Sandia National Laboratories

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Validation and Uncertainty Quantification: On the Leading Edge of Turbine Innovation

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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

What is V&V?

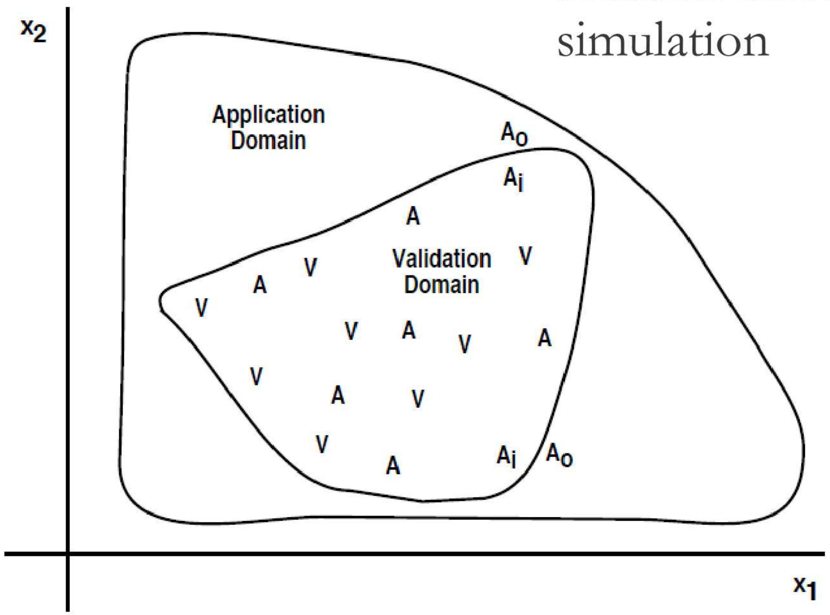
Verification, validation, and uncertainty quantification are integral parts of establishing a model's predictive capability for an intended application. > Decision Making

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



x_1 and x_2 are model parameters

Figure from Oberkampf and Trucano

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

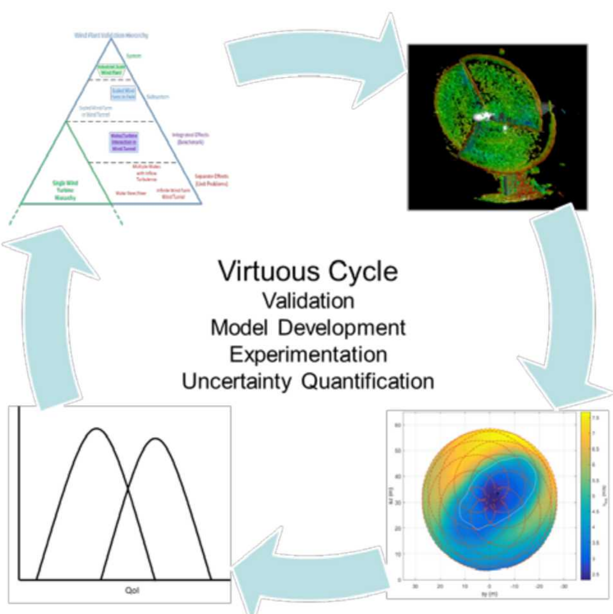
As wind turbine technology matures, the cost of testing and the required level of uncertainty demand a new approach.

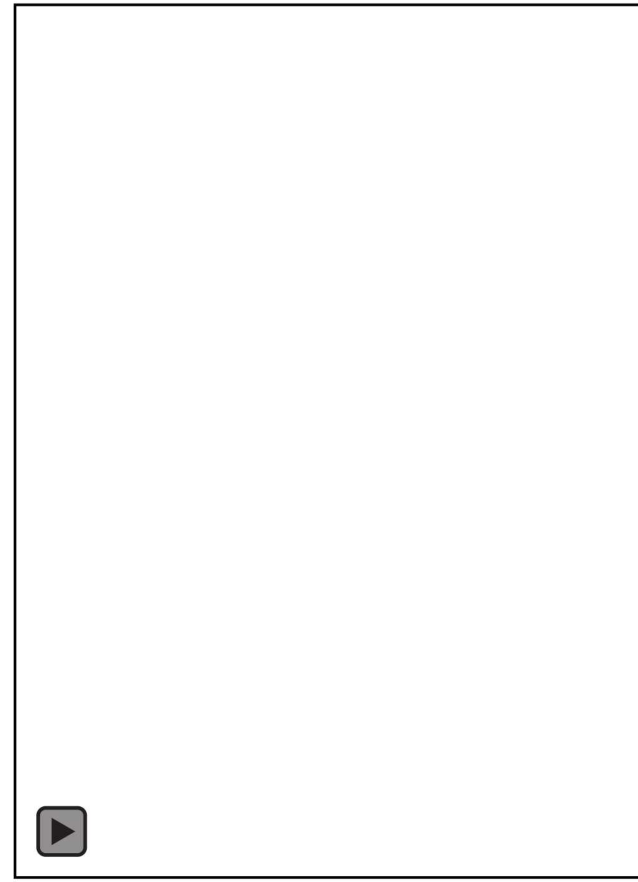
High fidelity models enable reduced development risk through pre-prototype qualification and optimization.

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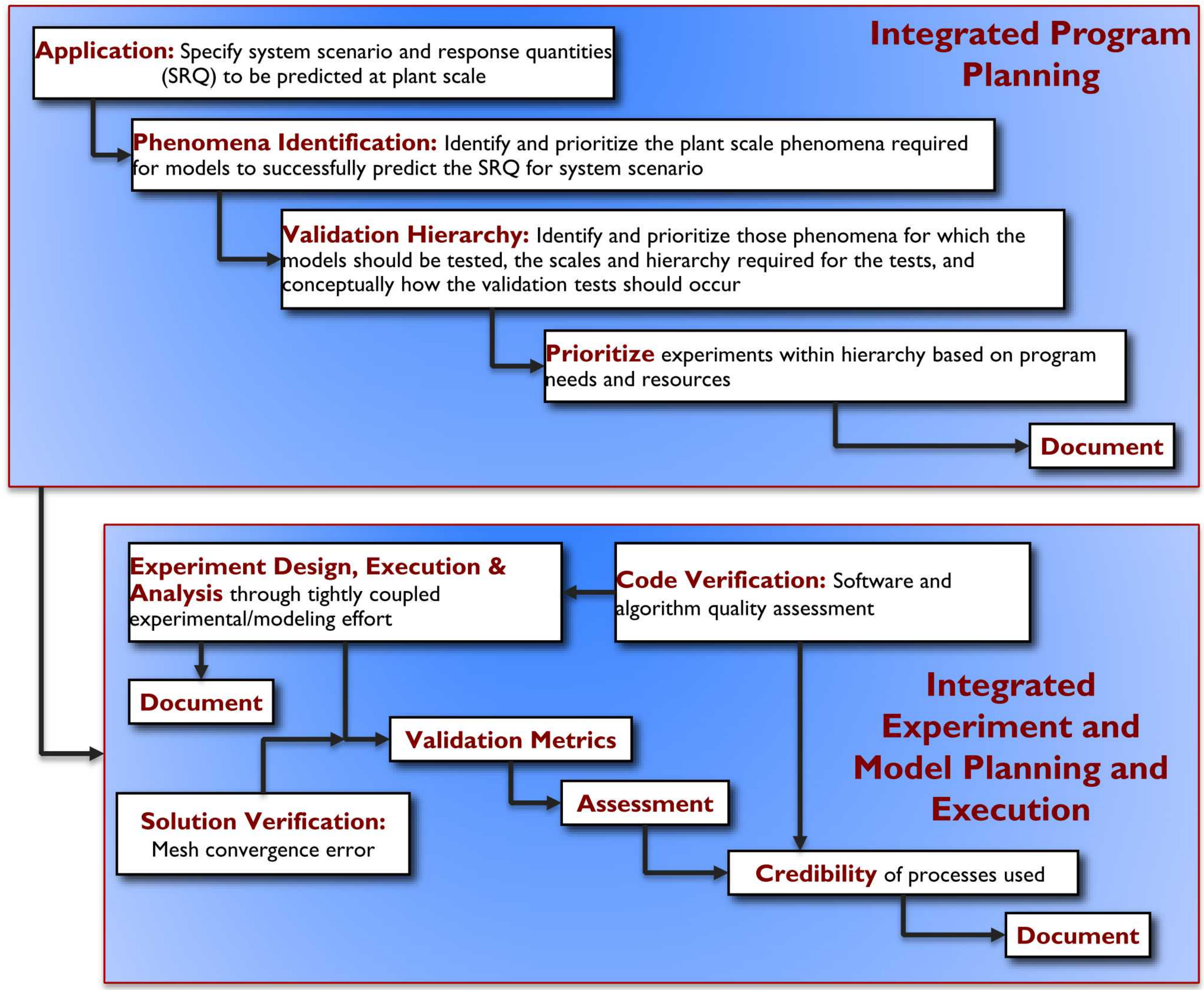
V&V Framework (2015 Hills, Maniaci, Naughton)

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



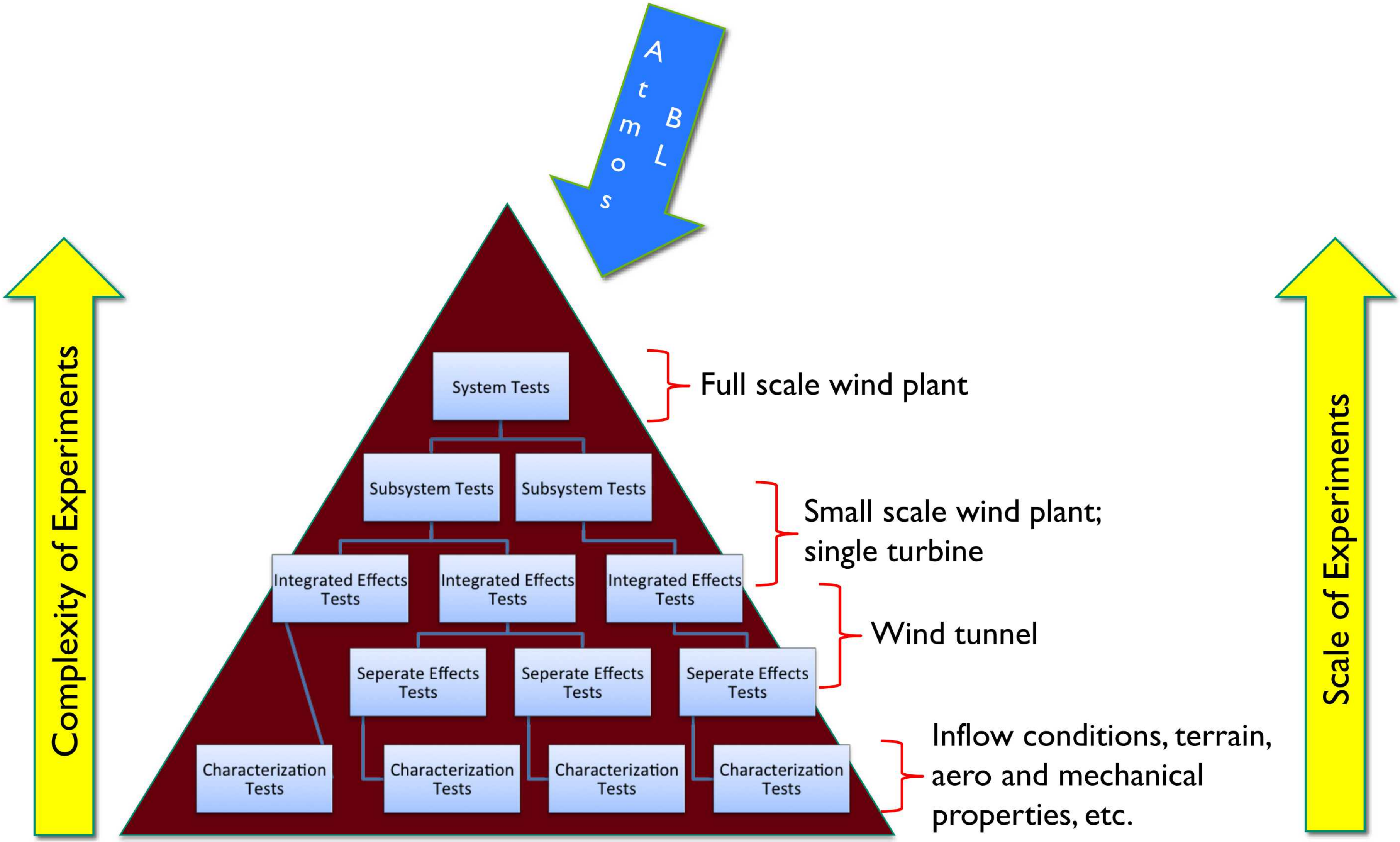
Backbone of Prioritization Process: PIRT

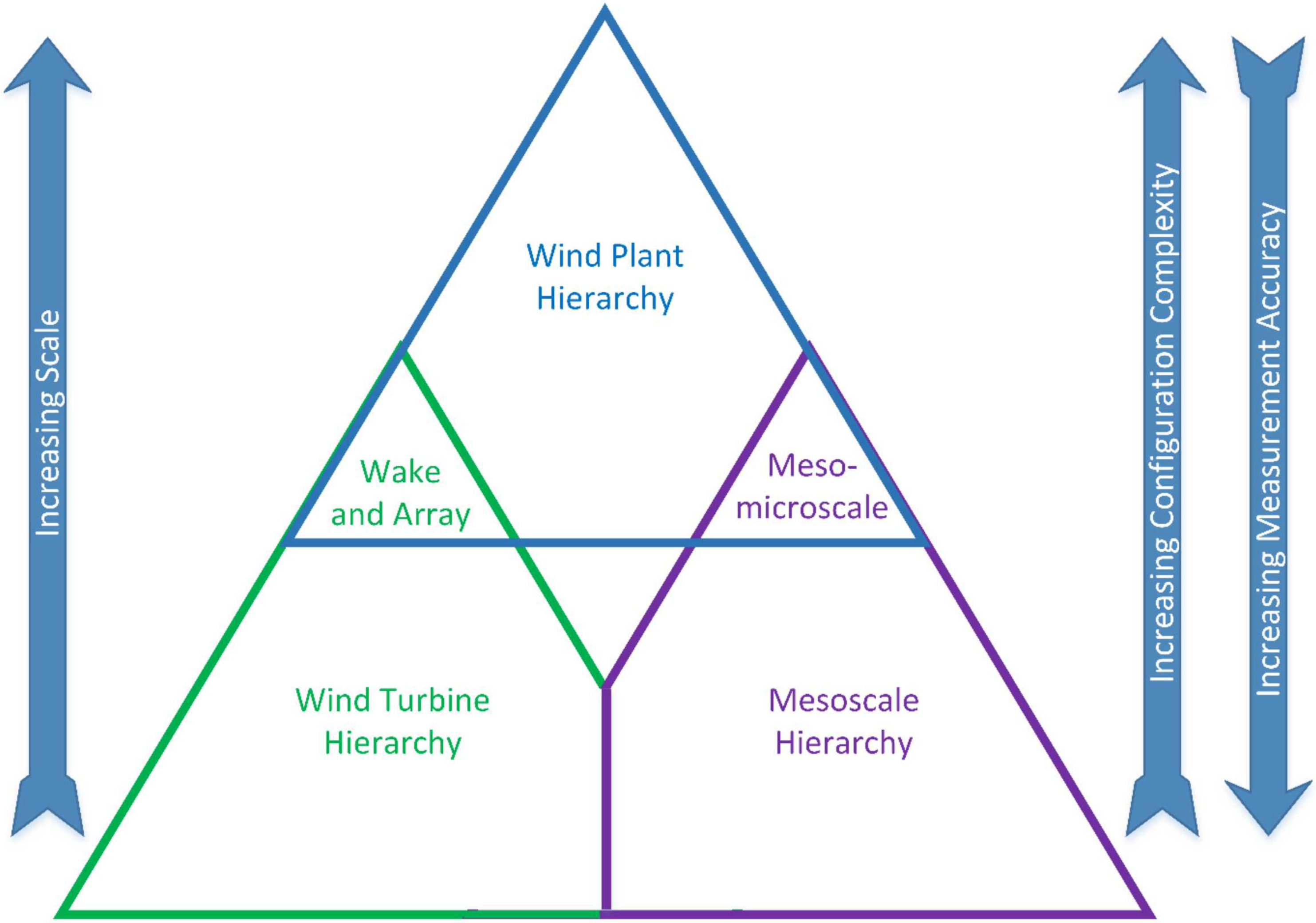
PIRT: Phenomenon Identification Ranking Table

