U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

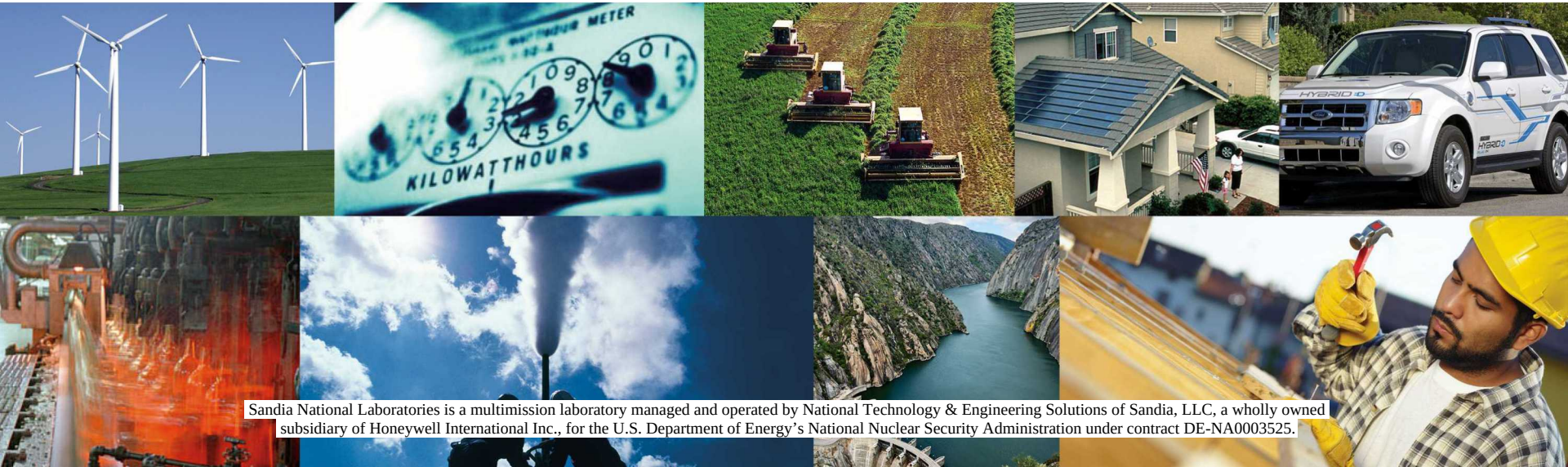
ATMOSPHERE TO ELECTRONS
U.S. DEPARTMENT OF ENERGY

SAND2019-14306PE

# Verification, Validation & Uncertainty Quantification

## SNL, NREL, PNNL

**David Maniaci**
Principle Member of Technical Staff
Sandia National Laboratories
Jonathan Naughton, Mike Eldred, Ryan King
November 21st, 2019

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# V&V/UQ Background and Context

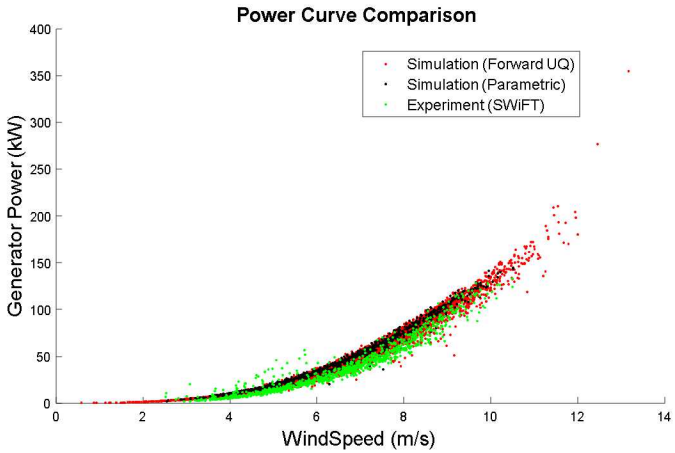
- Transform today's wind plant operating environment through advanced physics-based modeling, analysis, and simulation capabilities

- Approach
  - Development of high fidelity models 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

# Importance of V&V/UQ

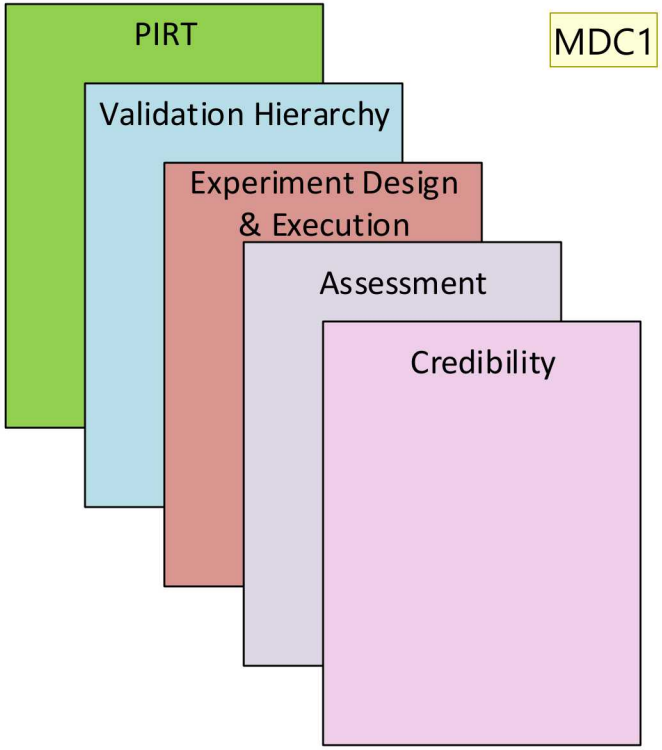
- **Recent reports indicate underperformance of large wind farms due to blockage effects**
  - Lower rate of return
- **The underperformance stems from inadequacy of the models used to predict such effects**
  - Models fail to capture relevant physics
  - New physics requirements are being introduced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

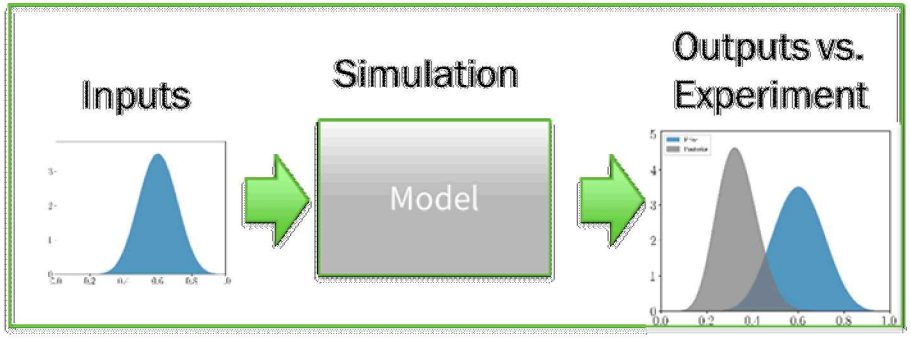
Horns Rev wind farm, DK; Photographer: Christian Steiness. 12 February 2008 at 13.00 (Hassager et al., 2013)



# Importance of V&V/UQ

- V&V/UQ are the processes by which we identify important physics and assess the level to which models capture them
- 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



