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Wind Energy High-Fidelity Model Verification and Validation Roadmap

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ABSTRACT

The development of a next generation high-fidelity modeling code for wind plant applications is one of the central focus areas of the U.S. Department of Energy Atmosphere to Electrons (A2e) initiative. The code is based on a highly scalable framework, currently called Nalu-Wind. One key aspect of the model development is a coordinated formal validation program undertaken specifically to establish the predictive capability of Nalu-Wind for wind plant applications. The purpose of this document is to define the verification and validation (V&V) plan for the A2e high-fidelity modeling capability. It summarizes the V&V framework, identifies code capability users and use cases, describes model validation needs, and presents a timeline to meet those needs.

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Specifically, thanks to Jonathan Naughton for many discussions and feedback about this document. The time of Alan Hsieh and Kenneth Brown is also greatly appreciated for technical reviews.

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EXECUTIVE SUMMARY

The development of a next generation high-fidelity modeling code for wind plant applications is one of the central focus areas of the U.S. Department of Energy (DOE) Atmosphere to Electrons (A2e) initiative. The code is based on a highly scalable framework, currently called Nalu-Wind. One key aspect of the model development is a coordinated formal validation program undertaken specifically to establish the predictive capability of Nalu-Wind for wind plant applications.

The validation program follows a formal verification and validation (V&V) framework, and is being implemented by tight collaboration between modelers, experimentalists, and validation specialists. The framework utilizes a hierarchical approach to validation, building from unit test cases to complete system tests.

Potential users for Nalu-Wind include the DOE Wind Energy Technologies Office, the DOE Office of Science, and wind industry manufacturers, developers, and owners. The most important use cases identified by the V&V team include the prediction of wind plant power performance and loads, the discovery of dominant phenomena governing wake evolution, and exploration of next-generation innovations to improve wind plant and turbine performance. These use cases map directly to items in the Phenomena Identification and Ranking Table (PIRT), which identifies priority physical phenomena required to predict wind plant performance.

Model validation needs were derived directly from the prioritized phenomena identified in the PIRT. These validation needs were divided into nine areas:

1. Mesoscale forcing and turbulence spin up and large eddy simulation (LES) subgrid-scale models in multiple atmospheric conditions
2. LES subgrid-scale models for accurate prediction of terrain-induced flow
3. Surface models for terrain/vegetation/roughness, heat flux, moisture, and radiation
4. LES subgrid stress models for prediction of wake effects and blade loads, in single, static, blade-resolved and actuator-line simulations
5. LES subgrid stress and hybrid Reynolds-averaged Navier-Stokes (RANS)/LES models for prediction of blade loads, in single, dynamic, blade-resolved and actuator-line simulations
6. Rotor aerodynamic and LES subgrid stress models for accurate prediction of wake phenomena

7. Models for wake evolution (formation, meandering, merging) in a wind farm (at least two turbines), where deep-array effects are not applicable
8. Models for wake evolution (formation, meandering, merging) in a wind farm with O(10) MW-scale turbines, where deep-array effects are important
9. Large-deformation structural dynamics and fluid-structure-interaction models.

The needed validation studies were mapped to a multiyear timeline of proposed or ongoing experimental campaigns. These campaigns represent the best estimate of what will be required to validate Nalu-Wind for all of the anticipated use cases, although prioritization can change as new knowledge is gained during the validation exercises. Current known experimental needs are described at the end of the document, which will feed into the planning of new experiments.

TERMS AND DEFINITIONS

A2e Atmosphere to Electrons initiative, U.S. Department of Energy

ABL atmospheric boundary layer

BL boundary layer

CFD computational fluid dynamics

CP rotor power performance coefficient

CT rotor thrust performance coefficient

D wind turbine rotor diameter

DGV Doppler global velocimetry

DOE U.S. Department of Energy

FSI fluid structure interaction

HFM high-fidelity model

IEMPE Integrated Experiment and Model Planning and Execution

IPP Integrated Program Planning

LDV laser Doppler velocimetry

LE leading edge

LES large eddy simulation

MMC meso-micro scale coupling

NREL National Renewable Energy Laboratory

P per revolution, as in 6 times per rotor revolution

PIRT Phenomena Identification and Ranking Table

PIV particle image velocimetry

R wind turbine rotor radius

RANS Reynolds-averaged Navier-Stokes equations

rpm rotations per minute

SCADA supervisory control and data acquisition

SNL Sandia National Laboratories

SME subject matter expert

SWiFT DOE/SNL scaled wind farm technology facility

TI atmospheric turbulence intensity

TKE turbulent kinetic energy

TSR tip speed ratio

U streamwise velocity

V&V verification and validation

WFIP Wind Forecast Improvement Project

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1. INTRODUCTION

The purpose of this document is to define the verification and validation (V&V) plan for the U.S. Department of Energy Atmosphere to Electrons (A2e) high-fidelity modeling capability. The V&V activity is a close collaboration between team members on the A2e-funded projects entitled Wake Dynamics, High-Fidelity Modeling (HFM), and Verification, Validation, and Uncertainty Quantification (VV&UQ). This document is meant to be a distillation of discussions and ideas that took place in several venues over the last 2 years, including the A2e Wind Plant Physics planning meeting [15], and the Phenomena Identification and Ranking Tables (PIRTs) that were generated in that meeting.

1.1. V&V FRAMEWORK

Test campaign planning and execution for the A2e initiative is being accomplished through a formal V&V process, as established in the "V&V Framework" document [7]. The validation directed program planning process is shown in Figure 1-1 and has been divided into two phases: Integrated Program Planning (IPP) and Integrated Experiment and Model Planning and Execution (IEMPE).

The IPP process is used to define, justify, and prioritize the hierarchy of validation experiments as relevant to the validation of models useful for the prediction 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 "V&V Integrated Program Planning for Wind Plant Performance" document outlines the validation process and applies it to wind plant performance prediction at a comprehensive level [9]. The result is a 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 meant for use as a guide for experiment planning, model development, and model application.

1.2. OBJECTIVE

The objective for wind plant performance modeling was agreed upon by modelers, experimentalists, and validation specialists from a broad cross section of the wind energy community.

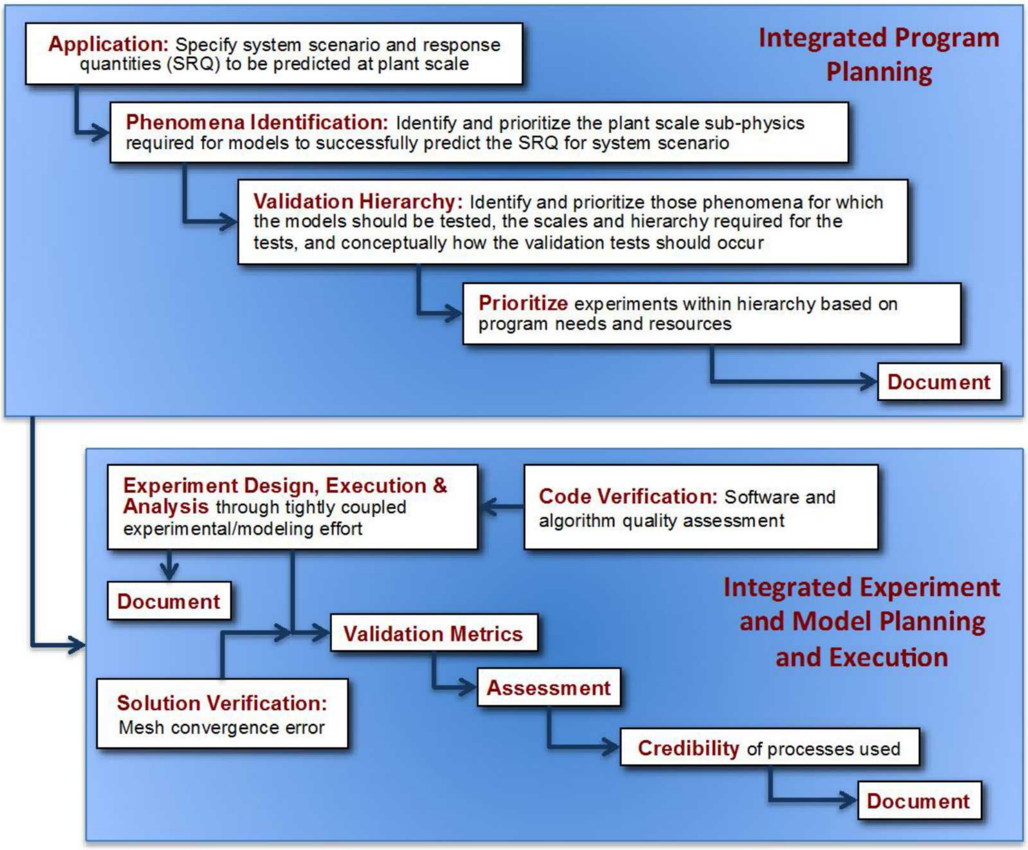

Figure 1-1. Validation directed program planning and implementation.

Objective for wind plant performance:

> 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 turbine design, wind farm development, and wind farm operations, as it affects both the overall power production and the uncertainty of the output. Optimizing production and minimizing risk has a favorable impact on a project's profitability. The ability to better predict wind plant performance can also reduce project finance cost and ease integration of wind in grid operations[9].

The modeling objective will determine methods for model calibration, characterization, and validation data that the experimentalists will provide to the modelers and validation specialists. Meeting this objective requires careful verification and validation of the computational models.

1.3. V&V WORKFLOW

The workflow for the V&V process (Figure 1-2) shows a general representation of the steps required to execute the validation studies that have evolved out of the V&V Framework. Each box represents a series of tasks, corresponding to a work breakdown structure used to estimate the resource requirements to execute the validation studies outlined in this document.

The V&V workflow shown in Figure 1-2 assumes that subject matter experts (SMEs) from each of the areas (Algorithm Development, Model Development, Validation, and Experimentation) are all involved in the first five stages of the workflow, which correspond to the IPP process at the top of Figure 1-1. The remaining stages correspond to the IEMPE process and involve more focused efforts within each work area, although tight integration and communication between the work areas is required for successful validation program execution. The final step involves making a decision that is either informed by the available research or is based on statistical evidence.

