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Overview of the V&V Framework

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U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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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

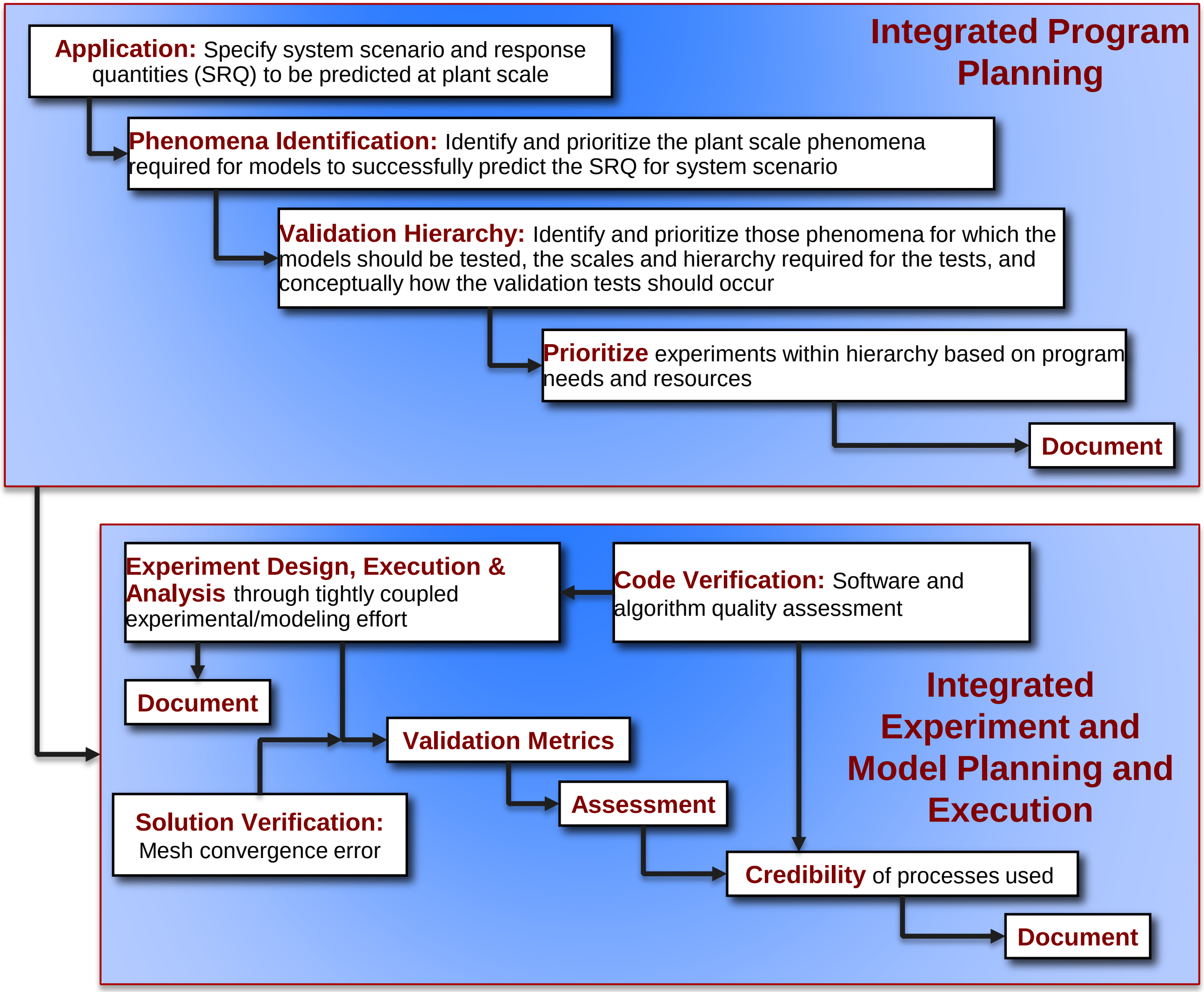
V&V Framework

Integrated Planning

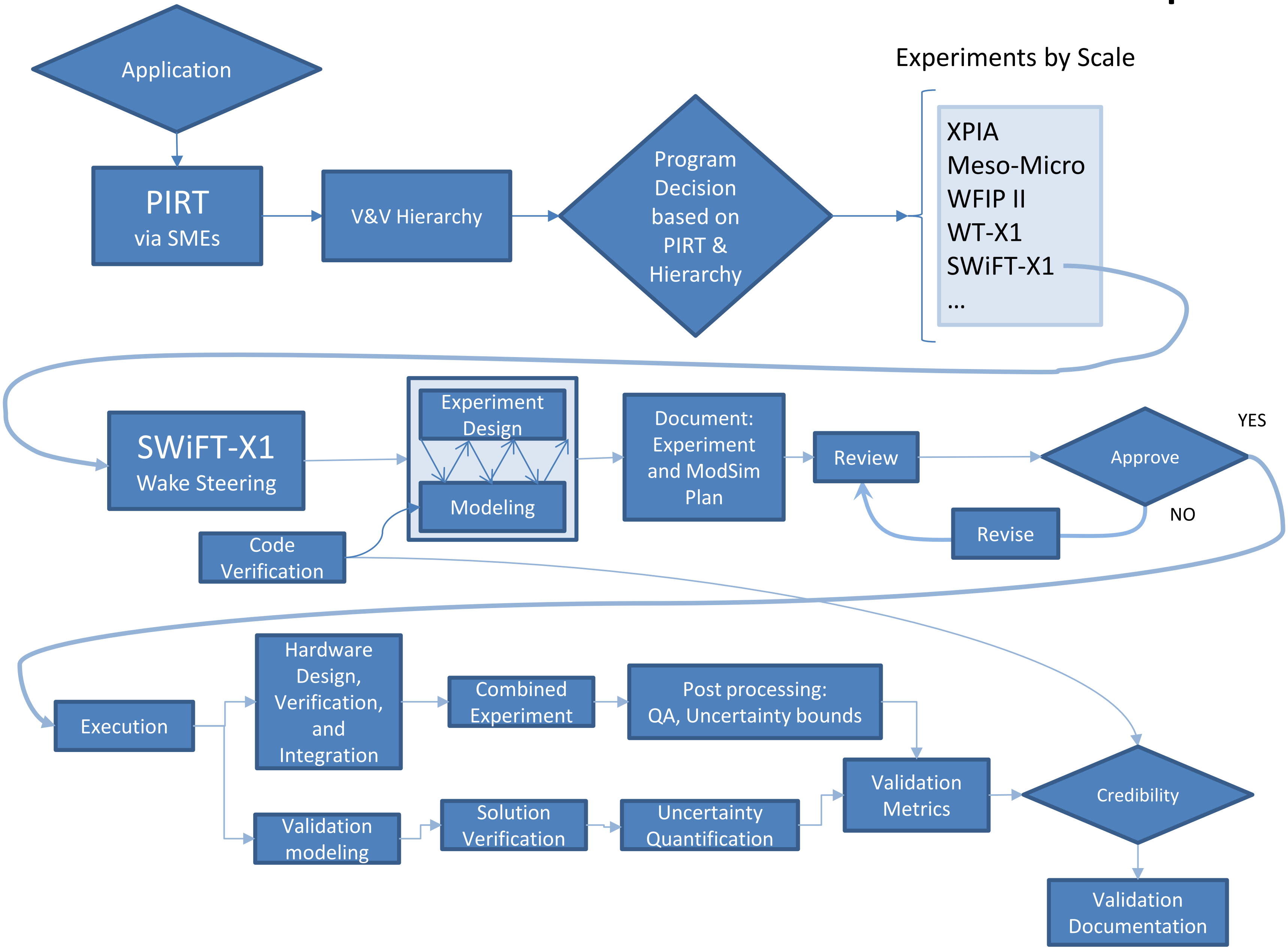
- Program leaders, modelers, software developers, experimentalists, V&V specialists

Validation Planning

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



Verification and Validation Process Example



Backbone of Prioritization Process: PIRT