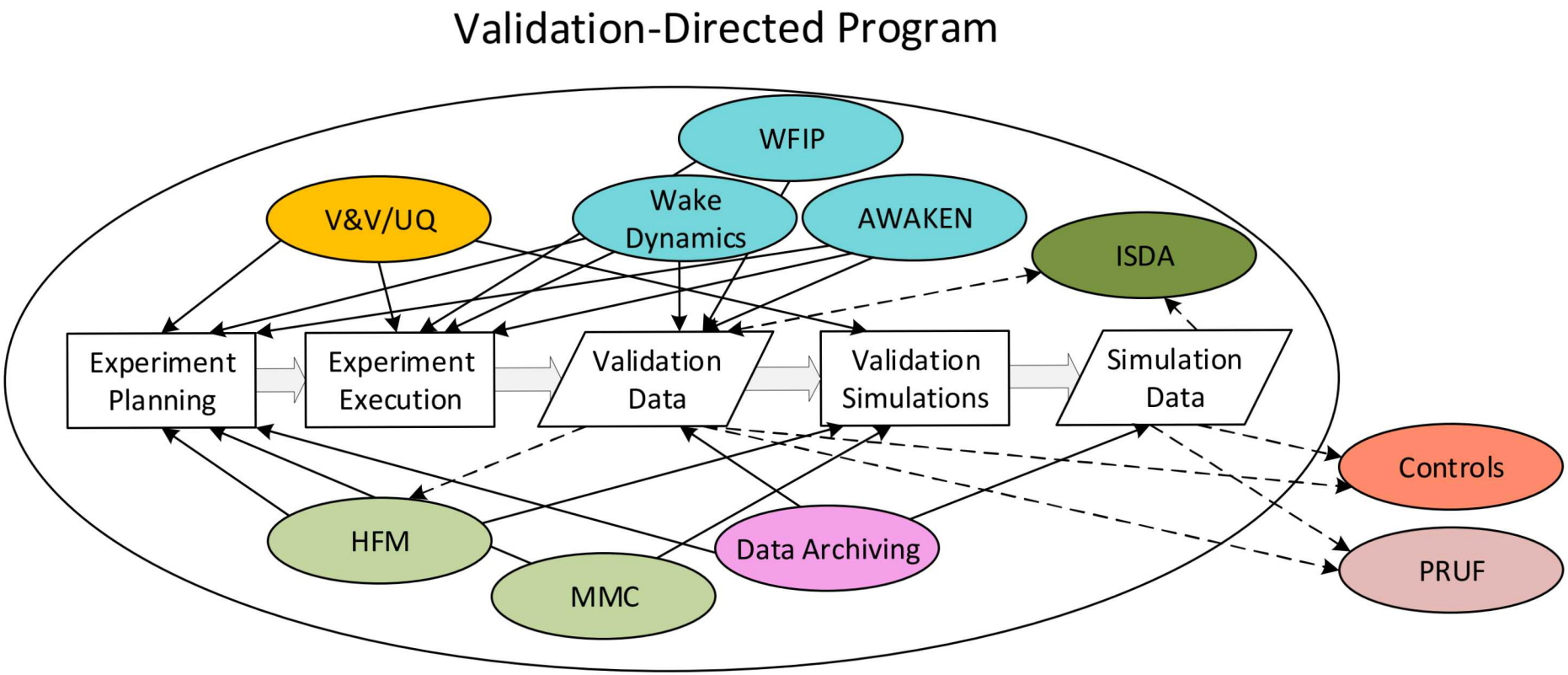
## Slide 4

**MDC1** Change PIRT to "Physics > PIRT"

Maniaci, David Charles, 11/18/2019

# Importance of V&V/UQ

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



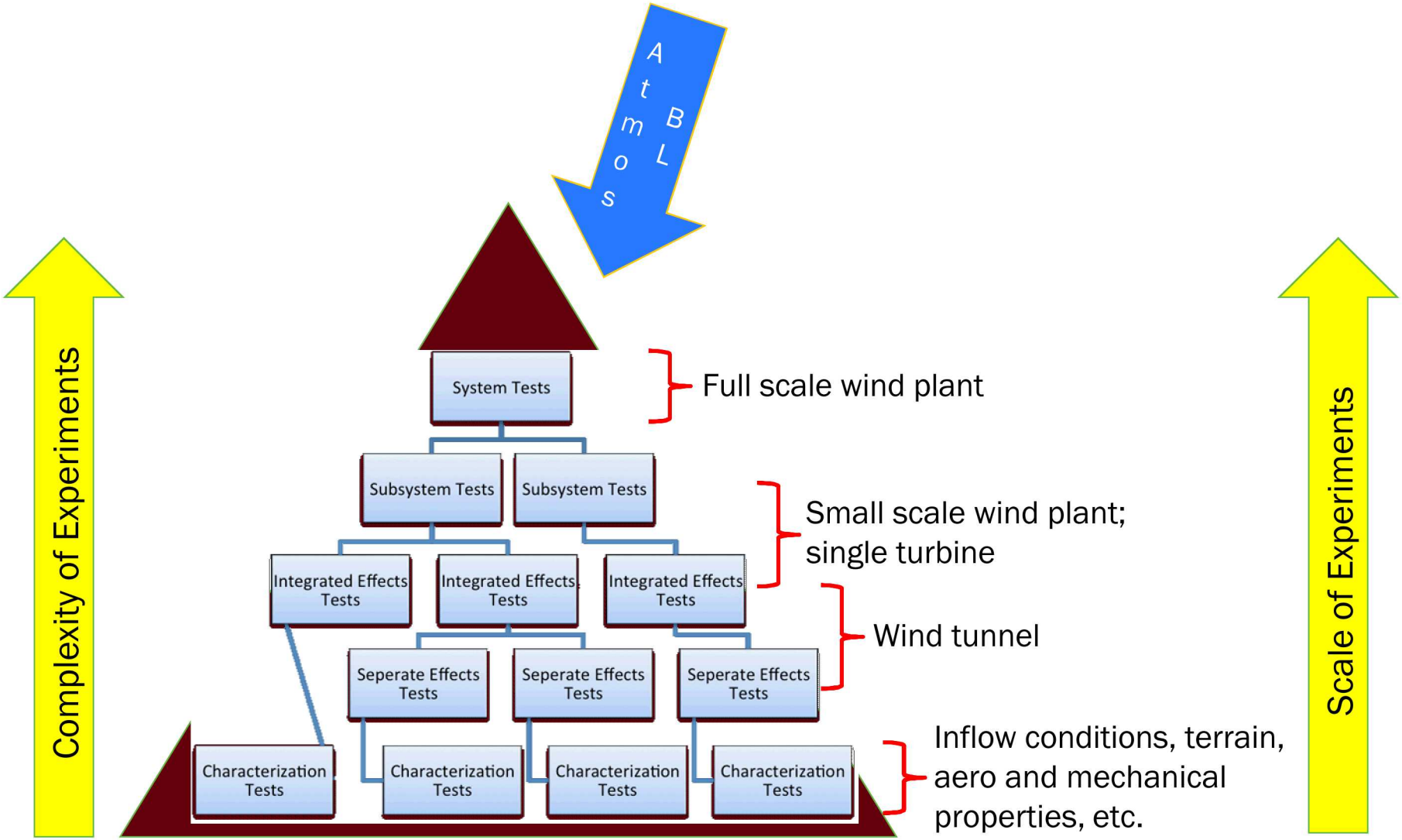
# Backbone of Prioritization Process: PIRT