- 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

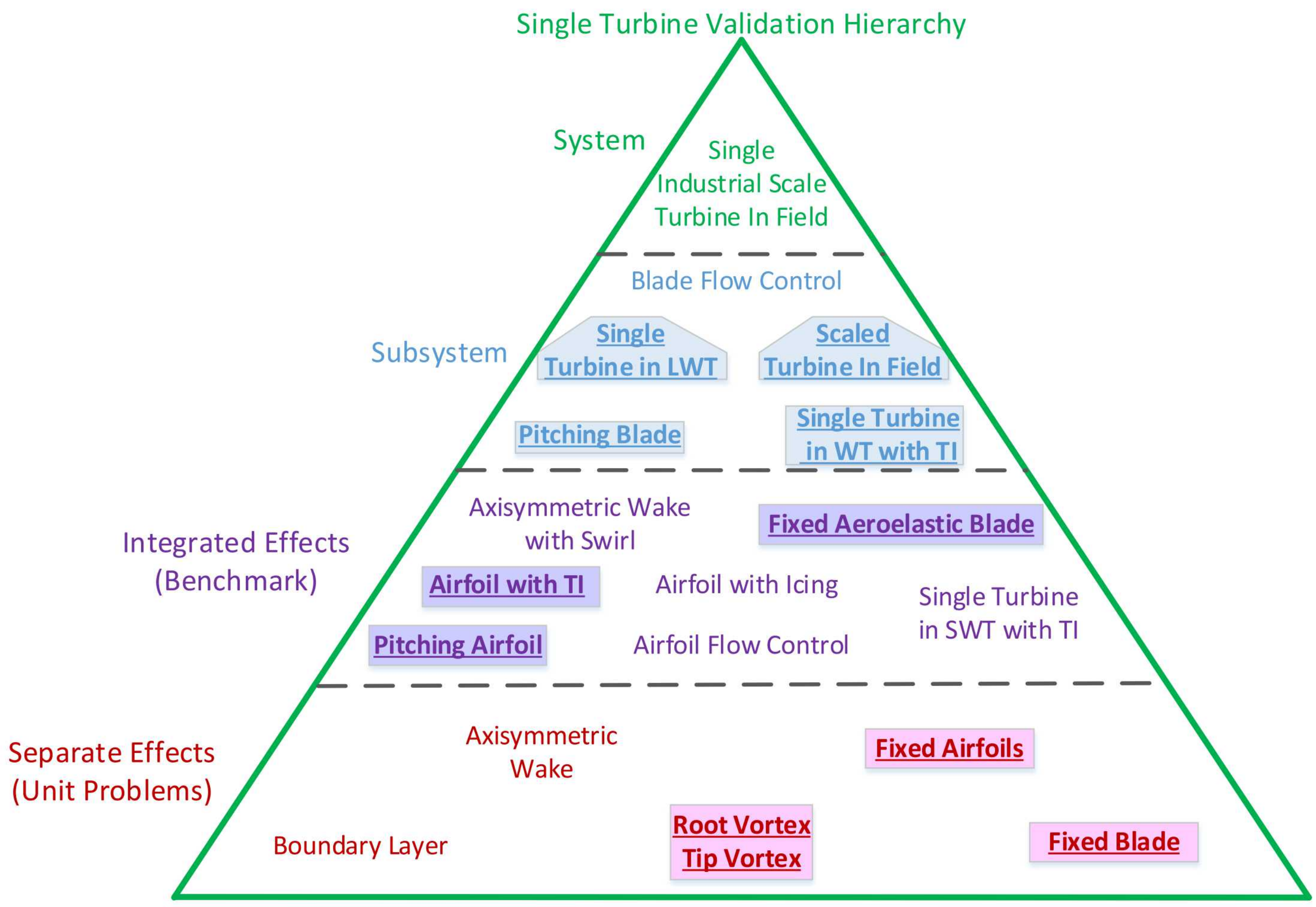
Phenomenon	Importance at Application Level	Model Adequacy		
		Physics	Code	Val
Turbine scale flow phenomena				
Blade Aero / Wake Generation				
Blade load distribution effects and rotor thrust	H	M	L	L
Tip and root vortex development, and evolution and merging	H	M	L	L
Vortex sheet and rollup (in addition 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




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

Wind Turbine Validation Hierarchy



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

D. Maniaci and J. Naughton, 2017

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

Experimental Measurement and CFD Model Development of Thick Wind Turbine Airfoils with Leading Edge Erosion

- Historically, wind turbine capacity factors have been overestimated by 15%.[1]
- This is attributed to annual wind intermittency, wind farm topography, and design performance over predictions.

Heavy blade erosion[2]

- One cause of performance loss is leading-edge surface roughness.
- Over time, blades suffer from erosive and additive roughness.

Collaboration between;

Sandia National Laboratories
Texas A&M University
University of California, Davis
Industry Partners

Technical Approach

Standards

Mechanisms
What causes it?

Technology Improvement

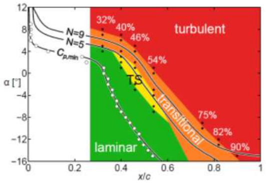
Erosion

Treatment
How to deal with it?

Aerodynamics
How is performance affected?

When should Erosion be remediated?

3M



When should Erosion be remediated?

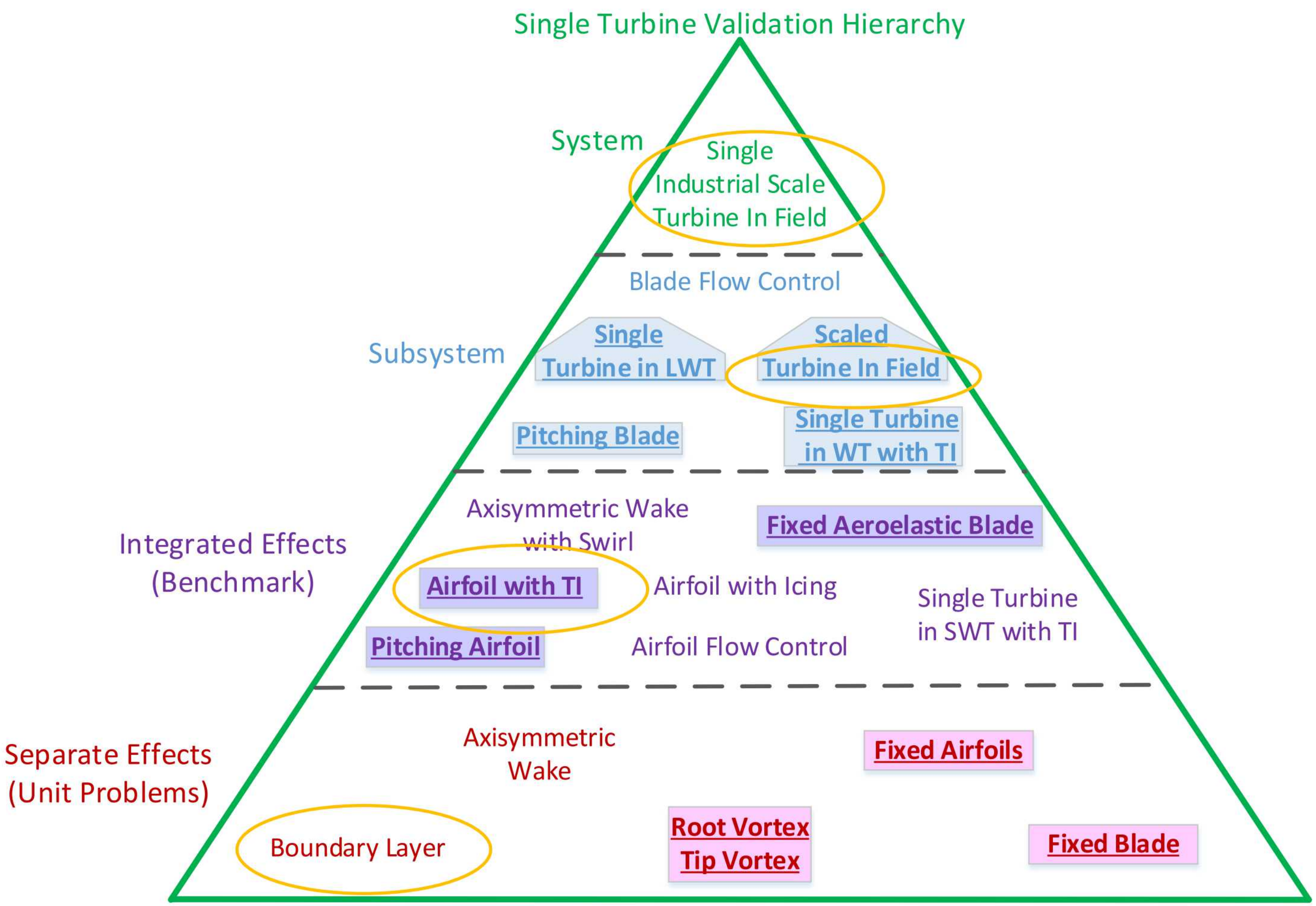
What is the performance impact of LEE?

Goal:

- Quantify Effects of Surface Contamination and Erosion on Wind Turbine Performance
- Develop and validate an airfoil roughness model to predict the effects of surface roughness and erosion

- Tasks:
  - ➢ Field measurements of surface roughness and erosion
  - ➢ Wind tunnel testing of effect of surface roughness and erosion on airfoil performance
  - ➢ Development of computational roughness model to account for effect on aerodynamic performance of airfoils, blades, rotors
  - ➢ Validate: Correlate wind tunnel and CFD results

Wind Turbine Validation Hierarchy



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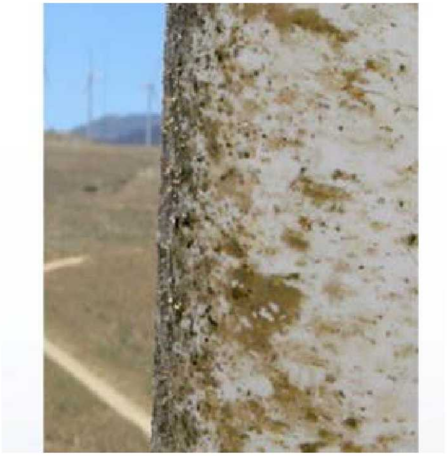
	Blade Aero/Wake Generation													**Testing Issues**	
	Blade Load Distribution Effects	Tip & Root Vortex Evolution	Vortex Sheet Evolution	Blade Generated Turbulence	Root Flow Acceleration	Boundary Layer Development	Surface Roughness Effects	Boundary Layer Near LE and TE	Rotational Augmentation	Dynamic Stall	Unsteady Inflow Effects	Blade Flow Control	Icing	Boundary Conditions	Scale Effects
Boundary Layer															
Physics Present	Missing	Missing	Missing	Missing	Missing	Entirely	Entirely	Missing	Missing	Missing	Mostly	Missing	Missing		
Physics Captured by Measurements	Missing	Missing	Missing	Missing	Missing	Entirely	Entirely	Missing	Missing	Missing	Mostly	Missing	Missing	Entirely	Entirely
Axisymmetric Wake (with Swirl)															
Physics Present	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Missing		
Physics Captured by Measurements	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Entirely	Entirely
Root/Tip Vortex															
Physics Present	Missing	Mostly	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Mostly	Missing	Missing		
Physics Captured by Measurements	Missing	Entirely	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Missing	Mostly	Missing	Missing	Entirely	Entirely
Fixed Airfoils (with flow control)															
Physics Present	Somewhat	Missing	Somewhat	Mostly	Missing	Mostly	Mostly	Mostly	Missing	Missing	Mostly	Entirely	Missing		
Physics Captured by Measurements	Entirely	Missing	Mostly	Entirely	Missing	Entirely	Entirely	Entirely	Missing	Missing	Mostly	Entirely	Missing	Entirely	Entirely
Fixed Blade (with Turbulent Inflow)															
Physics Present	Mostly	Entirely	Entirely	Entirely	Missing	Entirely	Entirely	Entirely	Missing	Missing	Mostly	Missing	Missing		
Physics Captured by Measurements	Mostly	Entirely	Entirely	Entirely	Missing	Somewhat	Mostly	Somewhat	Missing	Missing	Mostly	Missing	Missing	Entirely	Entirely

Types of Leading Edge Erosion and Surface Roughness

2D Step, Paint Chip or Repair

Rumsey, 2014

Contamination Roughness (Bugs)



Spruce, 2006

Light to Moderate Erosion, Random Pits

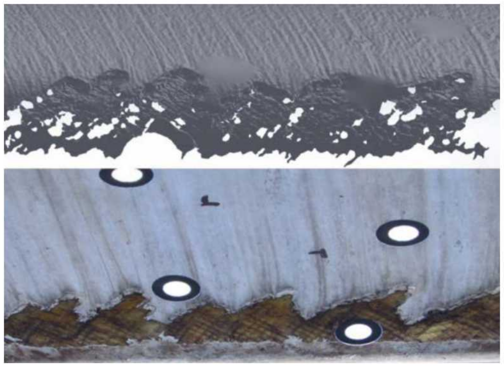
Rumsey, 2014

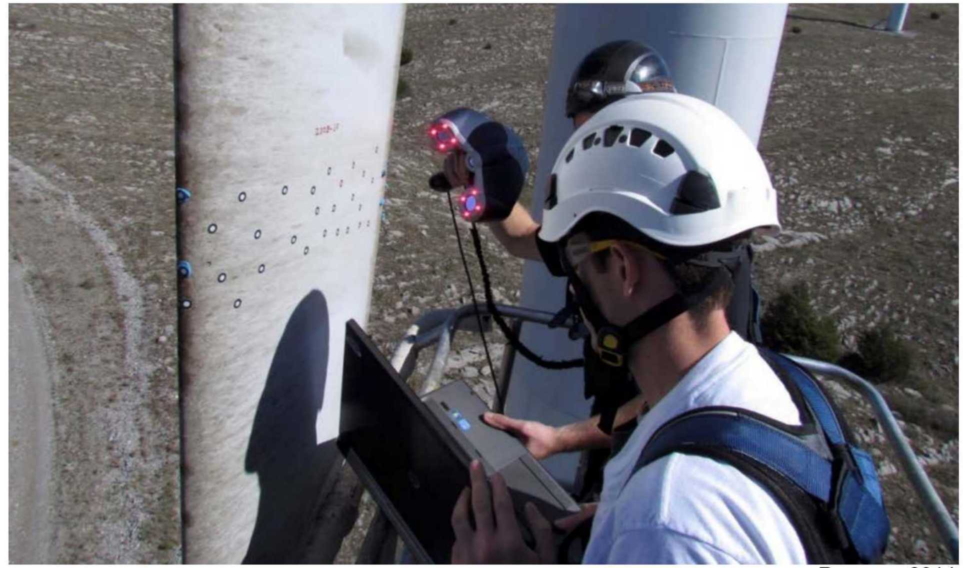
Heavy Erosion

Rumsey, 2014

Field Measurements

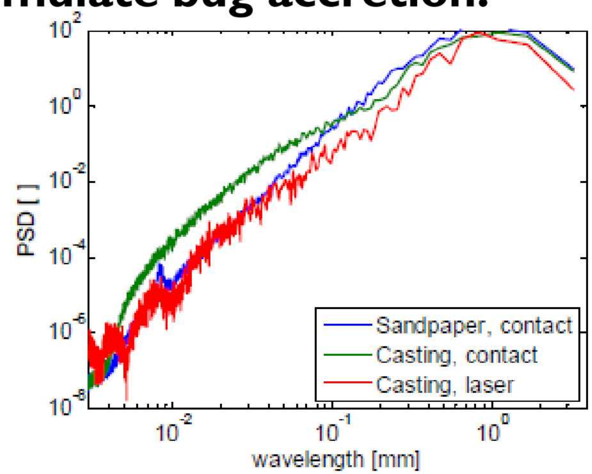
- **Creaform EXAscan Laser scanner used to capture roughness >1mm.**



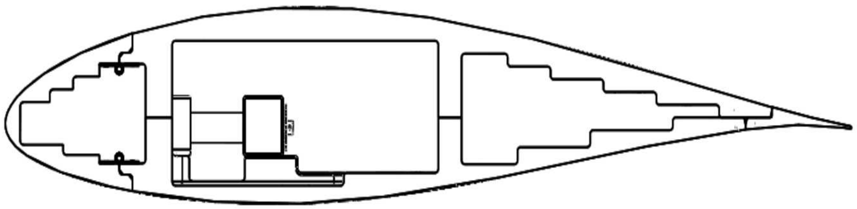


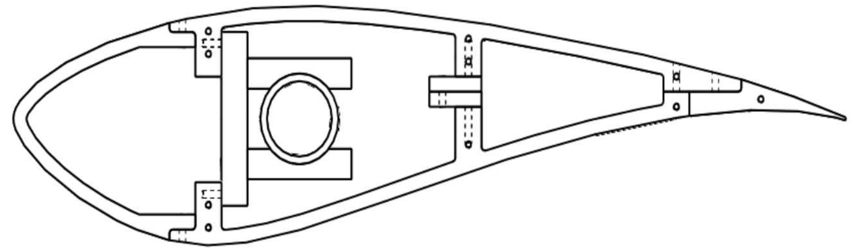
Rumsey, 2014

- **Casting and profilometer used to capture roughness < 3mm.**
- **NASA LEWICE code used to simulate bug accretion.**



Airfoil Wind Tunnel Models





NACA 63_3-418

Representative tip airfoil
18% thickness to chord ratio
Designed for high Lift/Drag ratio

SERI S814

Representative mid-span airfoil
24% thickness to chord ratio
Designed for wind turbines
Designed for high Lift/Drag ratio
Including decreased roughness sensitivity

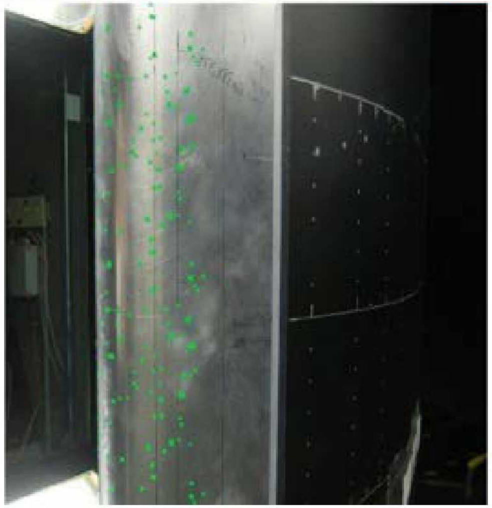
- Airfoils were tested using clean, trip-strip, and distributed roughness configurations at Reynolds numbers of 1.6×10^6, 2.4×10^6, 3.2×10^6, and 4.0×10^6; Maximum $Re_c = 5.0 \times 10^6$ to $\alpha = 4°$
- The NACA 63_3-418 was also tested with a forward facing step to simulate paint chipping, and a simulated eroded leading edge

