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V&V Integrated Program Planning for Wind Plant Performance

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ABSTRACT

The Department of Energy Atmosphere to Electrons (A2e) initiative has undertaken an experimental planning process for a validation directed program and an experimental planning process directed at improving simulations of wind plant performance. The validation process has been divided into two main sections: Integrated Program Planning, and Integrated Experiment and Model Planning and Execution. This document covers the Integrated Program Planning process in detail as it has been applied to the validation and assessment of models of various fidelity to predict wind plant performance. Three main parts of this process are presented in this document: the Phenomenon Identification and Ranking Table, the Validation Hierarchy, and the Prioritized Phenomenon and Experiment Mapping table. The document concludes with a description of validation program process next steps, which includes the planning and execution of integrated experiment and model campaigns.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AL	Actuator Line
BL	Boundary Layer
DOE	Department of Energy
HFM	High Fidelity Models
IEMPE	Integrated Experiment and Model Planning and Execution
IPP	Integrated Program Planning
LWT	Large Wind Tunnel
PIRT	Phenomenon Identification and Ranking Table
PPEM	Prioritized Phenomena Experiment Mapping
Sandia	Sandia National Laboratories
SME	Subject Matter Expert
SWT	Small Wind Tunnel
TI	Turbulence Intensity
V&V	Verification and Validation
WT	Wind Tunnel

1 INTRODUCTION

1.1 Role of Computational Modeling in Wind Energy Applications

Models, whether computational or analytical, are used in many aspects of wind turbine and wind plant design and analysis. Computational models are used to predict and optimize the performance of novel wind turbine designs. These models are also used to qualify that a design meets lifecycle loads and reliability requirements. Similarly, a range of models are used to predict the performance in wind plants, considering terrain effects and wind resource variability and uncertainty. Some models are useful for predicting the average performance of a wind plant, but not for predicting the performance of an individual turbine, making their usefulness deficient for optimizing the layout of a wind plant.

As wind turbine technology matures developing and designing innovative technology to improve wind turbine and wind plant performance will demand higher levels of model fidelity and accuracy. As the importance of modeling in the design, analysis, and decision-making processes increases, the importance of experimental data for model validation increases in parallel. The increasing system complexity, size, and cost of wind plants combined with more rapid development cycles will limit testing of full scale systems in complete operational environments. This limited testing will drive increased reliance on computational models, shifting the primary role of experiments from routine system testing and discovery to model validation. To this extreme, modeling can serve as a primary source of evidence to prove a system meets design requirements. Modeling and testing can also serve complimentary roles, since testing is often performed under a limited set of conditions due to a range of constraints (such as resources), and modeling can be utilized to extend system qualification to untested conditions. An example of complimentary application is the use of a limited set of meteorological measurements along with atmospheric models to predict the wind resource at a site at higher spatial and temporal resolution (interpolation) and over a larger area (extrapolation) than the measurements alone could provide.

1.2 V&V and Validation Directed Programs

If the move toward increased reliance on models for improving wind turbine and wind plant designs is to be successful, a methodical approach in assessing a model's capability is necessary. Verification and validation (V&V) are integral parts of establishing a model's predictive capability for an intended application. Validation is not a pass/fail exercise for a simulation. Rather it assesses the uncertainty of the predictive capability that the user can utilize to judge its suitability for a given application. Verification and validation are commonly defined as follows [ASME, 2009]:

- 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.

This document is focused on the validation process and how it leads to modeling and experiment planning. Verification processes are being planned concurrently and will be executed by the model development teams.

1.3 Overview of the Validation Program Process

The Department of Energy (DOE) Atmosphere to electrons initiative (A2e) V&V program has been developed through a formal framework adapted to the needs of the wind program [Hills et al., 2015]. As outlined in Figure 1, this process has two main parts: integrated program planning (IPP), and integrated experiment and model planning and execution (IEMPE). The integrated program planning process is used to define, justify, and prioritize the hierarchy of validation experiments as relevant to the modeling and simulation of wind plant performance. The IEMPE process is used to ensure that the experimental results are suitable to meet the model validation objectives defined in the IPP process.

The IPP process, outlined in the top of Figure 1, is the primary focus of the present document. This validation process includes:

- the high-level validation objective for wind plant performance prediction,
- the identification and description of the phenomena identified as having the highest priority for validating wind plant models,
- the identification of experiments at different levels of the validation hierarchy to meet the validation needs for the identified phenomena, and
- a mapping of the ability of each experiment to capture the various phenomena.

The IPP process leads to the integrated experiment and model planning and execution (IEMPE) process, which is outlined in the bottom of Figure 1. The IEMPE process involves:

- experiment design,
- data acquisition design,
- modeling to ensure that the conditions and scope of the experiments are sufficient to adequately test the model,
- execution of the experiment and the computational model for the experiment as it occurred,
- post-processing of the results including the evaluation of the validation measures and their uncertainties, and
- interpretation of the results.

The next step is defining the detailed objectives for the highest priority experiments, followed by detailed experiment planning and execution. Models of varying fidelity will be used to design these experiments. Initial experimental results will be used to calibrate and improve the models. The final experiment results will be compared to the modeling results, including estimates of uncertainty of the final quantities of interest. The results of each validation campaign will be used to provide a means for assessing model credibility for given applications, and to identify the gaps that remain. The Phenomenon Identification and Ranking Tables (PIRTs), hierarchies, and Prioritized Phenomenon Experiment Mapping (PPEM) process established in this document can then be revisited, and future combined experiment and modeling campaigns established to address the remaining gaps.

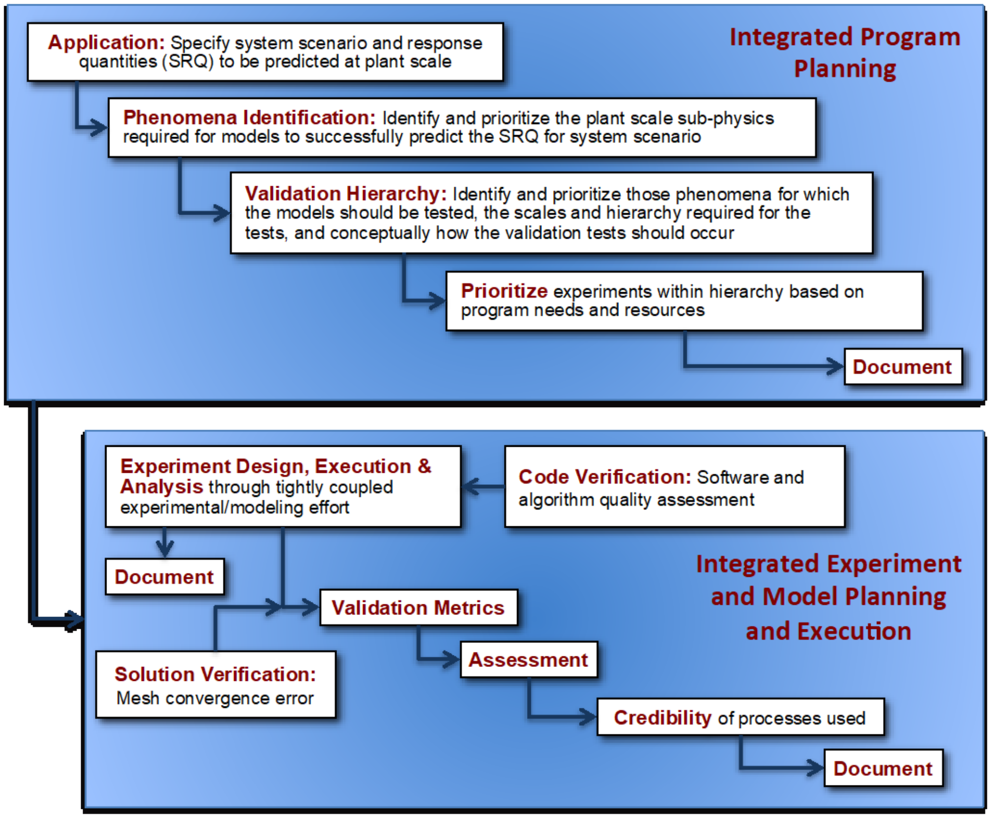

Figure 1 – Validation directed program planning and execution. The first phase of this process (Integrated Programming Planning) is the focus of this document.

1.4 Credibility of a Validated Model

Direct comparison between simulation model output and experimental data provides evidence of a model's simulation capability for the conditions tested. For wind turbine and wind plant analyses, a model is commonly used as a predictive tool, meaning it is utilized to simulate the performance of a system in a novel implementation and/or environment beyond the conditions tested. Confidence in the predictive capability of that model is based, in some form, on past experience. This experience is typically based on the working knowledge of the modeling tool users, who have applied it to a range of applications and have some working knowledge of how well it worked for those applications.

Validation is a process designed to formalize the process of determining and documenting how well a model simulates the important physical quantities for a given application as compared to validation quality experimental results. Credibility becomes important when a model must be used beyond the conditions tested, as is commonly required of engineering computational models.