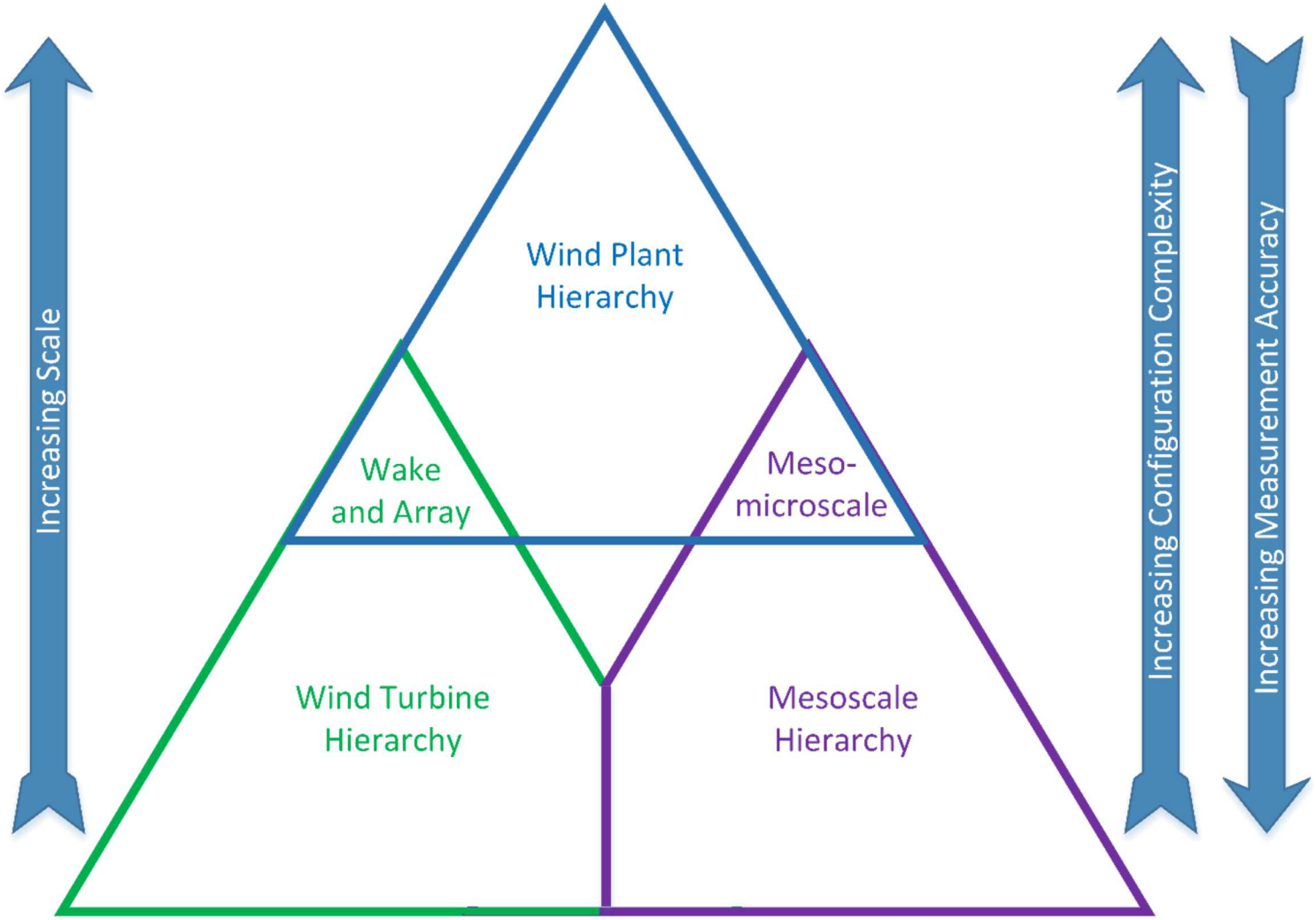
**PIRT: Phenomenon Identification Ranking Table**

- 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

# 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

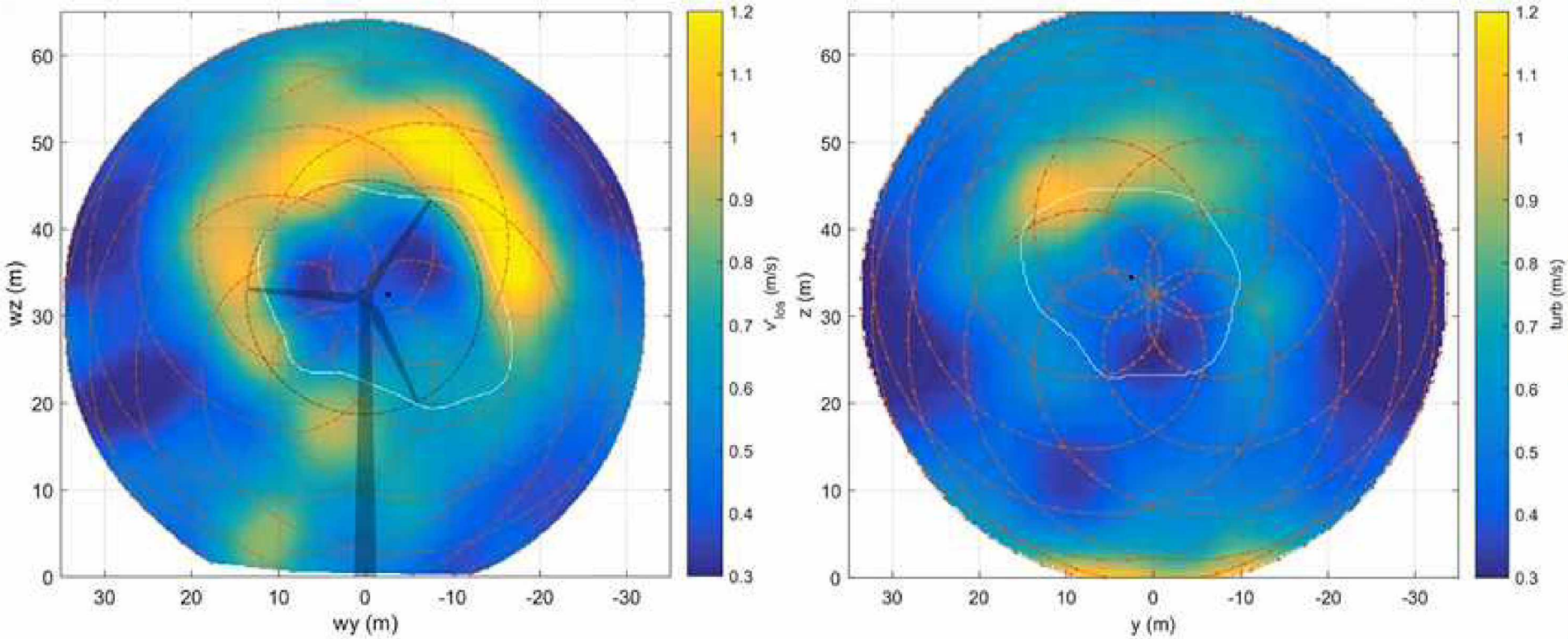
# A2e Validation Coordination Working Group

| 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
- Integration with IEA Task 31, 29, AWEA TR-1, and IEC V&V JWF

