



# WP3: V&V Framework and Uncertainty Quantification

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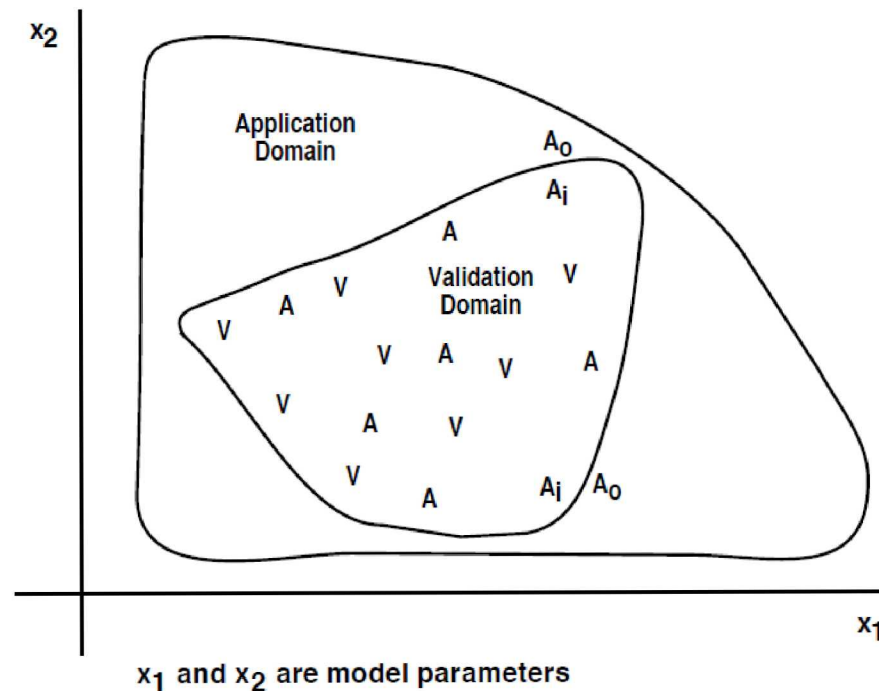
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# Outline

- V&V methodology for wind energy
- V&V Hierarchy
- Uncertainty Quantification
- Proposed cases

