

V&V Framework

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IEA Wind task 31, Wakebench Annual Meeting
Tokyo, Japan
April 17-19, 2018



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V&V Definition

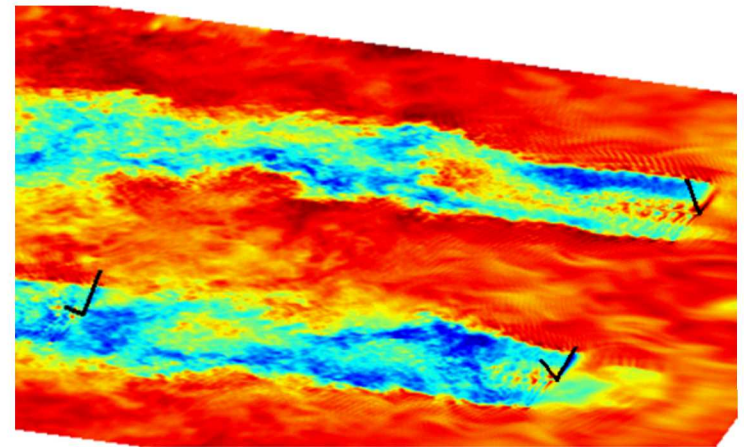
ASME definitions:

- **Verification:** The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model.
- **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.

Why invest in V&V?

> Increasing Role of Computational Modeling

- 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 MDC7
- The Verification and Validation Framework is the process to define the conditions where model predictions can be trusted



Slide 3

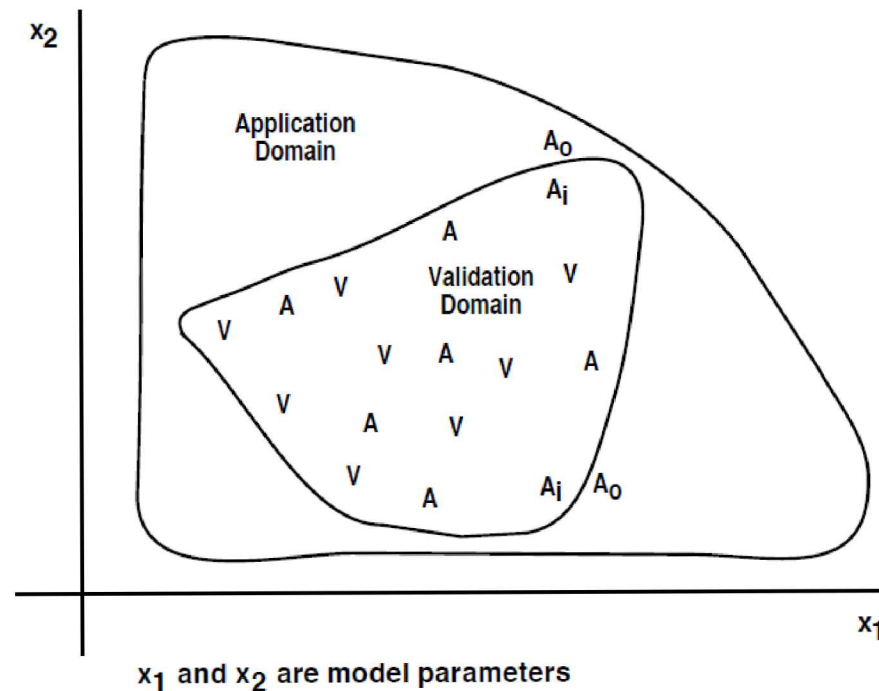
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Increasing system complexity, size, and cost are at odds with the demand for more rapid development cycles, increased validation precision and model fidelity can bridge this gap

Maniaci, David Charles, 4/20/2017

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.



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In some cases, models will prove to have less accurate results than anticipated, requiring higher fidelity measurements to assess what unaccounted physical processes or model process deficiencies are causing the model errors.

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What is a Validation Focused Program?

Goal

- Formalized highly collaborative approach to planning and executing joint experimental/modeling programs for the purpose of characterizing model accuracy for an intended application

Why?

- Provides a transparent, structured, documented approach for integrate program planning across scales
- Applicable to models of all fidelity, including reduced order models
- High quality data sets well suited for collaborative model validation efforts
- Quantifies prediction uncertainty for use by designers