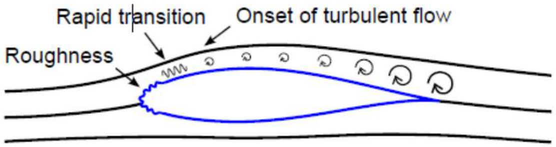
Wind Tunnel Testing

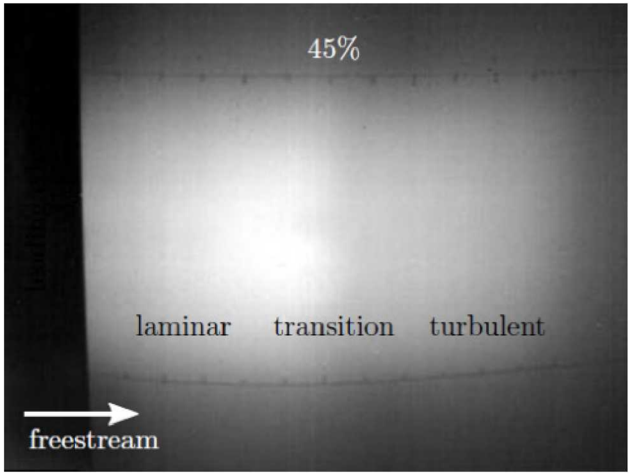
Measurements from the field used to parameterize roughness

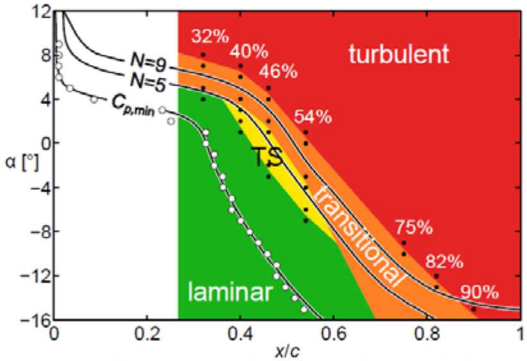
LE erosion wind tunnel models based on parameterized roughness elements

Large database of airfoil boundary layer characteristics

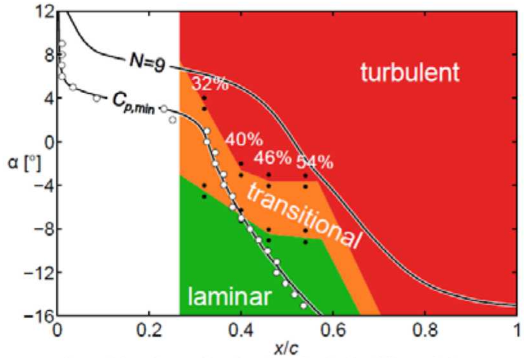








Smooth leading edge laminar/turbulent flow state



Low-*k* leading edge laminar/turbulent flow state

Wind Tunnel

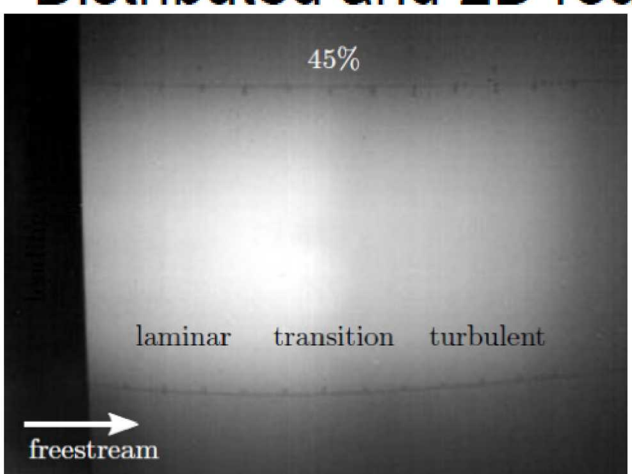
- Oran W. Nicks Low Speed Wind Tunnel at Texas A&M
- Closed return tunnel
- Test section 7 ft × 10 ft
- Maximum velocity of 90 m/s
- Blockage of 4.8%
- Turbulence intensity of 0.25%
- Maximum $Re_c = 3.6\times10^6$ based on $c_{l,\max}$ loading
- Maximum $Re_c = 5.0\times10^6$ to $\alpha = 4°$

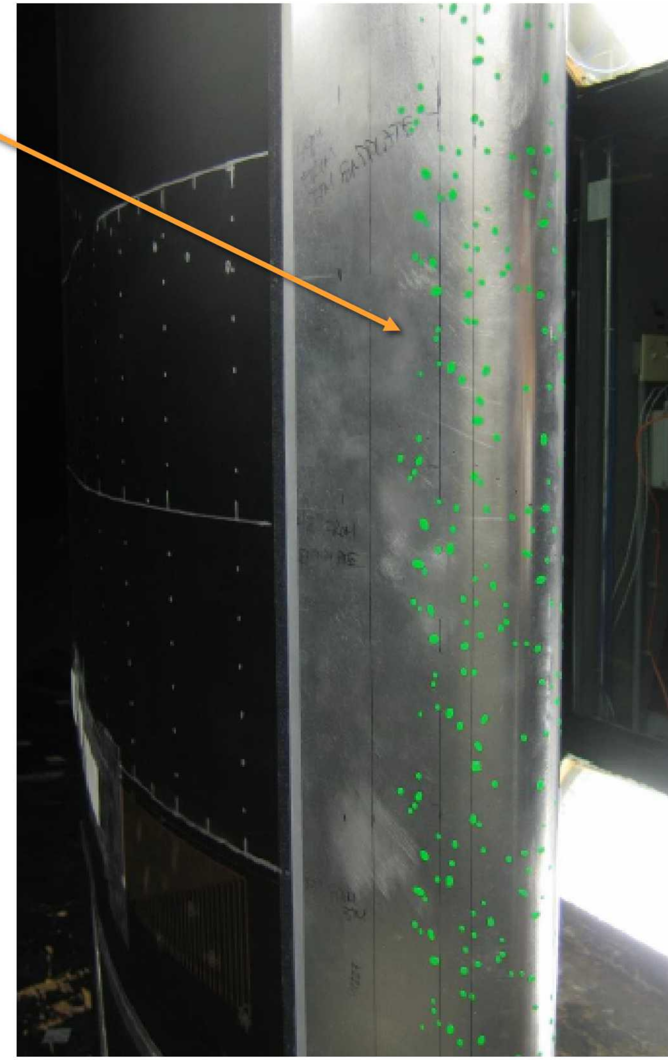
Leading-edge Erosion Study (LEES) Project
https://a2e.energy.gov/projects/lees

Model installed in wind tunnel

Configurations

- Clean
- Tripped
- Forward Facing Steps
  - Chipped paint 157μm
  - Straight step 157μm
- Distributed Roughness
  - 100 μm, 3, 9, 15% coverage
  - 140μm, 3, 6, 9, 12, 15% cov.
  - 200μm, 3% cov.
  - Distributed and 2D roughness

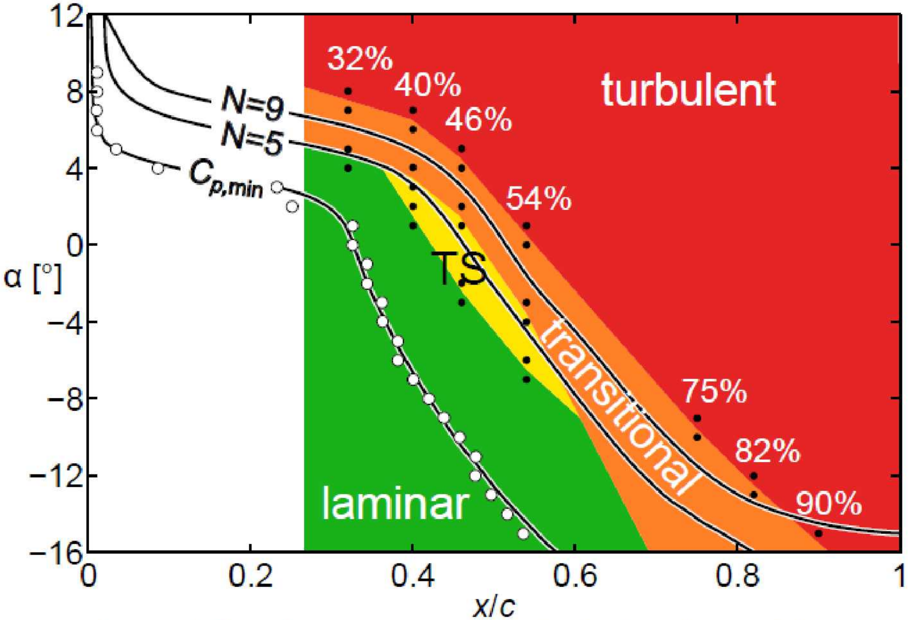




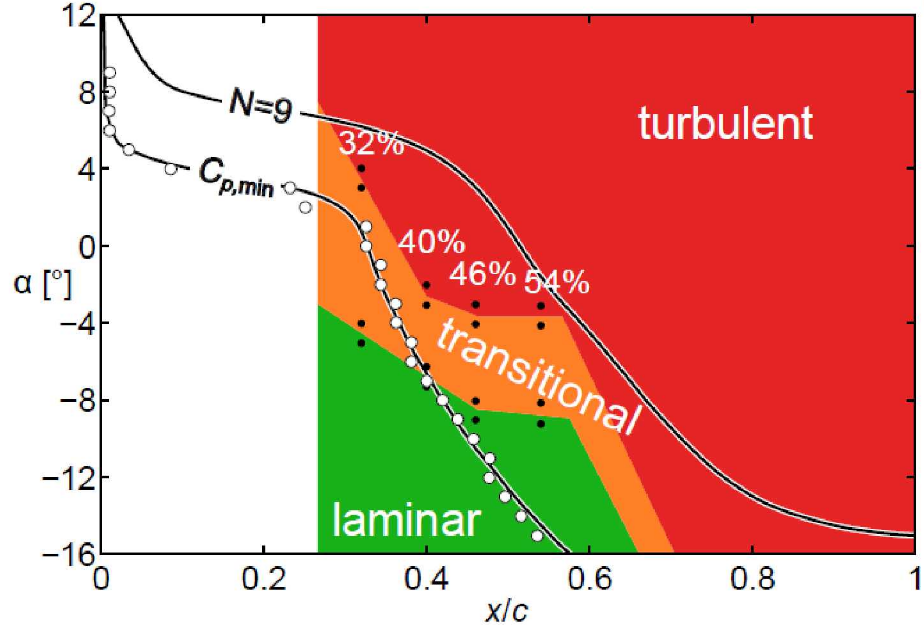
Simulated insect roughness (140 μm, 3% coverage) on NACA 63_3-418.

Leading-edge Erosion Study (LEES) Project
https://a2e.energy.gov/projects/lees

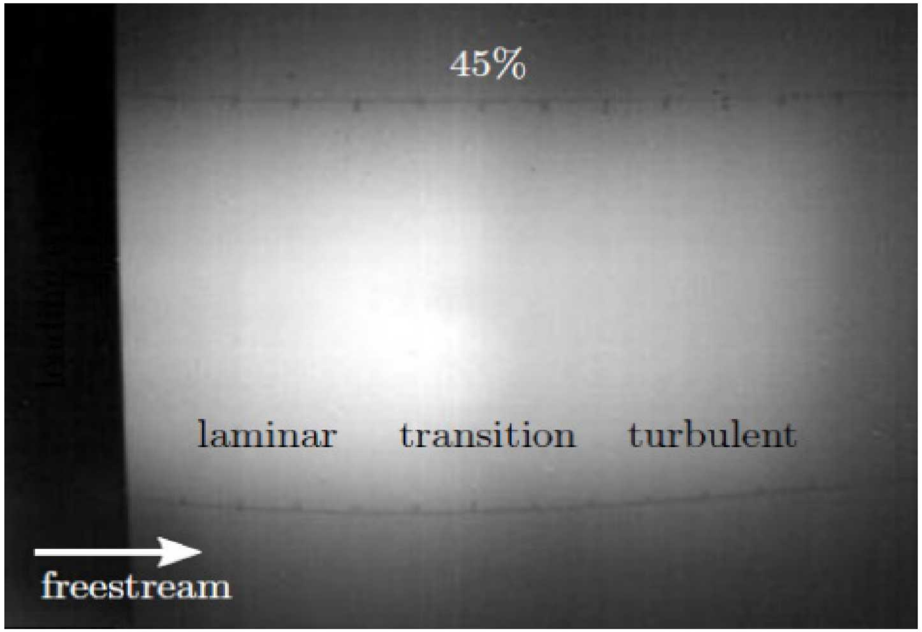
Wind Tunnel Testing: Transition Location (Model Calibration)