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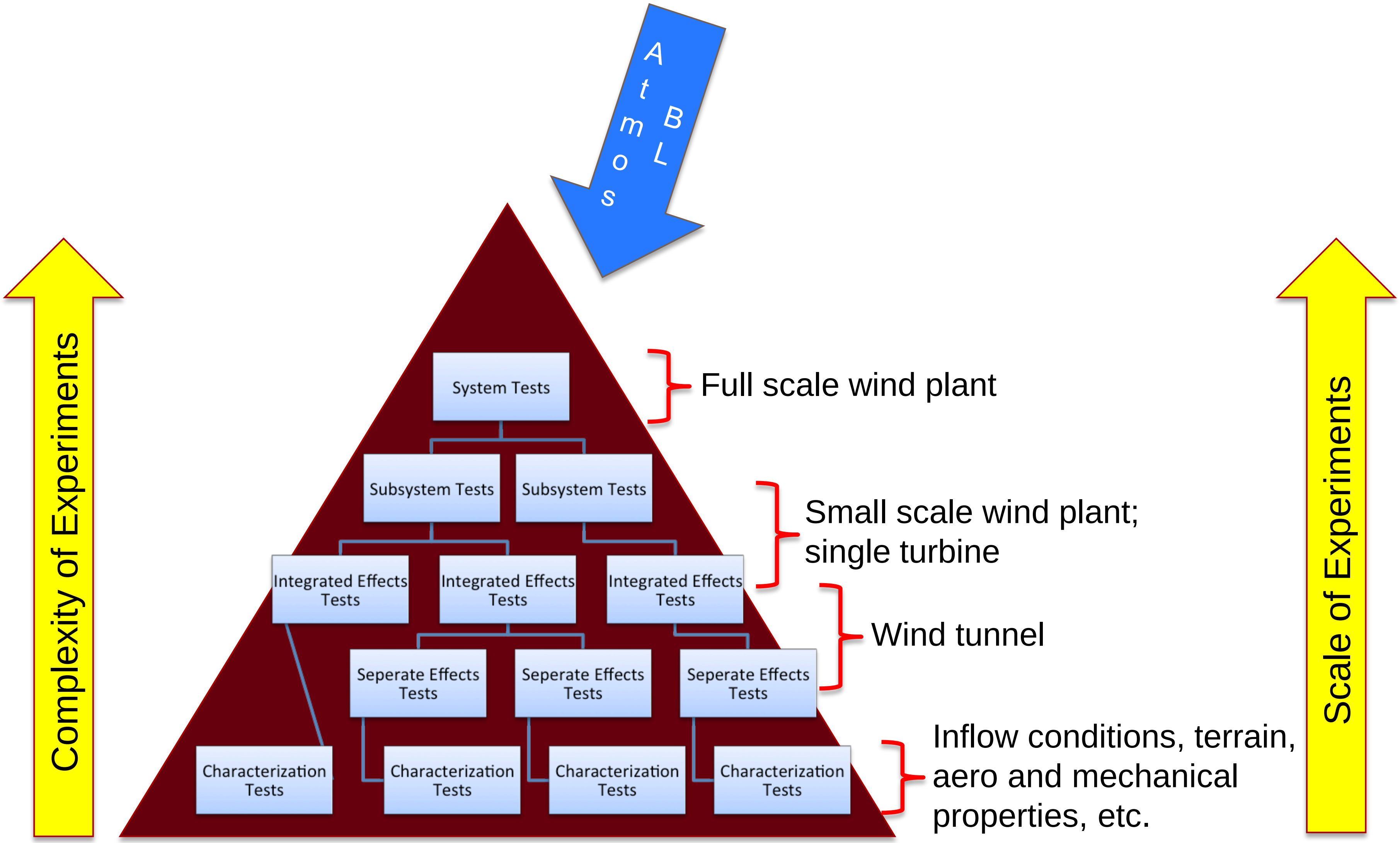
PIRT: Phenomenon Importance Ranking Table

- 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



Phenomena Identification Ranking Table (PIRT)

- These phenomena were identified through the Phenomena Identification Ranking Table (PIRT) process as high priority for model development and model assessment
- Created via stakeholder consensus, during multiple meetings attended by a broad cross-section of industry, university, and laboratory researchers during FY15.
- These key phenomena must be present in the validation experiments and adequately represented in the computational models.