# Experimental Uncertainty Assessment and Propagation

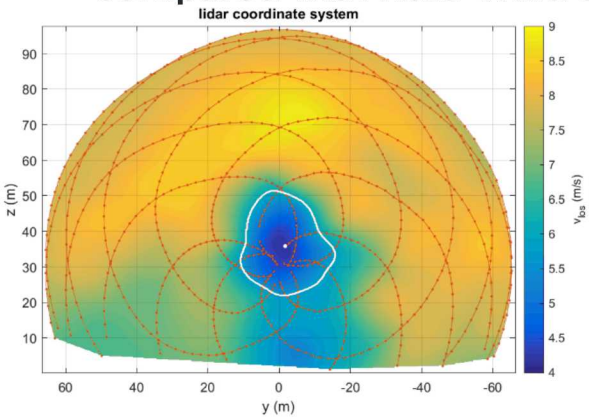
## Wake comparison, Measured and Simulated Lidar



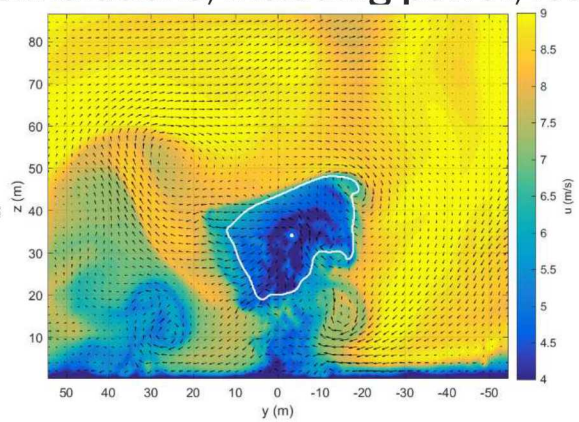

- Current work is focused on the quantification of the fundamental uncertainty of lidar measurements and how it propagates to wind plant metrics.

# Nalu-Wind Wake Assessment Metrics

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



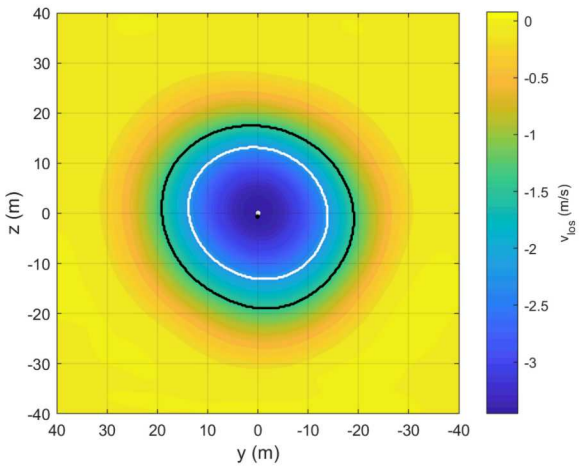

Sample of the wake date from the measured Spinnerlidar at the SWiFT facility.



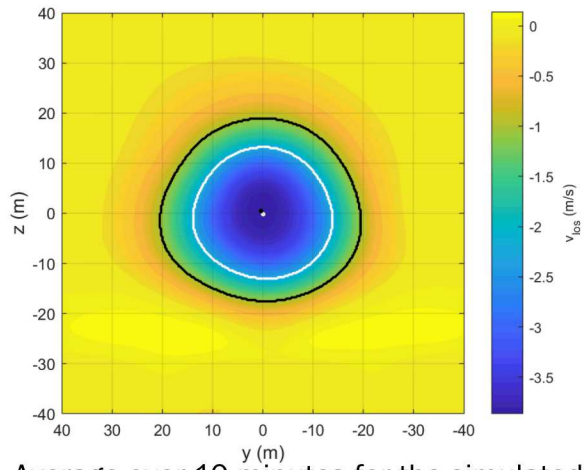

Nalu-Wind Simulated wake data 5D downwind.

| | 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 |

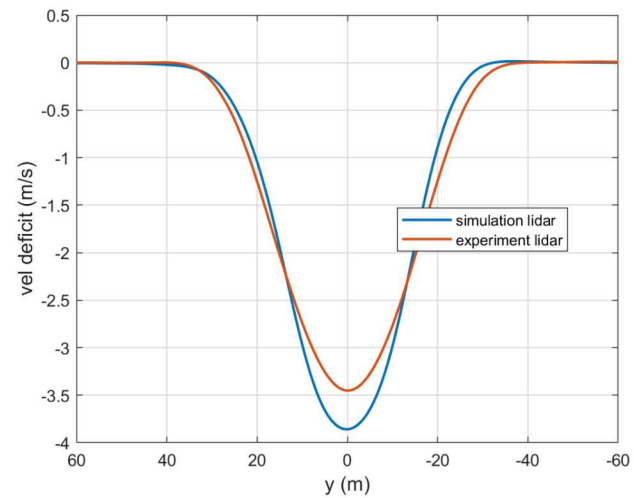
**Wind turbine power and loads metrics for wake dynamics.**




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



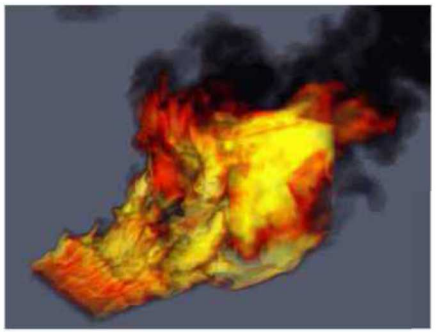

Average over 10 minutes for the simulated wake data 5D downwind, sampled to match the experimental lidar data.



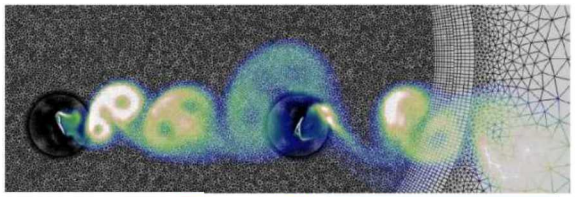

Comparison of wake velocity deficit for the experiment and the Nalu-Wind simulated lidar data.

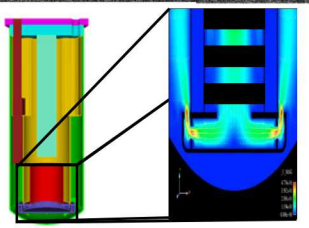
# UQ & Optimization: DOE/DOD Mission Deployment

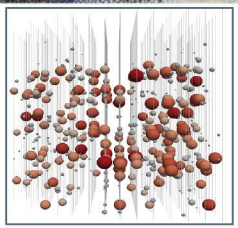
**Stewardship** (NNSA ASC)
**Safety in abnormal environments**



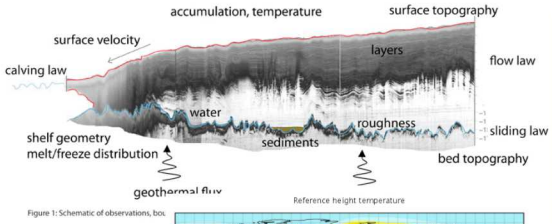
**Energy** (ASCR, EERE, NE)
**Wind turbines, nuclear reactors**

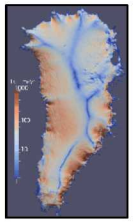


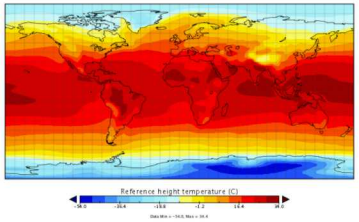




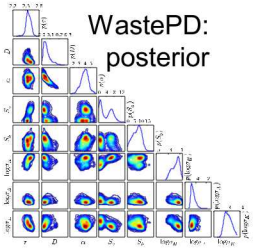
**Climate** (SciDAC, CSSEF, ACME)
**Ice sheets, CISM, CESM, ISSM, CSDMS**