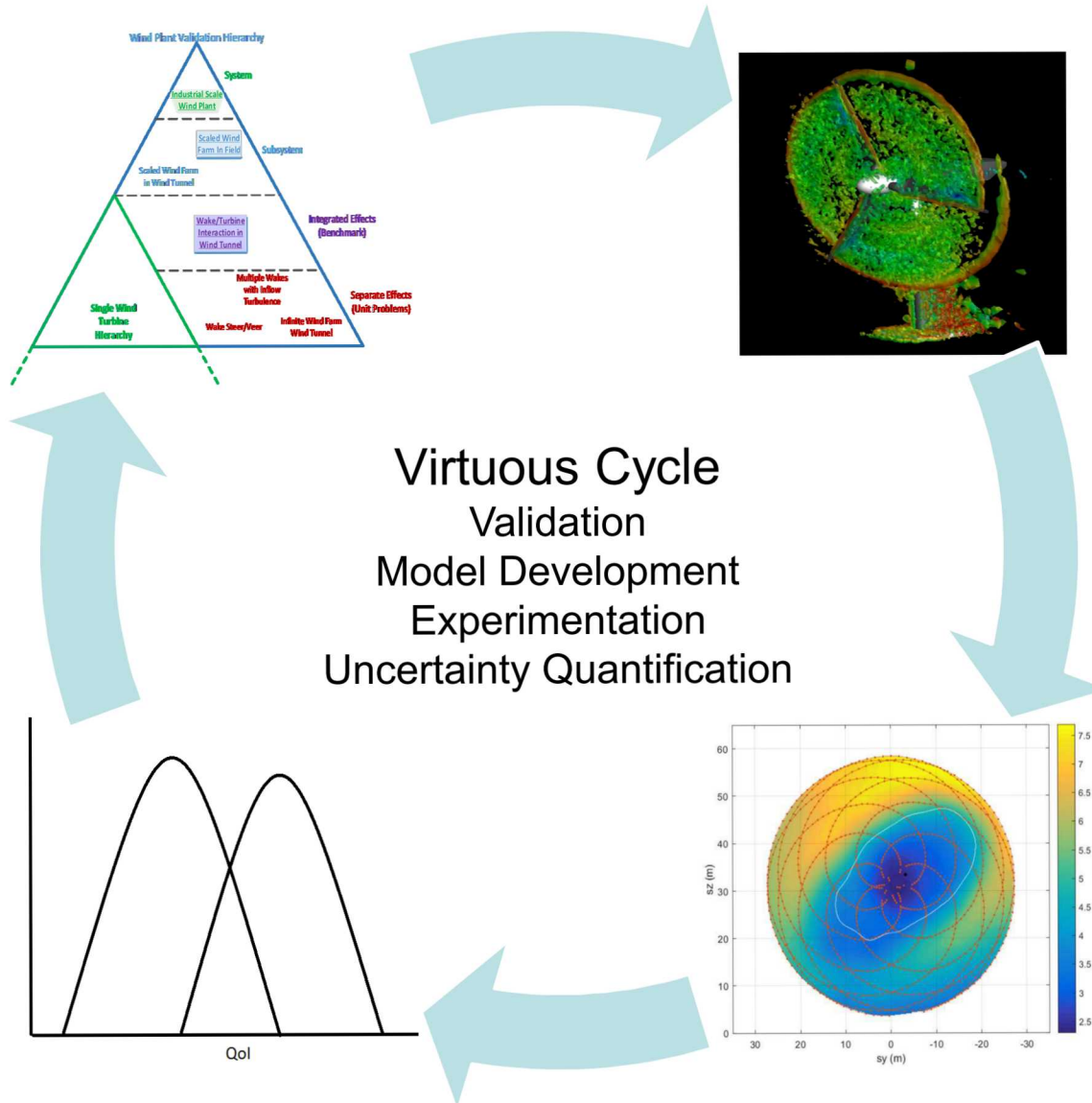
Foundation of framework used

- Framework developed for nuclear energy, SNL NW, and other programs
- Framework consistent with various ASME and AIAA V&V Guides, Codes and Standards

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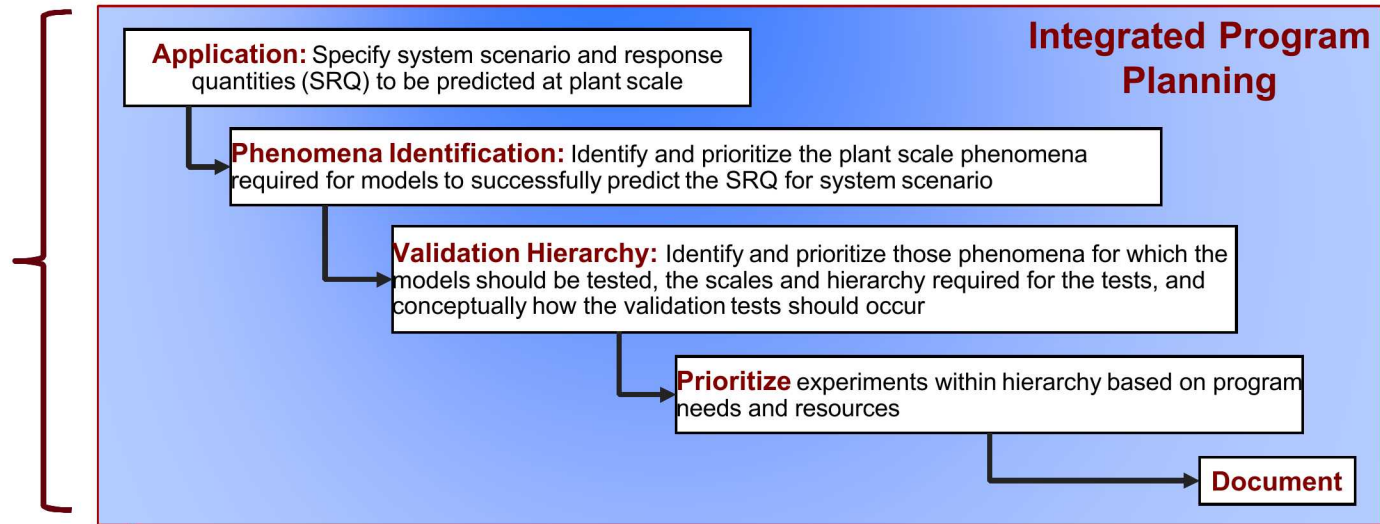