The present validation process relies on two tools to formally establish model credibility. The Phenomenon Identification and Ranking Table (PIRT) is used to identify the import physical phenomena for a given model application. The Validation Hierarchy shows how validation of a model through a combination of various experiments can build confidence in applying it to a new application. The Validation Hierarchy also shows how modeling and experiments can be used together to gain confidence in the understanding of a physical phenomenon. The assessment of model credibility for the phenomena identified in the PIRT for a specific application is based on formal modeling processes, which have six main elements [Oberkampf et al., 2007; Hills et al., 2015]. These elements are:

1. Representation or Geometric Fidelity: The level of detailed characterization of the system being analyzed, the specification of geometrical features of that system, and the model representation of the specification. For example, does the representation of a wind turbine blade pressure distribution as an actuator line significantly affect wake recovery predictions for a specific application scenario?
2. Physics and material model fidelity: The degrees to which models are physics based and calibrated, as well as the degree to which models are being extrapolated from the validation and calibration databases to the scenarios of application. For example, is a tuned wake model being applied to an atmospheric stability state outside of the range of the calibration data?
3. Code verification: The degree to which software errors (bugs) and algorithm deficiencies influence the simulation results. Credibility is established through formal process to minimize such errors; for example, software quality assurance processes, nightly regression runs, and code verification test suites.
4. Solution verification: The degree to which numerical solution errors and human procedural errors impact the simulation results. Error is minimized by establishing simulation workflow processes that eliminate user input errors. Credibility is established through evidence of equation solver convergence and grid convergence uncertainty quantification.
5. Validation: The degree of accuracy of the integrated physics and material models relative to experimental measurements for the conditions of the validation tests. The validation test likely has differences from the application scenarios of interest, and so the relevancy of the experimental conditions, physical hardware, and measurements must be established.
6. Uncertainty quantification and sensitivity analysis: The degree to which variability and uncertainty impact system performance and design margins. Credibility is established through robust identification and characterization of sources of uncertainty, the completeness of a sensitivity analysis to determine the primary contributors to uncertainty in the system response quantities, the accuracy of propagating uncertainties through the computational model, and the correctness of the interpretation of the resulting uncertainties in the system responses. For example, how does uncertainty in wind direction measurements affect the predicted model bias for predictions of the wake offset due to yaw offset?

These six elements are discussed in detail in the V&V Framework report [Hills et al., 2015], including an explanation of how to utilize them to characterize the overall risk of using a model for prediction.

1.5 Planning and Execution Documentation

A crucial step in the validation program process is documentation of the planning and execution stages. The list below represents an inventory of planning process documents both currently in use and planned for future use. These documents are listed here.

1. **V&V Framework** (September 2015) [Hills et al., 2015]: A comprehensive document on the development and execution of coordinated modeling and experimental 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. This document covers the definition of requirements and priorities for developing a predictive wind plant modeling and simulation environment. Additionally, it summarizes the identification and prioritization of wind plant physical phenomenon and the experimental data necessary to validate models for the associated quantities of interest.
3. **V&V Integrated Program Planning for Wind Plant Performance**: This document outlines the Integrated Program Planning (IPP) process and specifically applies it to wind plant performance prediction. The result is a comprehensive list of phenomena, how they relate in the validation hierarchy, and how they map to a detailed list of experiments. The phenomena and experiments listed in the IPP are broad and meant for use as a guide for experimental planning, model development, and model application.
4. **Test Objectives and Prioritization for Wind Plant Performance**: This document is 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. Due to the broad range of phenomenon identified in the IPP stage, a subset must be selected to be focused on, which can be selected based on model sensitivity analysis, uncertainty quantification, expert opinion, program priorities, available facilities, available measurement technology, and available resources. This sub-selection process can make use of the comprehensive PIRT, validation hierarchy, and PPEM developed in the previous stage to determine how the use of certain experimental facilities may only allow the study of specific phenomena. This document is planned for future development.
5. **Integrated Experiment Planning Summary**: The IEMPE process is summarized at the end of the present IPP document. This process will be documented as validation campaigns are conducted, and will be carried out in two steps, the first of which is the Integrated Experiment Planning Summary and Details of Execution document. This first document will include details of the validation test objectives, modeling performed for experiment design, justification and details of the instrumentation suite, logistical planning, and expected results. This document is planned for future development.
6. **Process Description, Results, and Next Steps**: This will serve as the second document in the coverage of the IEMPE process. It will cover the as-executed validation campaign process, results, and remaining gaps. The content will include the executed experiment summary, modeling of the experiment, measured and derived quantities for comparison, the

experiment and model uncertainty quantification processes, campaign results, and remaining validation gaps including proposed ways to address them. The remaining validation gaps may be due to expected limitations of the validation campaign or may be due to unexpected limitations of the model or experiment for the desired conditions. The gaps will be addressed by some combination of model development, uncertainty quantification process development, instrumentation development, new test campaigns, and re-visitation of the IPP process. The validation process is a cyclic, living process, due to the assumptions made in the phenomenon importance and modeling adequacy assessments in the beginning of the process, as well as assumptions about program priorities, which may change during the course of the validation program. This document is planned for future development.

1.6 IPP Document Intended Audience

This document differs significantly from Hills et al. in that it applies the V&V framework specifically to wind plant performance [Hills et al., 2015]. As a result, this document targets several specific audiences. ***V&V Specialists*** are familiar with V&V documents, standards, and methodology, and can use this document to plan, coordinate, and execute wind plant model validation campaigns. ***Model developers*** create and maintain the algorithms and codes that are utilized in the validation campaign. These algorithms are then used in the desired applications and can use this document to establish the set of physical phenomena and interaction between those physical phenomena that the model will be used to simulate. ***Model application experts*** can apply the model workflow to similar applications and scenarios and use this document to consider the limits and challenges in applying the model algorithms. ***Experimentalists*** have experience designing and executing experiments with similar phenomena and environmental scenarios to the planned validation campaigns and can use this document to establish the quantities that must be captured, measured, processed, and archived in experimental campaigns. The document is useful for ***program planners*** who can use this content to assist in prioritizing the experiments and corresponding validation efforts in light of the funding available. Finally, this report will be valuable for ***those responsible for archiving*** simulations results and experimental data obtained in the validation efforts by providing a framework for organizing the results to facilitate identification of data sets for current and future validation efforts.

2 INTEGRATED PROGRAM PLANNING

The integrated planning process consists of four important steps. First, objectives that identify the need for computational simulations are identified. Second, a Phenomena Identification Ranking Table (PIRT) is developed to prioritize physical and model-related phenomena. This PIRT identifies the gaps between current and desired simulation capabilities, and thus can be used to develop Validation and Verification efforts. The PIRT is then used to develop a Validation Hierarchy, which is a suite of experiments intended to study important phenomena individually as well as combined through an experiment hierarchy. Finally, a mapping of the suggested validation experiments onto the important phenomena is performed using a Prioritized Phenomenon Experimental Mapping (PPEM) process. Performing these steps permits a prioritization of the experiments to be performed, which can depend on specific program priorities and funding constraints. The subsequent sections apply these steps to the continued development of wind plant simulation capability.

2.1 Objective

The objective forms the base of the integrated program planning process. The objective of a validation-driven program must include what is to be predicted, the scenario, and the impact of the prediction on the decision process. The modeler (or analyst) will use the objective to define the expected use of the model and what quantities will be used in the design decision making process. The modeling objective defines the calibration, characterization, and validation data that the experimentalist will provide to the modelers and validation specialists. Meeting this objective requires careful validation of the computational models. The objective for wind plant performance and loads is as follows:

> Computational simulations will be used to predict the performance of wind plants under relevant operational conditions given terrain and plant configuration. Validated computations shall be able to predict both individual turbine and overall plant performance quantities of interest with an uncertainty that makes the predictions useful for a specific application. The simulation capability may then be used for power estimates, optimization of wind farm layout and control, and other wind plant related applications. The simulation capability will also be used to predict wind turbine system response and loads as well as other wind-turbine specific tasks. This simulation capability is critical to the wind farm development process as it affects both the overall power production and its uncertainty as well as wind plant lifetime. Optimizing production and minimizing risk has a favorable impact on a project's profitability. The ability to better predict wind plant performance can also ease integration of wind in grid operations.

The objective for wind plant performance modeling was created by more than a dozen modelers, experimentalists, and validation specialists from a broad range of the wind energy community.

2.2 PIRT

2.2.1 What is a PIRT and How is it Used?

Having defined the objective, the next step in Integrated Program Planning is identifying important phenomena to represent in the computational model in order to meet the objective. The Phenomena Identification Ranking Table (PIRT) identifies the necessary phenomena (sufficient to enable validation) and phenomena prioritization (to allow efficient execution of the validation program) necessary for a successful V&V campaign. As used in this application, the PIRT lists the important phenomena and evaluates model adequacy for each phenomena in terms of the physics models, code adequacy, and validation maturity. A gap analysis compares the importance of the phenomena with the ability of the model to represent that phenomena; results of this comparison are indicated by color codes (i.e. a stop light scheme). Additional columns can be added to the PIRT to suit program needs. For the present work, additional columns were added to create an extended PIRT to aid in program planning. These include a description of the issues associated with the identified gaps, proposed responses to mitigate the effect of the gaps, and priority of the responses from a programmatic point of view. It is important to note that not all phenomena need to be addressed at once, and that the PIRTs discussed here identify the most important phenomena. For more detail on the PIRT process, refer to Chapter 3 of the "V&V Framework" (Hills, Maniaci, & Naughton, 2015).

The PIRT is based on information gathered from all relevant sources and should be updated as activities progress. The initial elicitation approach serves to build consensus in the technical community by soliciting and accommodating a broad spectrum of perspectives.