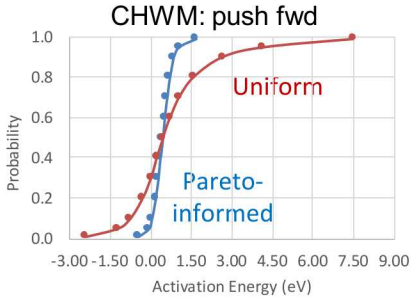


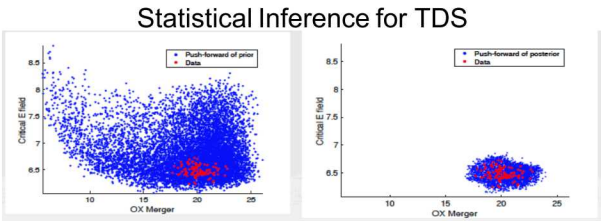






**Addtnl. Office of Science:**
(SciDAC, EFRC)
**Comp. Matls:** **waste forms / hazardous matls (WastePD, CHWM)**
**MHD:** **Tokamak disruption (TDS)**




**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)

# Uncertainty Quantification Development

## Previous: Forward UQ

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

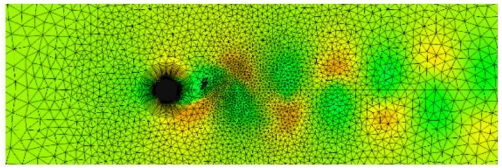
## Current: Inverse UQ and Nalu-Wind Integration

- Infer upstream conditions from SwiFT data sets
  - OpenFAST + WindSE (+ Nalu-Wind)
- Forward UQ using Nalu-Wind's fidelities
- Initial Optimization Under Uncertainty (OUU)

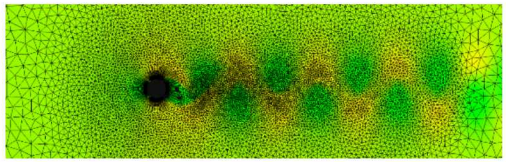
## Future: Optimal Experimental Design (OED)

- 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.

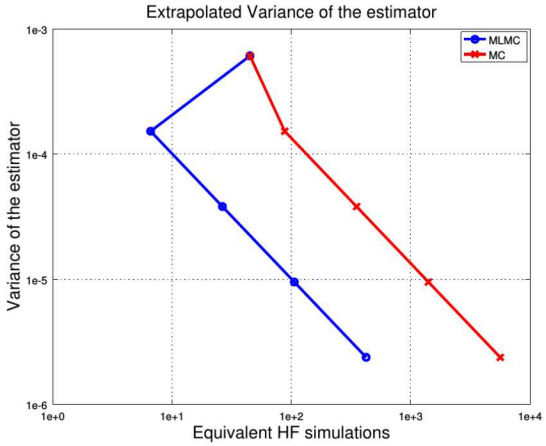


Medium Mesh: 4 hours time to soln.



| 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

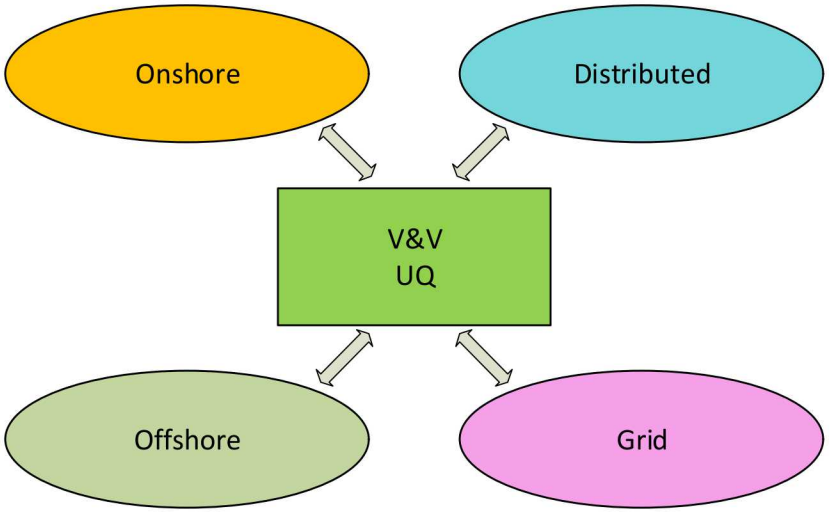


# VV&UQ Multi-year Goals

- **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 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.**

# Role for V&V Moving Forward

- **As A2e transforms, V&V/UQ will continue to play an important role**
  - All pillars of the wind program 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