Supporting Documents

Sandia National Laboratories

SANDIA REPORT
SAND2015-7455
Unlimited Release
Printed September 2015

V&V Framework

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SANDIA REPORT
SAND2015-9499
Unlimited Release
Printed October 2015

A2e High Fidelity Modeling: Strategic Planning Meetings

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A2e PIRT, Wind Turbine Scale

Phenomenon	Importance at Application Level	Model Adequacy: Physics	Model Adequacy: Code	Model Adequacy: Val	Issue/Comments	Response Including Scale	Interface
Blade Aero / Wake Generation							
Blade load distribution effects and rotor thrust	H	M	L	L	Integrates to Rotor Thrust-Torque; Rotor Load Model important for LES-ALM; Fully Resolved effected by grid & BL modeling parameters.	Some experiments done for validation. Important to measure for experiments where rotor loading is correlated to wake meas.	Blade
Tip and root vortex development, evolution and merging	H	M	L	L	Wake PIV Experiments performed, but error bars and QA/QC may be missing or unknown. Does not cover effect of inflow conditions.		
Vortex sheet and rollup (in addition to tip/root vortex)	M	M	M	L	Some experimental data available that indicates phenomenon are present and may be important to wake stability. Effect of separation	Further discovery experiments -> validation experiments.	
Blade generated turbulence characteristics (energetic scales at trailing edge)	H	L	L	L			
Root flow acceleration effect ('hub jet')	Unknown	M	L	L	Effects root dynamic pressure and loading.	Sensitivity Study to assess importance, qualitative data available.	Blade-Chord
Boundary layer development (transition, separation)	H	M	L	L	Affects airfoil tables -> AL methods. Affects fully resolved modeling requirements (grid, transition model). Depends on incoming turbulence intensity relevant to blade surface boundary layer, depends on surface quality (roughness, soiling, bugs, erosion). Importance uncertain.		Chord
Surface roughness effects (roughness, soiling, bugs, erosion)	H	L	L	L			Chord
Boundary layer details near leading and trailing edge	H	M	L	L			Chord
Rotational augmentation	H	L	L	L	Inability of HFM models to capture stall consistently.	Tests done on multiple rotor scales, need to assess gaps remaining from tests.	Chord
Dynamic stall	H	L	L	L	2D data based on non-specific wind turbine airfoils and/or are limited to lower Reynolds numbers than relevant to full-scale.	Tests done on multiple rotor scales, need to assess gaps remaining from tests.	Chord
Unsteady inflow effect (veer, shear, yaw, gusts, atmospheric stability, turbulence intensity, spectra, coherence)	H	L	L	L	Larger time scale than what affects blade surface BL, but faster than that allowed by steady-state on chord scale.		
Blade flow control	M	L	L	L			
Icing	H	L	L	L	Importance depends on region.		
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	Important for the far-wake and turbine-turbine interaction.		Wind Farm
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, atmos. stab.)	H	L	L	L	Full scale data often does not measure to top of turbine, limited to single vertical profile.		
Tower/rotor/nacelle wake interactions	H	M	L	L			
Aeroelasticity	H	M	L	L	Rated for very large blades.		
Aeroacoustics	H	M	L	L			

A2e PIRT, Wind Turbine Scale

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Wake vorticity diffusion and dissipation	H	L	L	L			
Asymmetry effects (ground plane, yaw, tilt, cone-angle)	M	M	L	L			
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Aeroelasticity	H	M	L	L	Rated for very large blades.		
Aeroacoustics	H	M	L	L			

A2e PIRT, Wind Plant Scale

Phenomenon	Importance at Application Level	Model Adequacy			Issue/Comments
		Physics	Code	Val	
Inflow turbulence/wake interaction					
Wind direction (shear/veer/assymetry)	H	L	M	M	gusts, low-level jet
Turbulence characteristics (intensity, spectra, coherence, atmospheric stability)	H	L	M	M	Includes how wake is affected by these phenomena.
Coherent turblence 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	side-flow is a special case, as well as the deep array
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	
Wind plant blockage effects and plant wake	M	M	M	L	
Acoustic Propagation	H	L	L	L	

A2e PIRT, Wind Plant Scale

Phenomenon	Availability of Adequate Validation Data	Recommended Scale of Experiments	Validation Data Requirements and Considerations
Plant Scale Phenomena	Low	Full Scale	Large array/internal boundary layer effect, vertical and lateral momentum flux, measure above and around wind plants and possibly above ABL height
Wakes	Low	Complimentary experiments at all scales	Merging, meandering, asymmetry, dissipation, near-to-far transition, steering, all dependent on atmospheric conditions, observations of wake centerline motion.
ABL - shear	Low	Complimentary experiments at all scales	Dependent on surface roughness which is difficult to quantify
ABL - veer	Low	Full Scale	Highly dependent on stability, so temperature profiles and ABL height measurements important
ABL - special events	Low	Full Scale	K-H waves, turbulence bursting, roll cells, phenomena are intermittment and dynamic
ABL - surface flux	Low	Complimentary experiments at all scales	Heat and moisture measurements have large spatial inhomogeneity
ABL - complex topography	Low	Full Scale	More complexity requires more instrumentation
ABL - all other	Medium	Check for existing data	