2.2.2 PIRT Development

During 2014 and 2015, several meetings were held for the development of a high-fidelity modeling effort for DOE's wind program. Over 70 subject matters experts (SMEs) contributed to the creation of a Phenomenon Identification and Ranking Tables (PIRT) for the wind plant applications during these meetings (see Womble et al., 2015 for a summary of one of these meetings). SMEs with experimental and computational focuses from industry, government labs, and academia were included in this process. The experimental-focused SMEs came from a range of experimental backgrounds relevant to wind plants;, for example, atmospheric scientists, wind turbine designers, instrumentation specialists, and veterans of prior experimental campaigns. Similarly, a range of computationally-focused SMEs were included with backgrounds in atmospheric, wind turbine, and wind plant simulations using simulation approaches ranging from Reynolds Averaged Navier Stokes (RANS) to Large Eddy Simulation (LES). Specialists in simulating basic aerodynamics and structural dynamics were also included. Finally, SMEs with a specialty in Validation and Verification methods were included to aid in focusing the SMEs on the PIRT development process. During this time, there was a complementary meeting that addressed computational platform issues [Womble et al., 2015].

The SMEs provided input to the PIRT development in several ways. First, they identified important phenomena, and then discussed the relative importance of the phenomena as a group, including the abilities of the computational models. Next, the group reached consensus concerning the importance of the phenomena and discussed experiments to address the prioritized phenomena. These SME meetings resulted in a range of output from meeting notes to formal reports (e.g. Womble et al., 2015).

A group of Validation and Verification Specialists that participated in the original SME meetings consolidated the discussion results to propose the final PIRTs. Phenomena identified in the individual meetings were then collapsed to eliminate redundancy; however, all phenomena deemed important by SME consensus were retained. The model adequacy of each phenomenon was then determined using the evaluations from the original meetings. A gap analysis was then performed by color coding the importance at the application level (High - red, Medium - yellow, and Low - green), and the model adequacy. The model adequacy was then color-coded relative to a phenomena's importance. If the model adequacy was the same as its importance (e.g. medium – medium), it was color-coded green, one level below its importance (e.g. medium-low), it was color-coded yellow, and if it was two levels below (e.g. high-low), it was color-coded red. In this way, phenomena with mostly red color-coding are considered to be the highest priority from a modeling/validation perspective, whereas those that are mostly green are the lowest priority. Some phenomena that were deemed to be less important and sufficiently modeled were then removed or consolidated. Once this color-coding process was complete, synthesis of the issues and responses raised by the SMEs at the original meetings were added to complete the PIRT.

2.2.3 Wind Turbine and Wind Plant PIRT

The results of applying the PIRT to the individual wind turbine and the wind plant are discussed below. Because the wind turbine is a subset of the wind plant PIRT, wind turbine results are discussed first.

2.2.3.1 Wind Turbine PIRT

The phenomena relevant to the wind turbine are discussed in this section, which corresponds to the expanded PIRT shown in Figure 2. These phenomena have been divided into three sub-sections: blade aerodynamics and wake generation, wake development, and other phenomena that do not fit clearly into the former two categories. The_**Blade Aero / Wake Generation**_section of the PIRT focuses on phenomenon related to the sectional forces acting on the wind turbine blade, how those forces respond to the inflow, and how those forces relate to the generation of the wake. The **Wake Development (growth/recovery)** section of the PIRT focuses on phenomenon relevant to how the wake changes in strength and structure after it is generated, and how it interacts with the inflow to the wind plant.

Blade Aero / Wake Generation

Blade load distribution effects and rotor thrust are related phenomena, as the load distribution integrates to the rotor thrust and torque. The rotor thrust is of primary importance to the strength of vorticity that makes up the wake, and the blade load distribution is directly related to the structure of the wake vorticity in the near wake region (typically defined as being within three diameters of the rotor).

The near wake development is important as it must be accurately modeled to characterize the turbine blade loading, fluid-structure interaction, and capture the far-wake physics; although the strength of the correlation between rotor loading and far-wake development is likely heavily influenced by inflow conditions. **Tip and root vortex development, evolution and merging** phenomena are important to the performance of the wind turbine generating the wake, as well as to downstream turbines affected by the wake. These vortex structures contain the majority of the vorticity and energy fluctuations that make up the wake, and their strength and evolution are intrinsically tied to the phenomenon of **vortex sheet and rollup (in addition to tip/root vortex).** A vortex sheet is shed from the trailing edge of each wind turbine blade and evolves to form and interact with the tip and root vortices. The **blade generated turbulence characteristics (energetic scales at trailing edge)** are created by the combination of coherent vorticity shed from the blade trailing edge and its interaction with the atmosphere and near-wake. Coherent vortex sources include the blade trailing vorticity (tip, root, and vortex sheets) as well as vorticity shed from the blade boundary layer. Coherent vortices are also shed from the turbine tower; however, these are more important for aeroacoustics as it is not a dominant vorticity source for wake generation. The **Root flow acceleration effect ('hub jet')** is a phenomenon caused by the combination of the interaction of the wake vorticity shed off of the blade root with the nacelle of the wind turbine, and there is evidence from wind tunnel tests that it has an influence on wake stability and recovery.

The **boundary layer development (transition, separation) phenomenon refers to the blade boundary layer (as opposed to the atmospheric boundary layer)** and is very important for the accurate prediction of blade loads. The boundary layer development is influenced by blade **surface roughness effects (roughness, soiling, bugs, erosion),** which vary significantly during turbine operation and can be challenging to measure and predict for an operational wind turbine. **Boundary layer details near the leading and trailing edge** relate to boundary layer development but were mainly included in the wind turbine PIRT as being important for blade aeroacoustics. **Rotational augmentation present on rotating blades** significantly amplifies blade force and moment production relative to more simplistic though less realistic fully attached blade flows. **This phenomenon** was considered to be challenging for measurement and for computation, because it generally is significantly three-dimensional and possesses a substantial time varying character. **Dynamic stall** has an important influence on blade loading, particularly in turbulent operating conditions that can be important for turbine design loads. It is a challenge to measure and to predict due to the combination of unsteadiness, nonlinearity, and three-dimensionality.

The **unsteady inflow effect (veer, shear, yaw, gusts, atmospheric stability, turbulence intensity, spectra, and coherence)** phenomenon refers to the effect of turbulence naturally present in the atmosphere on the wind turbine and its wake. Some important quantities within this category include vertical shear, horizontal shear, veer, turbulence intensity, wind direction variance, turbulence/gust scales, and atmospheric stability. **Blade flow control** can be used to enhance blade performance, alleviate loads, and reduce the acoustic signature; however, demonstration, reliability, and validation data are lacking. Blade **icing** phenomenon can have significant impacts to wind turbine performance and structural dynamics, but its importance depends on the regional climate of a wind plant.

Wake Development (growth/recovery)

The near wake development is important to model for the purpose of predicting the loading of an upstream turbine and is the initialization of what becomes the far wake. Predicting the far wake is most important for capturing the power and loading of downwind wind turbines, as the interaction of the far wake with the atmospheric flow field creates the unsteady inflow of downwind turbines. **Skew and meander of aggregate wake** refers to the gross movement and deflection of the far-wake, and how it interacts with downstream wind turbines. **Swirl instability** arises from rotation of the wake that affects the wake stability through the interaction of axial and tangential momentum. **Vortex merging** refers to the pairing and mutual inductance instability of wake vortex structures, which relates to the wake turbulence characteristics and leads to the gross properties of wake stability, mixing, and recovery. **Wake vorticity diffusion and dissipation** is important to wake recovery and far-wake properties that contribute heavily to turbine-turbine interaction. Wake **asymmetry effects (ground plane, yaw, tilt, and cone-angle)** influence the wake stability, recovery, meander, and vertical and horizontal deflection. The **inflow effect (shear, veer, yaw, turbulence intensity, turbulence spectrum, coherence, gusts, and atmospheric stability)** refers to the interaction of the atmospheric boundary layer with the wind turbine wake.

Other Effects

Tower/rotor/nacelle wake interactions have an effect on the blade loads and wake development but are primarily included here as a source of aerodynamic noise. **Aeroelasticity** captures the effects of the aerodynamic force on the blade through blade deformation. In turn, the modified blade shape alters the forces on the blade and thus the wake. **Aeroelasticity** is important for the blade design of any size turbine but requires additional model development and testing for very large blades. **Aeroacoustics** refers to noise generated by the wind turbine, which includes mechanical noise and aerodynamic noise generated at the blade trailing edge, tip, and root. This phenomenon is important for wind turbine siting.