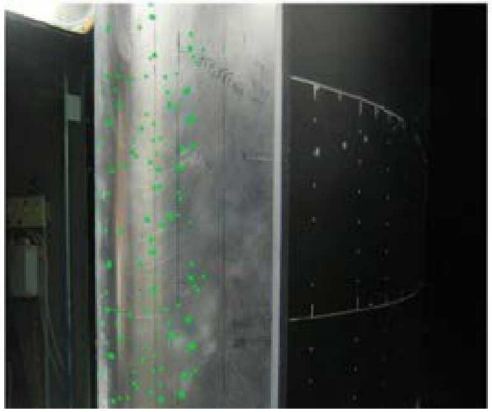


Smooth leading edge laminar/turbulent flow state



Low-*k* leading edge laminar/turbulent flow state

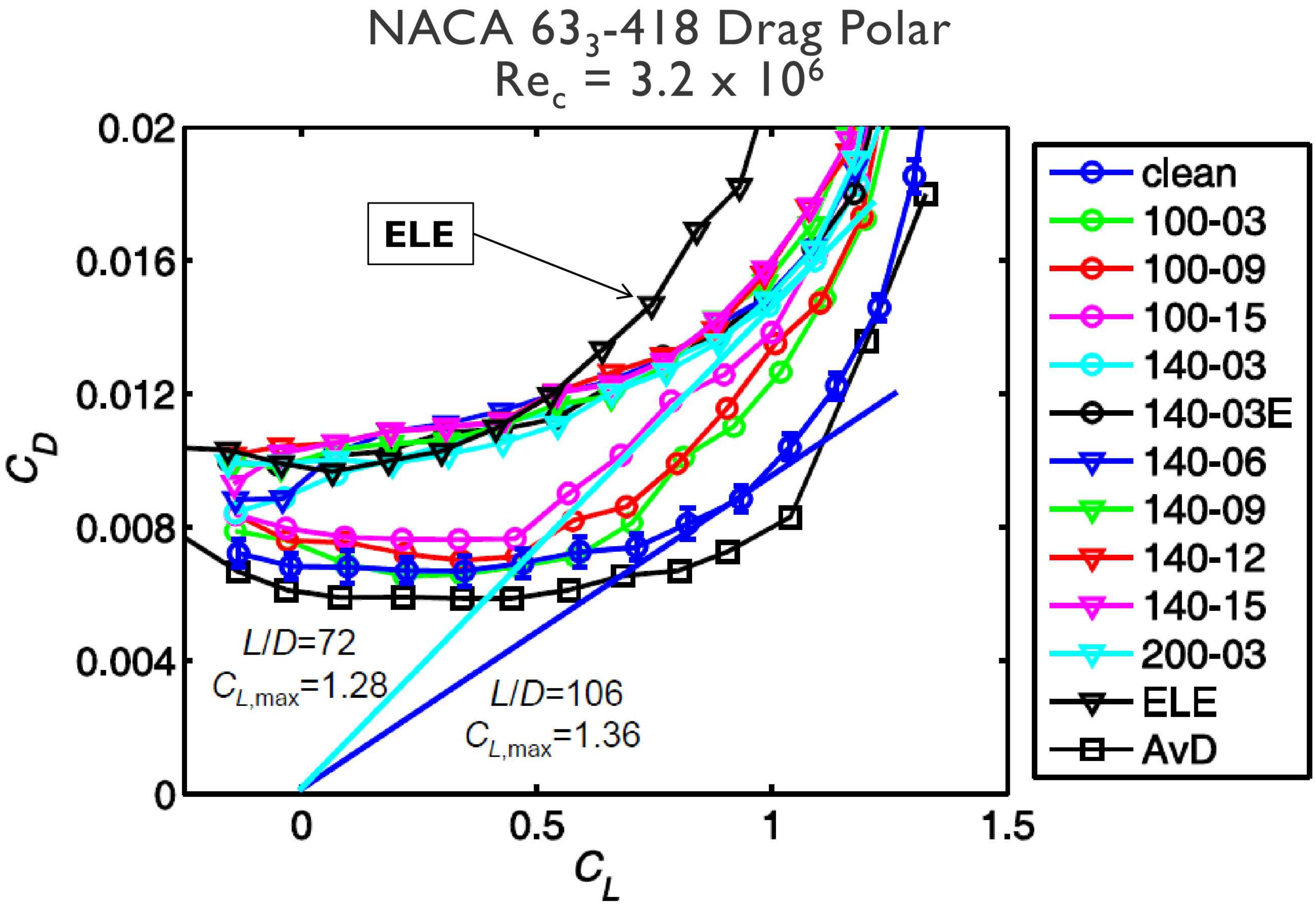




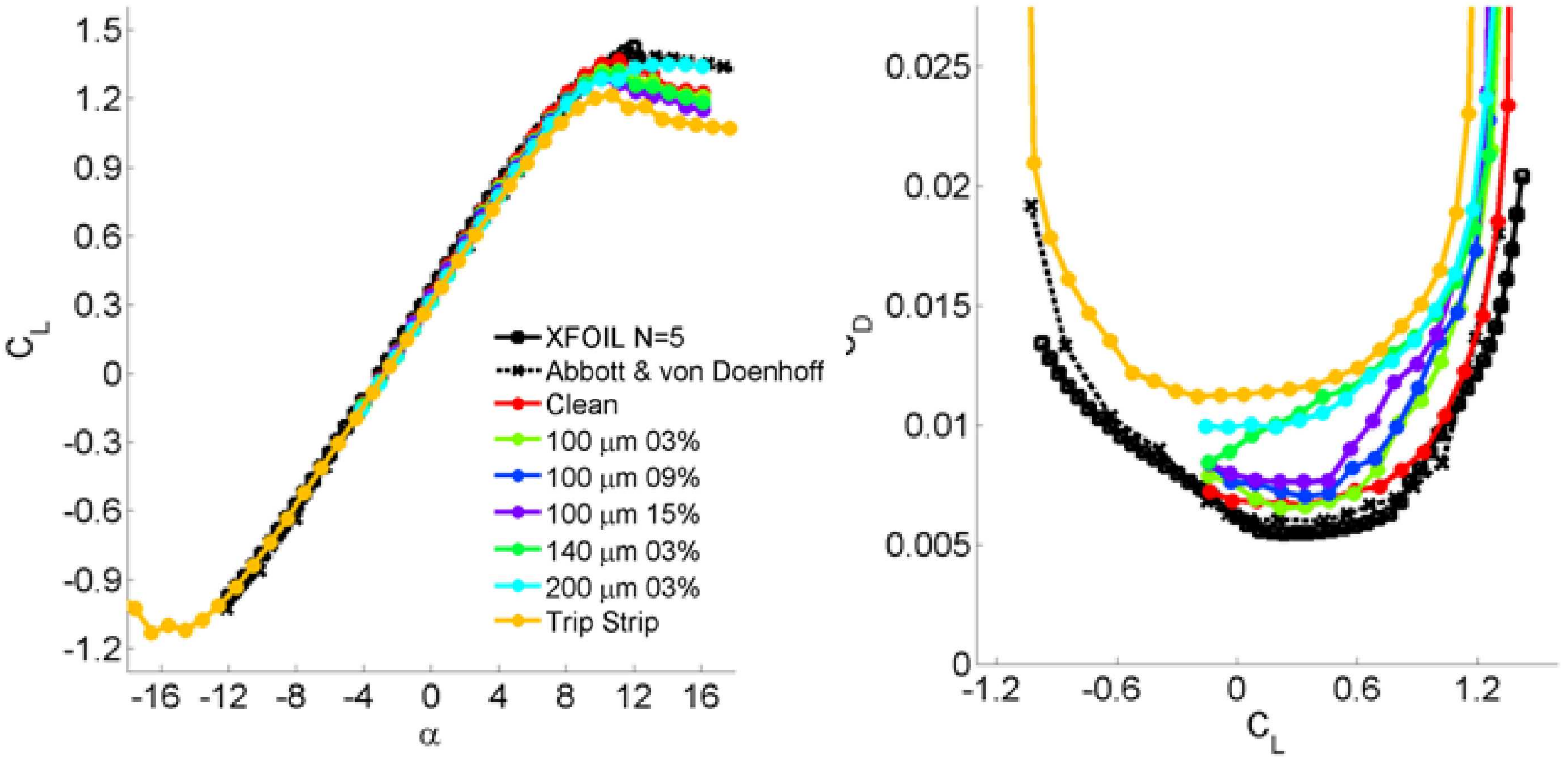
a2e.energy.gov/projects/lees

energy.sandia.gov

Wind Tunnel Testing: Lift and Drag (Model Validation)

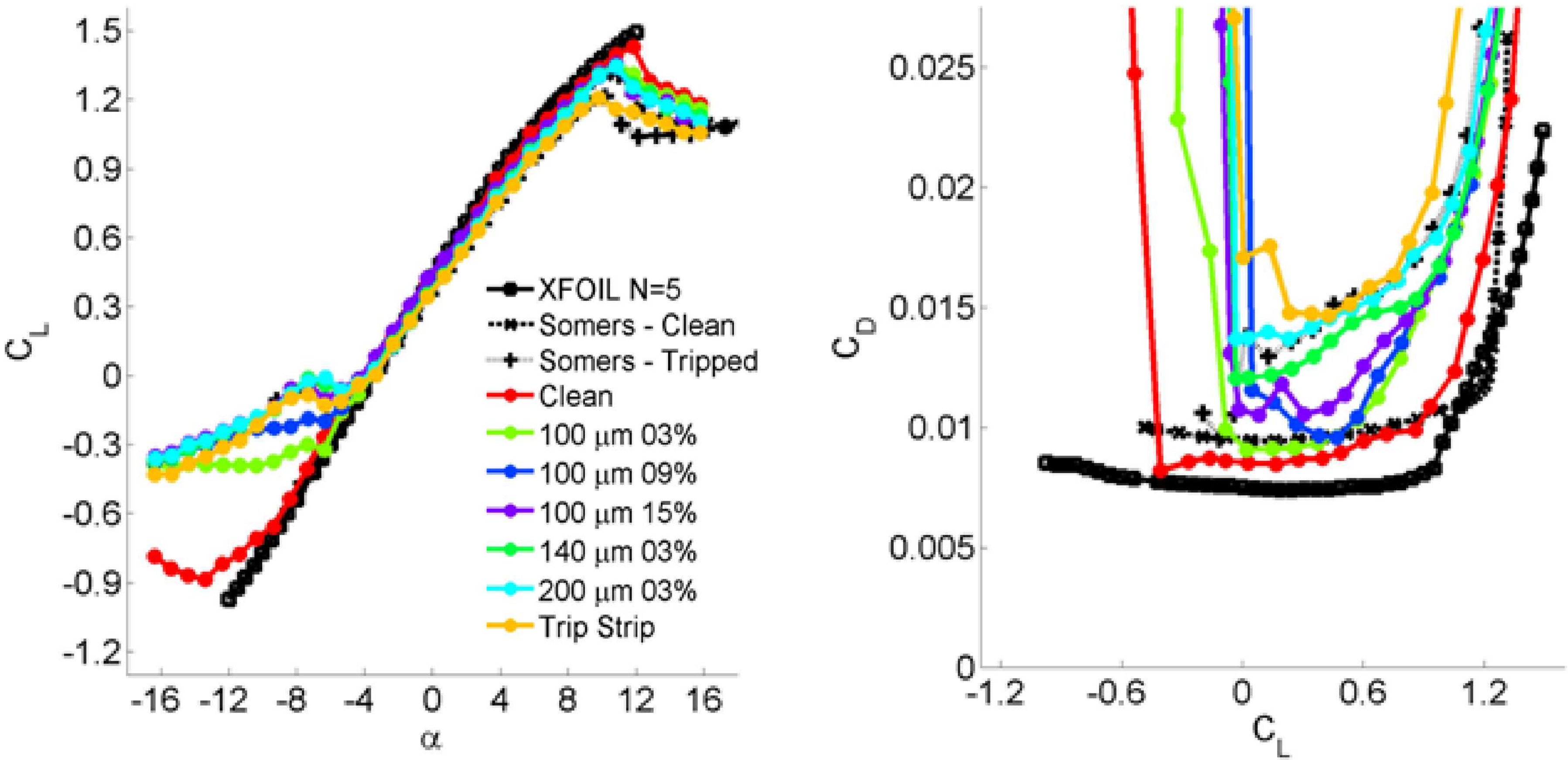


NACA 63_3-418



Lift and drag data for NACA 63_3-418 airfoil for various roughness conditions at Re = 3.2×10^6

SERI S814



Lift and drag data for SERI S814 airfoil for various roughness conditions at $Re = 3.2\times10^6$

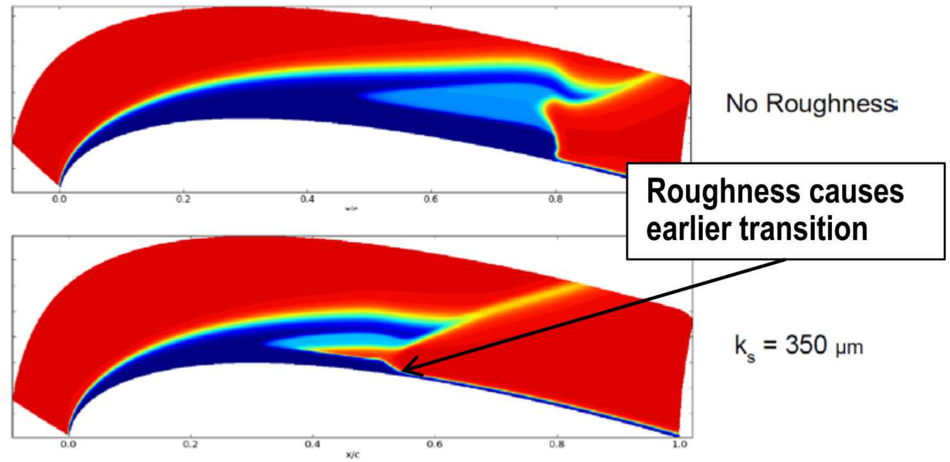
Reynolds Number Effects

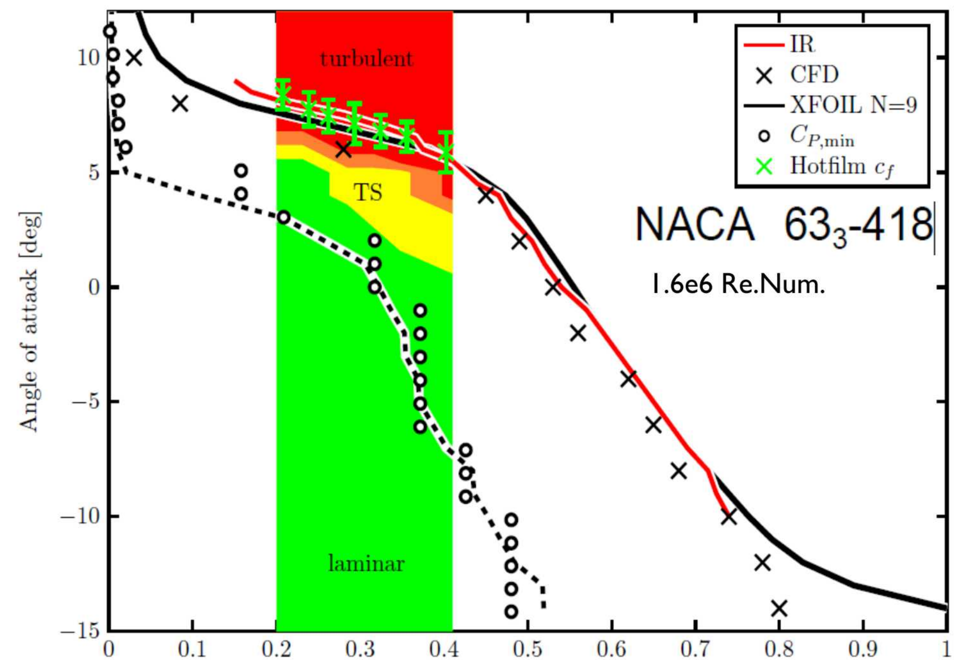
	S814 Clean			S814 Rough, 140um_03%		
ReynoldsNumber:	dCL/dalfa (1/rad)	cL_{max}	$(cL/cD)_{max}$	dCL/dalfa (1/rad)	cL_{max}	$(cL/cD)_{max}$
Re1.6e6	6.1	1.33	99.33	5.85	1.26	76.21
Re2.4e6	1.6%	3.8%	-10.3%	-6.6%	3.6%	-22.3%
Re3.2e6	2.6%	8.1%	-12.7%	0.8%	6.7%	-23.0%

	NACA 63_3-418 Clean			NACA 63_3-418 Rough, 140um_03%		
ReynoldsNumber:	dCL/dalfa (1/rad)	cL_{max}	$(cL/cD)_{max}$	dCL/dalfa (1/rad)	cL_{max}	$(cL/cD)_{max}$
Re1.6e6	6.73	1.31	146.53	6.58	1.24	104.18
Re2.4e6	-0.2%	1.9%	-26.6%	-4.0%	3.4%	-30.9%
Re3.2e6	-0.6%	5.1%	-27.9%	-0.6%	6.1%	-34.1%

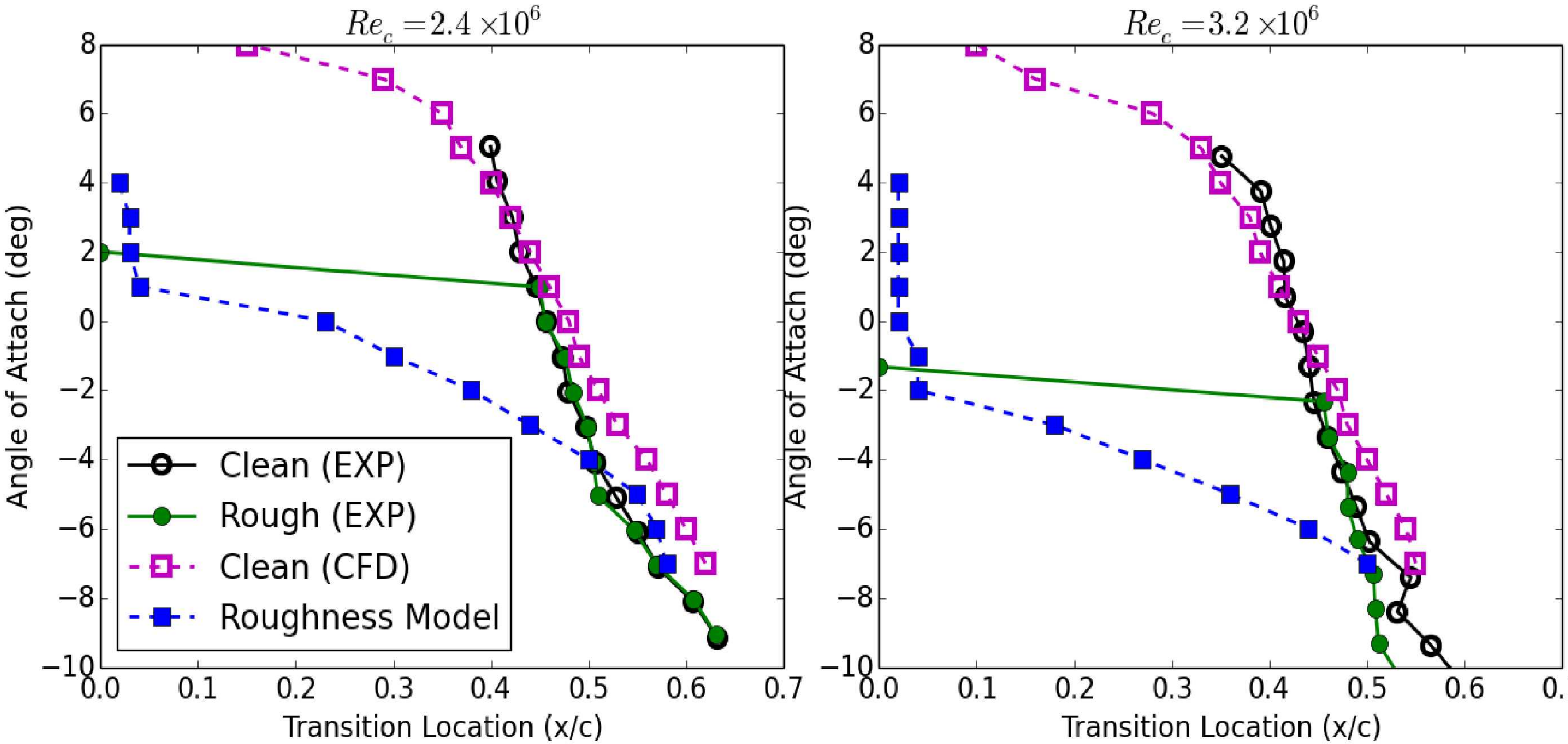
Model Development

- Created CFD model of leading edge erosion
- Tight interaction between modelers and experimentalists
- Detailed calibration and validation of model
- Two equation Turbulence Model w/ Transition Model and Roughness Model
  - Langtry-Menter paired with “Roughness Amplification” model increases system to five equations