Simulations required for the design of the validation studies and experiments, such as sensitivity studies, are assumed to take place under the Validation work area using currently proven modeling capabilities, whereas the Simulate Cases stage near the end of the workflow will utilize the application modeling capability developed in the Model Development and Algorithm Development work areas.

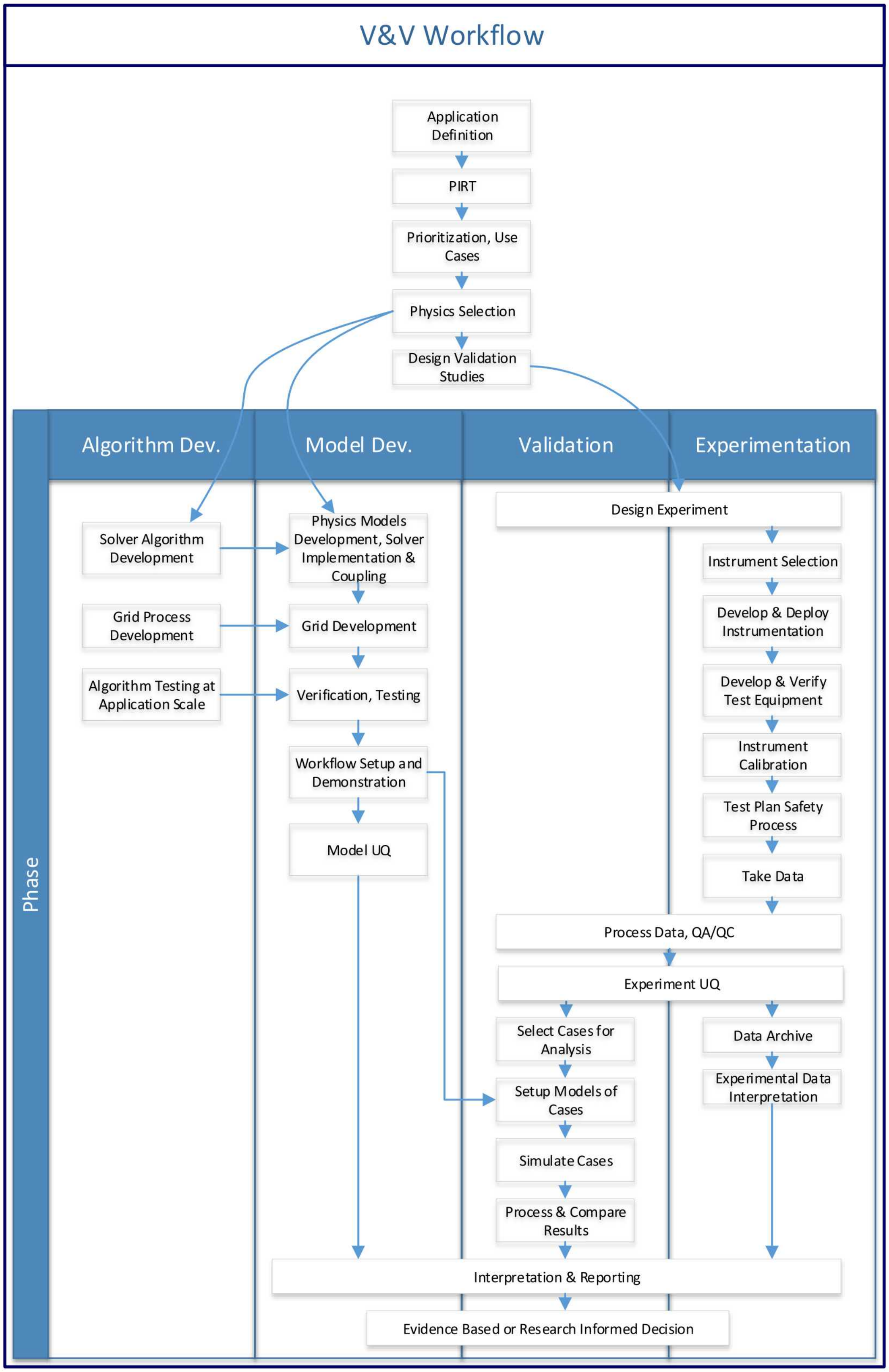

Figure 1-2. V&V workflow.

2. USERS AND USE CASES

The use cases of importance are highly dependent on the eventual customer for the high-fidelity modeling tools. Below is a list of potential customers and their preferred application of next-generation modeling tools.

2.1. USERS

- DOE Office of Science - interested in demonstration of highly scalable, high-fidelity simulation tools that perform well on future exascale computing platforms, and have the potential to impact scientific discovery.

- DOE Wind Energy Technologies Office - interested in a predictive simulation capability that will enable impactful research studies that improve understanding of wind plant complex flow, exploration of novel wind technology advances (e.g., controls and turbine configurations), and validation of lower-fidelity models. It is anticipated that the HFM capability will enable next-generation computationally efficient models.

- Industry Manufacturers - interested in simulation tools that lead to improved energy capture and higher reliability of wind turbines in a variety of operating environments. Manufacturers are interested in advancing models for turbine design and control, aeroelasticity, and local atmospheric forcing. Manufacturers are the most technologically advanced sector in the industry and may also directly apply high-fidelity models to turbine design.

- Industry Developers - interested in designing optimal plant layouts for maximum energy capture while satisfying reliability constraints. Also interested in quantifying and reducing uncertainties for long-term energy estimates in order to drive down the cost of capital. Developers are interested in advancing models of turbine and farm interaction with the atmospheric boundary layer (ABL) over decadal scales.

- Industry Owners - interested in maximizing overall energy capture of existing farms, reducing downtime, and maximizing turbine life. Owners are interested in advancing models for forecasting (day-ahead markets in the US) and interaction between turbines and farms at smaller timescales (hourly or less), including the application of wind farm control to maximize energy capture. Owners are also interested in the influence of changing atmospheric conditions on turbine lifetimes.

Note that there is overlap between the customers' interests and therefore it makes sense to choose use cases that are most beneficial to the greatest number of customers. Also note that there is increasing potential for industry to become more vertically integrated, particularly between the manufacturing and project development sectors.

2.2. USE CASES

The V&V team believes that the most important use cases can be categorized as prediction, discovery, and/or innovation. Important specific use cases under each category are as follows:

- Predict, e.g.,
  - Wind plant power performance and loads. This addresses i) fundamental studies on wind plant aerodynamics and the impact of weather/stability/terrain, which trickles to lower order models and also ii) wind plant controls studies.
  - Power production of a wind plant in flat terrain, with blade-root loads
  - Diurnal flow field in complex terrain (prior to wind plant installation)
  - Loads and wakes of a next-generation turbine (qualification)
  - Forensics analyses with data assimilation to understand extreme or unusual load events
- Discover, e.g.,
  - Dominant phenomena governing wake evolution
  - New modeling approaches for wind energy
- Innovate, e.g.,
  - Explore the design space of next-generation innovations to improve turbine and plant performance
  - Optimize new technology prior to demonstration testing.

3. MODEL VALIDATION NEEDS

3.1. MAPPING OF USE CASES TO PIRT ITEMS

In this section, we link the use cases to specific physical phenomena identified in the PIRTs. The PIRTs focus on phenomena across three dominant scales: the ABL (including mesoscale), the wind plant scale and the turbine scale. The PIRT tables can be found in Appendix A.

- Predict the ABL phenomena that drive wind plant performance and reliability
  - Terrain-induced flows
  - Surface heat flux
  - Surface roughness
  - Atmospheric stability
  - Geostrophic wind
  - Capping inversion
  - Diurnal transitions
  - Frontal passages
- Predict wind plant power performance and loads in relevant atmospheric conditions (e.g., with frontal passages, various stabilities)
  - Wake meandering
  - Wake mixing
  - Wake merging
  - Wake turbine interaction
  - Deep-array effects
- Predict blade-local, very near wake details
  - Blade load distribution
  - Dynamic stall

- Transition to turbulence
- Near wake flow/tip/root vortices
- 3-dimensional/rotational/finite blade effects
- Structural dynamics
- Blade surface roughness.

3.2. MAPPING OF PIRT PRIORITIES TO MODEL VALIDATION NEEDS

In this section, the specific validation needs are presented along with an overview of requirements for the associated validation exercises. Each item contains a description of the physics models, the objective of the validation campaign, a list of the relevant phenomena, a list of the primary and supplementary quantities of interest, and a description of the validation data requirements. These validation requirements were developed for current visions of next generation models, and will need to be updated as models and the problems they are applied to change.

1. Mesoscale forcing and turbulence spin up and large eddy simulation (LES) subgrid-scale models in multiple atmospheric conditions

   Objective: This effort aims to validate the effect of mesoscale forcing on the winds that affect the turbine and the entire wind plant. Within mesoscale-coupled wind plant large-eddy simulations, it is common to apply lateral boundary conditions derived from a mesoscale model in which the turbulence is completely modeled and not resolved, so resolved scale turbulence must be efficiently generated. This effort also validates turbulence "spin-up" techniques. Because we are speaking of microscale large-eddy simulations, the subgrid-scale stress model must also be validated. This effort overlaps significantly with the A2e mesoscale-microscale coupling project.

   Phenomena: The atmospheric phenomena to be modeled include: diurnal cycles, frontal passages, low-level jets, and any other events in which the mesoscale weather significantly affects the microscale weather.

   Quantities of Interest: The essential quantities of interest include:

   - Wind speeds and temperature profiles to top of ABL; 20 x 20 measurement points perpendicular to the primary wind direction.
   - Mean profiles of wind velocity, temperature, and turbulence statistics from the surface to the upper extent influenced by the wind plant.
   - Velocity spectra at multiple heights within the turbine and wake layer.

- Characterization of the structure of turbulence affecting the turbines and their wakes, such as horizontal and vertical coherence.