Phenomenon	Importance at Application Level	Model Adequacy			Issue/Comments	Response Including Scale	Interface
		Physics	Code	Val			
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.	Some experiments done for validation. Important to measure for experiments where rotor loading is correlated to wake	Blade-Wake
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.	Full-scale and sub-scale field sites, and wind tunnel testing.	Blade-Wake
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 uncertain.	Further discovery experiments -> validation experiments.	Blade-Wake
Blade generated turbulence characteristics (energetic scales at trailing edge)	H	L	L	L	Coherent vortices shed from blade, including how they interact with the atmosphere and near-wake.	Full-scale and sub-scale field sites. High bandwidth probes, flow imaging.	Blade-Wake
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).	Wind tunnel and field tests.	Chord
Surface roughness effects (roughness, soiling, bugs, erosion)	H	L	L	L	Directly influences boundary layer development and blade loads.	Wind tunnel and field tests. Full scale surface quantification.	Chord
Boundary layer details near leading and trailing edge	H	M	L	L	Relates to boundary layer development, and important for aeroacoustics.	Full-scale and sub-scale field sites	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	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	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.	Full-scale and sub-scale field sites, and wind tunnel testing.	Blade-Wake-ABL
Blade flow control	M	L	L	L	Can be used to enhance blade performance and alleviate loads.	Full-scale and sub-scale field sites, and wind tunnel testing.	Blade-Chord
Icing	H	L	L	L	Importance depends on regional climate (Northeast vs Midwest).	Full-scale and wind tunnel testing.	Blade-Chord
Wake Development (growth/recovery)							
Skew and meander of aggregate wake	H	L	L	L	Gross movement and deflection of far-wake.	Full-scale and sub-scale field sites, and wind tunnel testing.	Wake
Swirl instability	L	L	L	L	Interaction of axial and tangential momentum	Wind tunnel tests.	Wake
Vortex merging	L	L	L	L	Important for the far-wake and turbine-turbine interaction.	Sub-scale field sites and wind tunnel testing.	Wake
Wake vorticity diffusion and dissipation	H	L	L	L	Important to wake recovery and far-wake properties.	Sub-scale field sites and wind tunnel testing.	Wake
Asymmetry effects (ground plane, yaw, tilt, cone-angle)	M	M	L	L	Influence the wake stability, recovery, meander, and vertical and ho	Full-scale and sub-scale field sites, and wind tunnel testing.	Wake
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.	Full-scale and sub-scale field sites, and wind tunnel testing.	Wake-ABL
Tower/rotor/nacelle wake interactions	H	M	L	L	Primarily included for noise, also influence blade and wake.	Full-scale and sub-scale field sites	Turbine-Wake
Aeroelasticity	H	M	L	L	Rated for very large blades.	Full-scale and sub-scale field sites, and wind tunnel testing.	Blade
Aeroacoustics	H	M	L	L	Noise sources, mainly trailing edge, root, and tip.	Full-scale and sub-scale field sites and wind tunnel.	Blade-Chord

Figure 2 – Wind Turbine PIRT. High and medium priority phenomena.

2.2.3.2 Wind Plant PIRT

In this section, the phenomena important to the wind plant are discussed. The wind plant expanded PIRT is shown in Figure 3. The phenomena for the wind plant have been divided into three categories: Inflow/wake interaction, multi-turbine effects, and other. Phenomena listed here only include those with high or medium importance at the application level and a model adequacy at least one level below the importance.

Inflow Turbulence/Wake Interaction

In this category, there were five different phenomena related to the inflow that affect wake development at microscale level. The **wind direction** was identified as having an important bearing on wake development. The wind direction category included yaw, shear, veer, and asymmetry. Yaw is the misalignment of the turbine with the incoming flow. Shear is the variation of wind speed with height, whereas veer is the variation of wind direction with height. Finally, asymmetry captures those events in the atmosphere that cause lateral differences in the wind speed or direction, referred to as horizontal heterogeneity. Another phenomena of importance was the **turbulence characteristics** of the inflow, including turbulence intensity and its standard deviation, turbulence spectra, coherence of turbulence, turbulence length scales, and the effects of atmospheric stability. Turbulence intensity is a measure of the turbulence magnitude relative to the mean wind speed. The frequency distribution of the fluctuations is captured by the turbulence spectra. Coherence is a measure of how fluctuations between components are related as well as the region over which turbulence is correlated. The stability of the inflow from the perspective of the atmospheric boundary layer (stable, neutrally stable, or unstable) is important as it affects all those turbulence characteristics previously discussed. A special feature of inflow turbulence are **coherent turbulent structures** that typically develop in regions of high shear. For instance, such structures can be found in low-level jets and behind terrain features (e.g. flow over or around ridge features). **Surface conditions** broadly categorize all those features that affect the inflow. Surface roughness describes the state of the surface such as snow-covered, vegetation covered, or urban. The effect of a forest, termed a canopy, on land and wave state at sea also effect the inflow. The temperature difference of the ground and atmosphere leads to surface heat flux that also impacts the inflow. One of the largest impacts on the inflow can come in complex terrain where the topography directly influences the inflow. Finally, the **transport of momentum** in the atmospheric boundary layer in the presence of a wake has a large impact on the evolution of the wake. Both horizontal and vertical fluxes of momentum are important in this case.

Multi-Turbine Wake Effects

Six different phenomena pertain to the interaction of two or more wakes or the interaction of a wake and a downstream turbine. **Wake interaction, merging,** and **meander** are phenomena that govern the evolution of the wake. Interaction between wakes is important as it changes the way a wake would evolve were the other wake not present. A special case of wake interaction is when two or more wakes merge and act as a larger single wake. Meander is the unsteady and random spatial movement of the wake that can have large effects on downstream turbines. **Wake impingement** describes the interaction of the wake with a downstream turbine. Wakes that directly strike the downstream turbine (full impingement), those that only strike a portion of the downstream turbine (e.g. half impingement) as well as wakes that merely pass nearby a turbine are all of importance. **Wake dissipation** considers the rate at which a wake decays. This phenomenon affects both the momentum deficit and turbulence levels experienced by a downstream turbine. A special case of all these phenomena is the **deep array effect**. In large wind farms, the evolution and merging of many wakes yield a unique flow within a large wind farm, far from the first row.

With the increasing number of large wind farms, the use of **plant flow control for optimum wind plant performance** has become a research focus. Understanding the basic principles of how such control might be accomplished is an important research focus to assure optimum wind plan performance. Wind plant control can be accomplished by running the first row of turbines with lower energy extraction or by using yaw and tilt of upstream turbines to **steer the wakes** away from downstream turbines.

Other Effects

Several phenomena did not fit cleanly in a specific category. Among these were **wind plant blockage effects** and the **plant wake**. Wind plant blockage considers speed-up effects within and around a wind plant, whereas the wind plant wake considers the behavior of the aggregate of all the wakes downstream of the wind plant. Another important phenomenon is the **propagation of noise** from a wind plant, which could be expanded into further sub-physics. How noise propagates and its effect on the directionality and magnitude of the noise away from the wind plant is of interest.

The additional columns in the PIRT identify issues with each of these phenomena as well as the perceived necessary response. In addition, other scales with which a particular phenomenon might interact are also listed, when appropriate.

Through the development of the wind plant PIRT, the phenomena described above were identified as having a model deficiency relative to their importance and, therefore, should be studied. The next section is an overview of experiments meant to study these phenomena and provide data sufficient to validate computational models for their effects.

Phenomenon	Importance at Application Level	Model Adequacy			Issue/Comments	Response Including Scale	Interface	Planning Priority
		Physics	Code	Val				
Inflow Turbulence/Wake Interaction								
Wind direction (shear/veer/assymetry)	H	L	M	M	Wake sensitivity to gusts, low-level jets, etc. that promote three dimensional boundary layers	Wind tunnel and field tests.	ABL/Turbine	
Turbulence characteristics (intensity, spectra, coherence, stability)	H	L	M	M	Wake sensitivity to turbulence	Wind tunnel and field tests using real and psuedo ABL spectra	ABL	
Coherent turblence structure	H	L	M	L	Wake sensitivity to organized structures	Difficult to test, but could include both wind tunnel and field tests.	ABL	
Surface conditions (roughness, canopy, waves, surface heat flux, topography)	H	L	M	M	Wake sensitivity to changes in ABL due to surface features	Wind tunnel and field testing looking at changes in ABL	ABL	
Momentum transport (horizontal and vertical fluxes)	H	L	L	L	Wake sensitivity to momentum supplied by ABL. Side-flow is a special case, as well as the deep array.	Wind tunnel and field tests.	ABL	
Multi-Turbine Wake Effects								
Wake interaction, merging, meander	H	L	L	L	Physics behind unsteady wake behavior	Wind tunnel and field tests.		
Plant flow control for optimum performance	H	M	M	L	Strategies for optimizing the wind farm rather than individual turbines	Subscale and full scale field tests. Large controlled facility tests.		
Wake steering (yaw & tilt effects)	H	L	L	L	Effect of non-normal inflow on wake behavior. Useful for control.	Wind tunnel and field tests.		
Wake dissipation	H	L	L	L	Evolution toward a neglibly small wake	Wind tunnel and field test		
Wake Impingement (full, half, etc.)	H	L	L	L	Effect of upstream wake position on downstream turbine	Wind tunnel and field test		
Deep array effects (change in turbulence, etc.)	H	L	L	L	Emphasis on the behavior of the flow within the wind plant	Wind tunnel and full scale field test		
Other Effects								
Wind plant blockage effects and plant wake	M	M	M	L	Emphasis on the effect of the wind farm on cross-stream downstream regions	Wind tunnel and full scale field test	ABL	
Acoustic Propagation	H	L	L	L	Noise generation and propogation through a wind plant	Full-scale and sub-scale field sites	Turbine	

Figure 3 – Wind Plant PIRT, high and medium priority phenomena.

2.3 Validation Hierarchy

2.3.1 Development

The wind turbine and wind plant PIRTs enable the development of a validation hierarchy. The validation hierarchy represents a group of experiments that can address the important phenomena identified in the PIRT. For applications such as a wind plant, that involve many important physical phenomenon, a number of experiments of varying complexity are often required. There are several ways of categorizing these experiments based on their complexity, but here we will adopt that of Hills et al.: characterization tests, separate effects tests, integrated effects tests, subsystem tests, and system tests [Hills et al., 2015]. Figure 4 is the typical structure of a validation hierarchy showing how tests proceed from single-phenomenon (at the triangle base) to those that incorporate all-phenomena present in the real system (at the triangle peak). Often the scale of the experiments will also increase in parallel with the number of phenomena present. Note that there are other similar categorizations that have been proposed by others [Oberkampf et al., 2010; AIAA, 1998].