V&V Framework

(2015 Hills, Maniaci, Naughton)

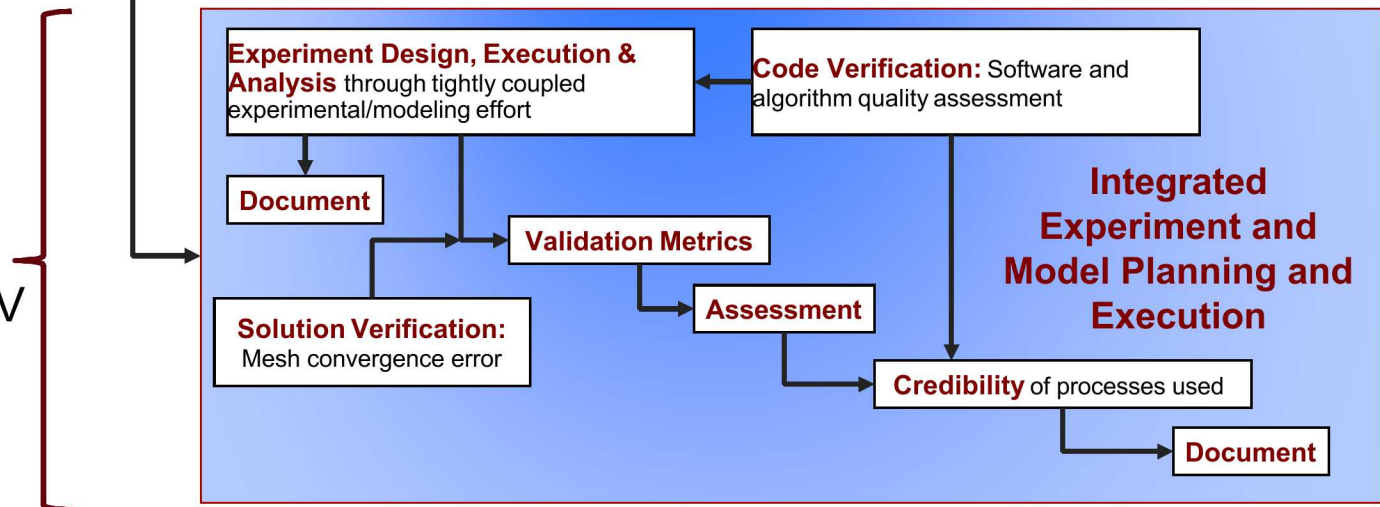
Integrated Planning

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



Validation Planning

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



Primary Stakeholders

- **National Funding/Research Organizations:** 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

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L2 stakeholders for A2e HFM and wake dynamics efforts
LOFT, 9/6/2017