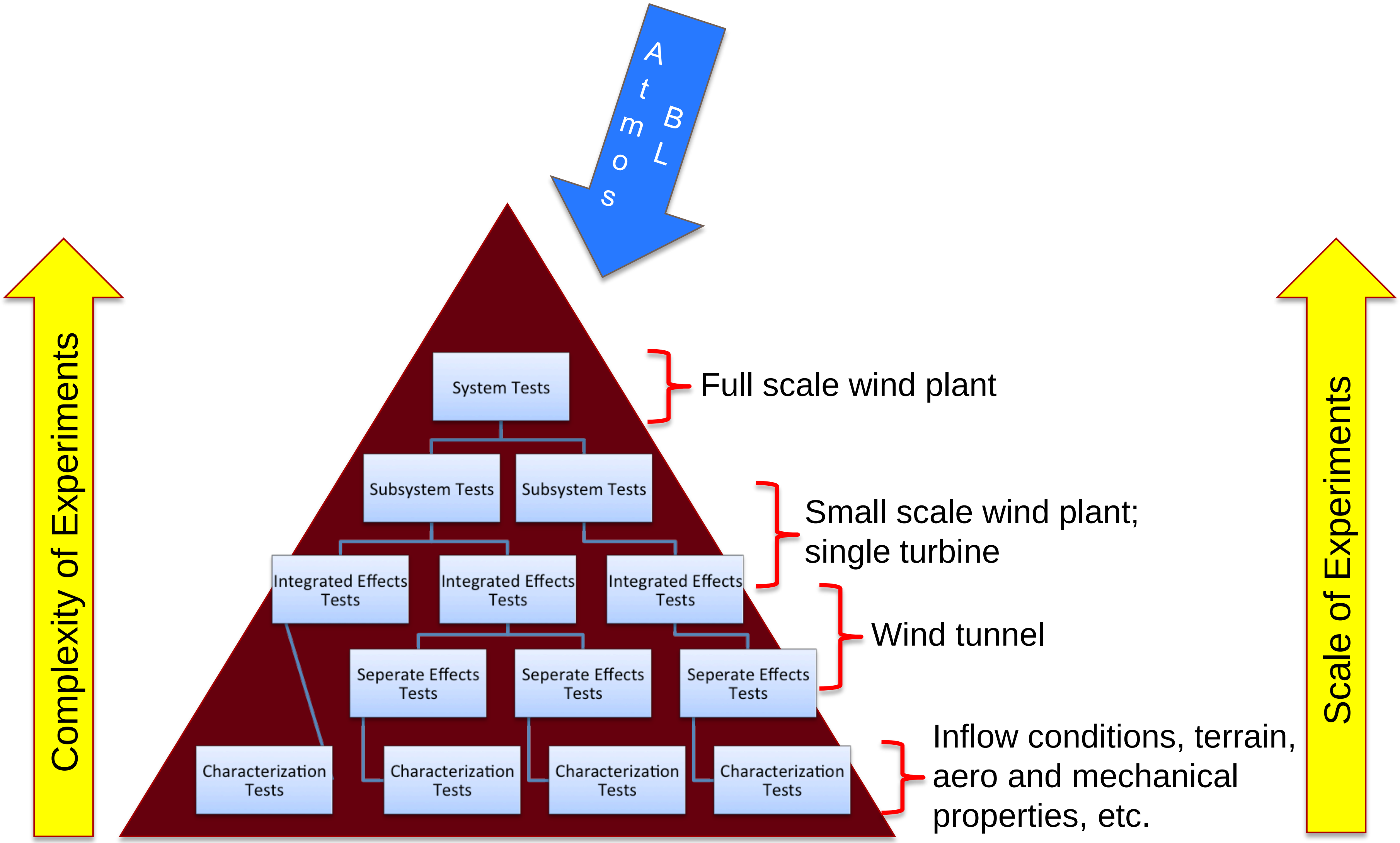
*From SAND Report SAND2015-9499, “A2e High Fidelity Modeling: Strategic Planning Meetings”

A2e PIRT, Summary of Physical Phenomena

Phenomenon
Inflow turbulence/wake interaction
Wind direction (shear/veer/assymetry)
Turbulence characteristics (intensity, spectra, coherence, atmospheric stability)
Coherent turblence structure
Surface conditions (roughness, canopy, waves, surface heat flux, topography)
Momentum transport (horizontal and vertical fluxes)
Multi-turbine wake effects
Wake interaction, merging, meander
Plant flow control for optimum performance
Wake steering (yaw & tilt effects)
Wake dissipation
Wake Impingement (full, half, etc)
Deep array effects (change in turbulence, etc.)
Wind plant blockage effects and plant wake
Acoustic Propagation