Supplemental Validation Quantities: Additional quantities that would benefit the validation process include:

- Surface heat, momentum, and moisture fluxes.
- Surface skin temperature and temperature of the first mesoscale model level.
- Profiles as described above but throughout the entire ABL, as opposed to just at the turbine level.
- Geostrophic wind (pressure gradient force) throughout the ABL.
- Measured subgrid-scale fluxes.
- Measured loads on a turbine as an indirect measurement of turbulence.

Required Geometry and Flow Conditions: To better understand the mesoscale forcing on the microscale weather, one needs a synoptic weather analysis and a good description of the terrain within the mesoscale region. Usually, the actual synoptic weather analysis does not contain enough information to fully characterize the mesoscale forcing of a microscale simulation, so mesoscale weather model data are extremely useful. Furthermore, a detailed description of the terrain and surface type in the microscale region of interest is necessary. To validate turbulence spin-up methods, one needs a good characterization of the turbulence levels and structure. The subgrid-scale model can be indirectly evaluated by assessing the accuracy of the mean profiles of velocity and temperatue and the resolved-scale turbulence–this assumes that if these resolved quantities are correct, then the subgrid-scale model must be working reasonably well. However, a more direct method is to directly measure the subgrid-scale quantities, and the region where subgrid-scale models have most influence is near the ground. In the A2e mesoscale-microscale coupling project, researchers are using both momentum budget components (tendencies) from a mesoscale model and source terms. Researchers should evaluate all the components of the tendencies that are input into the microscale, i.e., the tendency term that describes the advection, and the one that describes the large-scale pressure gradient.

Validation Data Requirements: Validation data should include, at minimum, vertical profiles of wind velocity and temperature at a 1 Hz minimum frequency from a tower that is at least 160 m tall with multiple measurement points along its height. Supplemental vertical profiles from remote sensing devices, like lidar, radar, and sodar, that reach higher altitudes would be highly useful. For example, having the potential temperature profile through the entire atmospheric boundary layer and above would be an extremely useful input to microscale flow solvers. Data should also include surface flux measurements. Ideally, there would be multiple measurement devices of each type geographically spread out over the mesoscale region, as has been done in the Second Wind Forecast Improvement Project (WFIP2) experiment. The use of a scanning remote sensing device would be useful in capturing near-instantaneous snapshots of the turbulence structure and how it changes during a mesoscale event. For the measurement of subgrid-scale quantities, one would need an array of point velocity and temperature measurement devices within a volume smaller than a typical microscale LES volume (10-30 m cube). A grid of microbarographs provides measured surface pressure gradients, which can be used to evaluate and validate the geostrophic wind. A grid of temperature, wind, and pressure profilers measuring tendencies across the boundary layer covering a 10–50 km horizontal range can help validate momentum budget components. It is important to note that the A2e mesoscale-microscale coupling project and WFIP 2 are working in this area and can provide guidance and validation data.

2. LES subgrid-scale models for accurate prediction of terrain-induced flow

   Objective: The objective of this effort is to validate the impact of the LES subgrid-scale model on flow over complex terrain.

   Phenomena: The phenomena of greatest interest here include the terrain's effect on the mean wind velocity, the location of flow separation, and the terrain-induced turbulence.

   Quantities of Interest: The main wind-energy-related quantities of interest include:

   - Vertical profiles of wind velocity, temperature, and turbulence statistics from the surface to above the wakes at multiple locations within the terrain field.
   - Velocity spectra at multiple heights throughout the terrain field.

   Supplemental Validation Quantities: Supplemental quantities that would aid in the validation process include:

   - Surface momentum, temperature, and moisture fluxes particularly across high gradients of terrain.
   - Surface skin temperature at O(10) m resolution.
   - Turbulence structure and coherence quantities.
   - Wind velocity and temperature histories over distribution as high as possible (at least as high as top of rotor); 20 points upwind and downwind of complex-terrain feature.
   - Time series of velocity and temperature at above points (for generation of statistical/derived quantities).
   - Reynolds stress profiles.
   - Temperature profiles.

Required Geometry and Flow Conditions: A high resolution (< 5 m) terrain and surface roughness map of the region of interest is required. This region of interest is assumed to be a volume equal in size to that simulated with a microscale large-eddy simulation over the terrain, so between 3 and 10 km in each horizontal direction is required. Furthermore, a terrain and roughness map over the larger surrounding region (at least 20 km beyond the region of interest), is required, but can be of lower resolution. The inflow conditions must be as well characterized as possible. This characterization, at very least, should include multiple meteorological mast or remote sensor measurements upwind of the region of interest. Having scanning lidar inflow plane measurements would be ideal. The inflow data should include both velocity and temperature information. The flow conditions characterization should also include an analysis of the mesoscale conditions that would likely be a combination of observations and model data.

Validation Data Requirements: To assess the subgrid-scale model impact on terrain-induced flow, multiple vertical profiles of wind velocity and temperature should be taken over interesting terrain features. For example, if the feature is a hill with a separation region on the lee side, a series of measurement devices should be placed along a line traversing the hill in the wind-aligned direction. These devices should measure from near-ground level to above the top of the rotor with at least a 30 m resolution. If this is done with remote sensing devices, it is difficult to glean turbulence statistics, so some measurements with meteorological masts should be performed. Further, high-frequency point measurements from devices like sonic anemometers will yield the information needed to compute velocity spectra. A series of short, inexpensive masts placed at a higher resolution could be a useful way to determine the separation location. For example, if 30 of these devices were placed on the lee side of a hill, the separation point could be well resolved. For gaining a more global picture of the effect of terrain on the flow, longer-range scanning lidar may be used, but difficulties may occur if terrain blocks the line of sight of the signal. To directly measure subgrid-scale quantities, an array of velocity and temperature measurement devices must be placed within a volume of typical LES grid cell size (10-30 m cube).

3. Surface models for terrain/vegetation/roughness, heat flux, moisture, and radiation

   Objective: The objective of this effort is to validate the interaction of the surface with the local environment and the ultimate impact on rotor winds and turbulence.

   Phenomena: The phenomena at play include surface roughness, terrain, heat flux, momentum flux (offshore waves), and potentially moisture flux.

   Quantities of Interest: In the context of wind turbine or wind/plant simulation, the simulation model must predict, to some desired level of accuracy, the following quantities:

- Surface shear stress.
- Changes in flowfield due to terrain.
- Changes in flowfield due to heat flux over diurnal cycle.
- Momentum flux and moisture flux are thought to be secondary at this point, but a sensitivity analysis may be needed to confirm.

Required Geometry and Flow Conditions: For testing of surface roughness, a range of roughness conditions should be considered, from short prairie grasses/soybeans to distributed trees and even full canopies. The current theory is unsophisticated and fundamental research may be required for prediction advancements. For terrain features, linear flow models are known to break down at 30-40% slopes, so a range of such terrains above that should be considered. Terrain should be varying in both vertical and horizontal directions. Lastly, heat flux varies greatly over a diurnal cycle and seasons and representative values for wind projects should be found. The interaction between surface roughness, terrain, and heat flux may also require more fundamental study as the most current theories often assume horizontal homogeneity.

Validation Data Requirements: The data for validation for surface roughness will likely be acquired in the field, although some unit testing in more controlled environments may be useful. Much of this data will likely originate from the atmospheric modeling community and a background survey should be done. Data should include vertical velocity profiles over a range of roughness values from smooth prairies to forested. Data should include velocity measurements at different vertical locations above the surface and horizontal resolution if the roughness is dispersed. The data should also include characterization of the roughness itself, such as the height, density, and porosity.

Heat flux measurements are most simply measured as the difference in temperature between two vertical points in the atmosphere, although more vertical and horizontal resolution of temperature is useful. A minimum of two points of measurement are required, with an ideal of 30 or more throughout the ABL.

Data for influence of terrain impacts are most relevant from full-scale measurements, given the scales that impact the flow over terrain. At a minimum, data should be velocity measurements (speed and direction) at multiple heights and horizontally spaced throughout the domain. More variation in terrain requires higher measurement resolution. A minimum of 10 points through a typical rotor plane should be the vertical resolution. Measurements of atmospheric boundary height are required. Since full-scale measurements are inherently coupled, data of heat flux and surface roughness are also simultaneously required.

4. LES subgrid stress models for the wake and blade loads, in single, static blade-resolved and actuator-line simulations

   Objective: The objective of this effort is to validate turbulence models for prediction of wind turbine blade aerodynamic load distributions and the resulting wake in the case of a static (nonrotating), rigid blade immersed in a turbulent, free-stream flow.

   Phenomena: The aerodynamic phenomena at play include blade boundary layer transition, blade boundary layer separation, generation of shed and trailed vorticity, turbulent mixing, and diffusion in the wake.

   Quantities of Interest: In the context of blade-resolved wind turbine or wind/plant simulation, the turbulence model must predict, to some desired level of accuracy, the following quantities:

   - Unsteady sectional blade loads.
   - Strength and distribution of shed vorticity due to unsteady inflow conditions, and its evolution downstream.
   - Strength and distribution of trailed vorticity, particularly the tip vortex, and its evolution downstream.

   Supplemental Validation Quantities: The following quantities will aid in understanding and improving deficiencies in the turbulence models for prediction of the above quantities of interest:

   - Blade surface pressure distributions.
   - Blade boundary layer transition location along the span.
   - Blade surface shear stress distributions.
   - Wake velocity field and associated single-point statistics.

   Required Geometry and Flow Conditions: The geometry can consist of a full blade or a blade section, of either constant or variable chord, twist, and airfoil section along the span. This must be a finite-span model with a free blade tip in order to generate a tip vortex. The airfoil section(s) should be at least an approximate representation of modern wind turbine airfoil sections. The experimental chord Reynolds number should be high enough such that the natural boundary layer transition occurs near enough to the leading edge such that lift and drag characteristics are qualitatively similar to the performance of typical wind turbine blade sections at full-scale Reynolds numbers. Roughly speaking, the chord Reynolds number should exceed at least 1 million. The flow conditions should be controlled such that the mean inflow profile is uniform, and measurable free-stream turbulence can be introduced with turbulence intensities of up to 10%. The free-stream Mach number should be less than 0.3.