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

V&V Hierarchy

Backbone of Prioritization Process: PIRT

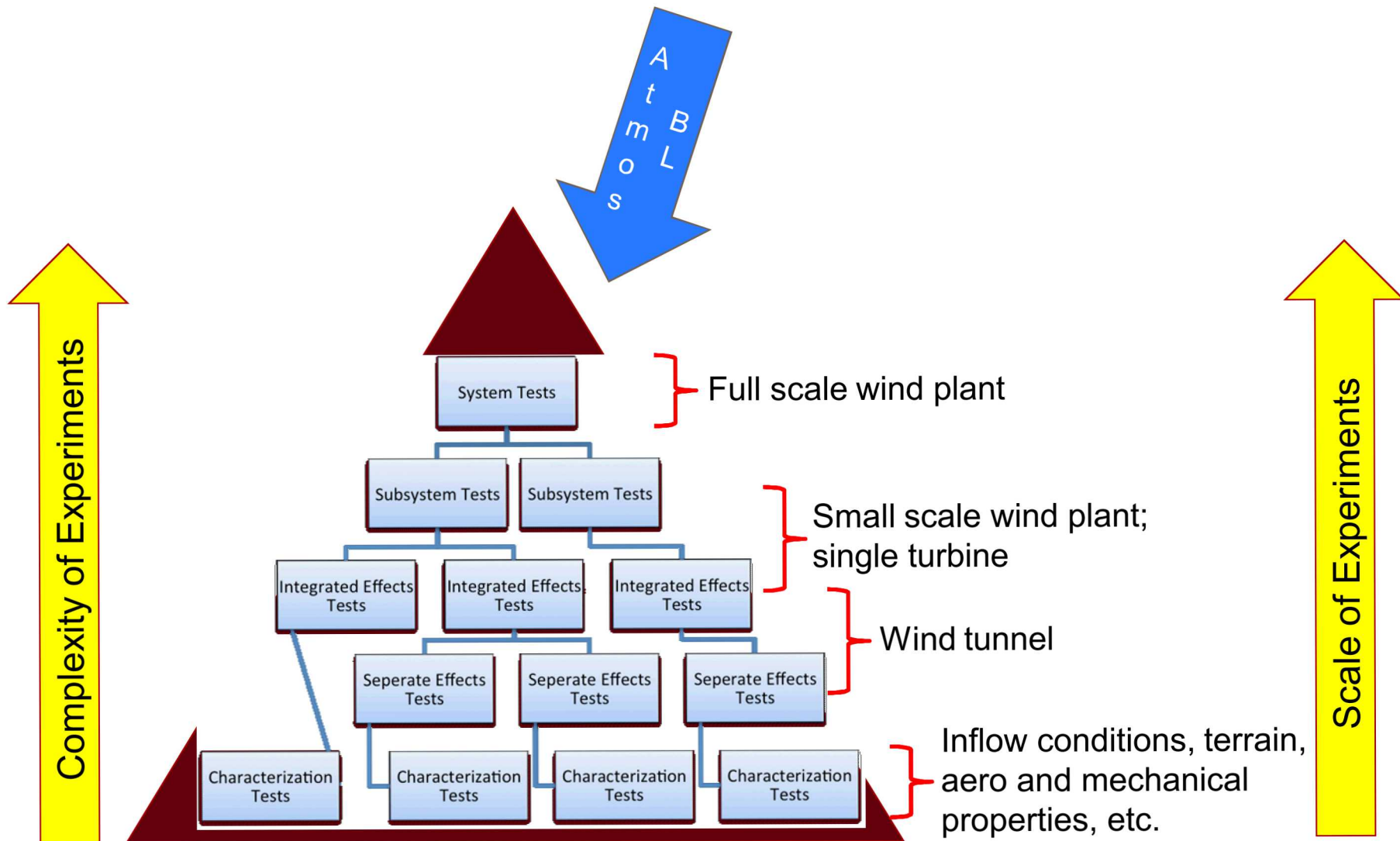
PIRT: Phenomenon

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



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