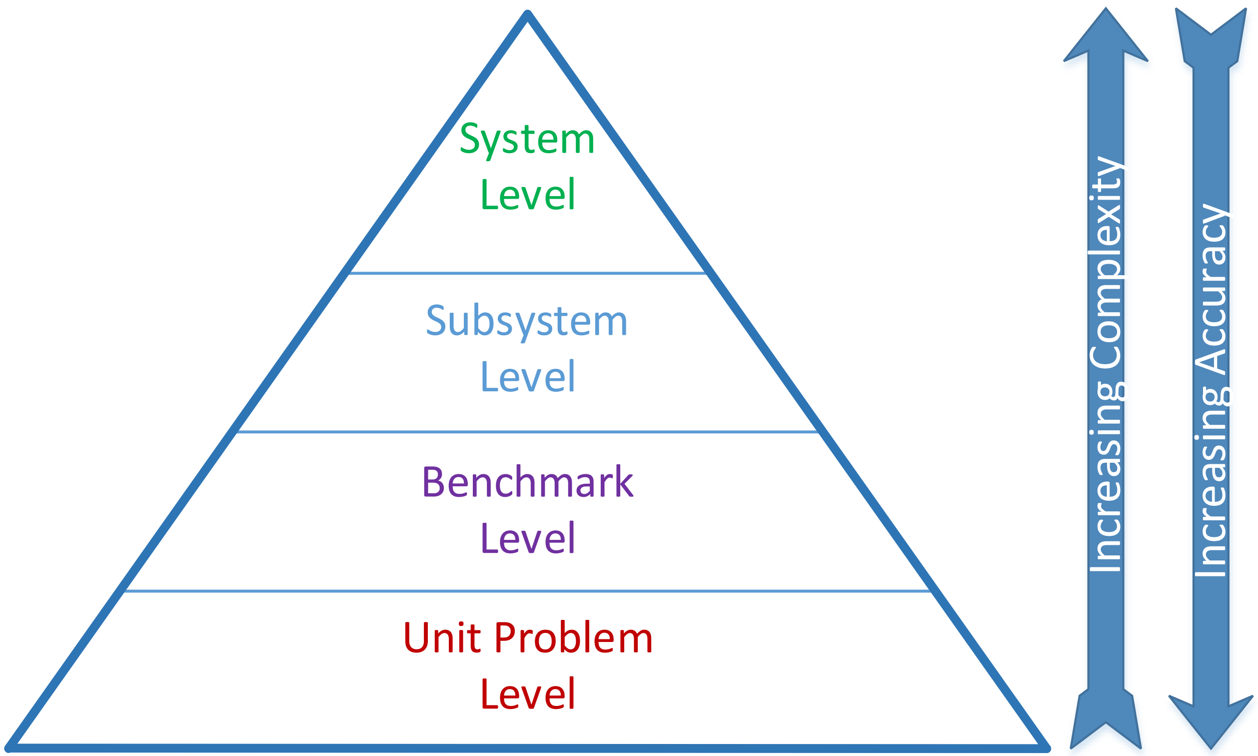
Phenomenon
Plant Scale Phenomena
Wakes
ABL - shear
ABL - veer
ABL - special events
ABL - surface flux
ABL - complex topography
ABL - all other