# Thank you

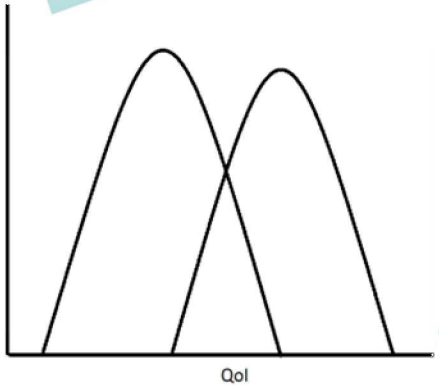
Virtuous Cycle

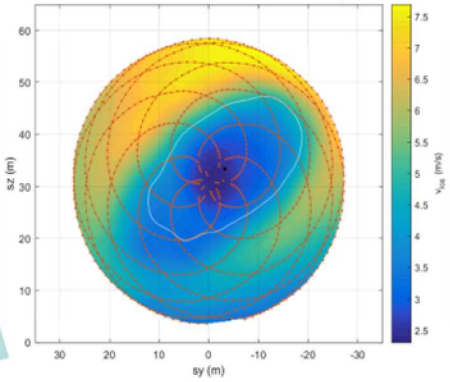
Validation

Model Development

Experimentation

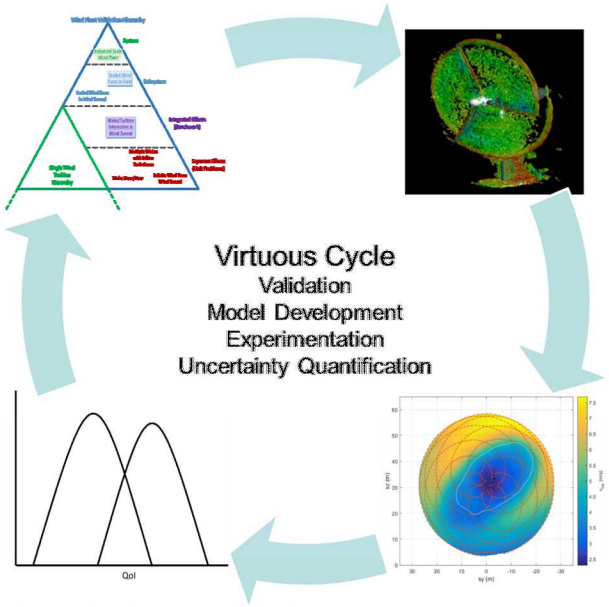
Uncertainty Quantification

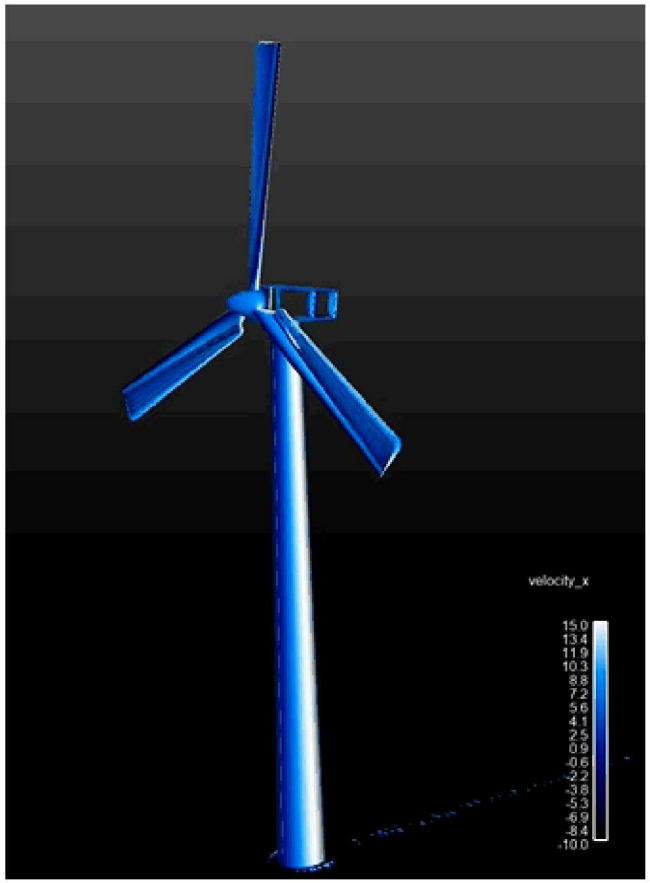


# High Fidelity Modeling (HFM) and Verification & Validation (V&V)

- 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

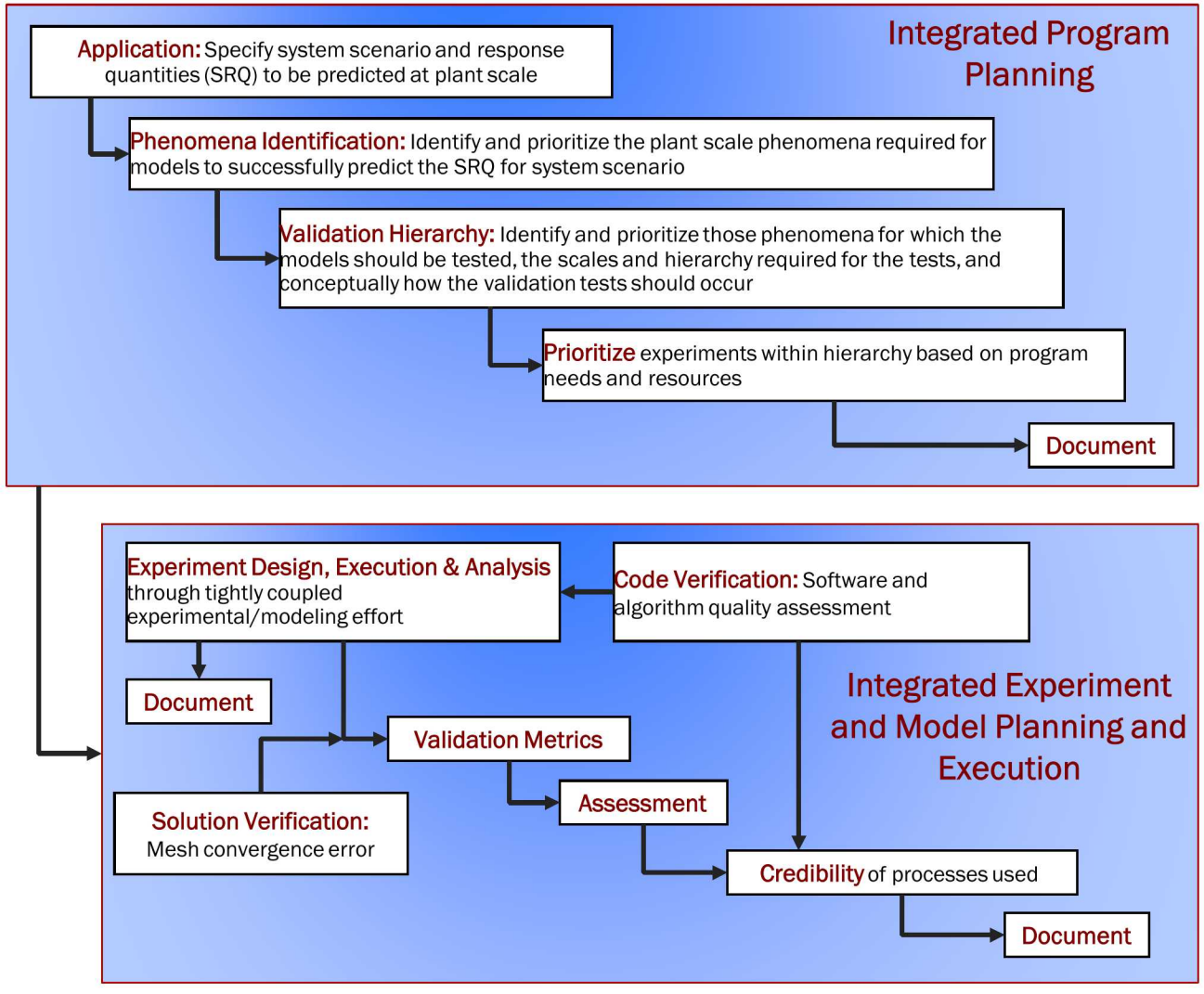
# V&V Framework (2015 Hills, Maniaci, Naughton)