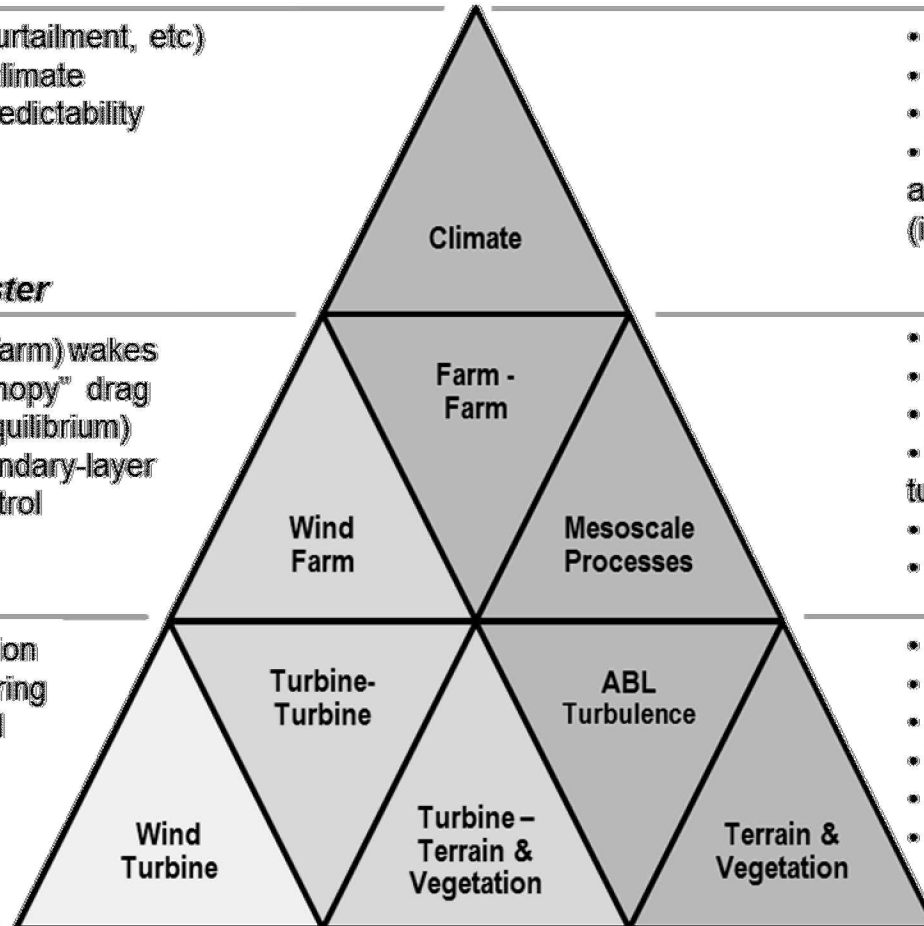
Wind Farm

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

Microscale

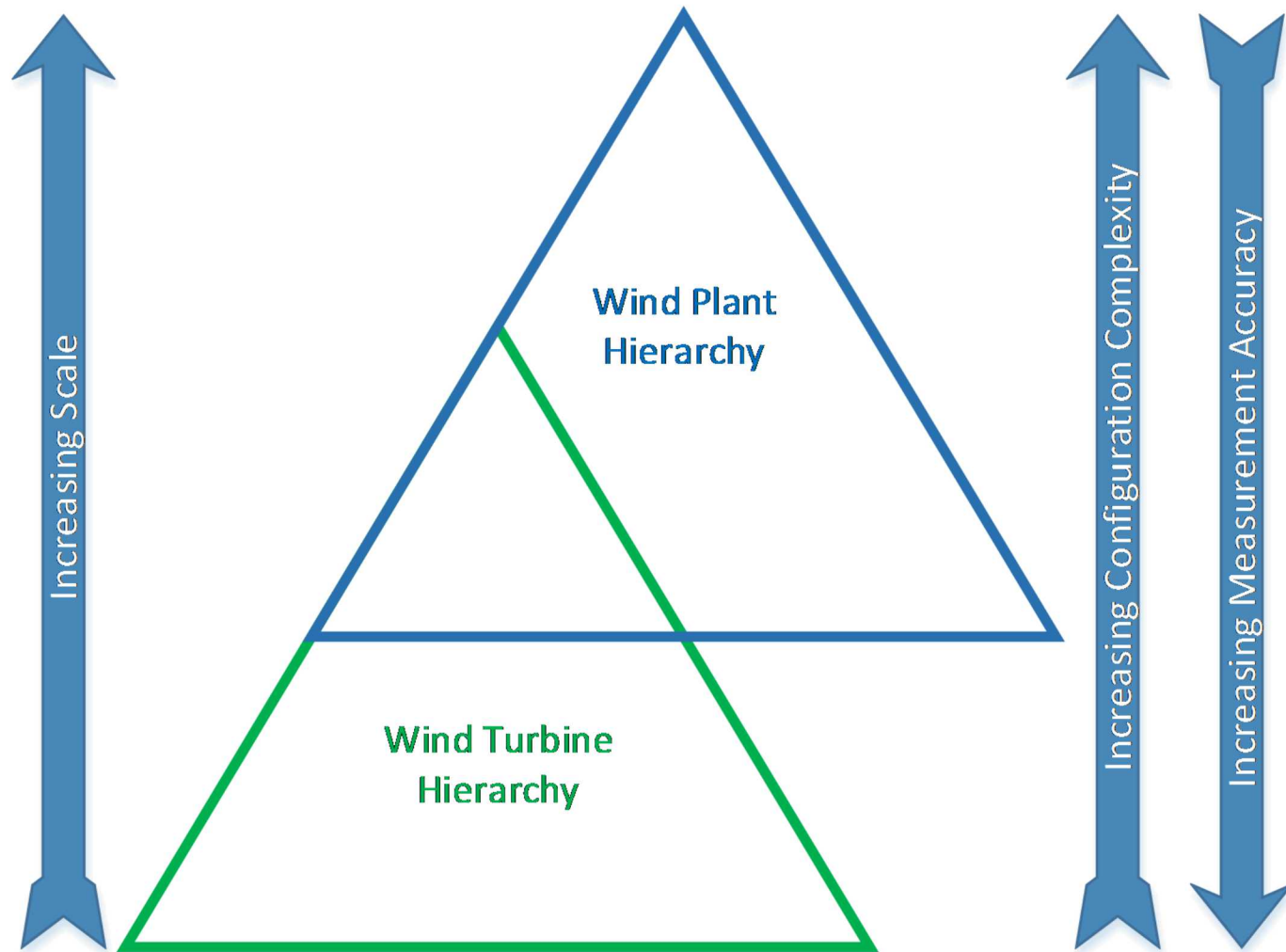
- Terrain flow-separation
- Elevation changes
- Forest canopy
- Roughness changes
- Atmospheric stability
- Air-sea interaction