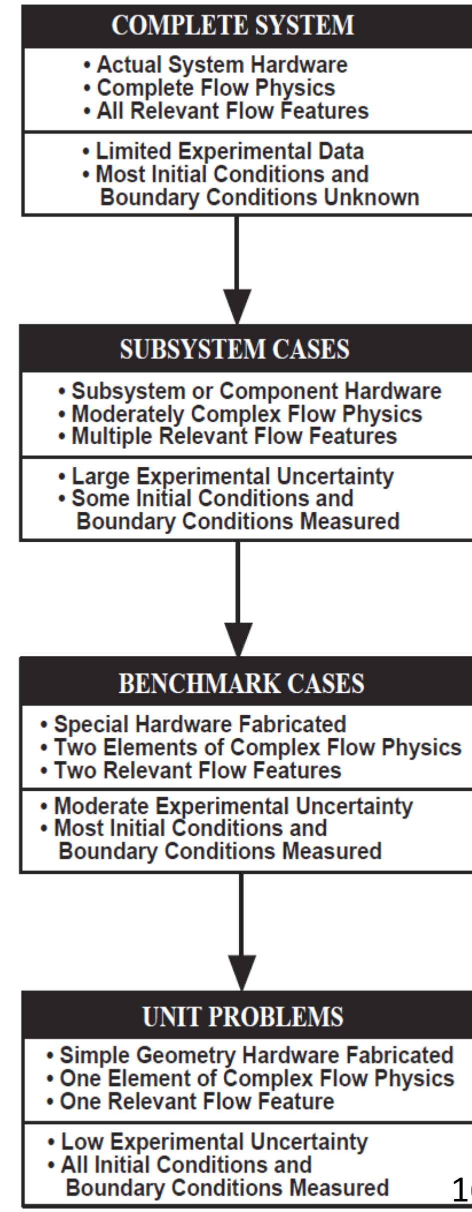
PIRT Leads to the Validation Hierarchy



V&V Process
Validation Hierarchy

Validation Hierarchy

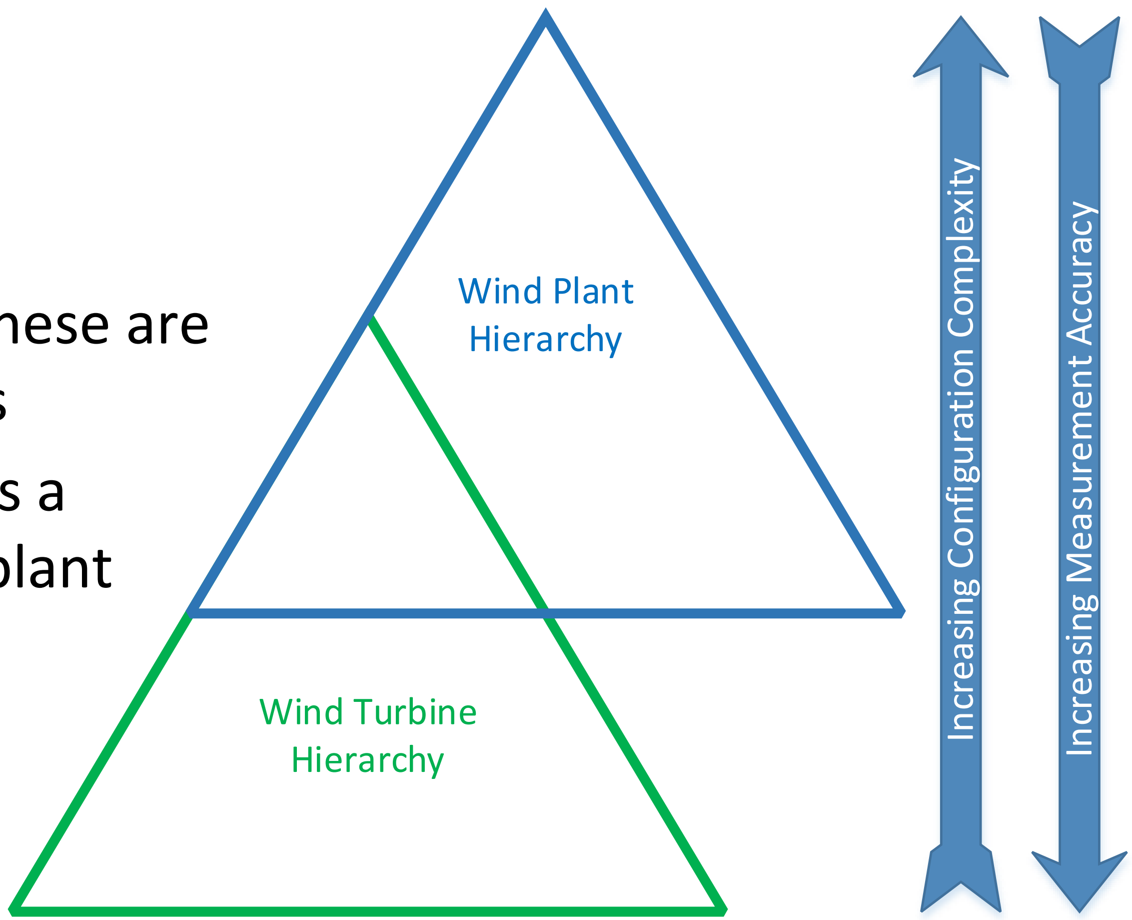




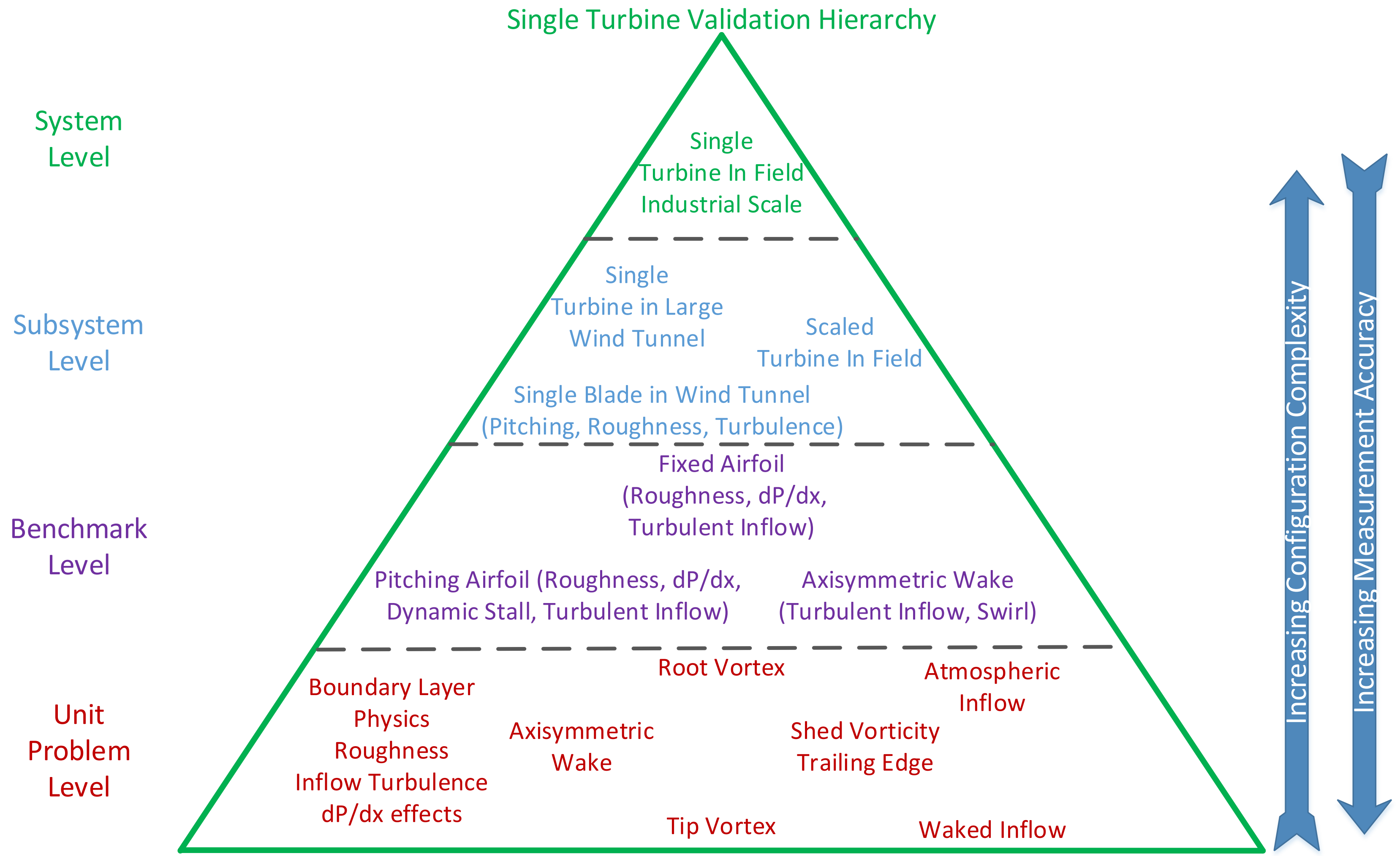
- Divides the complex engineering system of interest into progressively simpler tiers