## 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



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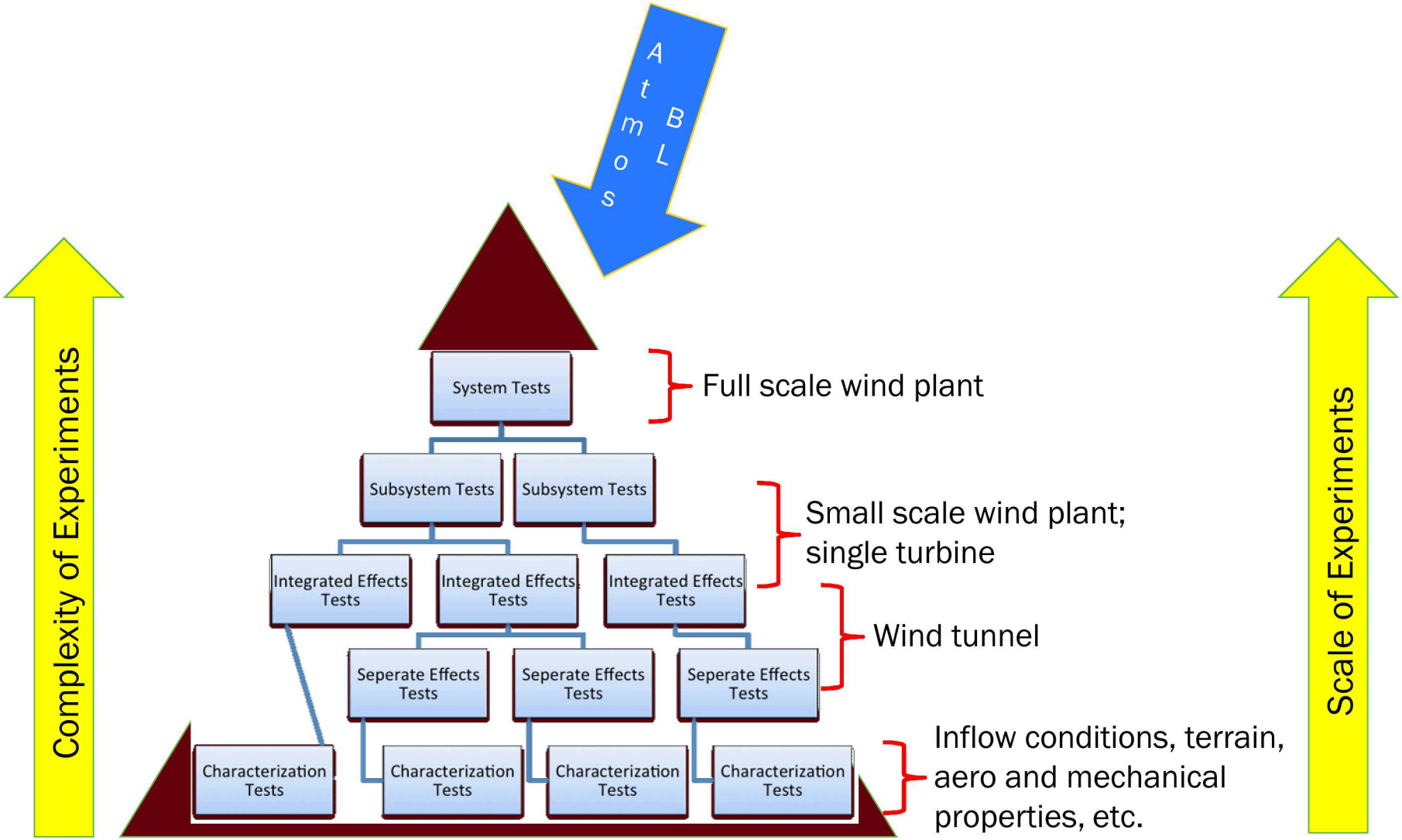
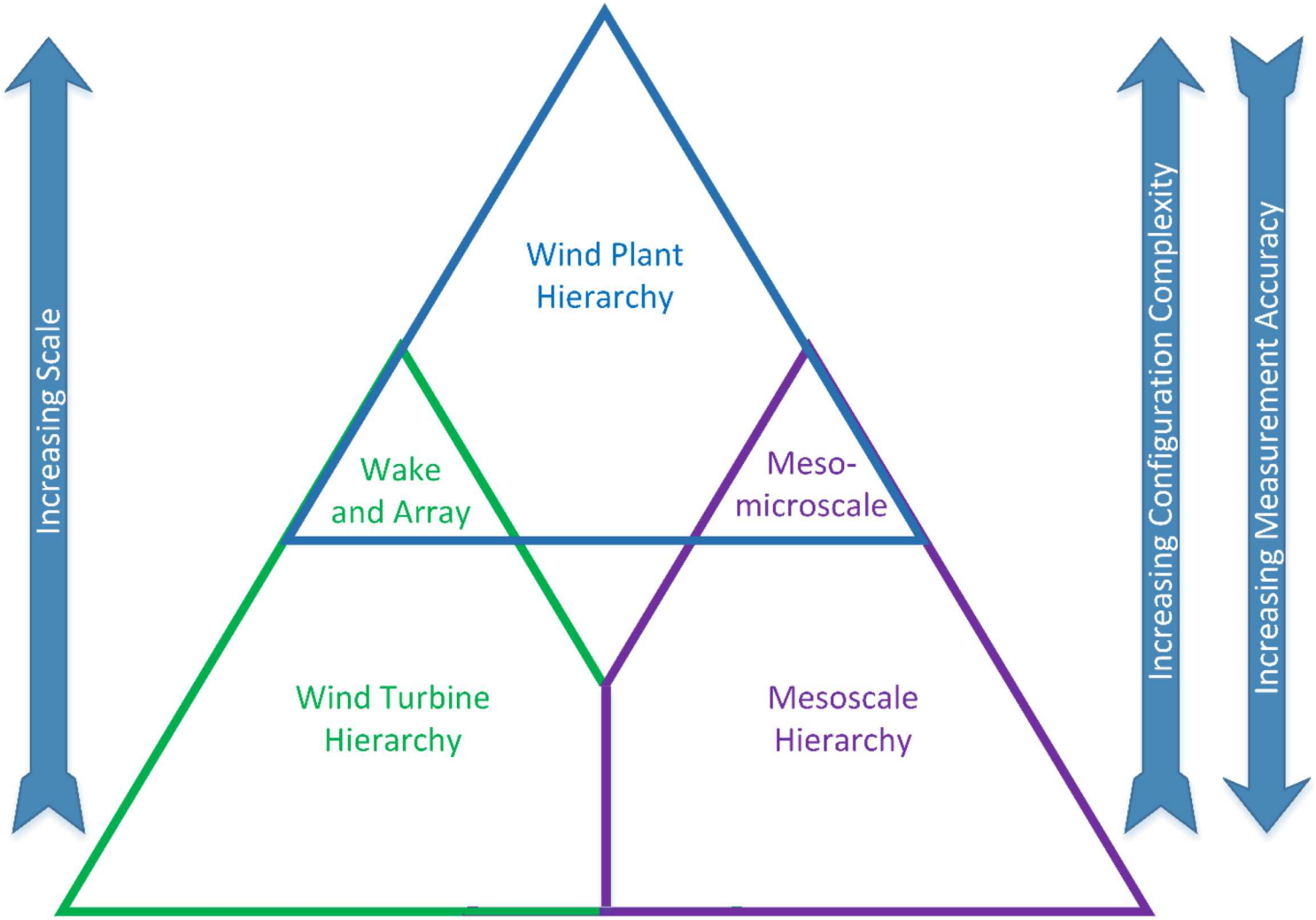
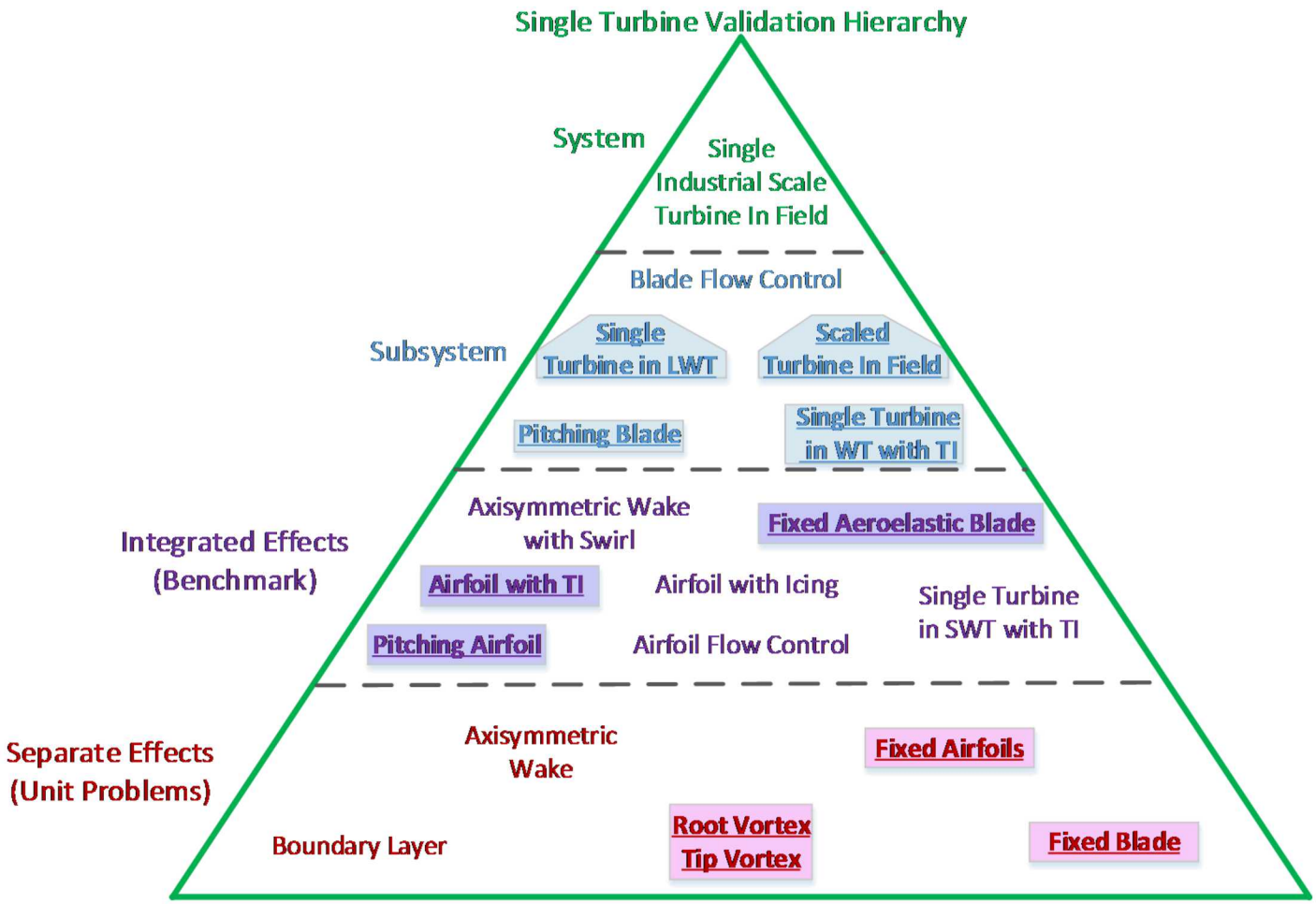
# PIRT Leads to the Validation Hierarchy