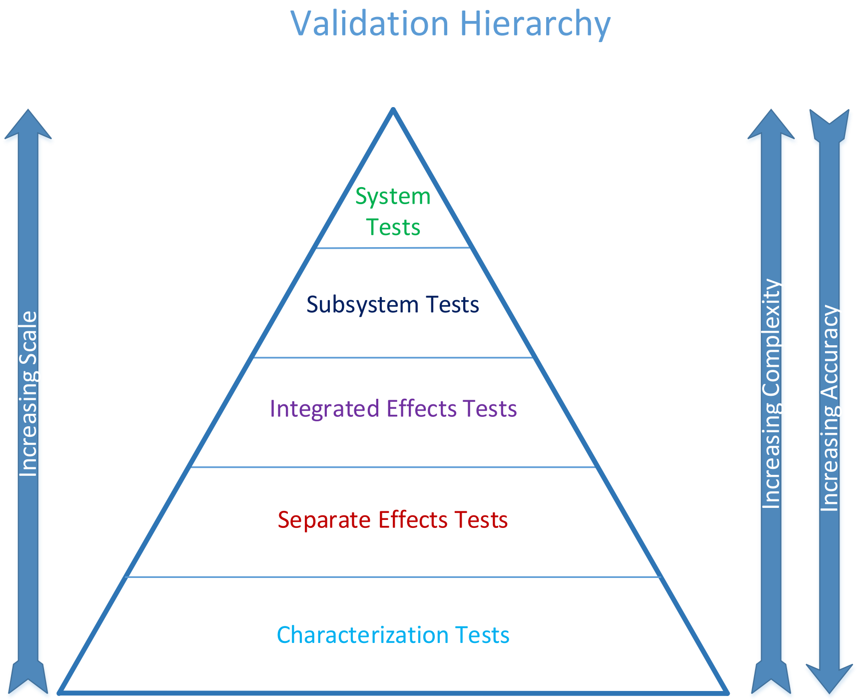

Figure 4 – General validation hierarchy

The five levels of experimental test categorization allow for building a series of tests that address the phenomena identified in the PIRT. Characterization tests involve identifying basic material or constitutive properties if they do not exist. Separate effects tests focus on a single phenomenon, whereas integrated effects tests would include two or more phenomena. Subsystem tests may include either testing of isolated components of the full system or subscale testing of the full system. Finally, system tests involve the full system in its application environment. When considered in the context of how these experiments will be used in the validation of computational models, the experiments in the hierarchy allow the simulations to ensure they are capturing the component physical phenomena before attempting to capture combined phenomena and later all the phenomena of the complete system. It is important also to note that the accuracy of the experimental results is typically very good low in the validation hierarchy, but typically decreases as the peak of the hierarchy is approached.

Before describing the hierarchy for the wind turbine and wind plant it is important to discuss how these hierarchies were determined. Using the developed PIRTs as described above, a small group of Subject Matter Experts (SMEs) identified a group of experiments that would address the high priority physical phenomena identified in the PIRT for the wind plant performance objective. These experiments were then classified into the different test categories and arranged into a validation hierarchy. Note that the experiments identified in the validation hierarchy may represent one or multiple experiments, but two or more of the experiments may be performed in the same test campaign using similar models. It is also important to understand that, in some cases, experiments may already exist that will fulfill the validation need.

2.3.2 Validation Hierarchies for the Wind Turbine and Wind Plant

For ease of understanding, separate hierarchies were developed for the wind turbine and for the wind plant. However, it is important to understand that these hierarchies are linked. As shown in Figure 5, the wind turbine hierarchy represents a subset of the wind plant hierarchy. Thus, the wind turbine hierarchy will be discussed first.

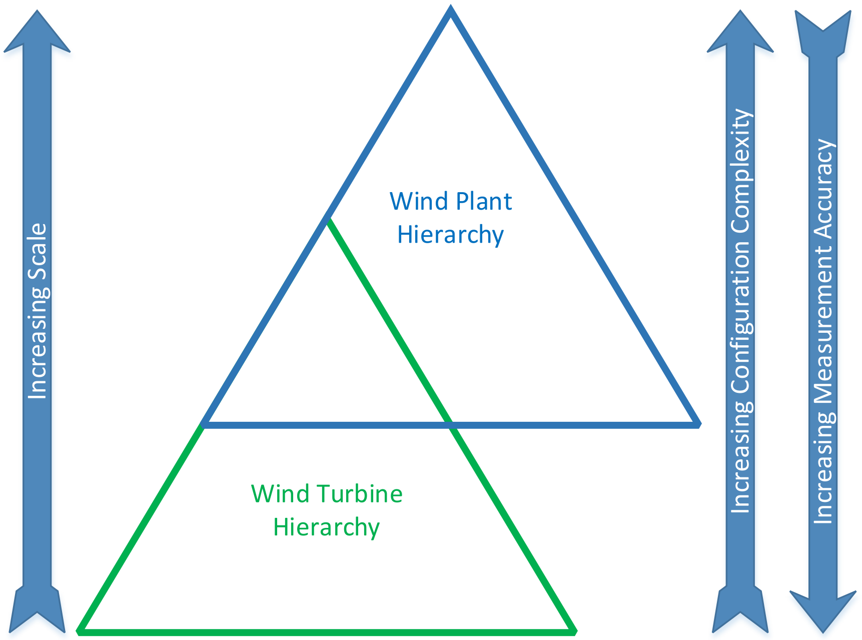

Figure 5 – Relationship between the wind turbine and wind plant hierarchies.

2.3.2.1 Wind Turbine Validation Hierarchy

The wind turbine validation hierarchy proposes experiments that would address the physical phenomena identified in the wind turbine PIRT. Figure 6 shows the turbine validation hierarchy including four complexity levels. No tests that would fall under the characterization tests category were identified. The tests are briefly described below, and the phenomena they address are discussed in the next section.

Starting with the separate effects tests, five different experiments were identified. A series of **boundary layer experiments** were identified that could address several phenomena in the PIRT. These experiments would be conducted in wind tunnels of both moderate and larger sizes. Such tests could address the range of phenomena identified as well as considering scaling effects associated with Reynolds number ranges. A series of test on **fixed airfoils** could provide data for validation as well as information for future experiments (such as scaled turbines). As with boundary layers, such experiments could be conducted in a range of wind tunnel facilities from inexpensive studies in smaller wind tunnels (test sections ~1m) to costlier tests in larger wind tunnels (~3+m test section) to address scaling issues. Similar tests could be performed on **fixed blades** that would provide the three-dimensional effects found on real blades. To address the need to better understand **root and tip vortices**, wind tunnel experiments on stream-wise vortex evolution would be useful. Such experiments could be performed at different scales and from generic vortices to more realistic vortices produced by blades. A fundamental flow that can aid in understanding wake evolution is the isolated **axisymmetric wake**. Note that this flow has received much attention over the years, and there are both data and theory available today that is sufficient for validation purposes.

The next level of complexity in the wind turbine validation hierarchy is where the majority of tests were identified. Building on airfoil flows studied at the separate effects testing level are several integrated effects tests including **airfoils with turbulent inflow**, **airfoils with icing**, **pitching airfoils**, and **airfoil flow control**. All tests combine the basic airfoil flow with one or more additional phenomena identified in the PIRT. Airfoils with turbulent inflow identify the effects of the high turbulence levels of the atmospheric inflow that wind turbine blades experience. The effects of icing on airfoils reveals the modification to the airfoil shape icing produces and its impact on airfoil performance. Pitching airfoils allow the unsteady nature of airfoil flows to be studied, as the flows over wind turbine blades are never steady. Of particular interest is the phenomenon of dynamic stall that may be tested under such conditions. Airfoils with flow control are another area of interest, as local flow control on wind turbine blades is being considered particularly as blades grow larger. With the exception of the icing experiment that requires a special test facility, it would be expected that these airfoil tests would be carried out in wind tunnel facilities of various sizes. A follow on to the fixed blade experiment, the **fixed aero-elastic blade** would add the additional complexity of a flexible blade and the flow/structure interaction it creates. Such tests would likely be carried out in a larger (~2-3 m test section) wind tunnel to allow for a large enough blade. Changing the focus from the blade to the wake, an additional complexity to the **axisymmetric wake** would be that wake with the addition of swirl and inflow turbulence intensity. Such experiments can actually be carried out in smaller wind tunnels (~ 1m test section) but require the ability to add turbulence to the flow. A follow on to the axisymmetric wake flows is the wake created by **a single small wind turbine** (~0.2m diameter) **in a small wind tunnel with turbulent inflow** that would add the effects of generating the wake from multiple blades and inflow turbulence to the wake behavior.