Application to Wind Turbine/Wind Plant

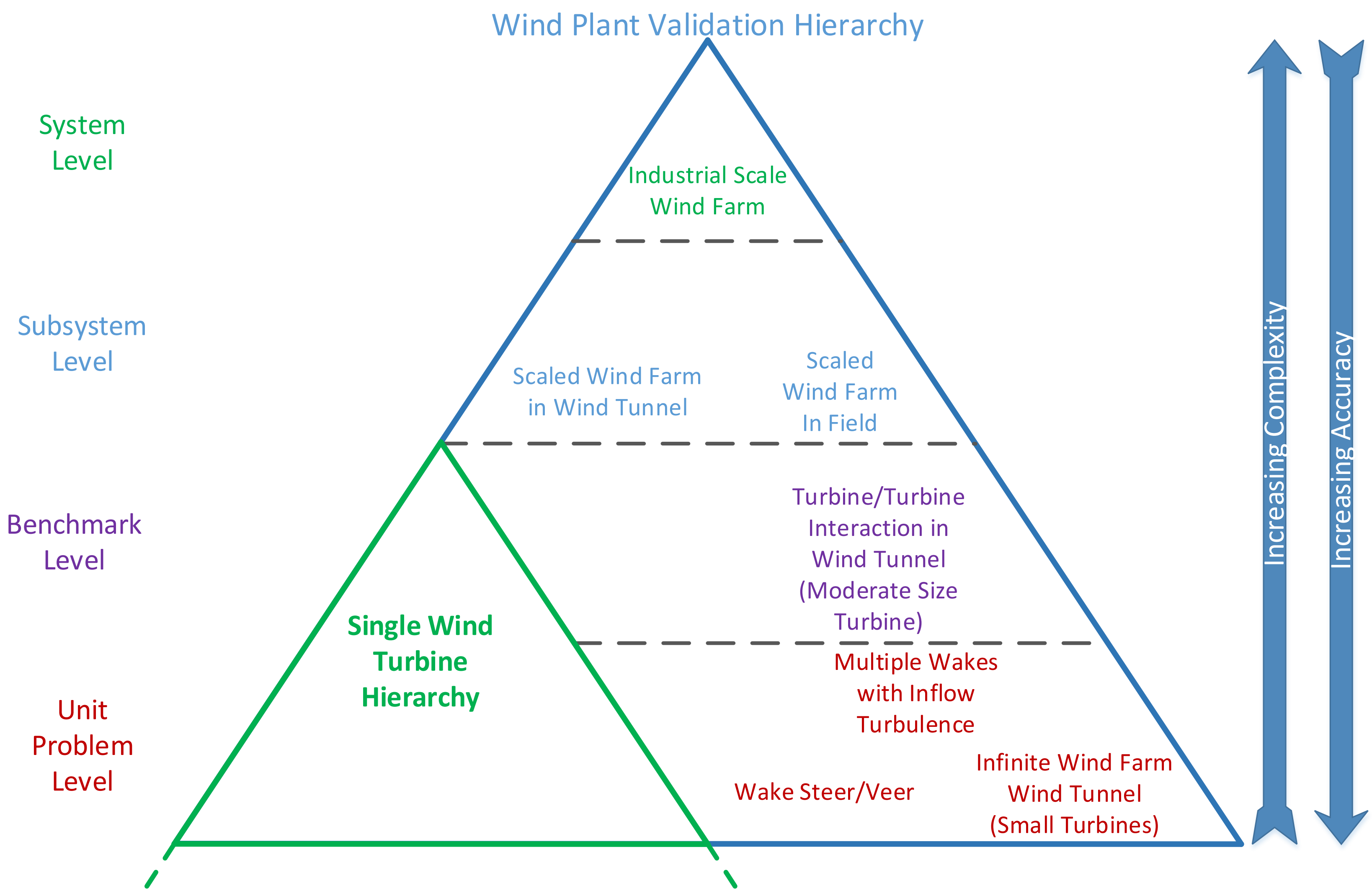
- Planning steps have been carried out
  - Wind turbine scale
  - Wind plant scale
- Important to consider these are not independent efforts
  - Wind turbine scale is a subsystem of wind plant scale



Wind Turbine Validation Hierarchy



Wind Plant Validation Hierarchy



Validation Hierarchy Leads to Validation Experiments

Validation is a process of characterizing model error, not a binary statement of model validity

Characteristics of a successful validation programs

- Highly collaborative – team includes experimentalist, modelers, V&V specialist
- Models are used during the design phase to
  - Assure that the experiments are sensitivity to the phenomena of interest
  - Help optimize the experiments, i.e. define sensor location, density, sampling rates, …
  - Assure that the experiments can be unambiguously modeled (failure to do this is the most common reason for the failure of a validation exercise)
- Estimates of data uncertainty and model prediction uncertainty play a key role in the model validation process
- Model credibility is established by following a formal verification and validation process

Definition of a Modeling Campaign:

1.) What is to be predicted?
2.) Under what scenario?
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?