# 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.



# Backbone of Prioritization Process: PIRT

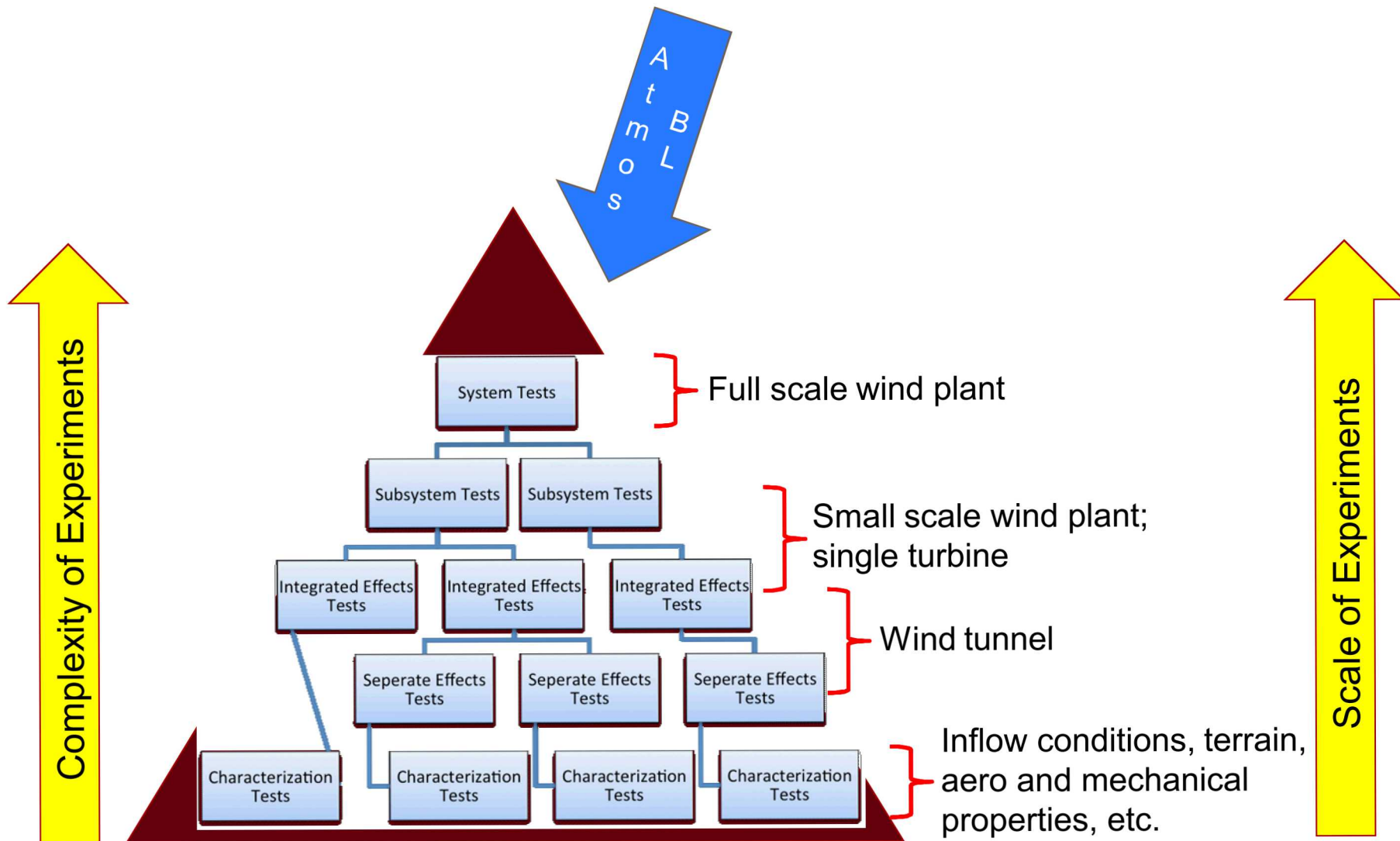
## PIRT: Phenomenon

### 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 |
| <b>Turbine scale flow phenomena</b>   |                                 |                |      |     |
| 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



# WAKEBENCH Validation Hierarchy

## ***Power System***

- Grid control (curtailment, etc)
- Feedback on climate
- Wind power predictability

## ***Climate***

- Climate change
- Interannual variability
- Seasonal variability
- Environmental factors affecting performance (icing, dust, etc)

## ***Wind Farm Cluster***

- Cluster (farm-farm) wakes
- Wind farm "canopy" drag
- Deep-array (equilibrium)
- Wind farm boundary-layer
- Wind farm control
- Far-wake

## ***Mesoscale***

- Weather events
- Coastal/mountains
- Meso-micro forcing
- Terra-incognita turbulence
- Free-atmosphere
- Coriolis