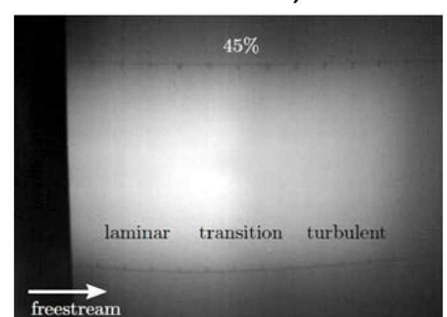




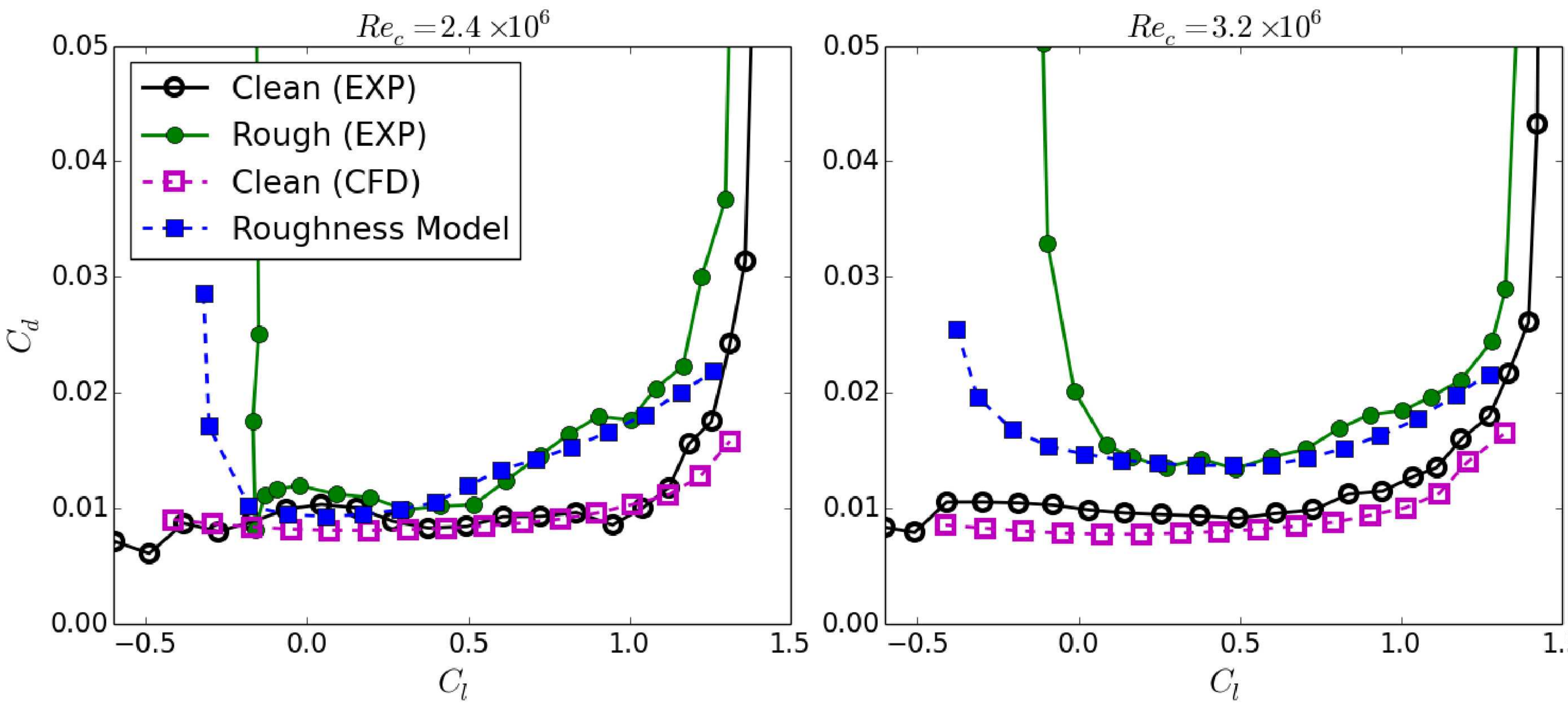
Model Application: Tuning



- Transition locations for upper surface of the SERI S814 airfoil for clean and rough configurations, roughness height 140 μm ($k/c = 172 \times 10^{-6}$) at 03% density roughness applied



Model Application: Validation



- Drag polars for the SERI S814 airfoil for clean and rough configurations, roughness height 140 μm (k/c = 172 × 10^{-6}) at 03% density roughness applied

Model Application: AEP Loss Prediction, NREL 5MW

Performance Prediction Using Computational Roughness Model

Analyzed NREL 5MW offshore turbine design

Airfoils analyzed using OVERFLOW-2 in both "clean" and a "rough" configuration corresponding to heavy soiling

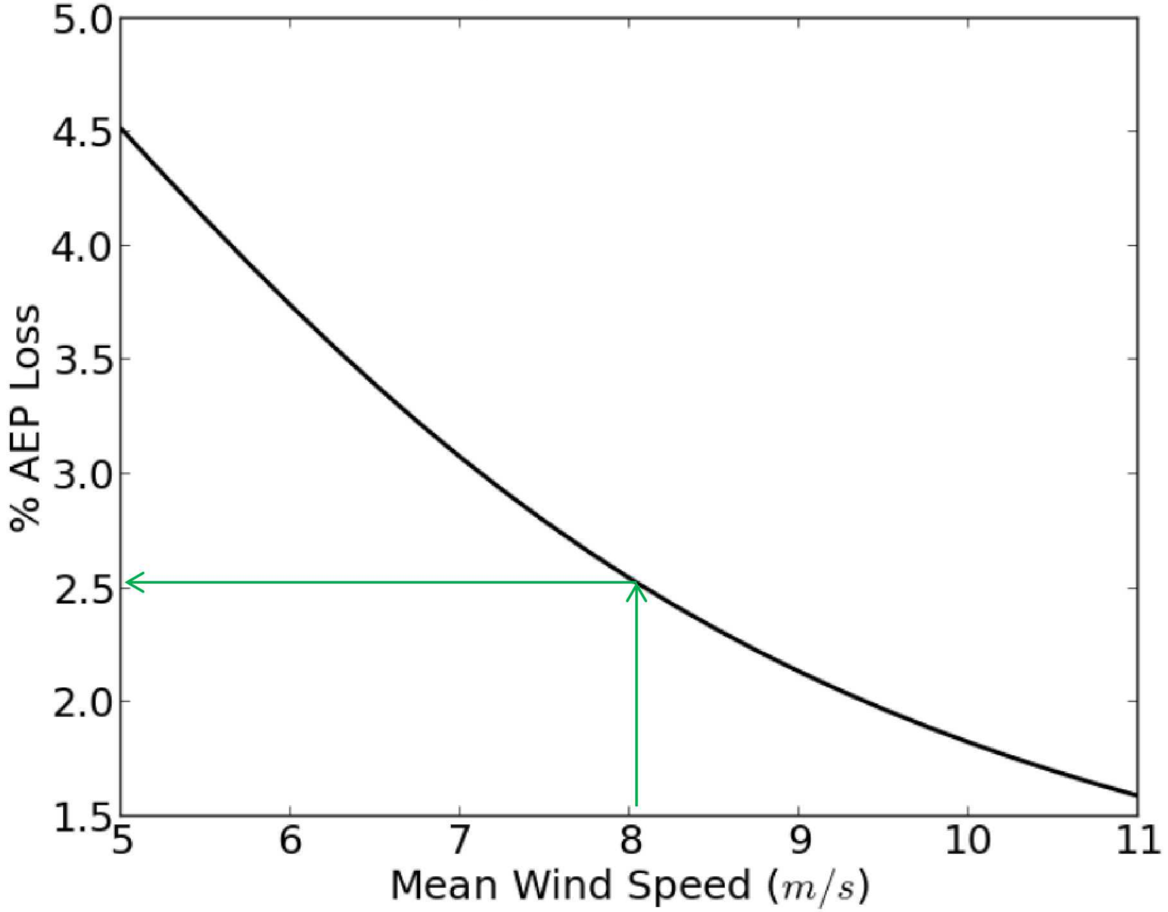
Roughness applied from 5% chord on lower to 5% chord on upper surface

Height of roughness set at $k/c = 240 \times 10^{-6}$

- k = 0.24 mm or 0.001 in. for a chord of 1 m

Case	Reduction in max C_l	Reduction in max L/D
140 μm at 15% (exp)	-7%	-42.0%
DU-97-W-300 (CFD)	-9.8%	-20.2%
DU-91-W2-250 (CFD)	-7.9%	-23.7%
DU-93-W-210 (CFD)	-15.2%	-24.8%
NACA 64-618 (CFD)	-8.3%	-34.0%

Model Application: AEP Loss Prediction, NREL 5MW



Predicted AEP loss for NREL 5-MW due to leading edge roughness

Power loss in Region II is ~ 5%

a2e.energy.gov

https://a2e.energy.gov/projects/lees

energy.sandia.gov

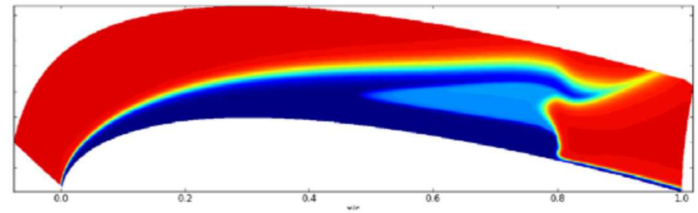
https://energy.sandia.gov/energy/renewable-energy/wind-power/blade-reliability/leading-edge-erosion/

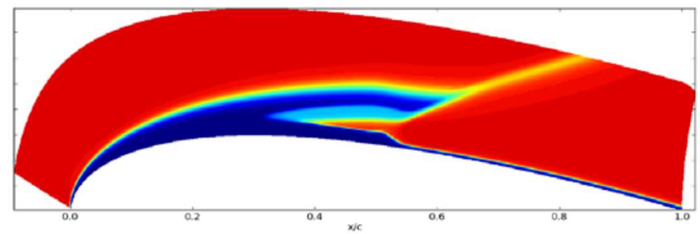
V&V: Integrated Model Planning and Execution

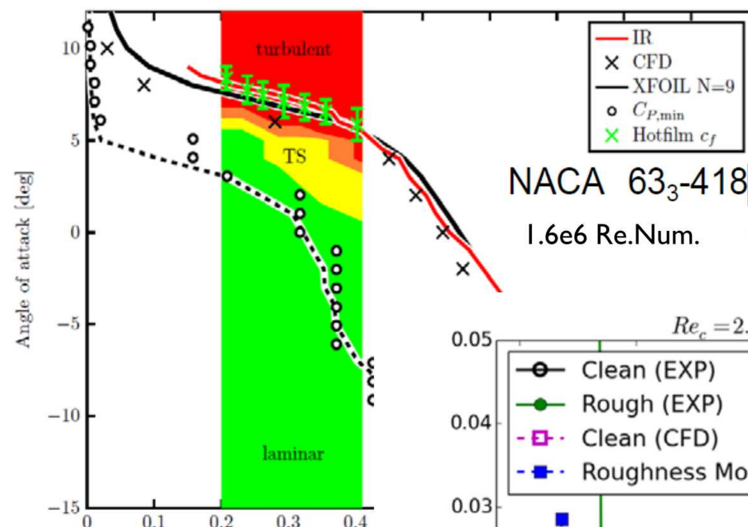
Model Development
- Concept
- Equation derivation
- Numerical implementation
- Verification

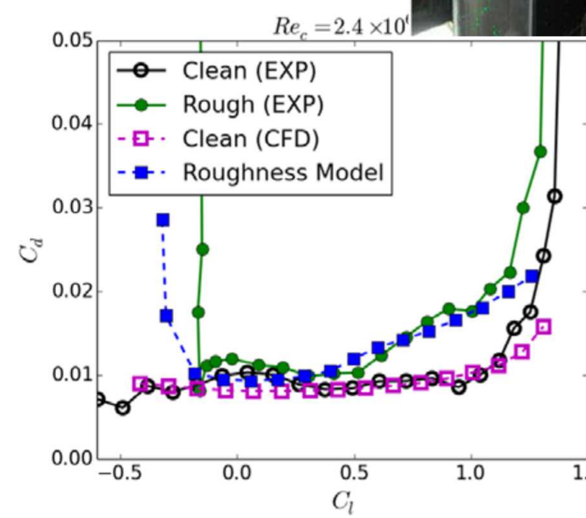
Calibration
- Experimentation
- Data Assimilation
- Uncertainty Analysis

Validation
- Experimentation
- Data Assimilation
- Comparison
- Uncertainty Quantification
- Credibility Assessment



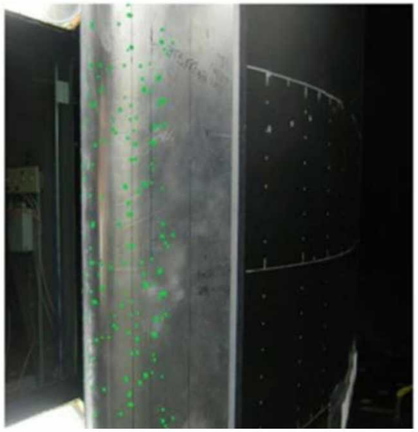






On the Leading Edge of Leading Edge Erosion

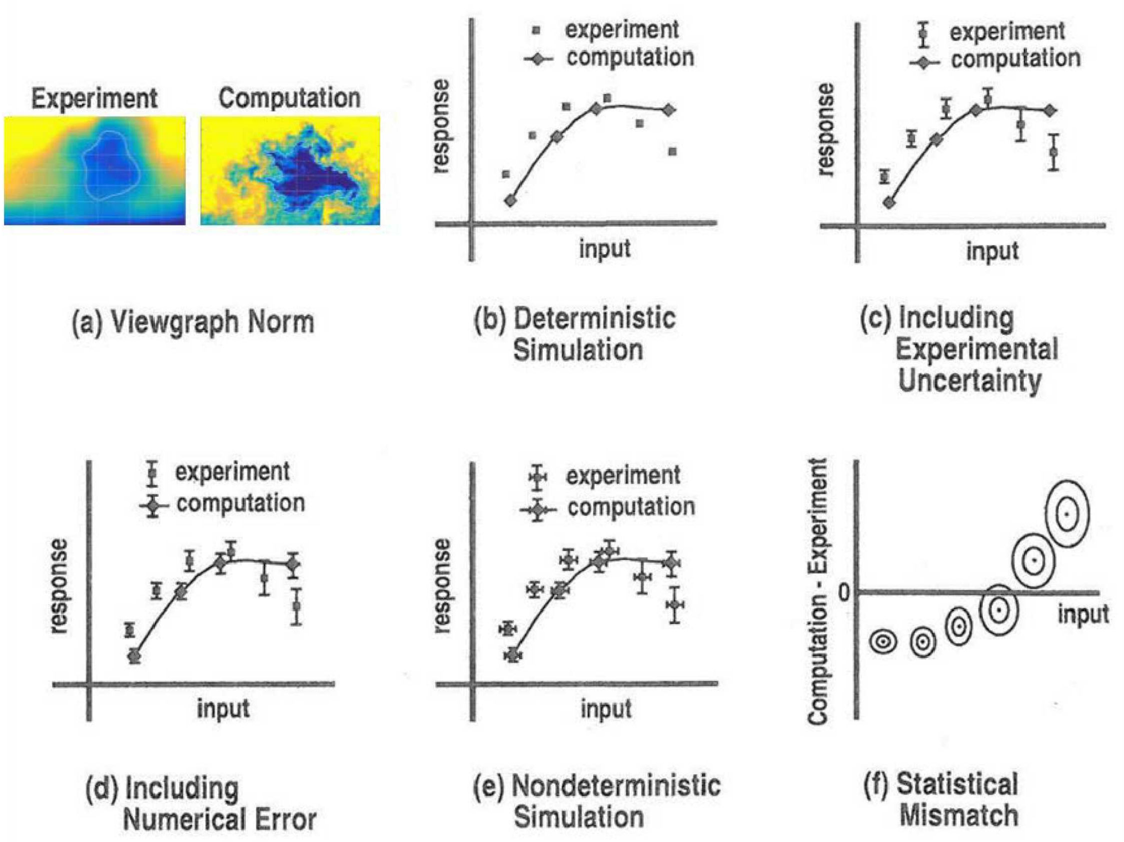
- Impact of Turbulence Intensity and Turbulence Spectra on roughness effects
- Reynolds number, airfoil thickness, and airfoil design impacts
- Probabilistic models of AEP and O&M:
  - Rain, Hail, bugs, dirt, etc.
  - Mechanical erosion material variability
  - Operational Variability (RPM, yaw, pitch)
  - Performance uncertainty (airfoils, surface, repairs, etc.)
- Design of add-ons and airfoils to mitigate performance impact
- Control of turbines to balance AEP and O&M
  - Value of power now vs. later



Uncertainty Quantification and High Fidelity Modeling

- Uncertainty Quantification (UQ) is critical to enable predictive numerical simulation for scientific discoveries and advanced engineering design.