   Validation Data Requirements: The data must be generated in a facility where boundary conditions can be very well-characterized. The inflow conditions encountered by the airfoil and blade must be measured, and must include detailed mean and root-mean square (RMS) velocity profiles, as well as velocity time series at several upstream locations from which velocity spectra can be calculated. Ideally, two-point velocity correlations would also be measured in order to fully characterize the oncoming turbulence. If in a wind tunnel, wind tunnel walls must be easily modeled, i.e., a solid wall configuration and not a porous wall configuration. Open-jet configurations are also to be avoided due to difficulty in modeling these.

Surface pressures should be measured at a minimum of several spanwise stations. Preferably, these would be unsteady pressure measurements with a temporal resolution of frequencies up to frequencies associated with large-scale vortex shedding under stalled conditions. Unsteady load on the overall blade model is required. Particle image velocimetry (PIV) velocity fields are needed in the wake in planes normal to the free-stream, from the trailing edge to 10 chords downstream. The particular velocimetry configuration is somewhat flexible; however, measurement of the evolution of the velocity/vorticity field associated with the tip vortex is required.

Measurements should be made of the location of onset and completion of boundary layer transition along the span of the blade. Blade surface shear stress measurements would be of great value for understanding model accuracy in the prediction of blade boundary layer development.

5. LES subgrid stress and hybrid Reynolds-averaged Navier-Stokes (RANS)/LES models for blade loads, in single, dynamic, blade-resolved and actuator-line simulations

   Objective: The objective of this effort is to validate turbulence models for prediction of wind turbine blade aerodynamic load distributions and the resulting wake in the case of a dynamic (pitching+non-rotating or rotating with yaw), rigid blade immersed in a turbulent, free-stream flow.

   Phenomena: The aerodynamic phenomena at play include dynamic stall, blade boundary layer transition, blade boundary layer separation, generation of shed and trailed vorticity, turbulent mixing, and diffusion in the wake.

   Quantities of Interest: In the context of blade-resolved wind turbine or wind/plant simulation, the turbulence model must predict, to some desired level of accuracy, the following quantities:

   - Unsteady sectional blade loads.
   - Strength and distribution of shed vorticity due to unsteady inflow conditions, and its evolution downstream.
   - Strength and distribution of trailed vorticity, particularly the tip vortex, and its evolution downstream.

   Supplemental Validation Quantities: The following quantities will aid in understanding and improving deficiencies in the turbulence models for prediction of the above quantities of interest:

- Blade surface pressure distributions with time history, >50 Hz or 50 samples per revolution.
- Blade boundary layer transition location along the span.
- Blade surface shear stress distributions.
- Wake velocity field and associated single-point statistics.

Required Geometry and Flow Conditions: The geometry can consist of a full blade or a blade section, of either a constant or variable chord, twist, and airfoil section along the span. This must be a finite-span model with a free blade tip in order to generate a tip vortex. The airfoil section(s) should be at least an approximate representation of modern wind turbine airfoil sections. The experimental chord Reynolds number should be high enough such that natural boundary layer transition occurs near enough to the leading edge such that the lift and drag characteristics are qualitatively similar to the performance of typical wind turbine blade sections at full-scale Reynolds numbers. Roughly speaking, the chord Reynolds number should exceed at least 1 million. The flow conditions should be controlled such that the mean inflow profile is uniform, and measurable free-stream turbulence can be introduced with turbulence intensities of up to 10%. The free-stream Mach number should be less than 0.3.

Validation Data Requirements: The data must be generated in a facility where boundary conditions can be very well-characterized. The inflow conditions encountered by the airfoil must be measured, and must include detailed mean and rms velocity profiles, as well as velocity time series at several upstream locations from which velocity spectra can be calculated. Ideally, two-point velocity correlations would also be measured in order to fully characterize the oncoming turbulence. If in a wind tunnel, wind tunnel walls must be easily modeled, i.e., a solid wall configuration and not a porous wall configuration. Open-jet configurations are also to be avoided because they are more difficult to model, adding additional uncertainty in comparisons to experimental measurements.

Surface pressures should be measured at a minimum of several spanwise stations. Preferably, these would be unsteady pressure measurements with resolution of frequencies up to frequencies associated with large-scale vortex shedding under stalled conditions. Unsteady load on the overall blade model is required. PIV velocity fields are needed in the wake in planes normal to the free-stream, from the trailing edge to 10 chords downstream. The particular velocimetry configuration is somewhat flexible; however, measurement of the evolution of the velocity/vorticity field associated with the tip vortex is required.

Measurements should be made of the location of onset and completion of boundary layer transition along the span of the blade. It would also be helpful for calibrating or validating models of blade boundary layer development to have surface shear stress measurements.

6. Rotor aerodynamic model and LES subgrid stress models for accurate prediction of the listed wake phenomena

   Objective: This effort will focus on validating the model's ability to predict a range of wake phenomena that are a priority to predict wind plant performance. The rotor aerodynamic model determines the primary initial conditions of the wake, and depends on the inflow velocity and wake model induction at the rotor plane. The ability to model the creation and evolution of the wake structures is directly dependent on the LES subgrid stress model, as well as having the required resolution to accurately model the primary energy containing flow structures in the wake.

   Phenomena: The relevant phenomena for blade aerodynamics and wake generation include capturing the blade load distribution and overall rotor thrust, the tip and root vortex development and evolution, the vortex sheet and its advection (roll-up), the blade-generated turbulence at the trailing edge, the root flow acceleration, and the effects of unsteady inflow. The relevant phenomena for validating a model's ability to capture wake development include the skew and meander of the aggregate wake, vortex merging, wake vorticity diffusion and dissipation, the effects of asymmetric rotor loading (due to the ground plane, yaw, tilt, cone angle, and individual blade pitch), and the effects of inflow on the above quantities (shear, veer, turbulence characteristics).

   Quantities of Interest: In the context of LES wind plant simulations, the combined rotor aerodynamic model and LES subgrid stress models must predict, to some desired level of accuracy, the following quantities:

   - Unsteady sectional blade loads and integral rotor power and thrust.
   - High-resolution velocity measurements of the inflow and wake flow field, specifically the advection and mixing of dominant flow structures. Velocity measurements at 20 x 20 points across the rotor at -1.5D, -1.0D, -0.5D, 0.5D, 1.0D, 1.5D, 2.0D, 3D, ... 7D (resolution in order to resolve mean velocity profiles in the wake, with more resolution required in regions of high shear).
   - Single point statistics at several locations in the inflow and wake (projections from rotor centerline and high fluctuation regions near wake edge, ~80% span, locations should be designed using pre-experiment simulations).

   Supplemental Validation Quantities: The following quantities will aid in understanding and improving deficiencies in the turbulence models for prediction of the above quantities of interest:

   - Velocity measurements at 50 x 50 points across rotor at -1.5D to >7D (resolution in order to resolve mean velocity profiles in the wake).
   - Time series of velocity at all points (for generation of statistical/derived quantities).

Required Geometry and Flow Conditions: A single turbine with rigid blades is required for this validation exercise. The inflow should be highly controlled such that it can be quantified on a statistical basis, which can be reproduced in simulations. Terrain should be flat. Multiple combinations of shear and turbulence intensity are required, with multiple temperature profiles (atmospheric stability) desired. Pretest simulations should be used to determine the most useful combinations of inflow parameters. A low-turbulence and low-shear baseline case is desirable. Wind tunnel testing is acceptable, with appropriate chordwise Reynolds numbers, and relevant combinations of spanwise loading and tip-speed ratio (TSR). Field testing can be acceptable if the inflow and wake can be adequately measured such that the initial and boundary condition uncertainty are reduced to sufficient levels.

Validation Data Requirements: The initial conditions and boundary conditions of each validation dataset must be well characterized, which include the inflow and blade loading. The aeroleastic effects on blade aerodynamics must be straightforward to quantify in the model, driving the requirement for rigid blades. The inflow shear, veer, turbulence intensity, turbulence spectra, and temperature profile must all be measured and have converged statistics for each test case, which is necessary to reduce uncertainty in simulating the actual measured test conditions. The boundary conditions must also be sufficiently quantified, which includes nonporous walls in a wind tunnel and flat terrain with quantified roughness and ground heat flux for field testing.

The blade spanwise loading must be quantified at several locations, with a minimum of five spanwise locations and the optimum distribution determined through simulations. The loading can be calculated through the bending moment at discrete stations; however, direct surface pressure measurement is preferable. The loading should be recorded as a function of blade azimuth, such that phase-locked averaging can be performed. All blade loading, inflow, and wake data should have synchronized time stamps, allowing for correlations to be developed between phenomena associated with each type of measurement.

The inflow and outflow (wake) velocity fields must be measured, with sufficient resolution, to resolve the inflow across the rotor disc and the regions of high shear in the wake. The turbulent kinetic energy (TKE) and velocity spectra are also desired at several points in the wake region, with minimum points in the upper and lower edges of the wake and wake centerline. It is desired to measure the TKE at many points in the wake to produce a field, as the points of primary interest may differ from pretest simulations.

7. Models for wake evolution in a wind farm as a function of a range of atmospheric conditions, where deep-array effects are not applicable

   Objective: The objective of this validation effort is to enable the assessment of models for simulating the evolution of wind turbine wakes (formation, meandering, merging) under a range of atmospheric conditions in a wind farm (at least two turbines). Models will be assessed on their ability to capture a wide range of interacting phenomena relevant to the impact of wakes on wind plant performance (power and loads), focusing on the interaction of wakes and turbines at the boundary of a wind plant.

Phenomena: The primary phenomena of this effort include the interaction of inflow turbulence with the wake, including wind direction, turbulence characteristics, coherent inflow structures, surface conditions, and momentum transport (not including the additional complexity present with the side-flow and deep array effects in large wind plants). Multiturbine wake phenomena are also of primary importance, including wake interaction, merging, meandering, yaw and tilt effects, wake dissipation, and wake impingement on downstream turbines.