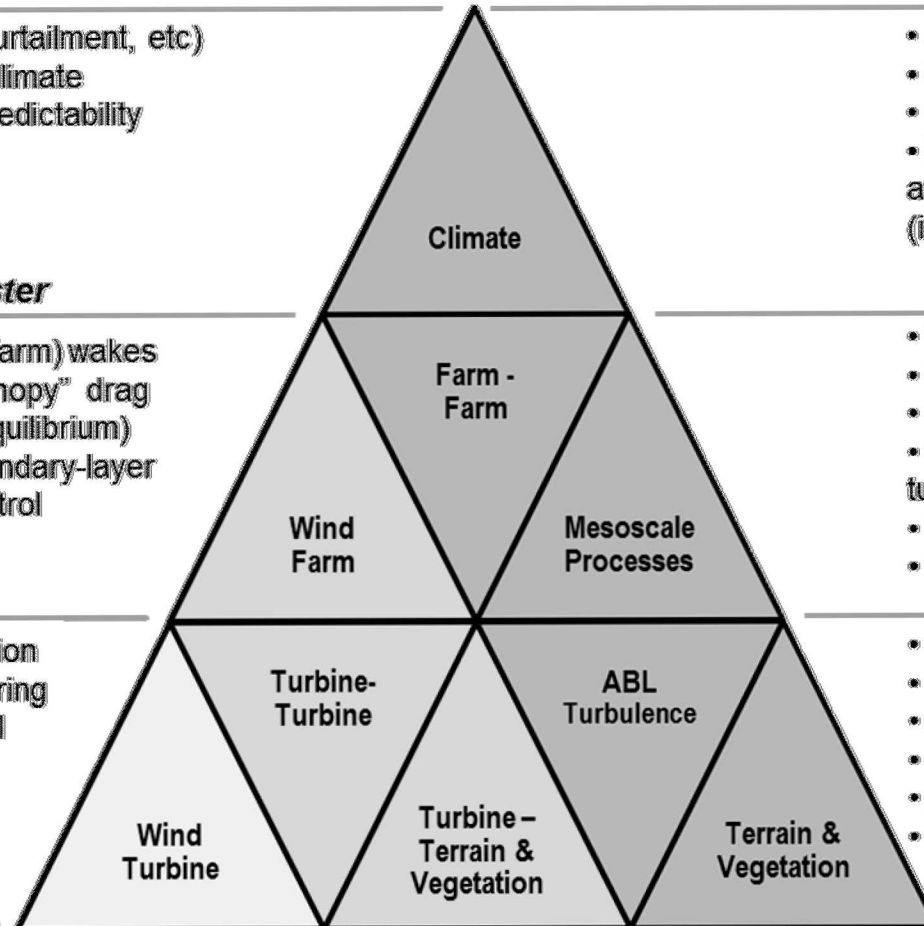
## ***Wind Farm***

- Wake interaction
- Wake meandering
- Turbine control
- Near-wake
- Fluid-structure interaction