Turbine

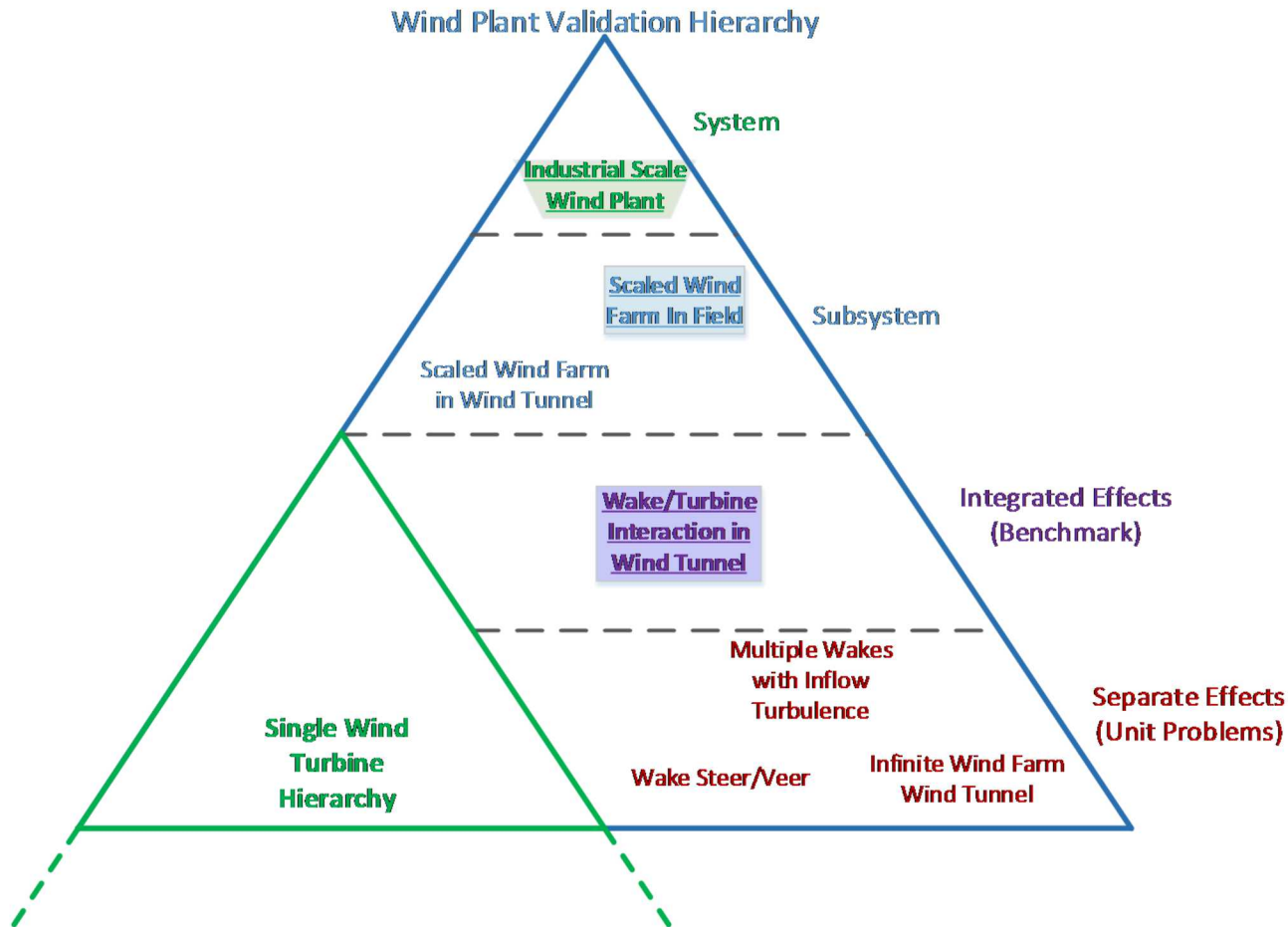


Surface-layer

A2e Validation Hierarchy



Wind Plant Validation Hierarchy



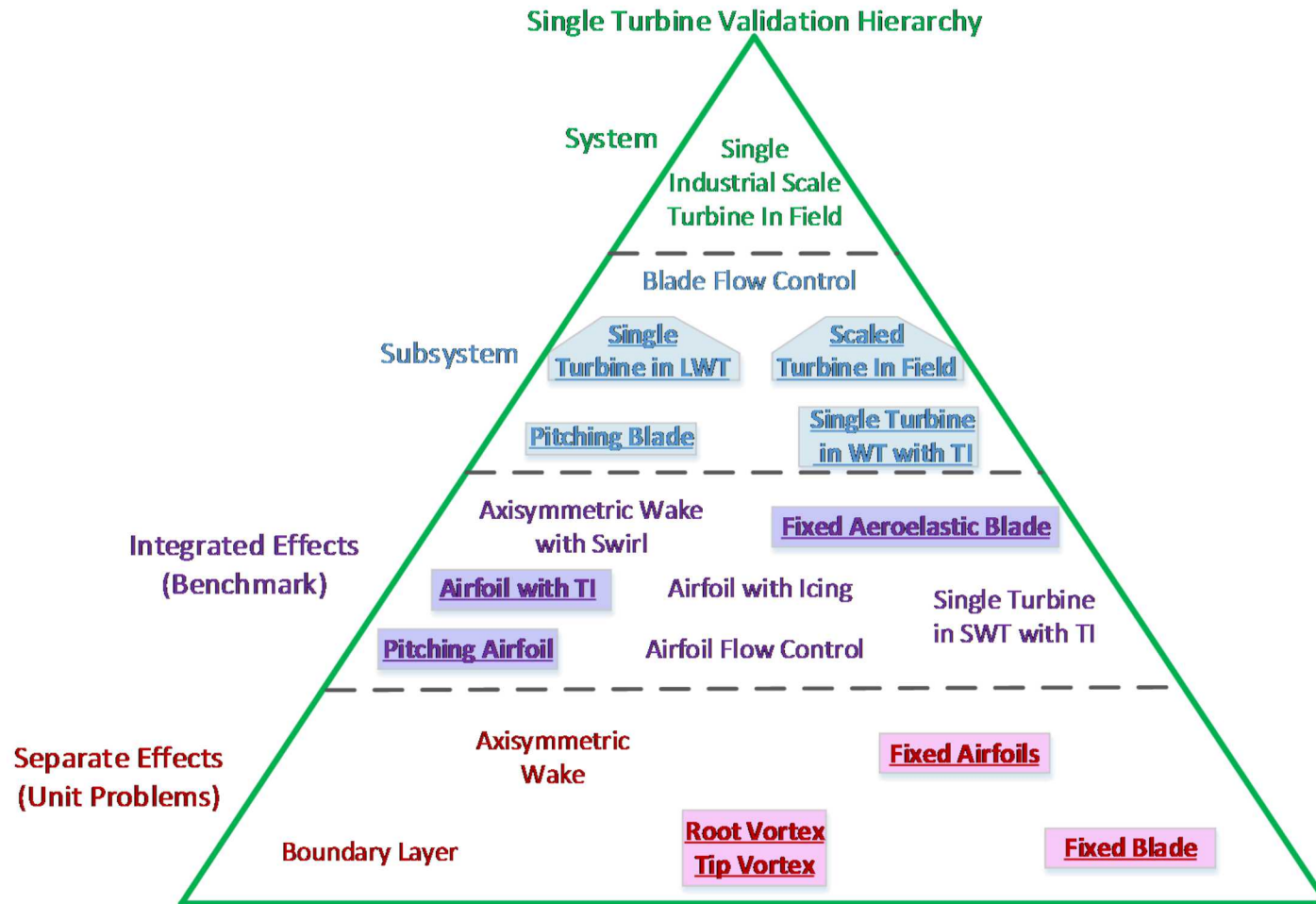
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SWiFT is one assesst within many that will be utilized to build confidence in Nalu's predictive capability.