Quantities of Interest: In the context of LES wind plant simulations, the complete set of inflow, rotor, and wake models must predict, to some desired level of accuracy, the following quantities:

- Time histories of the rotor thrust, power, azimuth, and individual blade root bending moment.
- Temperature profiles and surface heat flux.
- Inflow horizontal and vertical velocity profiles for each turbine.
- Vertical and horizontal velocity profiles of each wake at 1D increments to the downstream turbine or to 7D.
- Velocity profiles where two wakes are merging.

Supplemental Validation Quantities: The following quantities will aid in understanding and improving deficiencies in the turbulence models for prediction of the above quantities of interest:

- Blade spanwise loading time history.
- Cross sections of the wake velocity and turbulence intensity with a resolution of 2% of the rotor diameter from 1 to 10D downstream and at 1 to 2D upstream are desired at 1D increments.

Required Geometry and Flow Conditions: The complete turbine system must be defined, specifically the blade planform, structural properties, airfoil polars, tower properties, and gearbox efficiency. The turbine control parameters must be recorded, including azimuth, yaw, and pitch settings. The location of each turbine must be measured with a minimum 0.5 meter accuracy. The alignment and location of all instrumentation must be measured.

Terrain should be flat and surface roughness quantified. A follow-on validation study will include the interaction of the wake with complex terrain features. Subscale field testing is acceptable for a subset of atmospheric conditions. Some studies of detailed wake interaction can be studied in the wind tunnel at an appropriate Reynolds number, although higher Reynolds number field experiments with a range of atmospheric conditions is desirable, including a minimum of canonical stable, unstable, and neutral stability conditions. Field measurements must include temperature profiles and surface heat flux is highly desirable.

Multiple combinations of wake-turbine interaction are required, with the wake of one turbine interacting at various levels of impingement with a downstream turbine. These cases should include the wake moving within 1D of a downstream turbine, impinging on half of a downstream turbine, and directly on a downstream turbine. Due to wake meandering, impingement can be defined on a time average.

Validation Data Requirements: Due to the range of interacting phenomena, a range of simultaneous measurements is required for sufficient model validation. The inflow velocity of an upstream turbine is required as a time-accurate vertical profile, with a time-accurate measurement of the horizontal variations in the flow. The interaction of the wake with other wakes and with downstream turbines requires high-resolution velocity measurements, with a minimum of vertical and horizontal velocity profiles, and velocity cross sections (or scans) highly desired. The inflow temperature profile and velocity profile and statistics will be used as input conditions to be matched between measurements and simulations. The wake deficit strength, location, and parameterized shape will all be used as output quantities for comparison between measurements and models.

The time histories of the rotor thrust, power, and individual blade root bending moment are required, which will be used as intermediary quantities for upstream turbines, and output quantities for downstream turbines.

8. Models for wake evolution (formation, meandering, merging) in a wind farm with O(10) MW-scale turbines, where deep-array effects are important

   Objective: The objective of this effort is to validate the interaction of wakes within a large wind plant environment.

   Phenomena: The phenomena at play include wake formation, merging, meandering, and deep array effects.

   Quantities of Interest: In the context of wind turbine or wind/plant simulation, the simulation model must predict, to some desired level of accuracy, the following quantities:

   - Individual wake profiles.
   - Wind plant wake profiles.
   - Wind plant internal boundary layer growth.
   - Vertical and horizontal momentum flux into and out of the wind plant.

Required Geometry and Flow Conditions: For testing of wakes within a large wind plant environment, data from a large wind plant ($>$ 100 MW with a row length of more than four turbines) is required. The flow conditions should be representative of diurnal cycles for wind plants with a range of turbine spacings, in different terrain and surface boundary conditions. The flow conditions should also include nonstationary events, such as frontal passages, through the wind plants. Subscale unit testing in more controlled environments may be useful, but scaling studies are needed to confirm.

Validation Data Requirements: Data requirements are much the same as the wake evolution studies discussed above. They include vertical velocity profiles within the wind plant during normal operation and when the wind plant is in a non-uprating state. Measurements of undisturbed atmospheric inflow on all sides of the wind plant are also required in at least one location, although more resolution is better. These measurements should include vertical velocity profiles, temperature profiles, surface roughness, and heat flux and a measure of the ABL height. At least one set of atmospheric measurements should be made upwind, downwind, and within the plant. Measurements of velocity profiles across the rotor planes should be taken (with a minimum of 10 points across each rotor) at different turbines down the row and completely downwind of the plant. Planar measurements are also useful in both horizontal and vertical directions. Importantly, the measurements should extend above the rotor disks of turbines (at least one diameter), so the growing internal boundary layer of the wind plant can be characterized. Measurements of velocity profiles outside the wind plant in nondominant wind directions will be useful to measure horizontal momentum flux into the wind plant. Time resolution of measurements should be at least twice as fast as the dominant wake meandering time length scales.

9. Large-deformation structural dynamics models and fluid-structure-interaction models

Objective: Validate the structural dynamics models (e.g., blade and tower) under conditions for which blades undergo large deformations due to aerodynamic loading.

Phenomena: The phenomena at play include:

- Geometrically nonlinear structural motions, which may include bend-twist coupling for aeroelastically tailored blades.
- Fluid-structure interaction.

Quantities of Interest: In the context of wind turbine or wind plant simulations, the simulation model must predict, to some desired level of accuracy, the following quantities:

- Tip displacements.
- Span-wise blade deformation including twist.

- Span-wise blade loads.
- Blade root moments.
- Tower moments.
- Blade multiaxis acceleration.

It would be appropriate and useful to have associated rotor speed, blade-pitch angles, and power histories.

Required Geometry and Flow Conditions: To validate geometrical nonlinearities, it will be important that the blade experiences transverse tip deflections greater than 10% of the blade length. For aeroelastically tailored rotors, the first torsional mode should be low enough to get excited, e.g., less than 12P. A full-scale test is most likely required to capture the relevant structural dynamics. However, a subscale test would be acceptable if a structurally scaled blade could be configured that captures key phenomena, e.g., large deflections and bend-twist coupling. In addition to normal operation, blade standstill conditions (i.e., idling rotor with fully feathered blades) under extreme wind conditions are also very important to predict accurately as the resulting loads may drive the structural design. Flow conditions include a range of standard inflow conditions (diurnal cycle), nonstationary events (frontal passage), and a range of wake-turbine interaction similar to the wake development studies.

Validation Data Requirements: To complete this study, it will be important to have well quantified/validated airfoil data (lift, drag, pitching moment versus angle of attack) at various spanwise stations. The blade planform, profile, mass distribution, and structural properties must be well defined, including the full 6×6 cross-sectional mass and stiffness matrices at various spanwise stations. It is important that the turbine controller can be modeled accurately. A poorly tuned controller will produce variations in loads and power production (e.g., due to oscillations in closed-loop modes) that can dominate output signals and undermine analysis. It may also be important to measure the aerodynamic pressure distribution and local inflow angle at various blade stations. As with the other studies listed in this report, the inflow must be well characterized in time, including turbulence data. The quantities of interest can be statistical during stationary inflow conditions, but must have sufficient time resolution to capture gust events and blade modes at greater than 6P (with 9P-12P preferred).

3.3. SUMMARY OF MODELS

The nine model validation areas listed above focus on what the computational models need to do, whereas this list summarizes the model components that the results of computational simulations depend on for wind energy applications.

The primary models in need of validation are as follows:

- Actuator lines for rotor blade parametrization.
- LES subgrid models for the atmospheric boundary layer.
- Turbulence generation at the mesoscale-microscale interface.
- Capping inversion of the atmospheric boundary layer.
- Surface heat flux model.
- Surface roughness model.
- LES/RANS model near blade surface.
- Transition to turbulence model on blade surface.
- Solution sensitivity to grid shape and resolution.
- Structural dynamics and fluid structure interaction models.

4. PROPOSED VALIDATION CAMPAIGNS

4.1. MAPPING OF PIRT PRIORITIES TO EXISTING AND PROPOSED VALIDATION DATA SETS AND PRIORITIZATION

Nalu-Wind will be validated using a hierarchal approach, starting with independent unit-level physics models, and moving to coupled physics models, subsystem models, and system-level models, as outlined in the IPP document [9].

Subsystem validation studies are categorized by having better characterized boundary conditions, initial conditions, and outputs than system-level experiments. System-level experiments have more representative or actual geometry, flow conditions, and system responses than subsystem experiments, but have less characterized conditions and outputs. For a wind plant, the measurements are often limited due to the natural variability of the wind resource, measurement and geometry uncertainty, and cost and complexity associated in taking measurements around and within a wind plant.

The wind plant performance validation hierarchy can be divided into several primary physical scales, namely wind plant, wind turbine, and mesoscale phenomena. The wind turbine and wind plant areas overlap in wake and array phenomena, the mesocale and wind plant areas overlap with meso-microscale phenomena, and the mesoscale and wind turbine hierarchies overlap with the influence of atmospheric effects on wind turbine power and loads. These overlapping hierarchies are represented in Figure 4-1.

The following sequence of validation studies are envisioned using already existing and new data sets that will be gathered in future experimental studies. Note the increasing complexity in the sequences.

- ABL Observations
  - Flat terrain, varying stability ABL (neutral, unstable, stable)
  - Complex terrain ABL
  - ABL with operating wind farm
  - Complex terrain ABL with operating wind farm

- Wind plant observations
  - Offshore power performance data
  - Offshore structural loads
  - Full wind farm with wake detail in flat terrain
  - Subscale multiple turbine interactions
  - Full wind farm in terrain with wake detail
- Rotor and blade aerodynamics
  - Nonrotating tip vortex
  - Blade-resolved parked rotor
  - Subscale-resolved rotor
  - Rotating single turbine wake with resolved geometry.

These validation studies are mapped to the wind plant performance validation hierarchy in Figure 4-2. The mesoscale physics are not the focus of the models in this document; however, the A2e mesoscale-microscale coupling project is developing more detailed studies for this area that will be published separately.