## ***Microscale***

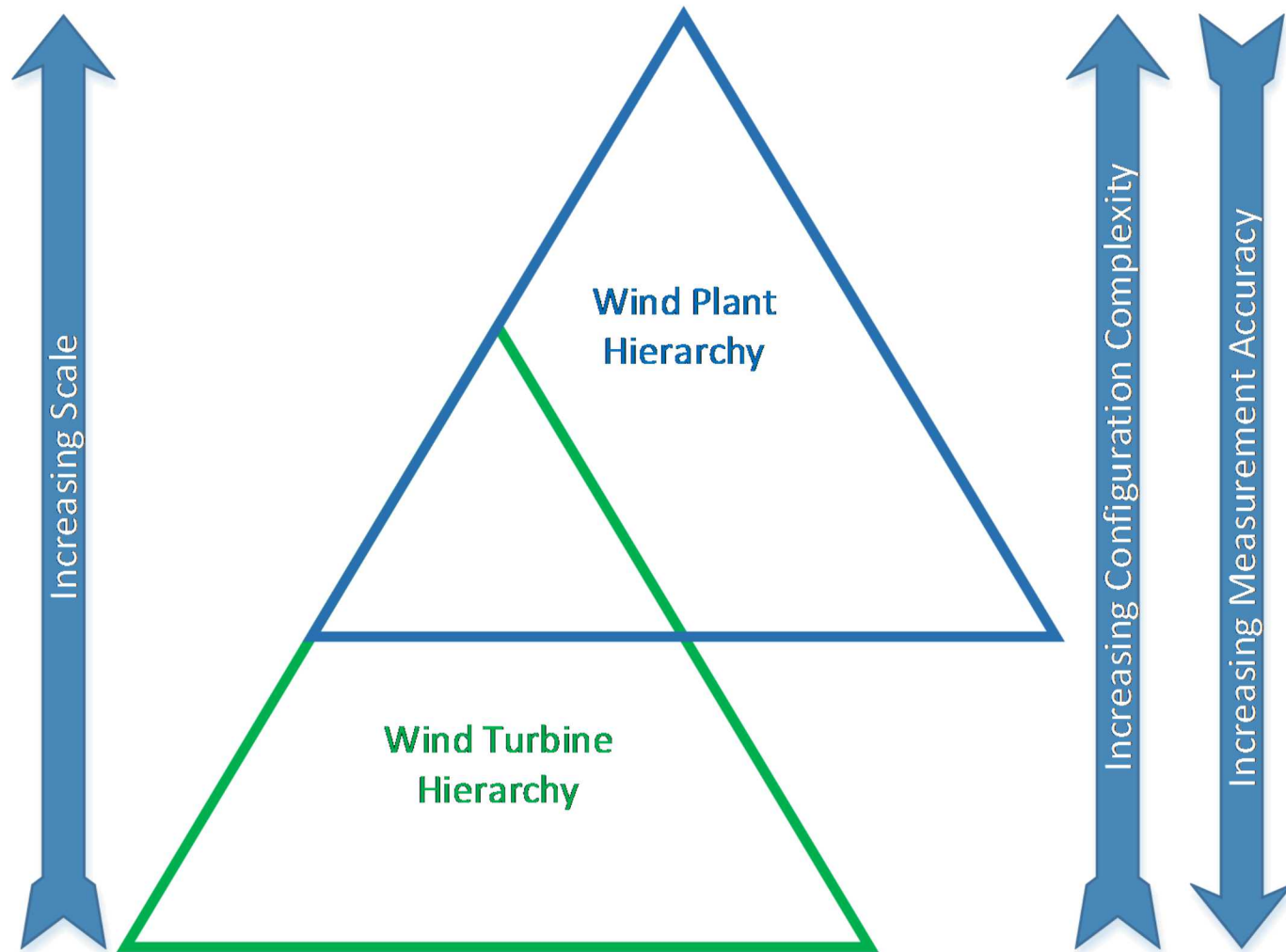
- Terrain flow-separation
- Elevation changes
- Forest canopy
- Roughness changes
- Atmospheric stability
- Air-sea interaction