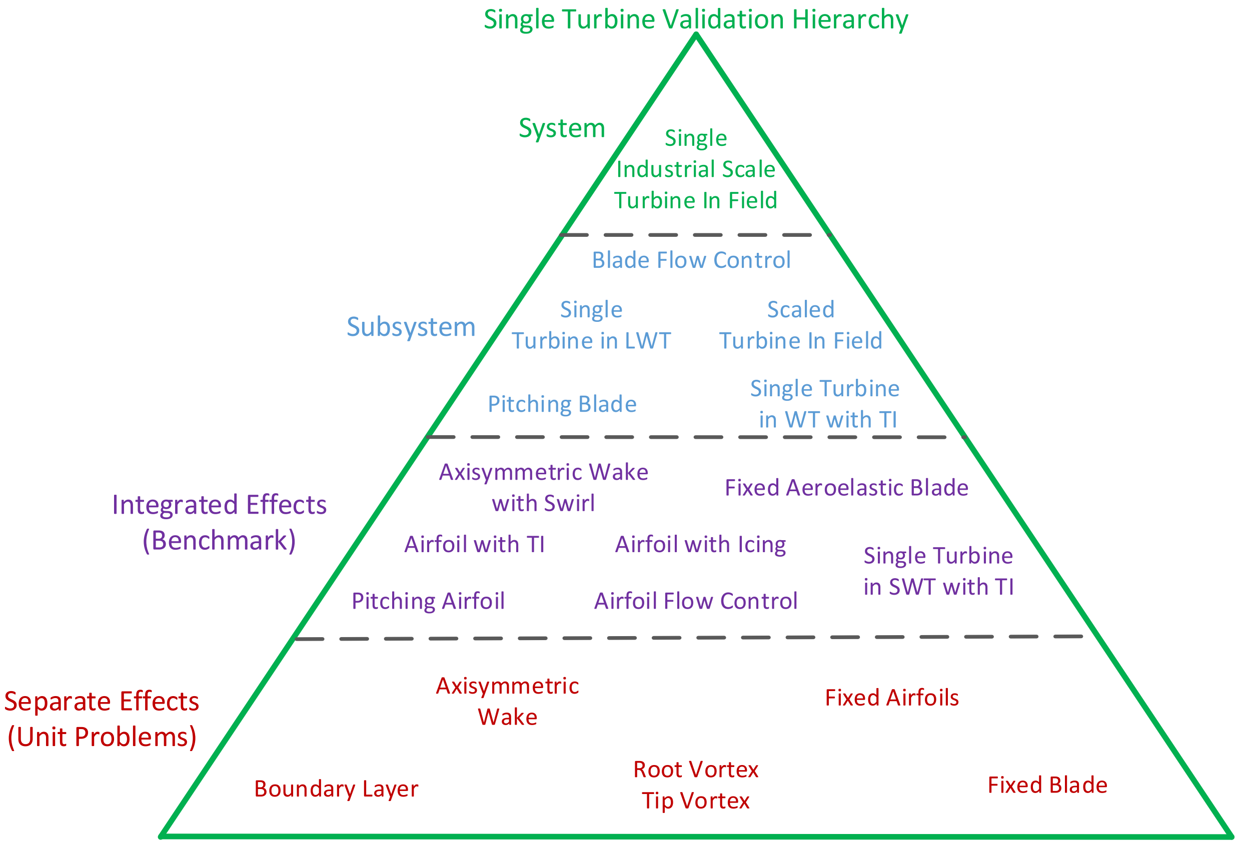

Figure 6 – Wind turbine validation hierarchy

Although integrated effects tests provide more information about the interaction of phenomena, subsystem tests start to capture the interactions in an environment closer to the real system. Building on the blade flows tested at the separate and integrated effects test levels, **pitching blades and blades with flow control** would be tested at this level. Both of these tests would likely be carried out in larger wind tunnels (test section ~3 m). Continuing the wind turbine tests at small scale would be the testing of a **single turbine in a wind tunnel with turbulent inflow**. It is expected that this test would occur in a wind tunnel with a wind turbine (D ~1m) experiencing turbulent inflow of various types. At this size, it would also be possible to perform some measurements on the blades, allowing the coupling between the blade flow and the wake. To complement this, **a very large wind tunnel test of a single turbine** (D~5m) could consider scaling effects and allow for more realistic conditions on the blades that could be captured during testing. A third turbine experiment would be a **scaled wind turbine in the field**, where the turbine (D~30m) would encounter real atmospheric flows and additional scaling effects would be captured.

At the system scale level, an **industrial scale turbine** (~100m) would be investigated. Although measurements on this scale are likely to be limited in resolution and have larger uncertainties than those conducted at other hierarch levels, all the relevant physics are present at this level, and thus it is an important piece of the validation process. Tests within existing wind farms as well as turbines located at test facilities would be expected as part of this effort.

2.3.2.2 Wind Plant Validation Hierarchy

As with the wind turbine, a validation hierarchy has been developed for the wind plant. As discussed previously, the wind turbine hierarchy is a subset of this hierarchy as indicated in Figure 7. Each of the tests in the four different complexity levels are discussed here, and the phenomena they address are considered in the next section.

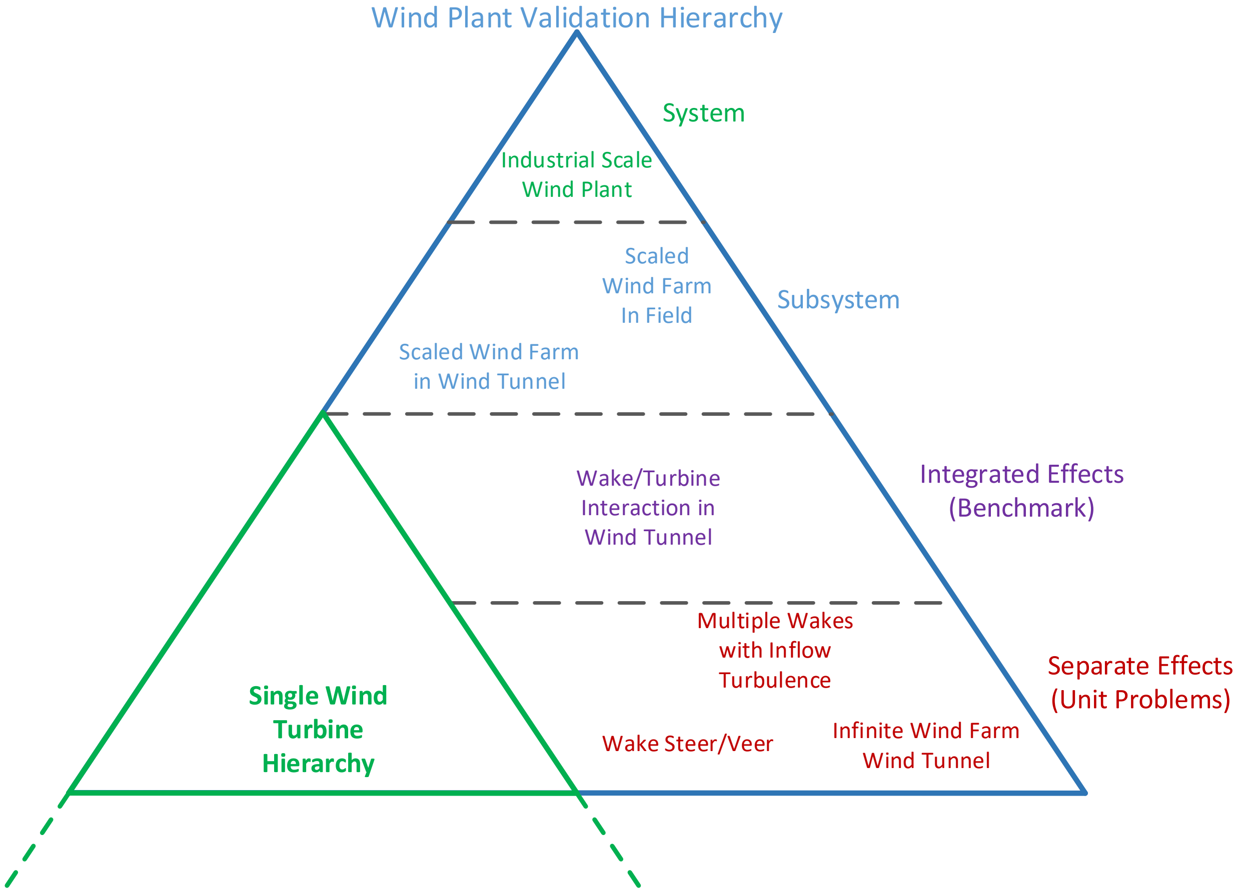

Figure 7 – Wind plant validation hierarchy

At the separate effects test level, three experiments unique to the wind plant couple with tests from the single wind turbine to provide a full complement of validation exercises at this level for the wind plant. It is expected that all flows would be carried out in wind tunnels. Building upon single turbine tests, a test using several small turbines (D~0.2 m) that produce **multiple wakes in the presence of inflow turbulence** would be considered. A related test would consider the **infinite wind farm**, where a sufficient number of rows of turbines would produce an asymptotic behavior of the flow within the wind plant and far downstream of the first turbines. A test that specifically considers the effect of **wake steer/veer** would be carried out using ~0.2 m wind turbine models with the goal of providing data that captures the important physics of these wind plant control strategies.

At the integrated effects test level, a wind tunnel test of a larger wind turbines (D~2.0m) with a focus of the **wake turbine interaction** at larger scale would be considered. This experiment could provide more relevant blade flows (though still small in Reynolds number) that could be used to assess scaling effects.

At the subsystem test level, two tests that would consider wind farm flows at different scales would be considered. A **scaled wind farm in a very large wind tunnel** using turbines ~2.0 m in diameter could consider the wind farm flow under controlled conditions. In such a test, wake behavior and control could be investigated in the presence of several turbines. Closely coupled to this test would be a test of a **scaled wind farm in the field**. Turbines with ~30 m diameter would be used, with a focus on the effect of atmospheric conditions on wake behavior in addition to other factors. Closely coupling these two tests would provide an excellent ability to investigate scaling effects.