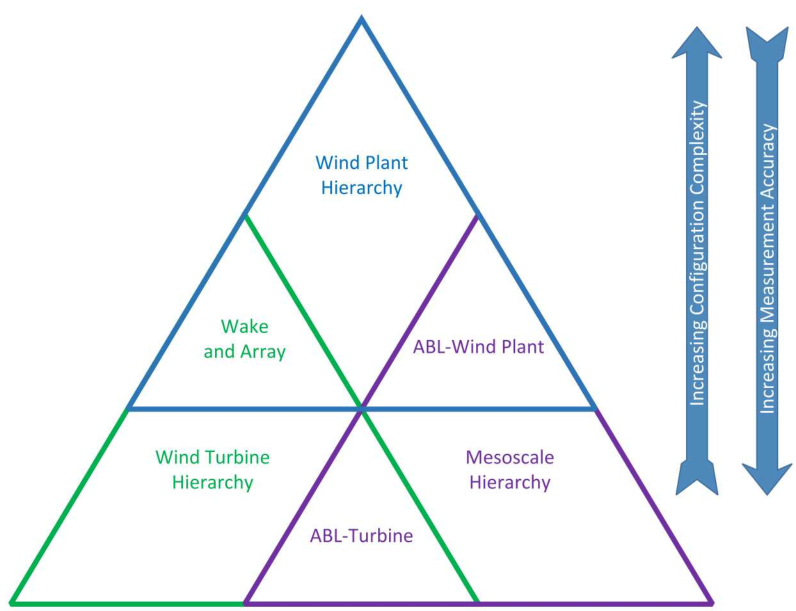

Figure 4-1. Validation hierarchy for wind plant performance, showing the overlap between the wind turbine, wind plant, and mesoscale hierarchies.

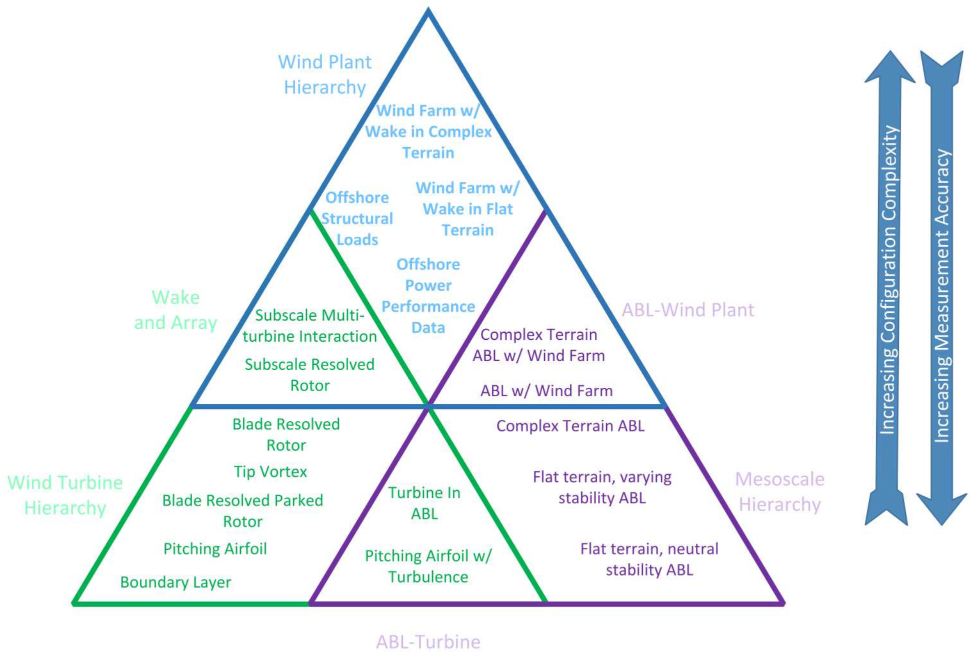

Figure 4-2. Validation studies mapped to the wind plant performance validation hierarchy.

The prioritization of the validation studies is performed according to the following criteria, as was started in the PIRT process, with the highest priority validation studies having:

1. Highest impact on wind plant power production and turbine reliability
2. Lowest physical understanding
3. Least mature computational model
4. Demonstration of exascale model scalability
5. Efficient use of existing DOE-owned facilities
6. Development of researcher expertise related to experimental observations.

Using a ranking scale from 1-3, each proposed validation study can be prioritized for each of these six criteria, and a composite score created as shown in Table 4-1.

Note that future prioritization of validation studies may benefit from sensitivity studies of computational models to address criteria number 1, where the relationship between physical models and their influence is not always well understood.

Using the PIRT priorities identified in Section 3, we can match the prioritized phenomena to the above list of suggested validation studies, as shown in the following tables along with a suggested timeline for execution. First, the experiments and how they address the atmospheric PIRT physics are shown in Table 4-2.

	Impact on A2e Objective	Low Physical Understanding	Least Mature Model	Demonstrates Exascale	DOE Facility Usage	Staff Expertise Maintenance	Composite Ranking
Single geometry resolved turbine with detailed wake	3	3	3	3	2	3	**2.83**
Wake scaling effect	3	2	2	3	3	3	**2.67**
Full wind farm with wake detail	3	3	3	3	1	3	**2.67**
Subscale turbine interaction	3	2	2	3	3	3	**2.67**
Combined ABL with wind farm power observations	3	3	3	3	1	3	**2.67**
Combined ABL and wind farm wake observations	3	3	3	3	1	3	**2.67**
Combined ABL, wind farm, and wind turbine observations	3	3	3	3	1	3	**2.67**
Multiple subscale, geometry-resolved turbines with wake detail	3	2	2	3	3	3	**2.67**
Combined ABL, wind farm, and wind turbine observations in terrain	3	3	3	3	1	3	**2.67**
Offshore full-scale wind plant power and loads	3	2	3	3	1	2	**2.33**
ABL in complex terrain	2	3	3	2	1	2	**2.17**
ABL simulation, flat varying stability	2	2	2	2	2	2	**2.00**
Rotating single-turbine wake with resolved blade geometry	3	2	2	3	1	1	**2.00**
Rotating single blade in yaw	2	2	2	3	1	1	**1.83**
Blade-geometry-resolved parked rotor	1	2	2	3	1	1	**1.67**
Pitching airfoil wind tunnel	1	2	2	3	1	1	**1.67**
Nonrotating blade-geometry-resolved tip vortex	1	1	1	3	1	1	**1.33**

Table 4-1. Prioritization for each validation study

	Terrain-Induced Flow	Surface Heat Flux	Atmospheric Stability	Surface Roughness	Geostrophic Wind	Capping Inversion	Diurnal Transitions	Frontal Passages
ABL simulation, flat varying stability		x	x	x	x	x	x	x
Offshore full-scale wind plant power and loads		x	x	x	x	x	x	x
Wake scaling effect		x	x	x	x	x		
Blade-geometry-resolved parked rotor								
ABL in complex terrain	x	x	x	x	x	x	x	x
Full wind farm with wake detail		x	x	x	x	x	x	x
Subscale turbine interaction		x	x	x	x	x		
Nonrotating blade-geometry-resolved tip vortex								
Rotating single-turbine wake with resolved blade geometry		x	x	x	x	x		
Combined ABL with wind farm power observations		x	x	x	x	x	x	x
Pitching airfoil wind tunnel								
Rotating single blade in yaw								
Combined ABL and wind farm wake observations		x	x	x	x	x	x	x
Single, geometry-resolved turbine with detailed wake		x	x	x	x	x		
Combined ABL, wind farm, and wind turbine observations		x	x	x	x	x	x	x
Multiple subscale, geometry-resolved turbines with wake detail		x	x	x	x	x		
Combined ABL, wind farm, and wind turbine observations in terrain	x	x	x	x	x	x	x	x

Table 4-2. Atmospheric boundary layer physics addressed by validation study

Next, the wind plant scale is shown in Table 4-3, and the turbine scale in Table 4-4. Lastly, matching the models from Section 3.3 to be validated with the validation studies — we can see which models are addressed in Table 4-5.

	Wake Meandering	Wake Mixing	Wake Merging	Deep Array	Wake Turbine Interaction
ABL simulation, flat varying stability					
Offshore full-scale wind plant power and loads	x	x	x	x	x
Wake scaling effect	x	x	x		x
Blade-geometry-resolved parked rotor					
ABL in complex terrain					
Full wind farm with wake detail	x	x	x	x	x
Subscale turbine interaction	x	x	x		x
Nonrotating blade-geometry-resolved tip vortex					
Rotating single-turbine wake with resolved blade geometry	x	x			
Combined ABL with wind farm power observations	x	x	x	x	x
Pitching airfoil wind tunnel					
Rotating single blade in yaw					
Combined ABL and wind farm wake observations	x	x	x	x	x
Single, geometry-resolved turbine with detailed wake	x	x			
Combined ABL, wind farm, and wind turbine observations	x	x	x	x	x
Multiple subscale, geometry-resolved turbines with wake detail	x	x	x		x
Combined ABL, wind farm, and wind turbine observations in terrain	x	x	x	x	x

Table 4-3. Wake physics addressed by validation study

	Transition, Blade BL	Dynamic Stall	Blade Load Distribution	Near Wake Flow	Finite Blade Effects	Structural Dynamics	Blade Surface Roughness
ABL simulation, flat varying stability							
Offshore full-scale wind plant power and loads							
Wake scaling effect		x	x	x	x	x	
Blade-geometry-resolved parked rotor	x	x	x				x
ABL in complex terrain							
Full wind farm with wake detail			x			x	
Subscale turbine interaction		x	x	x	x	x	
Nonrotating blade-geometry-resolved tip vortex	x		x		x	x	
Rotating single-turbine wake with resolved blade geometry	x	x	x	x	x	x	x
Combined ABL with wind farm power observations			x	x			
Pitching airfoil wind tunnel	x	x				x	x
Rotating single blade in yaw	x	x	x	x	x	x	
Combined ABL and wind farm wake observations			x	x			
Single, geometry-resolved turbine with detailed wake	x	x	x	x	x		
Combined ABL, wind farm, and wind turbine observations			x	x	x	x	
Multiple subscale, geometry-resolved turbines with wake detail	x	x	x	x	x	x	
Combined ABL, wind farm, and wind turbine observations in terrain			x	x	x	x	