## ***Turbine***

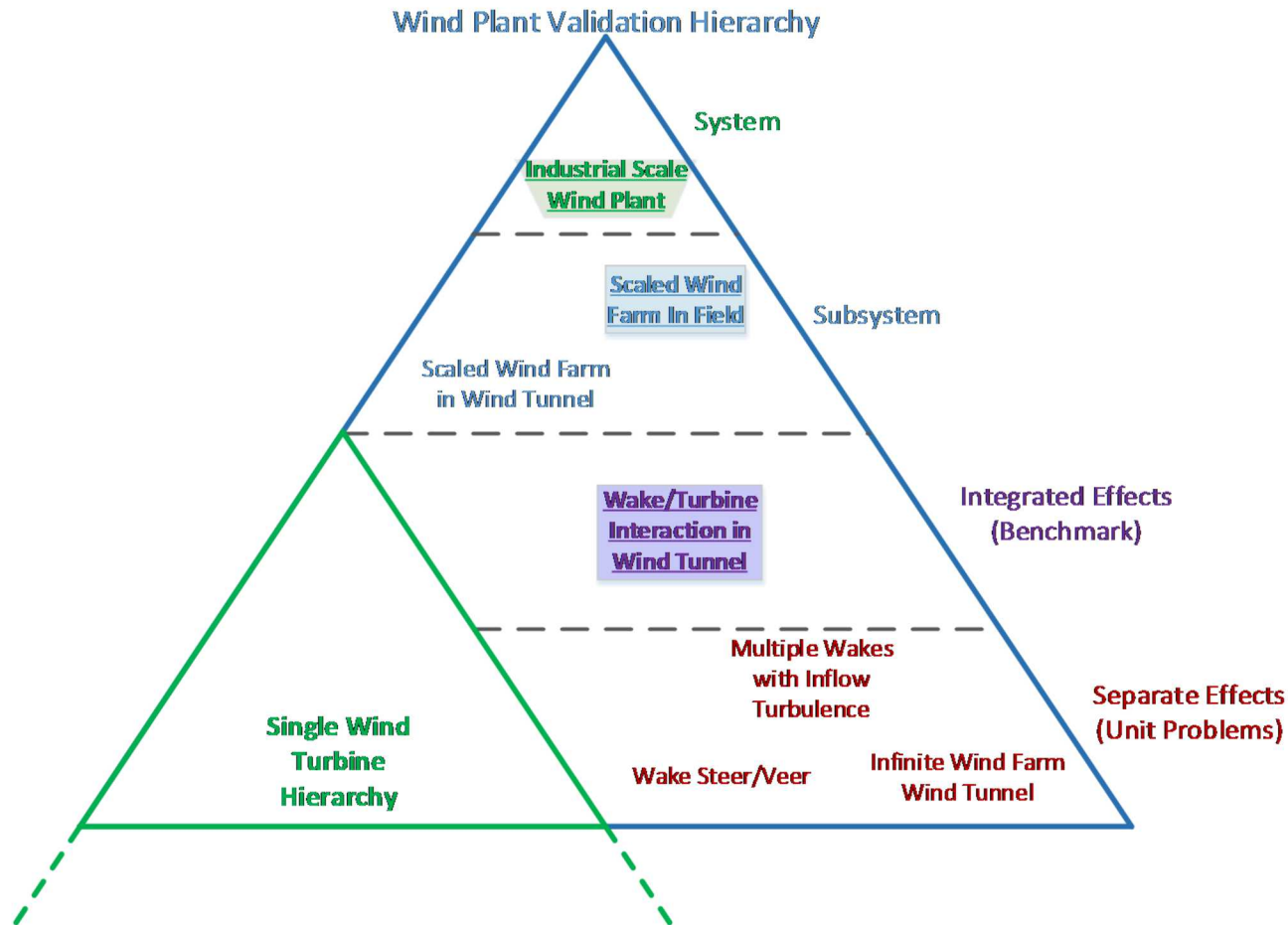


## ***Surface-layer***

# A2e Validation Hierarchy



# Wind Plant Validation