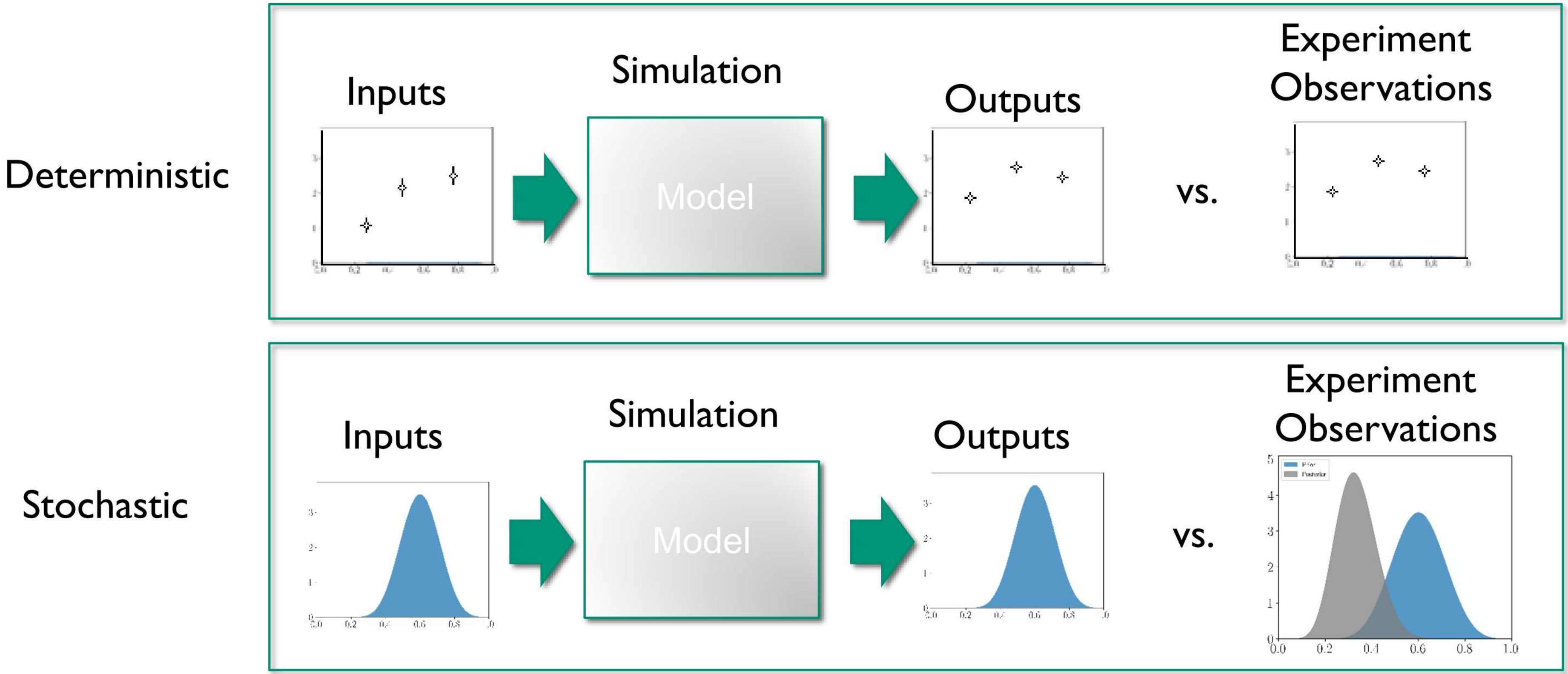
Levels of Precision



Modified from Oberkamf and Roy, 2012

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

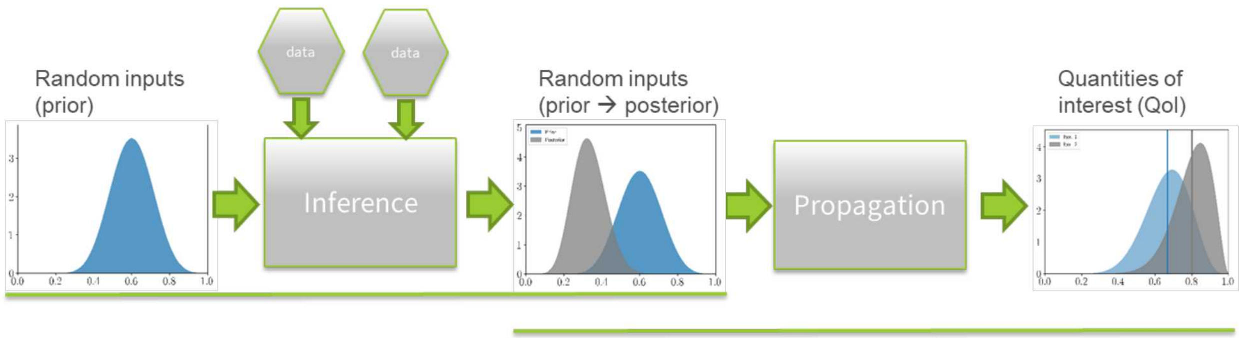


Modified from M. Eldred, 2019

Uncertainty Quantification Workflow

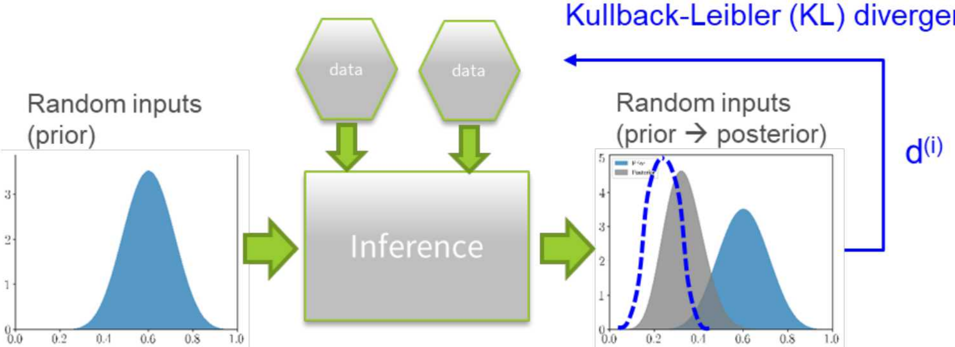
Characterization of input uncertainties through assimilation of data

Propagation of input uncertainties to response QoI

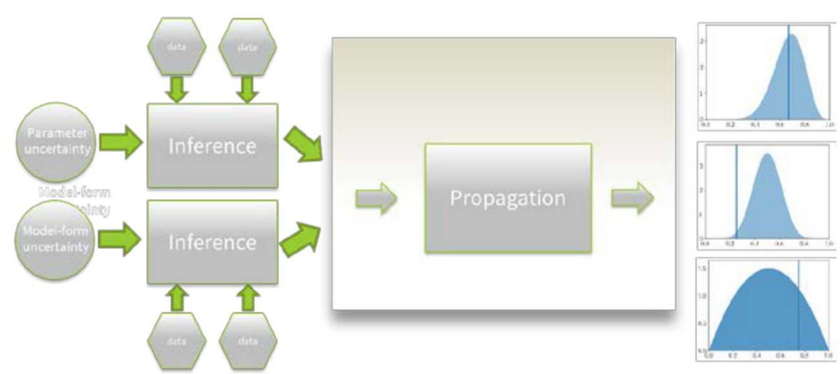


Optimal Experimental Design (OED) Workflow

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



Summary of Wind UQ Studies under A2e

Previous: Forward UQ

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

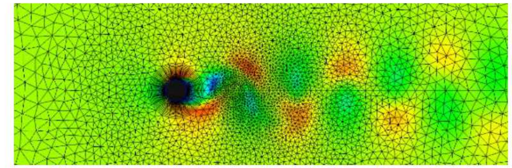
Current: Inverse UQ

- Infer upstream conditions from SwiFT data sets
  - OpenFAST + WindSE (+ Nalu)

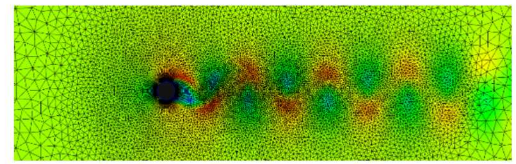
Future: OED / OUU

- 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.

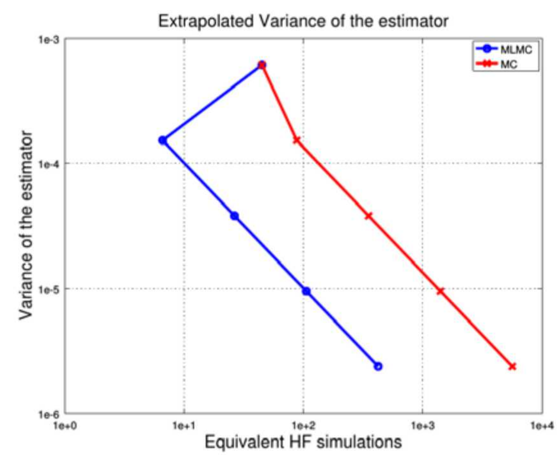


Medium Mesh: 4 hours time to soln.



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

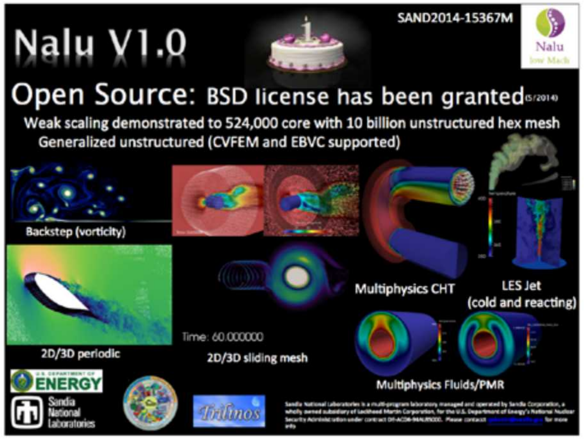
TABLE: Optimal MLMC samples allocation Vs MC allocation



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.

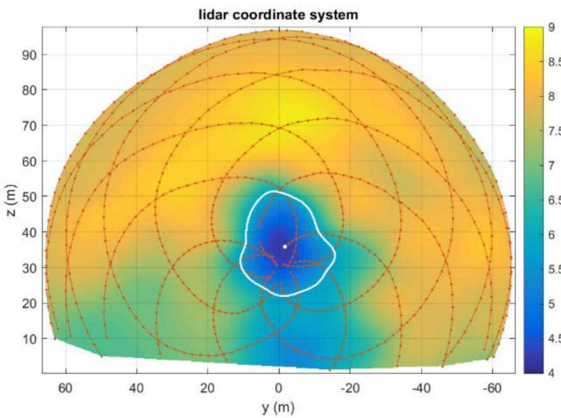
Case	Mesh size	Simulation time (seconds)	CPUs	Cost (CPU-hours)	Cost (relative)
OpenFAST		500	1	0.42	1
Coarse	100x50x50	2000	80	240	576
Medium	200x100x100	2000	160	960	2304
Fine	400x200x200	2000	400	6860	16500
Reference	800x200x200	2000	400	38400	91400

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

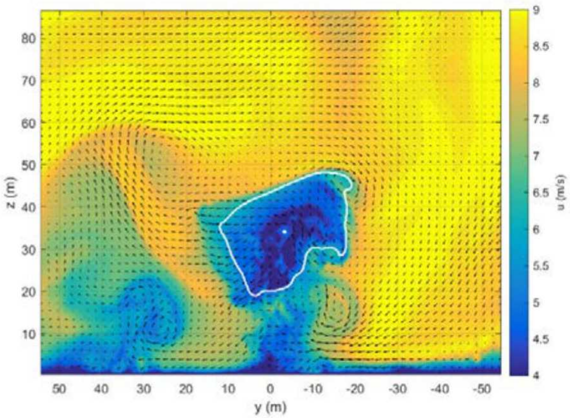
Wake comparison, Measured and Simulated Lidar

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.



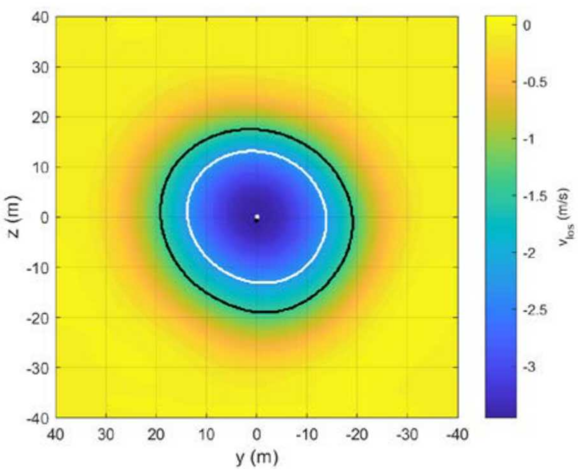
Sample of the wake date from the measured Spinnerlidar at the SWiFT facility.



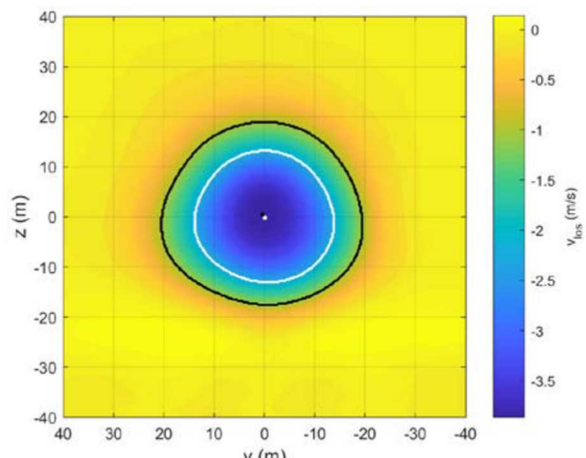
Nalu-Wind Simulated wake data 5D downwind.

	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

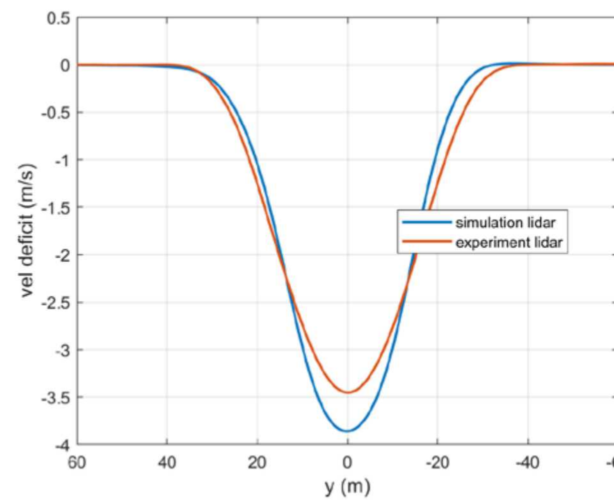
Upstream turbine (WTGa1) comparison between experimental and simulation results of the 10-minute averages of the mean out-of-plane (OOP) blade-root bending moment for the three blades (kN m), relative flapwise DEM (simulation/experiment) and generator power (kW) for yaw = 0° case.



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.

Turbine Innovation and Model Validation

(12) **United States Patent**
Kelley et al.

(10) **Patent No.:** **US 10,400,743 B1**
(45) **Date of Patent:** **Sep. 3, 2019**

(60) Provisional application No. 62/096,644, filed on Dec. 24, 2014.

(51) **Int. Cl.**
F03D 1/06 (2006.01)

(52) **U.S. Cl.**
CPC ***F03D 1/0633*** (2013.01)

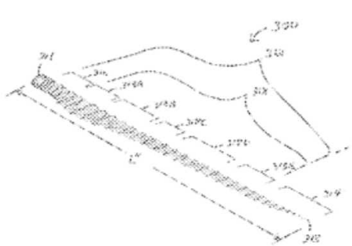
(58) **Field of Classification Search**
CPC F03D 1/0633
See application file for complete search history.

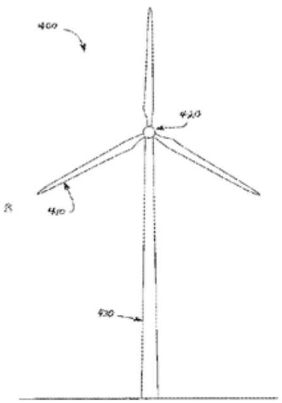
(74) *Attorney, Agent, or Firm* — Daniel J. Jenkins

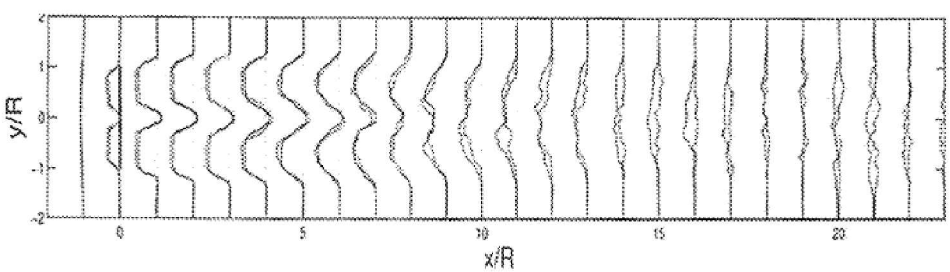
(57) **ABSTRACT**

A wind turbine blade having a geometry that decreases the distance downstream at which freestream momentum is recovered is disclosed. The blade design increases the loading on the inboard portion of the blade and unloads the tip portion relative to a conventional blade designed to maximize power coefficient. A wind farm having a reduced inter-turbine distance and including one or more wind turbines having the new blade designs is also disclosed.

15 Claims, 10 Drawing Sheets







- How will a computational model be used to predict the performance of a new concept?
- Can a computational model be used as the final evidence of the performance of a turbine?
- What physics must the model capture? What model parameters must be calibrated?
- What is the uncertainty in the model predictions? Is uncertainty low enough to make a credible decision?
- What experimental data is needed to calibrate and validate the model?

V&V: Communication and Documentation

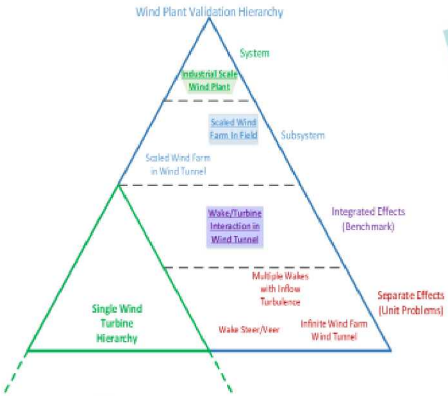
1. **IEA Task 31, Wakebench.** Working toward a collaborative validation process.
    1. WAKEBENCH Best Practice Guidelines for Wind Farm Flow Models First Edition (2015)
    2. WAKEBENCH Model Evaluation Protocol for Wind Farm Flow Models First Edition (2015)

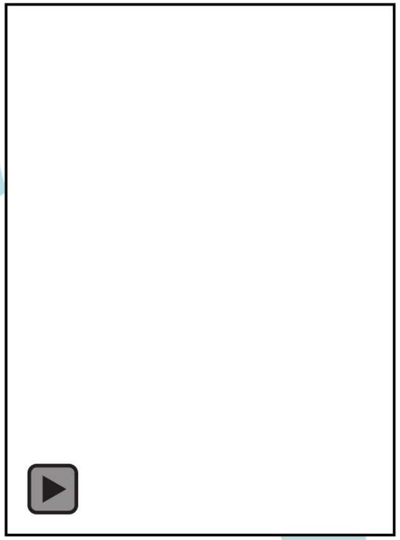
2. **V&V Framework** (September 2015): the development and execution of coordinated modeling and experiential programs to assess the predictive capability of computational models of complex systems through focused, well structured, and formal processes.