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Wind Turbine Validation Hierarchy



Phenomena Mapping to Model Capabilities and Experiments

Definition of a Modeling Campaign:

- 1.) **Model capabilities** (equations to be solved, IC/BC)?
- 2.) **Quantities of interest** to be predicted and used for the application?
- 2.) **Scenarios** under which the quantities will be predicted?
- 3.) **Impact** of the model results on final design decisions?

Definition of an Experimental Campaign:

































































- 1.) **Objective:** What will be validated and what are the test conditions?
- 2.) **Method:** How will this data be gathered? What is the setup and instrumentation?
- 3.) **Environment/Requirements:** What are the requirements and constraints on the test campaigns? What is the required resolution/accuracy/time-scale?
- 4.) **Desired Outcome:** What will success mean? How will it be quantified? How will this increase credibility at full scale?

PPEM (Prioritized Phenomenon Experiment Mapping)

Wind Plant

Physics Present/Physics Measured

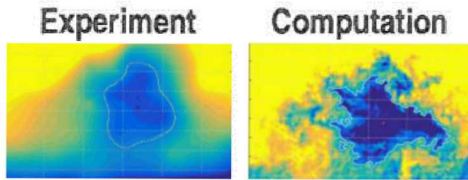
-  Entirely
-  Mostly
-  Somewhat
-  Limited
-  Missing

	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								
Physics Capture by Measurements								
Scaled Wind Farm in Field (20 m rotor)								
Physics Present								
Physics Capture by Measurements								
Scaled Wind Farm in VL WT (2 m rotor)								
Physics Present								
Physics Capture by Measurements								
Wake/Turbine Interaction in WT (2 m rotor)								
Physics Present								
Physics Capture by Measurements								