Hierarchy



## Slide 8

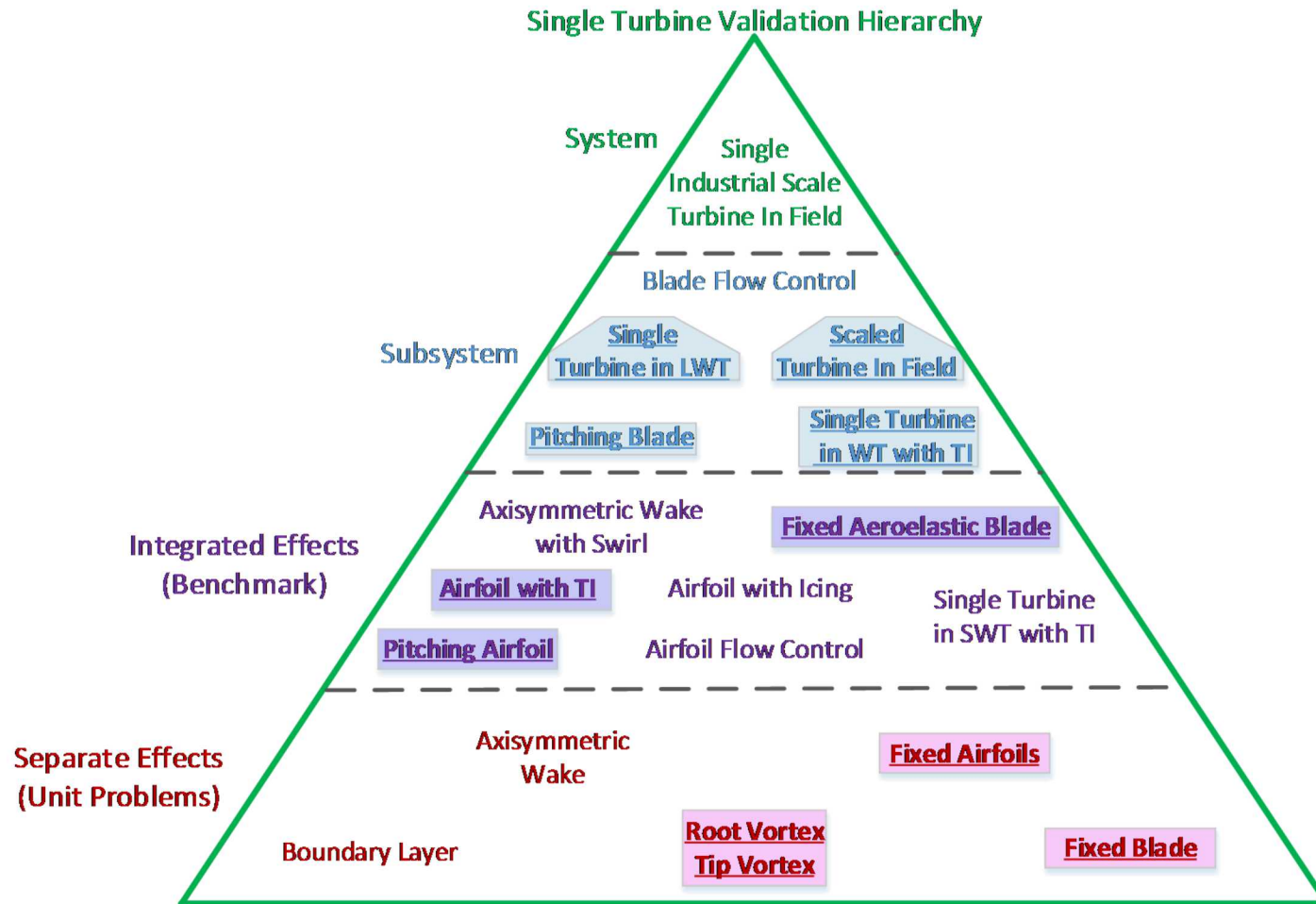
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### MDC4