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 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 |
| **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 |

# 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

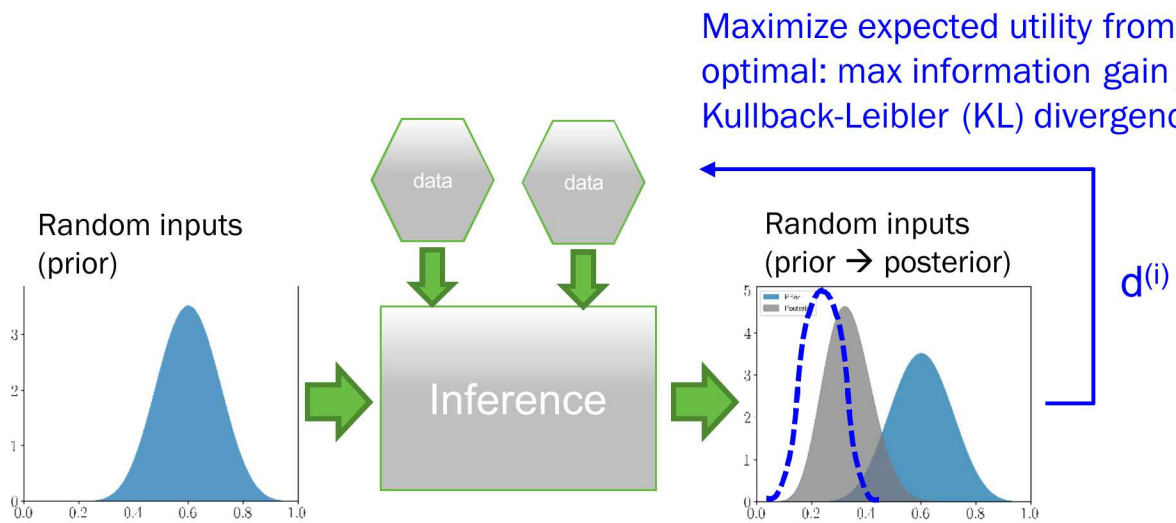
# Primary Stakeholders

- **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

# Optimal Experimental Design (OED) Workflow

**Characterization of input uncertainties** through assimilation of data

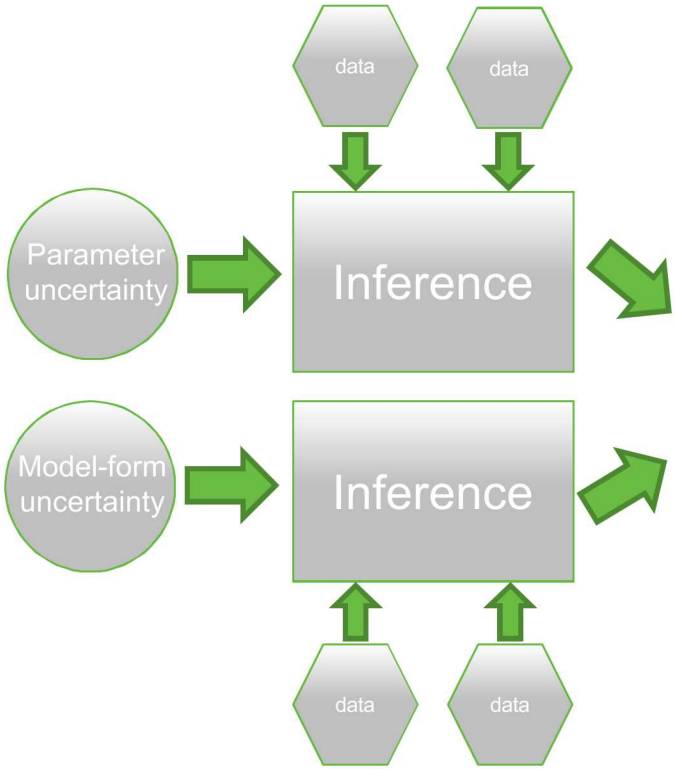
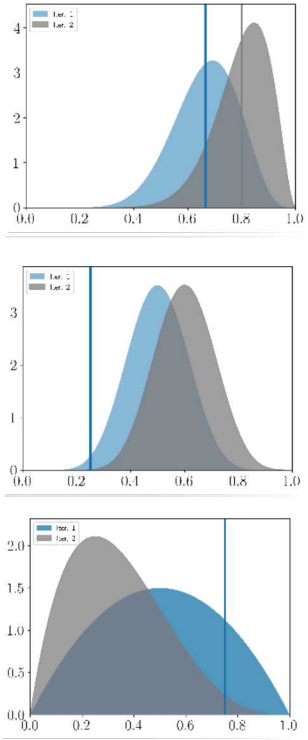
- Prior distributions based on *a priori* knowledge
- Observational data (experiments, reference solns.) → infer posterior distributions via Bayes rule
  - Use of data can reduce uncertainty in obj./constraints (priors are constrained)
  - Design using prior uncertainties can be overly conservative
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