Table 4-4. Blade physics addressed by validation study

	Actuator Line	LES Subgrid Model - ABL	Meso-Micro Turbulence	Capping Inversion	Surface Heat Flux	Surface Roughness	LES/RANS Subgrid - Blade	Transition, Blade BL	Grid Sensitivity
ABL simulation, flat varying stability		x	x	x	x	x			
Offshore full-scale wind plant power and loads	x	x	x	x	x	x			x
Wake scaling effect	x	x		x	x	x	x	x	x
Blade-geometry-resolved parked rotor							x	x	x
ABL in complex terrain		x	x	x	x	x			
Full wind farm with wake detail	x	x	x	x	x	x			
Subscale turbine interaction	x	x		x	x	x	x	x	x
Nonrotating blade-geometry-resolved tip vortex							x	x	x
Rotating single-turbine wake with resolved blade geometry		x		x	x	x	x	x	x
Combined ABL and wind farm observations	x	x	x	x	x	x			
Pitching airfoil wind tunnel							x	x	x
Rotating single blade in yaw							x	x	x
Combined wind farm and ABL observations	x	x	x	x	x	x			
Single, geometry-resolved turbine with detailed wake		x		x	x	x	x	x	x
Combined ABL, wind farm, and wind turbine observations	x	x	x	x	x	x	x	x	x
Multiple subscale, geometry-resolved turbines with wake detail	x	x		x	x	x	x	x	x
Combined ABL, wind farm, and wind turbine observations in terrain	x	x	x	x	x	x	x	x	x

Table 4-5. Models addressed by validation study

4.2. TIMELINE AND NEEDS FOR VALIDATION STUDIES

The timeline for validation will consist of two major branches: one that deals primarily with validation of blade-resolved simulations that will borrow significantly from validation data sets outside of wind energy applications, and one that will validate the larger scales that may not require full blade resolution. According to past research, the division between these two physical scales is the rotor radius length scale. Research at larger scales will focus on the physics important for wind plant interactions and the greater atmosphere. The larger-scale validation exercises may have significant overlap with existing atmospheric validation exercises.

Each year during the project, we envision a series of validation studies. Validation data set requirements will be matched with summaries of existing data sets being developed under the adjacent experimental campaigns task. Any data gaps in the timeline below will be identified as needed observations for future work. The following is a known list of current studies on the horizon with a basic description of each validation study.

4.2.1. Timeline of Validation Studies

This section provides detail on each proposed validation study. The studies are organized in phases meant to gradually fill in the validation hierarchy through combinations that would nominally each take 1-2 years. The studies in each phase are also designed to complement each other with a balance of unique and overlapping physics. This balance allows for covering a range of the validation hierarchy while also allowing for comparisons between different experiments to capture environmental or scale effects.

- Phase 1
    - ABL simulation, flat terrain, varying stability
        - Data set: 200 meter meteorological (met) tower data from Texas Tech University and data from the Sandia Scaled Wind Farm Technology (SWiFT) facility [8, 12]
        - Data type: Meteorological data from met towers, remote sensing of ABL height
        - Simulation: Mesoscale-microscale-coupled ABL with diurnal cycle
        - Models validated: Mesoscale-microscale coupling, surface heat flux, surface roughness, capping inversion, geostrophic wind, LES subgrid
    - Offshore full-scale wind plant power and loads validation
        - Data set: OWEZ (Windpark Egmond aan Zee) [2]

    * Data type: Turbine supervisory control and data acquisition (SCADA), meteorological data from met tower, turbine blade loads on two turbines
    * Simulation: Actuator line turbines coupled to FAST with microscale ABL
    * Models validated: LES subgrid, surface heat flux, surface roughness, capping inversion, geostrophic wind, turbine parameterization
  - Wake strength and mean deflection under a range of ABL conditions, single turbine
    * Data set: National Renewable Energy Laboratory (NREL)-GE1.5 and SWiFT lidar measurements [5]
    * Data type: Single-turbine SCADA, blade and tower loads, meteorological data from met tower, wake scans from lidar
    * Simulation: Actuator line turbines coupled to FAST with microscale ABL
    * Models validated: LES subgrid, surface heat flux, surface roughness, capping inversion, geostrophic wind, turbine parameterization
  - Wake strength, deflection, and shape under a range of ABL conditions, two turbine
    * Data set: SWiFT measurement campaign - two turbine
    * Data type: Two-turbine SCADA, blade and tower loads, meteorological data from met tower, wake scans from lidars
    * Simulation: Actuator line turbines coupled to FAST with microscale ABL
    * Models validated: LES subgrid, surface heat flux, surface roughness, capping inversion, geostrophic wind, turbine parameterization
  - Wake scaling effect
    * Data set: NREL-GE1.5 and SWiFT lidar measurements
    * Data type: Single-turbine SCADA, blade and tower loads, meteorological data from met tower, wake scans from lidar
    * Simulation: Actuator line turbines coupled to FAST with microscale ABL
    * Models validated: LES subgrid, surface heat flux, surface roughness, capping inversion, geostrophic wind, turbine parameterization.
- Phase 2
  - Nonrotating blade, tip vortex
    * Data set: McAlister and Takahashi, wing pressure and trailing vortex measurements [10]

    * Data type: Surface mean pressure profiles and tip vortex mean velocity profiles
    * Simulation: Actuator line
    * Models validated: LES/RANS subgrid, grid refinement and structure, advanced actuator line
- Nonrotating blade-geometry-resolved tip vortex
    * Data set: McAlister and Takahashi, wing pressure and trailing vortex measurements [10]
    * Data type: Surface mean pressure profiles and tip vortex mean velocity profiles
    * Simulation: Blade-resolved parked blade
    * Models validated: LES/RANS subgrid, transition, grid refinement and structure
- Wake strength, deflection, and shape under unsteady ABL conditions, two turbine
    * Data set: SWiFT measurement campaign - two turbine
    * Data type: Two-turbine SCADA, blade and tower loads, meteorological data from met tower, wake scans from lidars
    * Simulation: Actuator line turbines coupled to FAST with microscale ABL
    * Models validated: LES subgrid, surface heat flux, surface roughness, capping inversion, geostrophic wind, turbine parameterization
- Full wind farm with wake detail
    * Data set: Rødsand II
    * Data type: Turbine SCADA, meteorological tower, forward- and rearward-looking lidar on two turbines
    * Simulation: Actuator line turbines coupled to FAST with microscale ABL
    * Models validated: LES subgrid, surface heat flux, surface roughness, capping inversion, geostrophic wind, turbine parameterization
- ABL in complex terrain
    * Data sets: WFIP 2, Bolund Hill, Perdigao
    * Data type: Meterological towers, vertical profiling sodars, profiling radars, vertical profiling and scanning lidars, flux stations, turbine SCADA
    * Simulation: Mesoscale-microscale-coupled ABL with complex terrain boundary conditions

        * Models validated: Mesoscale-microscale coupling, surface heat flux, surface roughness, capping inversion, geostrophic wind, LES subgrid, terrain boundary conditions.

- Phase 3
    - Rotating tip vortex
        * Data set: Model Experiment in Controlled Conditions (MEXICO) [13] and New MEXICO experiments
        * Data type: Surface mean pressure profiles and tip vortex PIV planes
        * Simulation: Actuator line
        * Models validated: LES/RANS subgrid, grid refinement and structure, advanced actuator line
    - Rotating single-turbine wake with resolved blade geometry
        * Data set: Polytechnic University of Milan [1] or Norwegian University of Science and Technology (NTNU) [3] wind tunnel experiments of scaled wind turbine rotors with wake measurements
        * Data type: Wake measurements in a controlled environment; hot film, hot wire, and/or laser Doppler velocimetry (LDV) velocity profiles
        * Simulation: Blade-resolved spinning rotors in wind tunnel, advanced actuator line
        * Models validated: LES/RANS subgrid, transition, grid refinement and structure
    - Combined ABL with wind farm power observations
        * Data set: Commercial wind farm experiment
        * Data type: Full mesoscale observations, with detailed microscale including wind turbine power and terra incognita
        * Simulation: Mesoscale-microscale-coupled ABL with diurnal cycle and turbine actuator lines
        * Models validated: Mesoscale-microscale coupling, surface heat flux, surface roughness, capping inversion, geostrophic wind, LES subgrid, turbine parameterization
    - Pitching airfoil wind tunnel case
        * Data set: Ames Research Center data (oscillating airfoil experiments by McAlister, McCrosky, and Carr [11]) and/or university data set with PIV (e.g. Naughton)
        * Data type: Unsteady airfoil force, boundary layer, and wake measurements

        * Simulation: Pitching airfoil in wind tunnel
        * Models validated: LES/RANS subgrid, unsteady transition, grid refinement and structure
    - Blade-geometry-resolved parked rotor
        * Data set: NREL Phase VI wind tunnel experiment [4] and a precursor airfoil polar with boundary layer transition data
        * Data type: Unsteady surface pressures, limited single point wake measurements
        * Simulation: Blade-resolved parked rotor
        * Models validated: LES/RANS subgrid, transition, grid refinement and structure
    - Rotating single turbine blade resolved under yawed conditions
        * Data set: NREL Phase VI and/or MEXICO wind tunnel experiments, DANAERO MW field experiment [14]
        * Data type: Blade unsteady pressure measurements and wake velocity field (MEXICO experiment)
        * Simulation: Blade resolved spinning rotor in wind tunnel
        * Models validated: LES/RANS subgrid, transition, grid refinement and structure
    - Rotating single-turbine wake detail with resolved blade geometry
        * Data set: TBD
        * Data type: Wake measurements in a controlled environment under a range of inflow conditions; PIV or Doppler Global Velocimetry (DGV) [6] of complete wake
        * Simulation: Blade-resolved spinning rotors in wind tunnel, actuator line
        * Models validated: LES/RANS subgrid, transition, grid refinement and structure.
- Phase 4
    - Combined ABL and wind farm wake observations
        * Data set: Commercial wind farm wake experiment
        * Data type: Full mesoscale observations, with detailed microscale including high-fidelity wakes and terra incognita
        * Simulation: Mesoscale-microscale-coupled ABL with diurnal cycle and turbine actuator lines

    * Models validated: Mesoscale-microscale coupling, surface heat flux, surface roughness, capping inversion, geostrophic wind, LES subgrid, turbine parameterization

  - Single geometry-resolved turbine in the field with detailed wake measurements

    * Data sets: SWiFT and/or NREL-GE1.5 with high-resolution wake measurement system

    * Data type: Detailed microscale including high-fidelity turbine blade and wakes

    * Simulation: ABL with blade-resolved turbine

    * Models validated: LES subgrid, surface heat flux, surface roughness, capping inversion, geostrophic wind, LES subgrid, LES/RANS subgrid, transition, grid refinement and structure.