SWiFT is one assesst within many that will be utilized to build confidence in Nalu's predictive capability.

Maniaci, David Charles, 4/19/2017

# Wind Turbine Validation Hierarchy

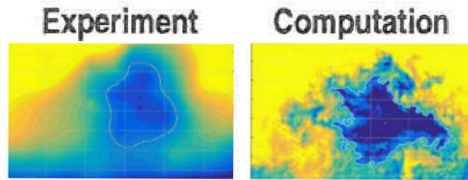


# Uncertainty Quantification

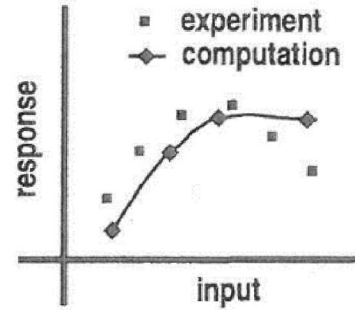
- The uncertainty quantification process determines the degree to which output quantities of interest are influenced by the uncertainty in input quantities and parameters
- The process depends on a model to propagate the input and parameter uncertainties to the output quantities
- Additional uncertainty is introduced by unquantified or variable error in the model
  
- Takeaway: Model and measurement uncertainty are interconnected and are used together to make a decision.

# Uncertainty Quantification

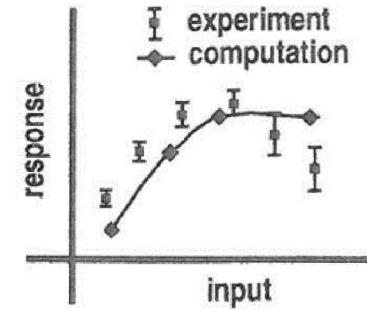
## Levels of Precision



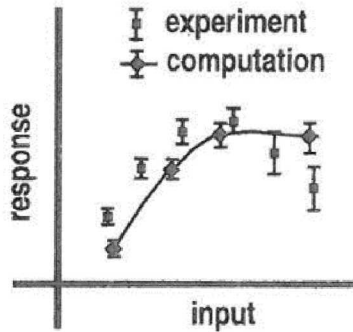
(a) Viewgraph Norm



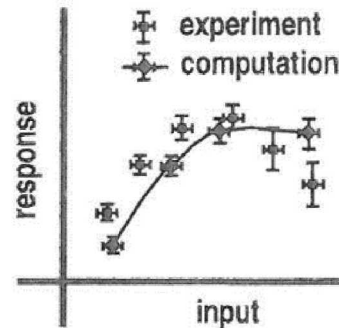
(b) Deterministic Simulation



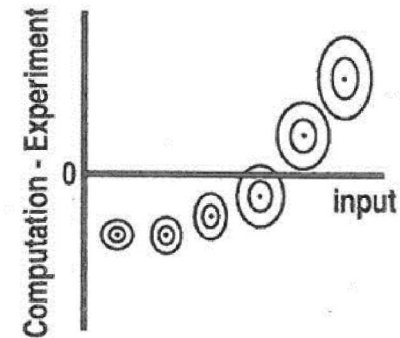
(c) Including Experimental Uncertainty



(d) Including Numerical Error



(e) Nondeterministic Simulation



(f) Statistical Mismatch

Modified from Oberkampf and Roy, 2012

# V&V/UQ Goals in Work Package 3

- Development of V&V strategies and the prioritization of validation efforts
- Formation of best practices for model assessment
- Apply uncertainty quantification (UQ) methods to wind energy applications
  - Experimental and model data application

# V&V/UQ Goals in Work Package 3

## Tasks

- Task 3.1: PIRT analysis and V&V strategy
- Task 3.2: Best practice procedures

## Deliverables

- D3.1: 3<sup>rd</sup> edition of Model Evaluation Protocol (M36)
- D3.2: 3<sup>rd</sup> edition of best practice procedures (M36)
- D3.3: White paper on wind farm flow modelling and evaluation (M36)

## Milestones

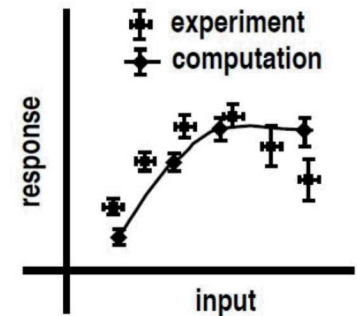
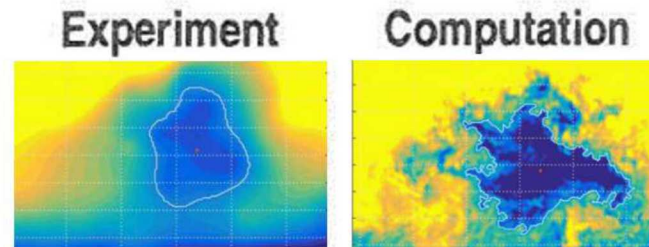
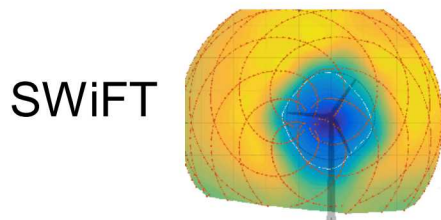
- M3.1: Unified PIRT implemented (M12)

# Proposed VV&UQ Cases

# Case: SWiFT UQ

**Objective:** Conduct Uncertainty Quantification on experimental data from SWiFT data sets for inflow, turbine, and wake quantities of interest.

**Outcome:** A quantitative assessment of experimental uncertainty and model prediction uncertainty using probabilistic methods for turbine and wake quantities of interest.



# Multi-level Uncertainty Quantification with LES

Demonstrated an order of magnitude reduction in computational cost for a cylinder flow problem by coupling Nalu (CFD) to DAKOTA (UQ) and using a multilevel UQ approach.

## Problem description

- (Laminar) Flow over a cylinder ( $Re=10-750$ )
- Input parameters: Density and Viscosity
- QoI: Coefficient of Drag
- 4 levels of mesh resolution