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.

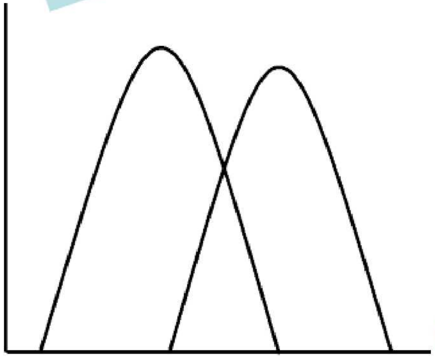
5. **A2e High Fidelity Modeling Validation Roadmap** (October 2019): This document outlines a comprehensive validation program for high fidelity wind plant models.

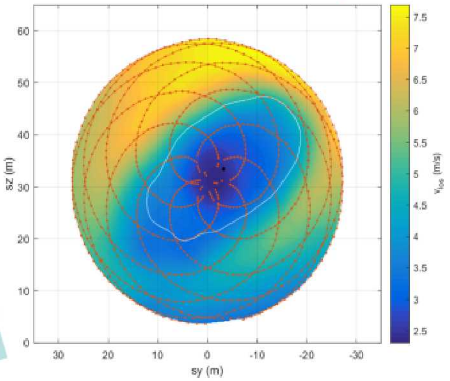




Virtuous Cycle

Validation
Model Development
Experimentation
Uncertainty Quantification

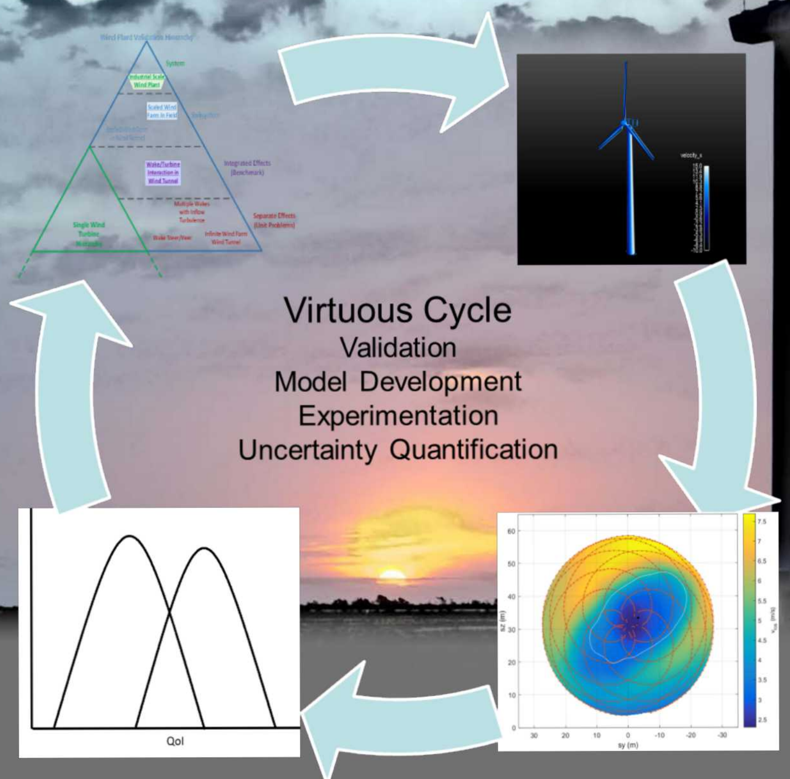




V-27 Nalu Simulation, M. Barone, S. Domino, and C. Bruner, 2017

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.



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

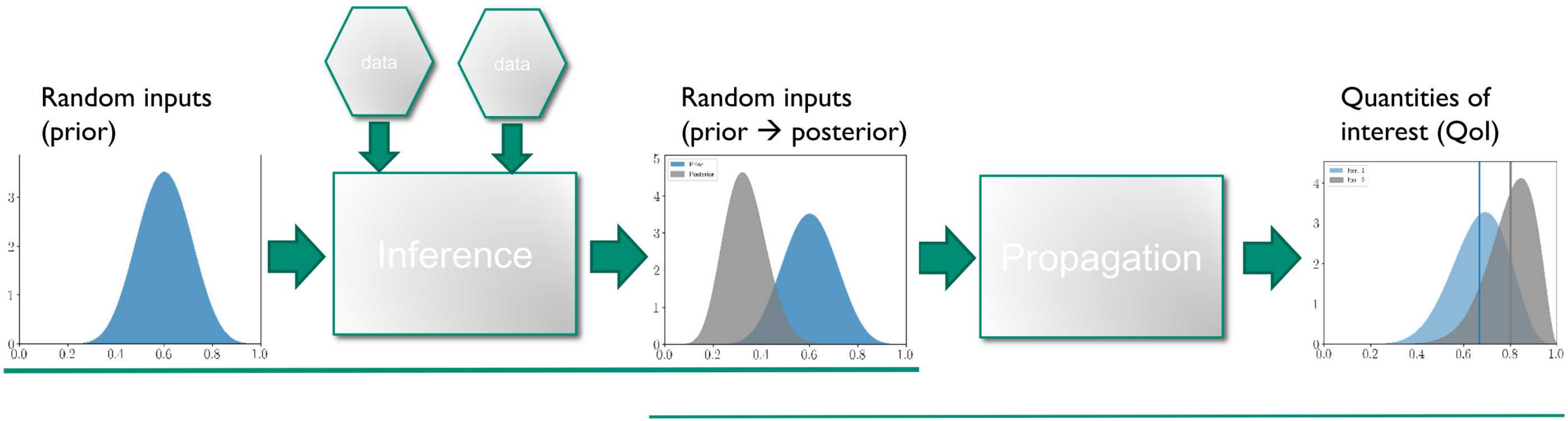
Develop and demonstrate uncertainty quantification tools and processes for wind energy applications

Engage with the public to disseminate results and progress on a regular basis.

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

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)
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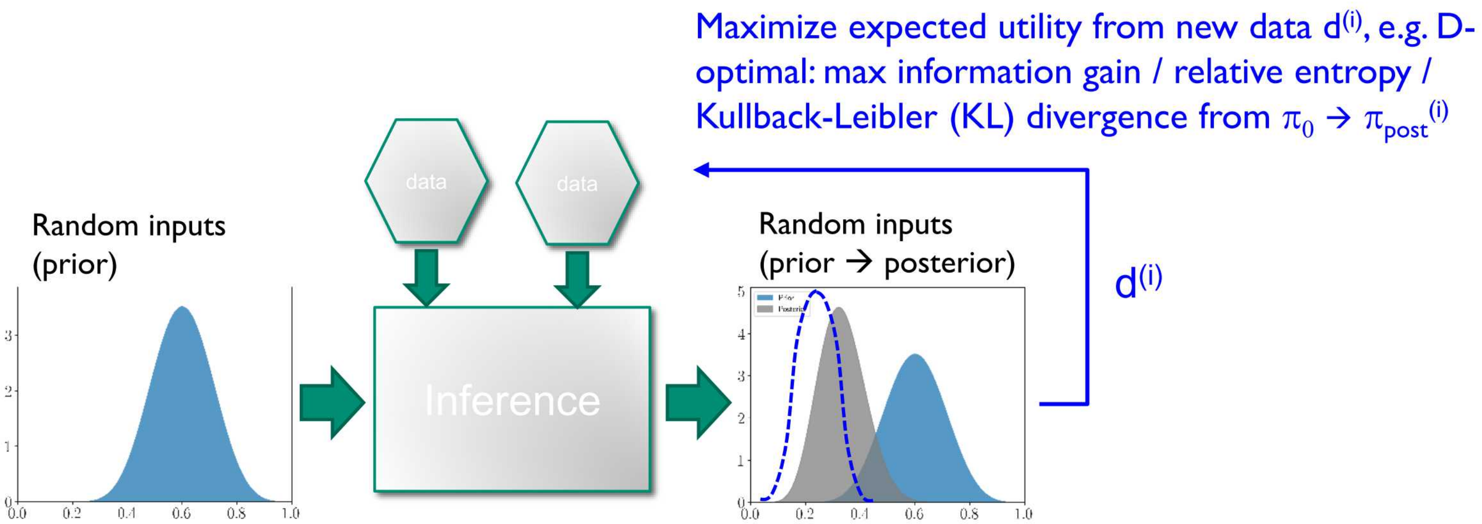


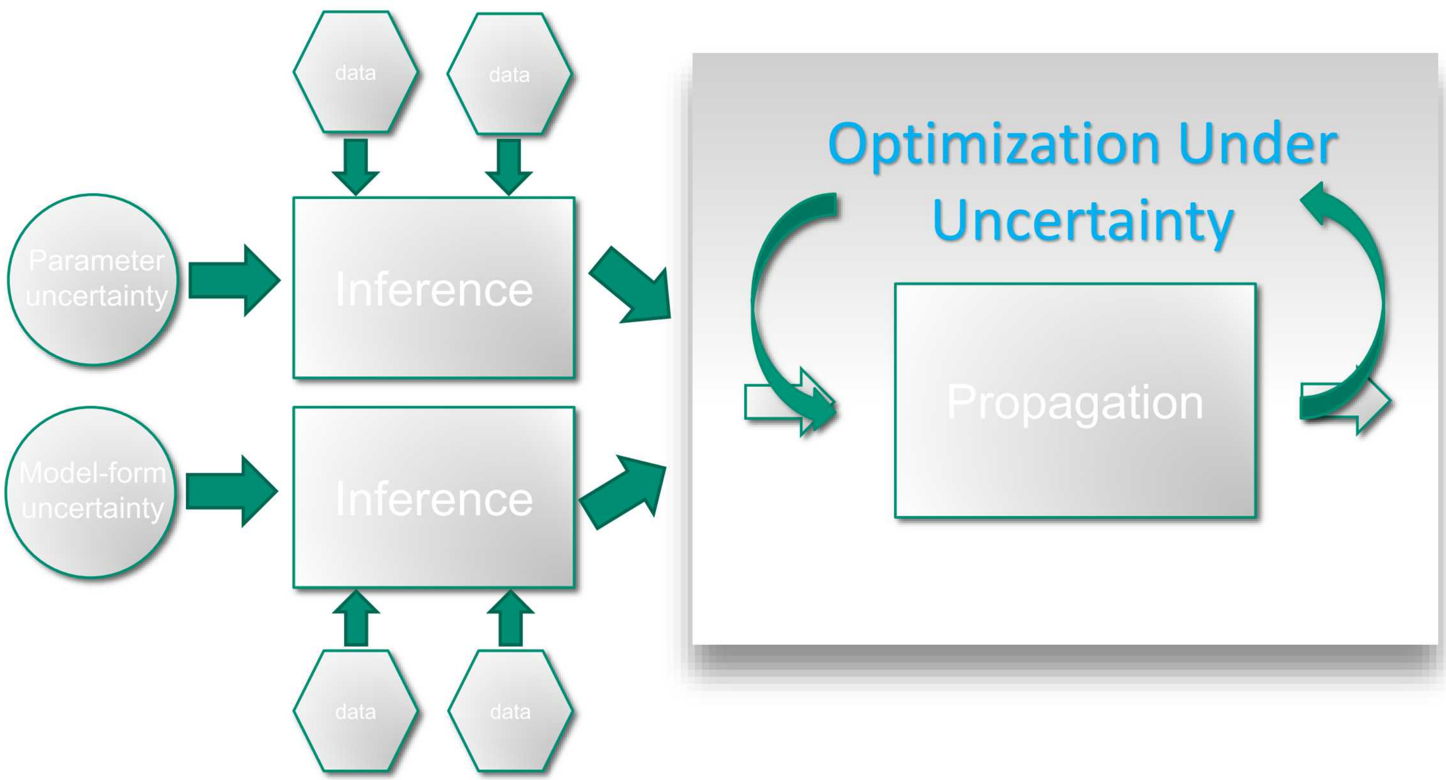
Optimization Under Uncertainty (OUU) Workflow

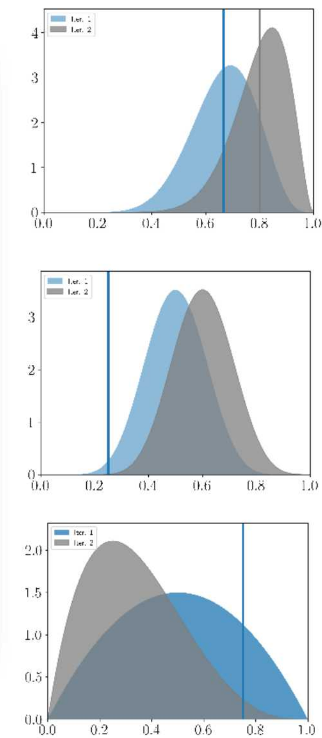
Roll up of capabilities

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

Achieve desired statistical performance

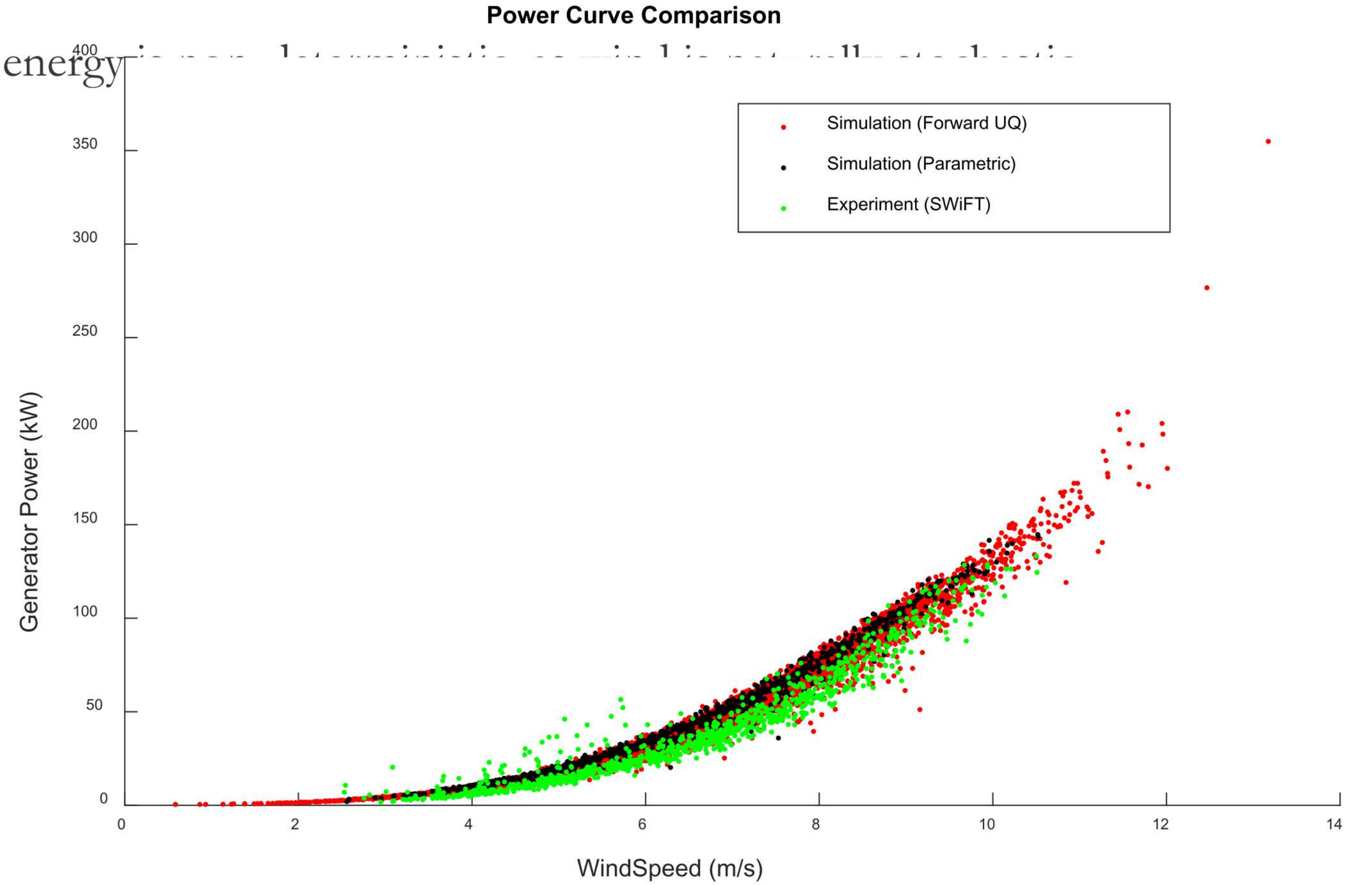
- Common OUU goals:
  - Robustness → minimize QoI variance
  - Reliability → constrain failure probability