The full system test would obviously involve an industrial scale (many turbines with D~100m) wind plant. This test (or tests) would have to be carried out at an existing wind farm, and the data obtained from such investigations would likely be limited, both in resolution and accuracy. Nonetheless, such tests are important, as they capture all physical phenomena in the real system.

This list of experiments may not be exhaustive and the need for additional experiments may arise as these tests are undertaken. Nonetheless, these experiments constitute a preliminary scoping of the work needed to provide a complete set of validation cases. In the next section, the physical phenomena that are addressed by each of the tests are considered followed by an assessment of how well the measurements of these phenomena could be conducted.

2.4 Prioritized Phenomena Experiment Mapping (PPEM)

It is important to assess if the experiments proposed as part of the validation hierarchy are addressing the phenomena identified in the PIRT charts. For this purpose, an evaluation of the proposed experiments ability to capture the phenomena was developed. The Prioritized Phenomena Experiment Mapping (PPEM) is the result. The PPEM addresses two issues: (1) whether the phenomenon in the PIRT are present in the experiment, and (2) how likely the phenomenon is to be captured in a particular experiment. In this way, the PPEM can be used to quickly identify which tests capture which phenomenon.

The PPEM tables generated for both wind turbine and wind farm cases are presented in Figure 8Figure 12. A five-level ranking system is used in the PPEM for easy interpretation of the tables. In the tables, the phenomena are listed across the top, whereas the tests are given on the left-hand side. For each test, whether each of the phenomena is present is rated as well as the degree to which that phenomenon might be measured. In addition to identifying the phenomena addressed by a test, two items arose consistently during meetings with the Subject Matter Experts (SMEs): to what level can the boundary conditions be quantified and how does the test contribute to testing scale effects.

The PPEM tables for the wind turbine case are provided in Figures 8-11. Figure 8 provides the PPEM for the separate and integrated effects tests for the blade/aero phenomena, whereas Figure 9 presents the PPEM for the same tests, but for wake development and other effects. Figures 10 and 11 show the PPEM for the same phenomena, but for the system and subsystem tests. The strength of these PPEMs is that it is clear to see what phenomena are addressed by a specific test. For instance, in Figure 8, it is clear that Boundary Layer tests will address only a few phenomena, but they will provide excellent measurements of those phenomena with well characterized boundary conditions. From a modeling perspective, such experiments will provide a means of characterizing to what degree a model captures these physics. In contrast, Figure 10 shows that a scaled turbine in the field captures many of the blade physics of interest, but it is much harder to measure those physics and to quantify the boundary conditions. Nonetheless, such data are useful for determining to what extent a model can capture the multiple phenomena present in such complex flows. Such complex and fundamental experiments work together not only to allow an assessment of the performance of a model on the complex flow, but also provide a means of identifying what physics the model is missing if it cannot predict the complex flow to the desired level. This is a critical feature of the validation hierarchy that allows for model improvement and validation.

At the wind plant level, a PPEM has also been developed and is shown in Figure 12. In this single PPEM, all levels of testing (separate effects through system tests) and all the prioritized phenomena are included on a single page. Again, the PPEM shows that the validation hierarchy allows for fundamental experiments measured with a great deal of precision but with limited physics as well as complex experiments with most of the phenomena present, but with a limited capability of measuring them.

In summary, the PPEMs along with the PIRTs and the validation hierarchy, when fully developed, provide both an objective means of prioritizing the order in which experiments should be conducted as well as a roadmap for validating numerical models. This is the strength of a validation-directed program.

Physics Present/Physics Measured

◉ Entirely
◒ Mostly
○ Somewhat
◓ Limited
● Missing

	Blade Aero/Wake Generation	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	**Testing Issues**	Boundary Conditions	Scale Effects
Boundary Layer																	
Physics Present		●	●	●	●	●	◉	◉	●	●	●	◒	●	●			
Physics Captured by Measurements		●	●	●	●	●	◉	◉	●	●	●	◒	●	●		◉	◉
Axisymmetric Wake (with Swirl)																	
Physics Present		●	●	●	●	●	●	●	●	●	●	●	●	●			
Physics Captured by Measurements		●	●	●	●	●	●	●	●	●	●	●	●	●		◉	◉
Root/Tip Vortex																	
Physics Present		●	◒	●	●	●	●	●	●	●	●	◒	●	●			
Physics Captured by Measurements		●	◉	●	●	●	●	●	●	●	●	◒	●	●		◉	◉
Fixed Airfoils (with flow control)																	
Physics Present		○	●	○	◒	●	◒	◒	◒	●	●	◒	◉	●			
Physics Captured by Measurements		◉	●	◒	◉	●	◉	◉	◉	●	●	◒	◉	●		◉	◉
Fixed Blade (with Turbulent Inflow)																	
Physics Present		◒	◉	◉	◉	●	◉	◉	◉	●	●	◒	●	●			
Physics Captured by Measurements		◒	◉	◉	◉	●	○	◒	○	●	●	◒	●	●		◉	◉
Pitching Airfoil																	
Physics Present		○	●	○	◒	●	◒	◒	◒	●	◉	◒	●	●			
Physics Captured by Measurements		◒	●	◓	◓	●	◓	◓	◓	●	◉	◒	●	●		◉	◉
Airfoil with Icing																	
Physics Present		○	●	○	◒	●	◒	◒	◒	●	●	◒	●	◉			
Physics Captured by Measurements		●	●	●	●	●	●	●	●	●	●	●	●	◉		○	◉
Fixed Aeroelastic blade																	
Physics Present		◒	◉	◉	◉	●	◉	◉	◉	●	●	◒	●	●			
Physics Captured by Measurements		○	◉	◒	○	●	●	●	●	●	●	◒	●	●		◒	◉
Single Wind Turbine (Small) in Wind Tunnel																	
Physics Present		◓	◓	◓	◓	◓	◓	◓	◓	○	○	◒	●	●			
Physics Captured by Measurements		●	●	●	●	○	●	●	●	◓	◓	◒	●	●		◒	◉

Figure 8 – Prioritized Phenomena Experiment Mapping (PPEM) for the wind turbine case. This figure considers the Blade/Aero Phenomena and their mapping to separated effects and integrated effects tests.

Physics Present/Physics Measured

◉ Entirely
◒ Mostly
○ Somewhat
◓ Limited
● Missing

	Wake Development						**Other Effects**			**Testing Issues**	
	Skew and Meander of Wake	Swirl Instability	Vortex Merging	Wake Vorticity Diffusion and Dissipation	Asymmetry Effects	Inflow Effects	Tower/Rotor/Nacelle Wake interactions	Aeroelasticity	Aeroacoustics	Boundary Conditions	Scale Effects
Boundary Layer											
Physics Present	●	●	●	●	●	●	●	●	●		
Physics Captured by Measurements	●	●	●	●	●	●	●	●	●	◉	◉
Axisymmetric Wake (with Swirl)											
Physics Present	●	◉	●	◒	◒	◒	●	●	●		
Physics Captured by Measurements	●	◉	●	◉	◉	◉	●	●	●	◉	◉
Root/Tip Vortex											
Physics Present	●	●	●	●	●	●	●	●	●		
Physics Captured by Measurements	●	●	●	●	●	●	●	●	●	◉	◉
Fixed Airfoils (with flow control)											
Physics Present	●	●	●	●	●	●	●	●	●		
Physics Captured by Measurements	●	●	●	●	●	●	●	●	●	◉	◉
Fixed Blade (with Turbulent Inflow)											
Physics Present	●	●	●	●	●	●	●	●	●		
Physics Captured by Measurements	●	●	●	●	●	●	●	●	●	◉	◉
Pitching Airfoil											
Physics Present	●	●	●	●	●	●	●	●	●		
Physics Captured by Measurements	●	●	●	●	●	●	●	●	●	◉	◉
Airfoil with Icing											
Physics Present	●	●	●	●	●	●	●	●	●		
Physics Captured by Measurements	●	●	●	●	●	●	●	●	●	○	◉
Fixed Aeroelastic blade											
Physics Present	●	●	●	●	●	●	●	●	●		
Physics Captured by Measurements	●	●	●	●	●	●	●	●	●	◒	◉
Single Wind Turbine (Small) in Wind Tunnel											
Physics Present	○	○	○	○	◒	◒	○	●	●		
Physics Captured by Measurements	◉	◉	◉	◉	◉	◒	◒	●	●	◒	◉

Figure 9 – Prioritized Phenomena Experiment Mapping (PPEM) for the wind turbine case. This figure considers the Wake Development and Other Phenomena and their mapping to separated effects and integrated effects tests.

Physics Present/Physics Measured

- ◉ Entirely
- ◒ Mostly
- ○ Somewhat
- ◓ Limited
- ● Missing

	Blade Aero/Wake Generation	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	**Testing Issues**	Boundary Conditions	Scale Effects
Pitching Blade (with Flow Control)																	
Physics Present		◒	◉	◉	◉	●	◉	◉	◉	●	●	◒	◒	●			
Physics Captured by Measurements		○	◉	○	○	●	◓	◓	◓	●	◒	◒	◒	●		◉	◉
Turbine in WT (~1 m rotor), Turbulent Inflow																	
Physics Present		◒	◒	◒	◒	◒	◒	◒	◒	◒	◒	◒	◒	●			
Physics Captured by Measurements		○	◒	◓	◓	◒	◓	◓	◓	◒	◒	◒	◒	●		◒	◉
Turbine in VL WT (~5m rotor)																	
Physics Present		◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	●	●	●			
Physics Captured by Measurements		◒	◒	○	○	◒	○	○	○	◉	◒	●	●	●		◒	◉
Scaled Turbine in Field (~30m rotor)																	
Physics Present		◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	●	◉			
Physics Captured by Measurements		◒	○	○	○	○	◓	○	◓	◒	○	◒	●	○		○	◉
Industrial Scale Turbine in Field (~120m rotor)																	
Physics Present		◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	◉	●	◉			
Physics Captured by Measurements		○	◓	◓	◓	◓	◓	◓	◓	○	◓	○	●	◓		◓	◉

Figure 10 – Prioritized Phenomena Experiment Mapping (PPEM) for the wind turbine case. This figure considers the Blade/Aero Phenomena and their mapping to subsystem and system tests.