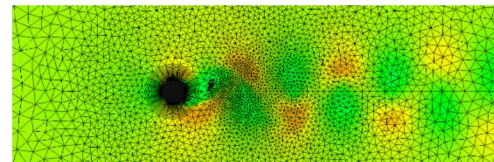
## UQ approach

- Multilevel sampling-based estimator to accelerate convergence

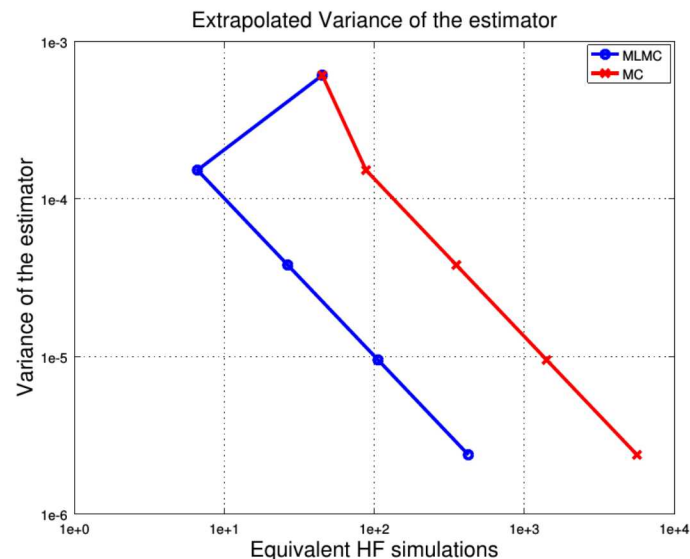
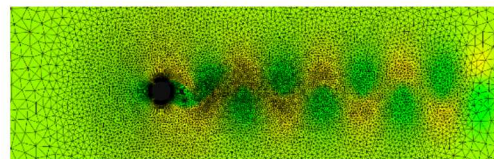
## Impact

- Sampling methods are well suited for UQ problems with extremely high dimensionality (such as wind farm LES)
- Convergence is guaranteed for non smooth QoIs
- Demonstrated order of magnitude improvement in accuracy/cost of Multilevel estimators (MLMC) relative to conventional Monte Carlo (MC) for the cylinder problem

Coarse Mesh: 10 minute time to soln.



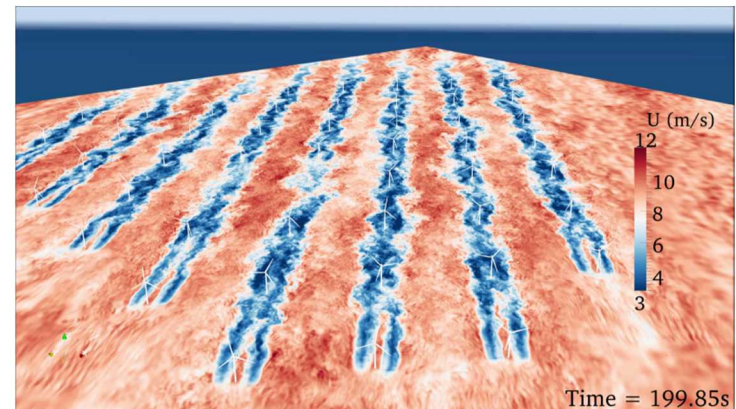
Medium Mesh: 4 hours time to soln.



# Case: Horns Rev UQ

**Objective:** Conduct Uncertainty Quantification on experimental data from Horns Rev data sets for similar quantities of interest. Assess model prediction using probabilistic methods.

**Outcome:** A quantitative assessment of experimental uncertainty and model prediction uncertainty using probabilistic methods for turbine and wake quantities of interest.



Full-scale wind farm simulation,  
Lillgrund wind farm (Churchfield)

# Overarching Questions

- What is the balance between studies focused on validation for model predictions and studies focused on scientific discovery and understanding?
- How can we use estimates of aleatory and epistemic uncertainty from measurements to drive simulations for inference/validation?
- How can we use simulations to estimate aleatory and epistemic uncertainty in measurements?
- How can VV&UQ based on lower levels of the V&V Hierarchy be used to estimate uncertainty of full system model predictions?

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** (July 2016): This document outlines the integrated program planning (IPP) process and applies it to wind plant performance prediction.

# V&V Framework Summary

- V&V is useful for establishing the predictive capability of a model for an intended application.
- A validation focused program is highly collaborative and requires an interdisciplinary team
- The PIRT is the backbone of the process as it defines validation campaign priorities.
- Defining the goal and priority of modeling and experimental campaigns is crucial
- Model, UQ, and Validation experts should be engaged throughout the process

# 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.*