- Phase 5

  - Combined ABL, wind farm, and wind turbine observations

    * Data set: Commercial wind farm wake experiment

    * Data type: Full mesoscale observations, with detailed microscale, terra incognita, high-fidelity wakes, and turbine loads

    * Simulation: Mesoscale-microscale-coupled ABL with diurnal cycle and multiple resolved turbines

    * Models validated: Mesoscale-microscale coupling, surface heat flux, surface roughness, capping inversion, geostrophic wind, LES subgrid, LES/RANS subgrid, transition, grid refinement and structure

  - Multiple subscale geometry-resolved turbines in the field with detailed wake measurements

    * Data set: SWiFT with a high-resolution wake measurement system

    * Data type: wake strength, location, and dynamics; blade deflection, twist, acceleration, and load distribution; horizontal and vertical inflow velocity transects

    * Simulation: Microscale ABL and multiple resolved turbines

    * Models validated: Surface heat flux, surface roughness, capping inversion, geostrophic wind, LES subgrid, LES/RANS subgrid, transition, grid refinement and structure.

- Phase 6

  - Combined ABL, wind farm observations, and wind turbine observations in complex terrain

* Data set: TBD
* Data type: Full mesoscale observations, with detailed microscale including high-fidelity wakes and terra incognita in complex terrain
* Simulation: Mesoscale-microscale-coupled ABL with diurnal cycle and multiple resolved turbines in complex terrain
* Models validated: Mesoscale-microscale coupling, surface heat flux, surface roughness, capping inversion, geostrophic wind, LES subgrid, terrain boundary conditions, LES/RANS subgrid, transition, grid refinement and structure.

Note that plans for validation studies will continue to morph as the studies are executed, new physics are prioritized or discovered, new data sets become available, and models develop. The nominal validation campaigns outlined in this document will be laid out in more detail through future reports, addressing gaps in experimental data and instrumentation.

4.2.2. Known Experimental Needs

The schedule above describes validation studies based on the current understanding of data and validation studies that exist or are currently planned. At this time, there are also known gaps in validation data that are highlighted below.

- Wind Plant and Mesoscale
  - Terra Incognita — or Latin for unknown land — is the area of little study lying between the traditional scales of engineering and atmospheric interest. Boundary-layer parameterizations used in the current generation of mesoscale models utilize the assumption that no turbulent eddies are explicitly resolved. This assumption can be violated when the horizontal resolution of the mesoscale model is shrunk past some critical value, the so-called "terra incognita" [16]. At this point some, but not all, aspects of the eddies are explicitly resolved by the mesoscale model in a way that is independent of the turbulence parameterization, leading to erroneous results. Terra incognita issues arise at horizontal grid spacings between 100 m and 1 km.
  - Surface Moisture - Very little is known about the impact of surface moisture flux and sensitivity studies should be performed via simulations to determine importance.
  - Surface Roughness - Current state of the art for surface roughness models of ABLs is based on a log-scale constant that is often tuned to local observations. Higher-fidelity validation data may be needed to perform many of the validation studies above.
  - High-Fidelity Wakes - Current observations in the field are coarse due to fidelity of existing instrumentation, even at the SWiFT facility scale. New instrumentation may be needed.
- Wake Scale
  - Wake measurements in a controlled environment under a range of inflow conditions. PIV, DGV, or other remote sensing techniques inside of controlled environment wind tunnels may be required.
  - Development of the wake for a rotor in dynamic stall with detailed flow measurements in the near wake, using hot wire probes, LDV, or PIV. The importance of the unsteady flow structures released from the trailing edge during dynamic stall is uncertain; therefore, this is not a priority. Numerical studies could be performed to predict the importance of dynamic stall to wake development after unit- and subsystem-level validation studies have been performed for dynamic stall and wake development.

- Turbine Blade Scale
  - Blade surface roughness - In the field blade, surface roughness can degrade turbine performance by 10% or more over time. New models and validation data are required to predict this impact. Wind tunnel tests of airfoils with a range of roughness are available, and many wind turbine airfoils have been tested with transition tape or standard roughness. It is desired to quantify the blade surface condition during any rotor field tests. For wind plants, measuring blade surface conditions is likely impractical, the lack of which will result in uncertainty of the transition location along the blade, which propagates as uncertainty in the loads and power.
  - Cross-flow transition - Data are available for airfoil laminar to turbulent transition model validation; however, transition can be affected by cross-flow instabilities and pressure gradients along a blade. This effect is dominant near the blade tip and root.

5. CONCLUSION

This document summarizes the initial planning of validation experiment campaigns to establish the predictive capability of the high fidelity models in Nalu-Wind for wind plant applications. The development of this next-generation, high-fidelity, highly scalable modeling code for wind plant applications is one of the central focus areas of the U.S. Department of Energy (DOE) Atmosphere to Electrons program.

The proposed Nalu-Wind validation program follows a formal verification and validation (V&V) framework. The V&V team comprises model developers, analysts, experimentalists, and validation specialists. The V&V framework utilizes a hierarchical approach to validation, building from unit test cases to complete system tests.

Potential users for Nalu-Wind were identified as the DOE Wind Energy Technologies Office and the DOE Office of Science, as well as wind industry manufacturers, developers, and owners. The V&V team identified the most important model use cases, which are the prediction of wind plant power performance and loads, the discovery of dominant phenomena governing wake evolution, and the exploration of next-generation innovations to improve wind plant and turbine performance. These use cases were mapped to items in the Phenomena Identification and Ranking Tables (PIRTs) for wind turbine and wind plant physics.

Model validation needs were derived directly from the prioritized phenomena identified in the PIRT. These validation needs correspond to needed validation studies, which hierarchically aligned in a multiyear timeline of proposed or ongoing experimental campaigns. These campaigns represent the best estimate of what will be required to validate Nalu-Wind for all of the anticipated use cases, although prioritization can change as new knowledge is gained during the validation exercises. Current known experimental needs were described at the end of the document, which will feed into the planning of new experiments.

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APPENDIX A. PHENOMENA IDENTIFICATION AND RANKING TABLES

Tables A-1, A-2, and A-3 show the Phenomena Identification and Ranking Tables (PIRTs) for the different scales created during the Atmosphere to Electrons (A2e) strategic planning process [15]. An explanation of the general PIRT process can be found in [7], and the categories in the wind plant and wind turbine PIRTs are more thoroughly explained in [9]. The mesoscale physics are not the primary focus of the models in this document, hence the mesoscale PIRT included here is less comprehensive than what would be developed for validating models mainly focused on predicting mesoscale phenomena. More detailed mesoscale and microscale modeling PIRTs are being developed as part of the A2e program's mesoscale-microscale coupling (MMC) project.

A2e PIRT

Wind Turbine Scale

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 and 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	Affects 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 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	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 horizontal deflection	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
Other Effects							
Tower/rotor/nacelle wake interactions	H	M	L	L	Primarily included for noise generation, 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

Table A-1. A2e PIRT wind turbine scale.

A2e PIRT

Wind Plant Scale

Phenomenon	Importance at Application Level	Model Adequacy: Physics	Model Adequacy: Code	Model Adequacy: Val	Issue/Comments	Response Including Scale	Interface
Inflow Turbulence/Wake Interaction							
Wind direction (shear/veer/asymmetry)	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
Multiturbine Wake Effects							
Wake interaction, merging, meander	H	L	L	L	Physics behind unsteady wake behavior	Wind tunnel and field tests	Wake/ABL
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/ABL
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/ABL
Wake dissipation	H	L	L	L	Evolution toward a neglibly small wake	Wind tunnel and field test	Wake/ABL
Wake impingement (full, half, etc.)	H	L	L	L	Effect of upstream wake position on downstream turbine	Wind tunnel and field test	Wake
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	Wake/ABL
Other Effects							
Wind plant blockage effects and plant wake	H	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 propagation through a wind plant	Full-scale and subscale field sites	Turbine

Table A-2. A2e PIRT wind plant scale.

A2e PIRT

Mesoscale

Phenomenon	Importance at Application Level	Model Adequacy: Physics	Model Adequacy: Code	Model Adequacy: Val	Issue/Comments	Response Including Scale	Interface
Mesoscale phenomena							
Representation of winds and turbulence through the atmos. boundary layer and/or top of rotor	H	L	M	L		WFIP II	Meso
Wind plant repesentation (i.e., drag effect of turbines)	M	L	na	L			Plant-Meso
Cross-scale effects							
Mesoscale turbine scale icing	M	M	M	H			Meso-Turb.
Low-level jets and atmos. waves	H	M	L	L			Meso
Ramp events (fronts, thunderstorms, sea breeze, stability changes)	M	H	M	L			Meso
Extreme wind events	H	U	L	L			Meso
Mesoscale/plant scale							
Wake interaction, ABL turbulence-(Stability)	H	L	M	L			Wake-ABL
Wake interaction, low-level jet	H	L	M	L			Wake-ABL
Mesoscale turb. to LES turb. models	H	L	L	L			Meso-Turb.
Mesoscale to plant inflow	H	M	L	L			Meso-Plant
Plant wake to mesoscale	M	L	L	L			Plant-Meso
Terrain effects	H	L	L	L			ABL-Meso
Surface conditions (including waves)	H	L	L	L			Surface
Full plant-scale vertical energy transfer (plant/atmos.)	H	L	L	L			Plant-Meso

Table A-3. A2e PIRT mesoscale.

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