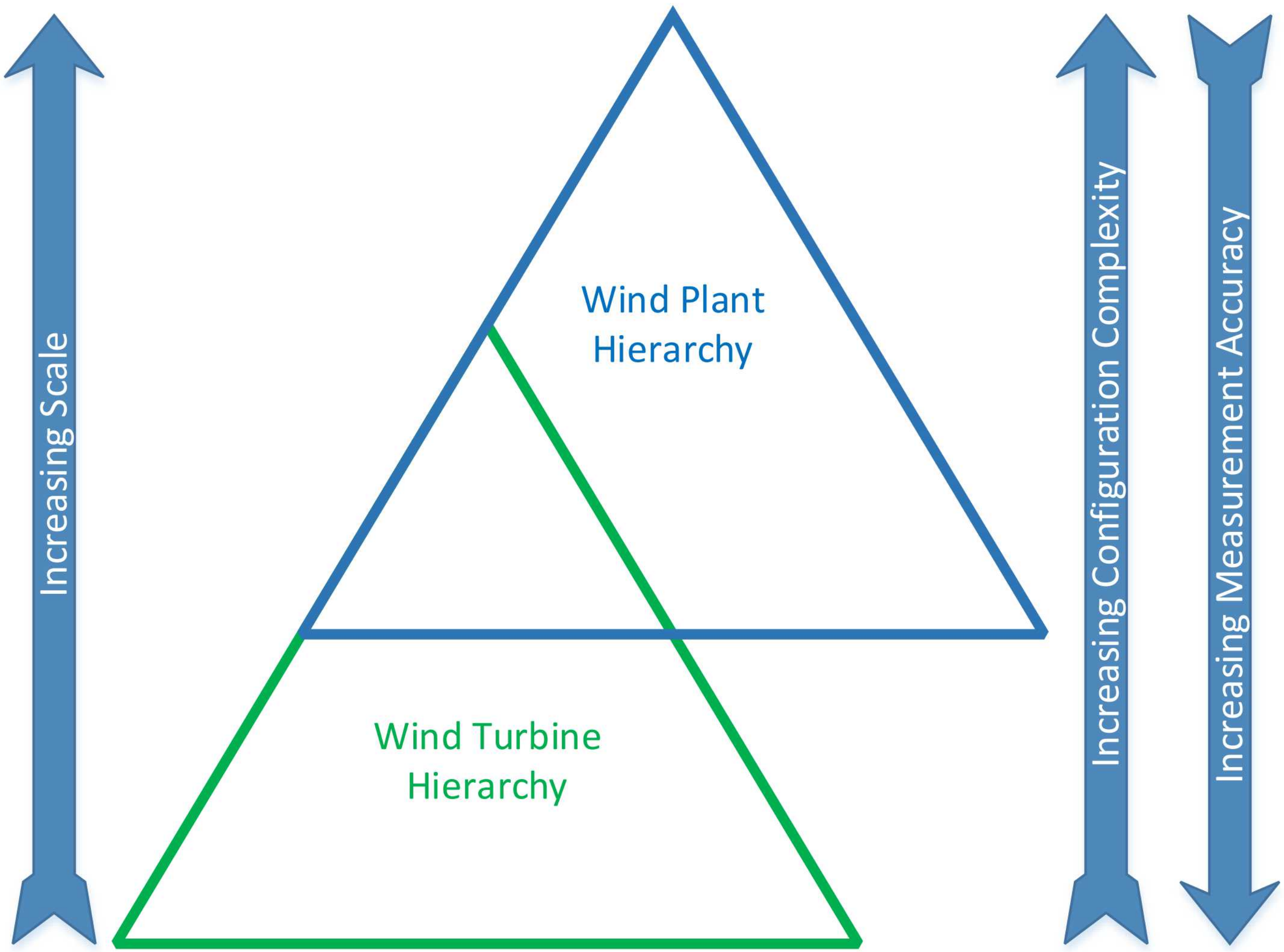
Wind Turbine Power Curve Example

Wind energy

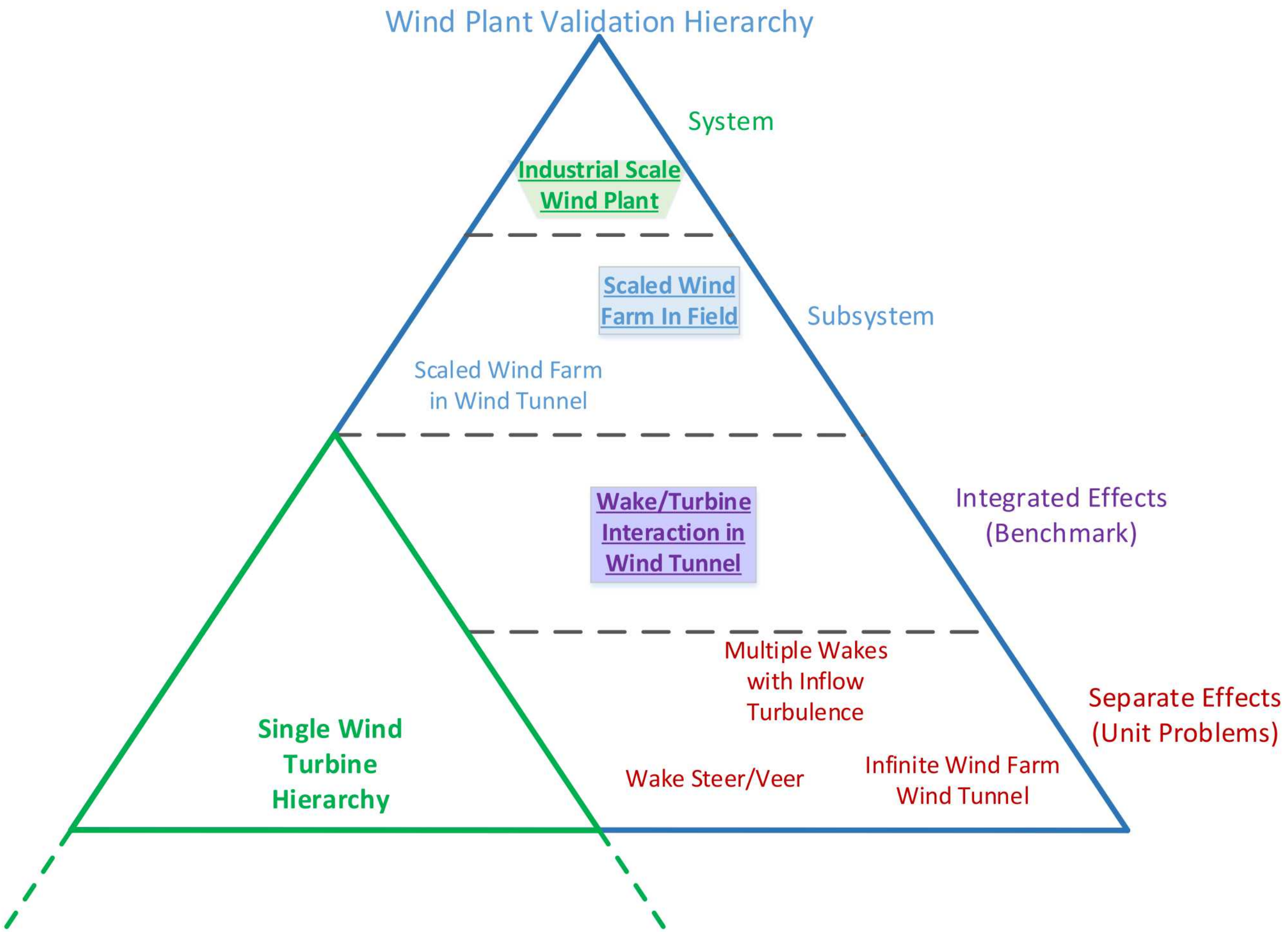


A. Hsieh, WESC 2019

Validation Hierarchy



Wind Plant Validation Hierarchy



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)

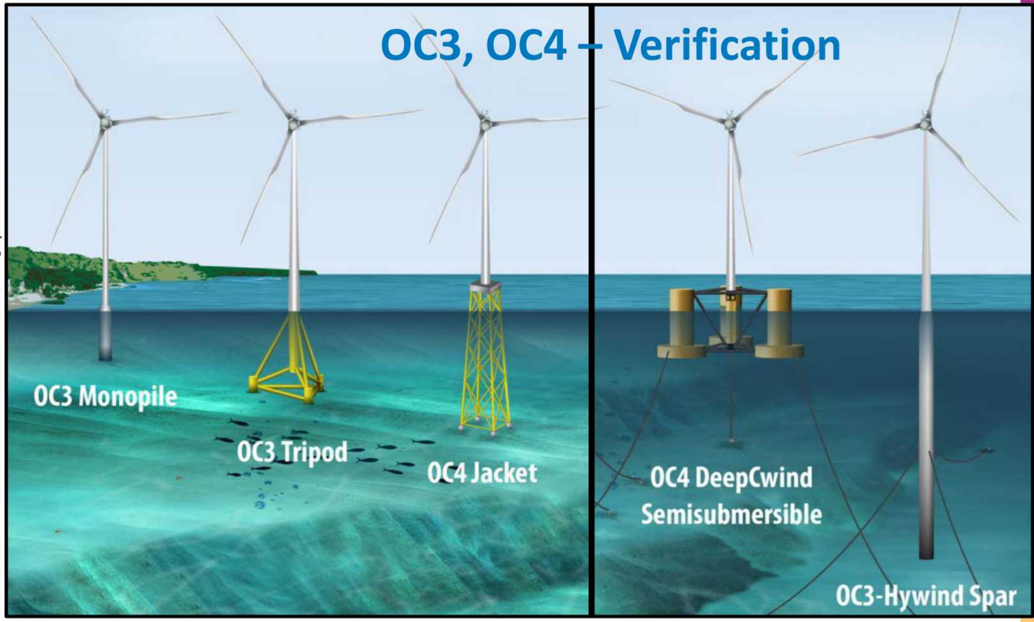
Offshore Code Comparison Collaboration (OC3) – run under IEA Wind Task 30

Verify and validate the engineeringlevel 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

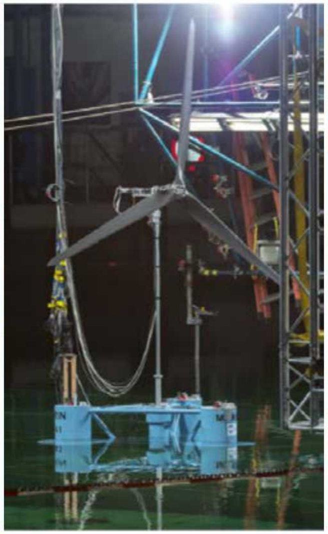
Group models benchmark problems, and compares solutions between codes and to measurement data from scaled testing and full-scale prototypes

- Identify errors, examine differences in modeling theories/approaches, improve tools, train analysts, identify R+D needs



OC5 - Validation

Phase I

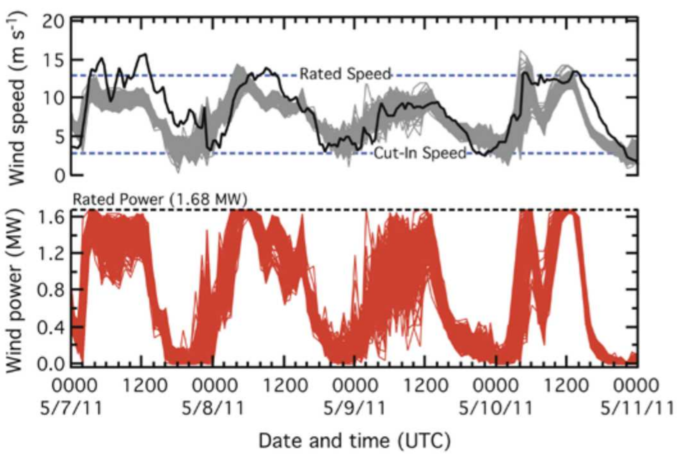


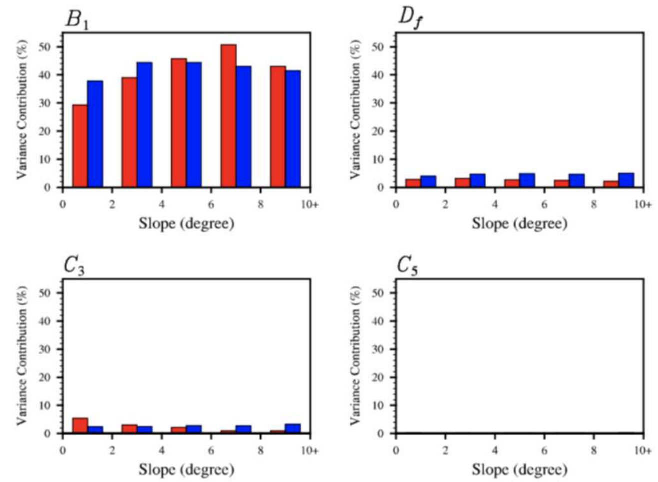
Phase II

Phase III

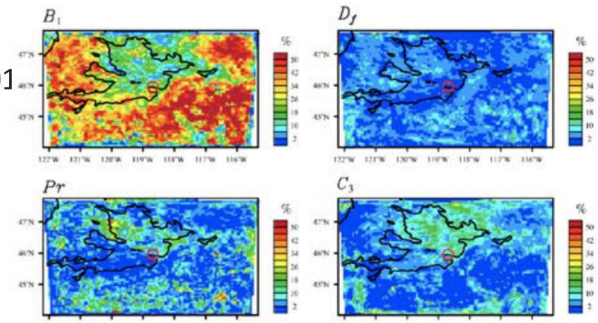
Mesoscale Uncertainty Quantification
(Berg, Kravitz, et al.)

- 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

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?

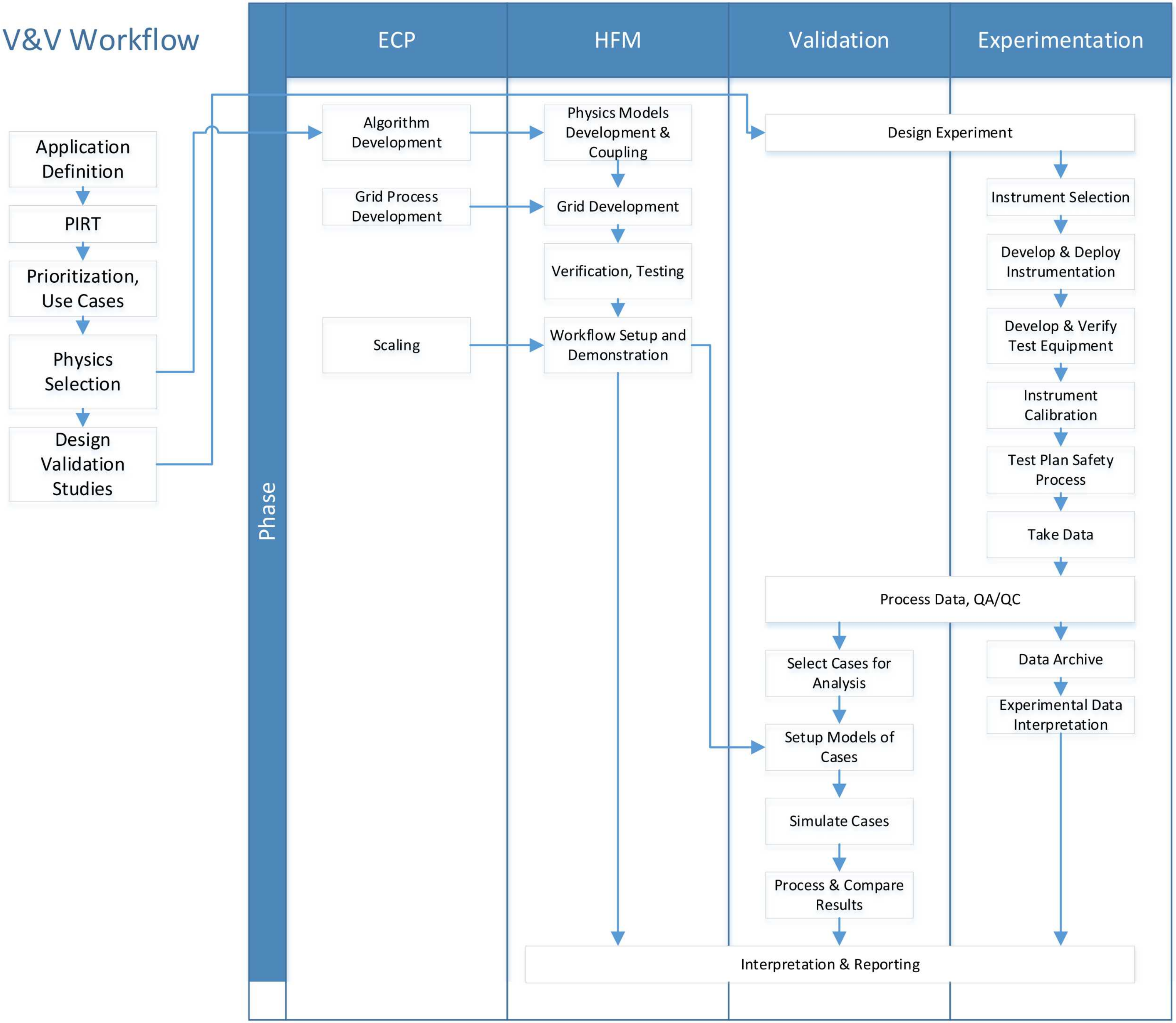
Wake UQ:

- 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



ECP
HFM
Validation
Experimentation
Phase
Application Definition
PIRT
Prioritization, Use Cases
Physics Selection
Design Validation Studies
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