Physics Present/Physics Measured

- ⊙ Entirely
- ◒ Mostly
- ○ Somewhat
- ◓ Limited
- ● Missing

	Wake Development	Skew and Meander of Wake	Swirl Instability	Vortex Merging	Wake Vorticity Diffusion and Dissipation	Asymmetry Effects	Inflow Effects	**Other Effects**	Tower/Rotor/Nacelle Wake interactions	Aeroelasticity	Aeroacoustics	**Testing Issues**	Boundary Conditions	Scale Effects
Pitching Blade (with Flow Control)														
Physics Present		●	●	●	●	●	●		●	●	●			
Physics Captured by Measurements		●	●	●	●	●	●		●	●	●		⊙	⊙
Turbine in WT (~1 m rotor), Turbulent Inflow														
Physics Present		◒	◒	◒	◒	◒	◒		◒	◒	○			
Physics Captured by Measurements		◒	◒	◒	◒	◒	◒		◒	○	◒		◒	⊙
Turbine in VL WT (~5m rotor)														
Physics Present		○	⊙	⊙	⊙	⊙	●		⊙	◒	◒			
Physics Captured by Measurements		◒	◒	◒	◒	○	●		◒	○	◒		◒	⊙
Scaled Turbine in Field (~30m rotor)														
Physics Present		⊙	⊙	⊙	⊙	⊙	⊙		⊙	◒	◒			
Physics Captured by Measurements		○	○	○	○	○	○		○	○	◒		○	⊙
Industrial Scale Turbine in Field (~120m rotor)														
Physics Present		⊙	⊙	⊙	⊙	⊙	⊙		⊙	⊙	⊙			
Physics Captured by Measurements		◓	◓	◓	◓	◓	◓		◓	◓	◒		◓	⊙

Figure 11 – Prioritized Phenomena Experiment Mapping (PPEM) for the wind turbine case. This figure considers the Wake Development and Other Phenomena and their mapping to subsystem and system tests.

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)	Deep Array Effects	**Inflow Turbulence Wake Interaction**	Wind Direction	Surface Conditions	Turbulence Statistics	Momentum Transport	**Acoustic Propagation**	**Testing Issues**	Boundary Conditions	Scale Effects
Infinite Wind Farm in Wind Tunnel (~0.2 m rotor)															
Physics Present		◒	○	○	◒	◒		◒	◓	○	◒	◓			
Physics Captured by Measurements		⊙	⊙	⊙	⊙	⊙		⊙	⊙	⊙	⊙	◓		⊙	⊙
Multi Wakes with Inflow Turbulence (~0.2 m rotor)															
Physics Present		◒	○	○	◒	○		○	◓	◒	◒	◓			
Physics Captured by Measurements		⊙	⊙	⊙	⊙	⊙		⊙	⊙	⊙	⊙	◓		⊙	⊙
Wake Steer/Veer (~0.2 m rotor)															
Physics Present		○	◒	◓	◒	◓		○	◓	○	○	◓			
Physics Captured by Measurements		⊙	⊙	◒	⊙	⊙		⊙	⊙	⊙	⊙	◓		⊙	⊙
Wake/Turbine Interaction in WT (~2 m rotor)															
Physics Present		◓	◒	◓	◒	◓		○	○	◒	◒	◓			
Physics Captured by Measurements		◒	◒	○	⊙	◒		⊙	⊙	◒	◒	◒		◒	⊙
Scaled Wind Farm in VL WT (~2 m rotor)															
Physics Present		◒	◒	○	◒	○		⊙	○	○	○	○			
Physics Captured by Measurements		◒	◒	◒	⊙	◒		⊙	⊙	◒	◒	◒		◒	⊙
Scaled Wind Farm in Field (~30 m rotor)															
Physics Present		⊙	⊙	◒	⊙	◒		⊙	◒	◒	◒	◒			
Physics Captured by Measurements		○	○	◓	○	◓		◒	◒	○	◓	◒		◓	⊙
Industrial Scale Wind Plant (~120 m rotor)															
Physics Present		⊙	⊙	⊙	⊙	◒		⊙	⊙	⊙	⊙	⊙			
Physics Captured by Measurements		◓	◓	◓	◓	◓		○	◒	◓	◓	◒		◓	⊙

Figure 12 – Prioritized Phenomena Experiment Mapping (PPEM) for the wind plant case. This figure considers the Wake Development and Other Phenomena and their mapping to subsystem and system tests.

2.5 Summary of Integrated Program Planning

This section considered Integrated Program Planning (IPP) from a Validation and Verification (V&V) perspective. Phenomena Importance Ranking Tables (PIRTs) have been developed using input gathered from many Subject Matter Experts (SMEs) with expertise related to measurement or simulation of wind plants or some component of wind plants. Using the PIRTs and the Validation Hierarchy, Prioritized Phenomena Experimental Mapping tables have been developed. The results of this effort provide a means for prioritizing experimental and computational validation and verification efforts that will result in specific campaigns. The next step in the Validation and Verification approach is Integrated Experimental and Model Planning and Execution, as briefly discussed below.

3 Integrated Experimental and Modeling Planning and Execution

The purpose of Integrated Program Planning (IPP) is to provide a basis for the next step, which is carrying out the simulations and modeling. Of course, some existing experiments may already be useful for addressing some of the phenomena identified here, and an effort to identify and catalogue those experiments is a useful effort. However, many experiments and modeling efforts will be required to fully realize the validation and verification effort laid out here. Referring back to Figure 1, the second part of the Validation and Verification process is the Integrated Experiment and Model Planning and Execution. The first step in this is Experiment Design, Execution, and Analysis.

Multiple scales of experiments will be required to obtain gross coverage of the wind plant aerodynamics V&V hierarchy to meet program priorities focused on wind plant performance. The planning and execution of integrated model and experiment campaigns will be done by a team of wind energy researchers from academia, industry and the national labs with expertise and focus in modeling, experimentation, and V&V planning and execution activities related to wind plant performance. These combined simulation and experimental campaigns have been termed test campaigns, and the goal of such campaigns will be referred to as test objectives. The development of test objectives can be based on information gained from existing wake aerodynamics measurements as well as the analysis of simulation results.

The test objectives will be developed to address physical phenomena identified as high priority by the Phenomenon Identification and Ranking Table (PIRT) for wind turbine and wind plant aerodynamics presented in the present document. Each test objective will explicitly address a specific set of phenomena, which will sum to the cumulative coverage of the validation hierarchy.

Although the test objectives will be primarily focused on model validation, other types of experiments are possible. Experiments have a range of types, including technology demonstration, model validation, model calibration, phenomena discovery, mathematical model development, or phenomena exploration.

Each of the test objectives will follow a specific format comprised of five components. The content of each of these objectives is described below.

Introduction:
What is the combined model and experimental test objective, including what quantities will be compared and what the focus of the test will be (discovery, exploration, demonstration, validation, or qualification)?

Configuration:
How will the test items be setup and controlled? What are the important environmental conditions?

Justification:
Considering the PIRT, Hierarchy, and PPEM, what is the justification of a particular test? How will the results be used to support the full-scale analysis of a wind farm? What are the PIRT items that

are addressed by this test? What are the instrumentation needs? How can program needs support this validation exercise, and vice-versa? How will this expand or utilize existing data-sets?

QoI (Quantities of Interest):
What quantities will be compared and at what resolution? One QoI can support several PIRT items, and vice-versa.

Instrumentation:
What will be used, what is needed, and how will simulations be used to support both? Can current instrumentation support resolution required for comparison?

The Integrated Program Planning portion of the wind plant validation effort is complete at this point. Its results may be used to guide the development of the objectives for the individual test campaigns to be developed in the near future as the validation effort progresses.

4 SUMMARY

The primary focus of the model validation referenced in this document is to accurately predict, assess and optimize wind plant performance utilizing High Fidelity Modeling (HFM) tools to understand and accurately predict the fundamental physics and complex flows of the atmospheric boundary layer, interaction with the wind plant, and the response of individual turbines to the complex flows within a wind plant. However, there are several wind energy applications that necessitate using HFM alongside lower fidelity, computationally efficient models including fatigue analysis, design optimization, and uncertainty quantification.

The Integrated Program Planning process has been presented in this document as it has been applied to the validation and assessment of models of various fidelity to predict wind plant performance. Three main parts of this process were presented in this document: Phenomenon Identification and Ranking Table, the Validation Hierarchy, and the Prioritized Phenomenon and Experiment Mapping table. This document is a stepping point and reference for the planning and execution of integrated model and experiment campaigns ranging in scale and complexity.

Although this Integrated Program Planning document was primarily developed to guide the validation and verification efforts within the U.S. Department of Energy's Wind Program, the results can be used to guide similar efforts funded by other agencies or conducted by groups from other countries. Ideally, by having a clear set of validation needs identified, a comprehensive validation dataset focused on wind plant modeling will be developed over the next several years.

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