Wind Plant, PIRT Mapping to Experiment

Physics Present/Physics Measured

- ● (red) Entirely
- ◒ (red) Mostly
- ○ Somewhat
- ◓ Limited
- ● Missing

	Multi-Turbine Wake Effects	Interaction, Merging, Motion	Steering (Yaw/Tilt Effects)	Wake Dissipation	Wake Impingement (Full/Half/Near)	**Inflow Turbulence Wake Interaction**	Wind Direction	Surface Conditions	Turbulence Statistics	Momentum Transport	**Acoustic Propagation**	**Testing Issues**	Boundary Conditions	Scale Effects
Industrial Scale Wind Farm in (60 m rotor)														
Physics Present		Entirely	Entirely	Entirely	Entirely		Entirely	Entirely	Entirely	Entirely	Entirely			
Physics Capture by Measurements		Limited	Limited	Limited	Limited		Somewhat	Mostly	Limited	Limited	Mostly		Limited	Entirely
Scaled Wind Farm in Field (20 m rotor)														
Physics Present		Entirely	Entirely	Mostly	Entirely		Entirely	Mostly	Mostly	Mostly	Mostly			
Physics Capture by Measurements		Somewhat	Somewhat	Limited	Somewhat		Mostly	Mostly	Somewhat	Limited	Mostly		Limited	Entirely
Scaled Wind Farm in VL WT (2 m rotor)														
Physics Present		Mostly	Mostly	Somewhat	Mostly		Entirely	Somewhat	Somewhat	Somewhat	Somewhat			
Physics Capture by Measurements		Mostly	Mostly	Mostly	Entirely		Entirely	Entirely	Mostly	Mostly	Mostly		Mostly	Entirely
Wake/Turbine Interaction in WT (2 m rotor)														
Physics Present		Limited	Mostly	Limited	Mostly		Somewhat	Somewhat	Mostly	Mostly	Limited			
Physics Capture by Measurements		Mostly	Mostly	Somewhat	Entirely		Entirely	Entirely	Mostly	Mostly	Mostly		Mostly	Entirely
Wake Steer/Veer (0.2 m rotor)														
Physics Present		Somewhat	Mostly	Limited	Mostly		Somewhat	Limited	Somewhat	Somewhat	Limited			
Physics Capture by Measurements		Entirely	Entirely	Mostly	Entirely		Entirely	Entirely	Entirely	Entirely	Limited		Entirely	Entirely
Multi Wakes with Inflow Turbulence (0.2 m rotor)														
Physics Present		Mostly	Somewhat	Somewhat	Mostly		Somewhat	Limited	Mostly	Mostly	Limited			
Physics Capture by Measurements		Entirely	Entirely	Entirely	Entirely		Entirely	Entirely	Entirely	Entirely	Limited		Entirely	Entirely
Infinite Wind Farm in Wind Tunnel (0.2 m rotor)														
Physics Present		Mostly	Somewhat	Somewhat	Mostly		Mostly	Limited	Somewhat	Mostly	Limited			
Physics Capture by Measurements		Entirely	Entirely	Entirely	Entirely		Entirely	Entirely	Entirely	Entirely	Limited		Entirely	Entirely

Wind Plant, PIRT Mapping to Experiment

Physics Present/Physics Measured

- Entirely
- Mostly
- Somewhat
- Limited
- Missing

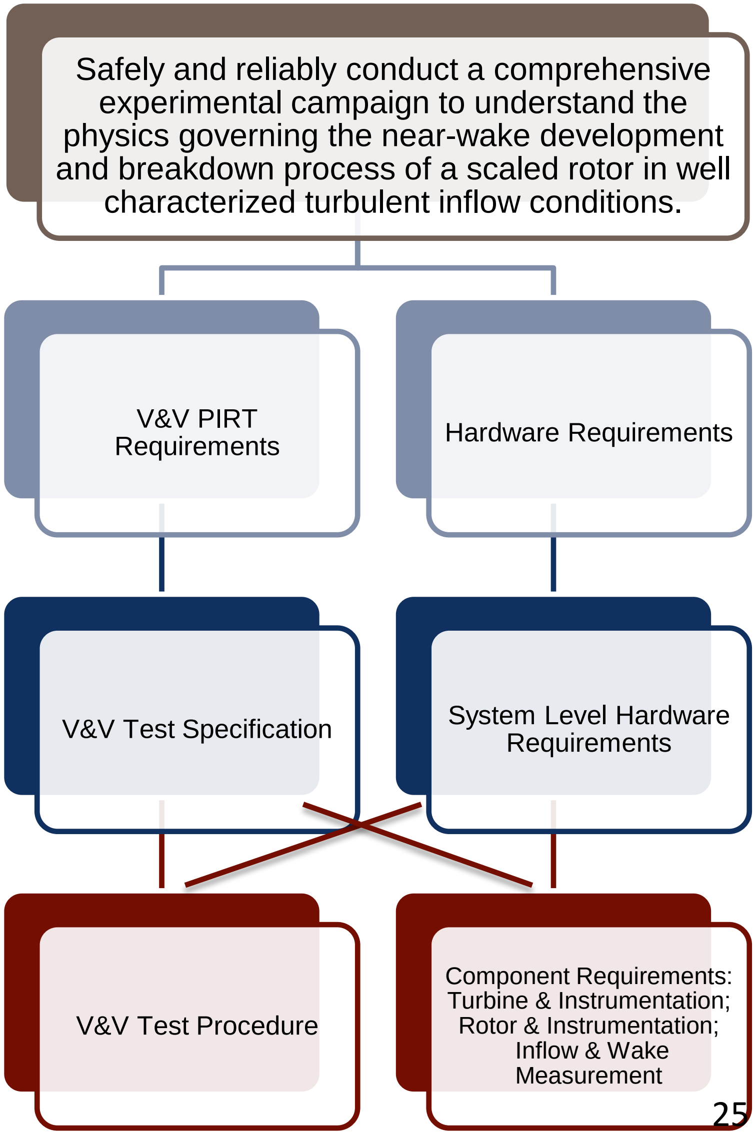
	Multi-Turbine Wake Effects	Interaction, Merging, Motion	Steering (Yaw/Tilt Effects)	Wake Dissipation	Wake Impingement (Full/Half/Near)	**Inflow Turbulence Wake Interaction**	Wind Direction	Surface Conditions	Turbulence Statistics	Momentum Transport	**Acoustic Propagation**	**Testing Issues**	Boundary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

Validation data request

- An example Validation Data requirement:
  - Objective: quantify distribution of blade spanwise load
  - Method: surface pressure measurements and/or spanwise strain measurements
  - Environment: clean uniform inflow, turbulent inflow with quantified turbulence character and shear character
  - Success criteria: measurement data available with quantified inflow including uncertainty bounds.
- Important to design experiment such that it can be openly modeled
  - Perform sensitivity analysis to select surface pressure measurement locations

SWiFT test requirements schema

- Design of new test hardware for SWiFT could be done based on known operational envelopes and using standard rotor design practices and standard farm flow measurements.
- At the same time, design of a V&V test campaign begins with the PIRT process, which determines a test campaign specification, which leads to a test procedure.
- Interdependency 1: The test campaign specification drives aspects of test hardware and test instrumentation.
- Interdependency 2: The hardware operational requirements drives aspects of the V&V test procedure.



Thank you