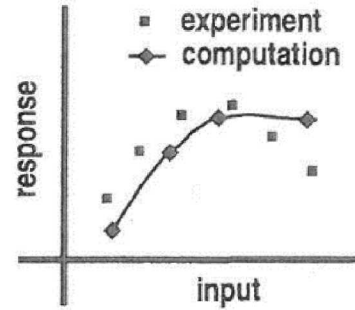
Uncertainty Quantification

MDC2 Uncertainty Quantification

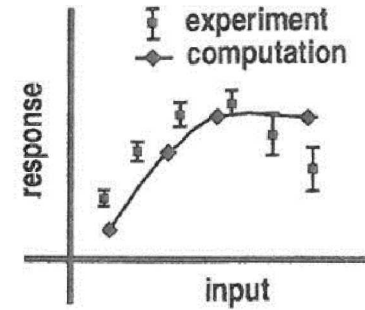
Levels of Precision



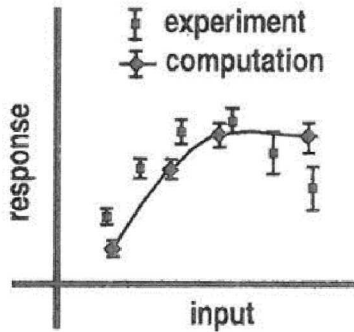
(a) Viewgraph Norm



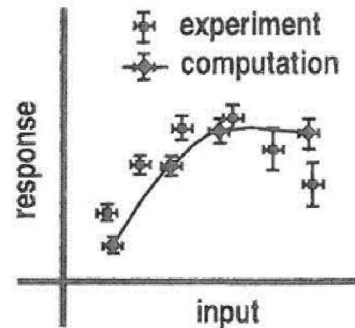
(b) Deterministic Simulation



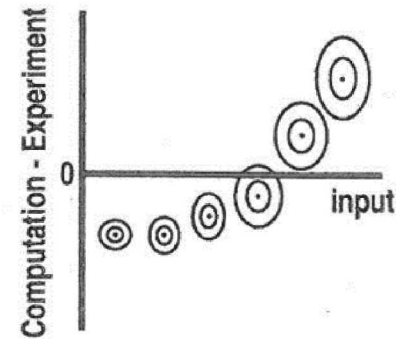
(c) Including Experimental Uncertainty



(d) Including Numerical Error



(e) Nondeterministic Simulation



(f) Statistical Mismatch

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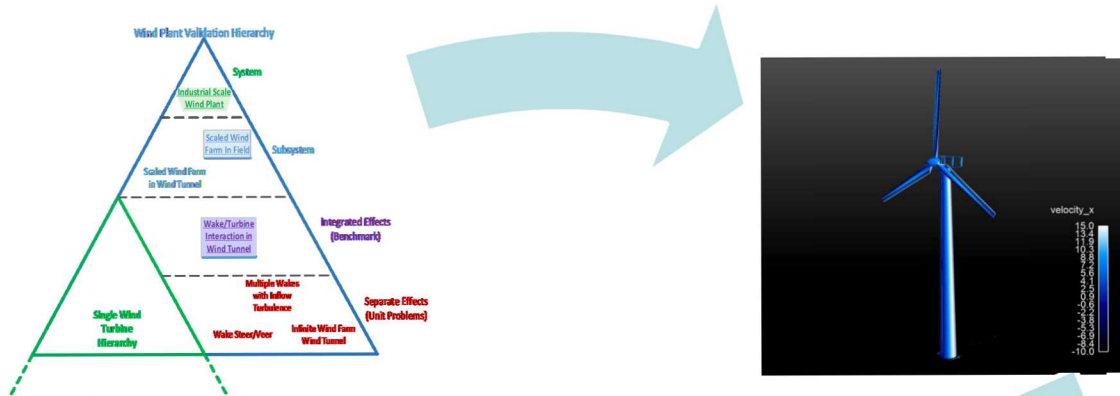
V&V/UQ Goals in Work Package 3

- 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

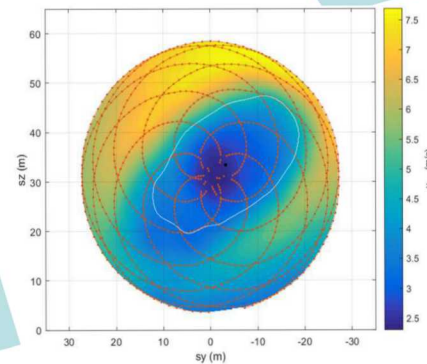
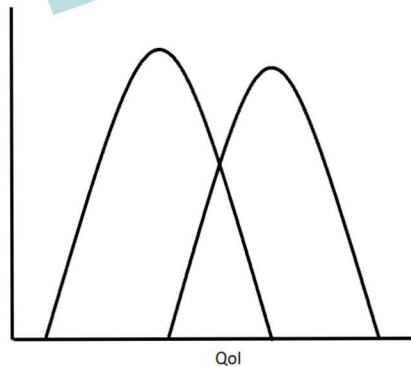
V&V Framework Summary

- 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



Virtuous Cycle
Validation
Model Development
Experimentation
Uncertainty Quantification



A2e V&V: Communication and Documentation

1. **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.
2. **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.
3. **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.
4. **Test Objectives and Prioritization for Wind Plant Performance** (July 2016): An intermediary step between the comprehensive information in the IPP document and the detailed planning needed in the integrated experiment and model planning and execution (IEMPE) stages.
5. **Integration into 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)

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: 3rd edition of Model Evaluation Protocol (M36)
- D3.2: 3rd 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)

Wind Turbine PIRT

Phenomenon	Importance at Application Level	Model Adequacy		
		Physics	Code	Val
Blade Aero / Wake Generation				
Blade load distribution effects and rotor thrust	H	M	L	L
Tip and root vortex development, 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 at trailing edge)	H	L	L	L
Root flow acceleration effect ("hub jet")	Unknown	M	L	L
Boundary layer development (transition, separation)	H	M	L	L
Surface roughness effects (roughness, soiling, bugs, erosion)	H	L	L	L
Boundary layer details near leading and trailing edge	H	M	L	L
Rotational augmentation	H	L	L	L
Dynamic stall	H	L	L	L
Unsteady Inflow effect (veer, shear, yaw, gusts, atmospheric stability, turbulence intensity, spectra, coherence)	H	L	L	L
Blade flow control	M	L	L	L
Icing	H	L	L	L
Wake Development (growth/recovery)				
Skew and meander of aggregate wake	H	L	L	L
Swirl instability	L	L	L	L
Vortex merging	L	L	L	L
Wake vorticity diffusion and dissipation	H	L	L	L
Asymmetry effects (ground plane, yaw, tilt, cone-angle)	M	M	L	L
Inflow effect (shear, veer, yaw, turb. intensity, turb. spectrum, coherence, gusts, atnos. stab.)	H	L	L	L

Wind Plant

PIRT

Phenomenon	Importance at Application Level	Model Adequacy		
		Physics	Code	Val
Inflow Turbulence/Wake Interaction				
Wind direction (shear/anisotropy)	H	L	M	M
Turbulence characteristics (intensity, spectra, coherence, stability)	H	L	M	M
Coherent turbulence structure	H	L	M	L
Surface conditions (roughness, canopy, waves, surface heat flux, topography)	H	L	M	M
Momentum transport (horizontal and vertical fluxes)	H	L	L	L
Multi-Turbine Wake Effects				
Wake interaction, merging, meander	H	L	L	L
Plant flow control for optimum performance	H	M	M	L
Wake steering (yaw & tilt effects)	H	L	L	L
Wake dissipation	H	L	L	L
Wake impingement (full, half, etc.)	H	L	L	L
Deep array effects (change in turbulence, etc.)	H	L	L	L
Other Effects				
Wind plant blockage effects and plant wake	M	M	M	L
Acoustic Propagation	H	L	L	L