonstration
Design Experiment
Instrument Selection
Develop & Deploy Instrumentation
Develop & Verify Test Equipment
Instrument Calibration
Test Plan Safety Process
Take Data
Process Data, QA/QC
Select Cases for Analysis
Setup Models of Cases
Simulate Cases
Process & Compare Results
Data Archive
Experimental Data Interpretation
Interpretation & Reporting

Mapping Current Work to Proposed Tasks

- **Validation Coordination and Application**
  - A2e Validation Coordination Meeting, documents
- **Meteorological Uncertainty Quantification**
  - Quantify uncertainty propagation through WRF based on model inputs and model parameterizations (under MMC)
- **Wind Turbine Uncertainty Quantification**
  - Sensitivity Analysis (under ISDA)
  - SWiFT Wake Steering loading probabilistic analysis
- **Wind Plant Validation and Uncertainty Quantification**
  - Rødsand II Analysis
  - Validation Study of Nalu for the OWEZ Wind Plant
  - Bigelow Canyon Validation
  - SWiFT: Experiment UQ, Data Assimilation and OED
- **Uncertainty Quantification Methodology Development and Application**
  - Successful deployment of Multilevel-Multifidelity Uncertainty Quantification (MLMF-UQ) Publication/presentation of first MLMF-UQ wind application at ECCOMAS-2018 conference
  - UQ with DAKOTA and FAST.Farm