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Wind Energy Instrumentation Development Roadmap

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ABSTRACT

The current instrumentation for observing the complex flow fields in and around wind plants struggles to match the fidelity of existing simulation tools. As a result, these measurement limitations create a hurdle for validating and assessing the quality of the wind plant numerical models. This roadmap for instrumentation development recommendations was created to offer guidance on narrowing the gap between measurement and simulation fidelity. A process was established to identify where gaps in instrumentation exist for wind energy test campaigns by analyzing the capabilities of instrumentation for capturing the various important phenomena at the necessary resolution for both the science goal and validation objectives. To this end, a multi-disciplinary team of experts on instrumentation, wind energy, and atmospheric science was assembled to identify these significant instrumentation needs. A recommendation for instrumentation to be developed is provided, and the framework developed through this process is expected to be useful to the design of future test campaigns. The mapping tools developed for this process will be distributed as part of a future International Energy Agency Wind Technology Collaboration Program task on instrumentation development.

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EXECUTIVE SUMMARY

Current state-of-the-art instrumentation for observing the complex flow fields in and around wind plants is challenged to provide the necessary measurements and quantities of interest to validate high-fidelity models. These instruments generally lack the required temporal and spatial resolution for detailed model validation. Validation is the process of determining the level to which a model implementation, or code, accurately represents the real-world physics necessary for the intended use of the model. Validation is important to ensure the implementation of a model can be trusted for the conditions they have been validated for to perform design, to perform virtual experiments, and research new technologies. The validation process inherently requires comparison between model simulation data and experimental data, both of which have limitations in relation to real work physics. These measurement limitations create a hurdle for assessing the quality of wind plant numerical model predictions relative to the physics in realistic environments. The primary goal of this Instrumentation Development Roadmap (IDR), developed in this report, is to clarify the measurement needs and gaps and provide recommendations that will narrow the gap between validation needs and instrumentation capabilities. Once developed, the new instrumentation capabilities will adequately measure the necessary quantities of interest with reduced uncertainty to improve the confidence in wind plant validation exercises. The IDR identifies the measurements and instruments that are required for future test campaigns to meet both the science goals and validation plans of the wind energy community. Much like developing and maintaining computational models, obtaining key instruments and developing the expertise to use them for a series of experimental campaigns will increase overall efficiency and testing capabilities.

The IDR establishes a framework for assessing measurement needs, instrumentation gaps, and the feasibility of instrumentation technology for future field tests. A process was created for determining which instruments could capture important phenomena at the resolution necessary for both the science goals and validation needs. This process included many scales of phenomena important for wind energy, ranging from the wind turbine blade boundary layer through the wind plant to mesoscale forcing. The developed tools provide a general mapping from the measurement categories to these phenomena, independent of experiment goals. A multi-disciplinary team of instrumentation, wind energy, and atmospheric science experts was necessary to create the mapping and ranking between important phenomena. This general mapping then can be used by future experiment planning efforts once a ranking or mapping of the important phenomena to the experiment goals is determined. Combined, these two steps provide a prioritization of measurements requirements to meet the experimental goals. The mapping tools will be distributed as part of a future International Energy Agency (IEA) Wind Technology Collaboration Program (TCP) task on instrumentation development. The tools exist as spreadsheets for others to use this process in experimental planning and instrumentation identification.

The roadmap development started by identifying instrumentation that would benefit for the American WAKE experimeNt (AWAKEN) campaign by applying this mapping process to the AWAKEN science goals (Moriarty et al., 2024; Moriarty, 2020). The process evolved into a roadmap for instrumentation development that builds upon the Atmosphere to Electrons (A2e) Validation and Verification (V&V) coordination effort (Maniaci et al., 2024; Maniaci & Naughton, 2019); Rotor Aerodynamics, Aeroelastics, and Wake (RAAW) experiment validation objectives (Brown et al., 2024; Doubrawa et al., 2024; Herges et al., 2024); and near-term high-fidelity model (HFM) validation requirements (Maniaci et al., 2020) relevant to current and future campaigns. These activities are part of a larger effort to improve the ability to capture the many quantities of interest related to phenomena important for wind energy. Including these quantities of interest in the IDR

mapping process ensures a more complete guide for instrumentation development recommendations.

To transition from measurement categories to specific instrumentation recommendations, a feasibility score was defined for each instrument to help categorize them into stages of development and how well they meet the measurement needs. The feasibility score indicates the suitability of an instrument to capture the measurement needs, its development cost and time, development uncertainty, and logistics for deployment. The usefulness of an instrument for a particular study is affected by its ability to be developed to a mature state in time for that study. Additionally, instruments with the ability to measure important phenomena but requiring significant development efforts are identified. All instruments discussed in this work are relevant to wind energy experiment campaigns to various degrees, and applying the mapping and feasibility framework to a given application separates critically important instruments from those that may provide extra value but are not strictly required to achieve a science goal.

Following this method, development of instruments can be prioritized from the ranking results of instruments that can provide measurements of critical phenomena but are not yet fully deployable. Some of the highest priority instruments can be ready in 1 – 3 years and possibly deployed in near-term field tests, whereas others will take 4 – 10 years to develop and will need investment now to be ready for future measurement campaigns.

- The highest priority instruments for development in the short term (1 – 3 years) are
    1. blade distributed strain/photogrammetry instrumentation,
    2. unsteady blade pressure instruments,
    3. tethered balloon systems with a distributed temperature system (DTS) and sonic anemometers capable of capturing turbulence as a met tower would,
    4. next generation profiling lidars capable of turbulence characterization and
    5. lidar upgrades such as synchronized Doppler lidar and motion stabilized lidar.
- The instruments most important for development in the long term consist primarily of instruments capable of capturing high spatial resolution velocity measurements such as
    1. ground-based, large-scale particle image velocimetry,
    2. acoustic tomography, and
    3. long-range continuous wave lidar.

The instrumentation ranking order is only a relative ranking, and all the identified instruments are considered important to future wind energy field tests. Evaluating measurement needs, pertinent wind plant phenomena to the goals of an experiment, and near-term HFM validation requirements is a multifaceted problem. The results of applying these tools are expected to evolve over time as additional information is gained on the physics and phenomena being observed, the priority of the phenomena change, and as new experiments are designed to observe targeted phenomena in different environments. The results reveal the importance of considering both the instrumentation limits as well as scale, environment, and turbine system knowledge limits determining the research objectives of the experiment.

The process and tools developed here should be updated regularly as new phenomena are identified or prioritized for emerging applications. The scoring and weighting used in this effort may not be universal to all projects. However, the framework developed here should be useful for many future experiments by providing guidance in the selection of instrumentation, much like what has been realized in this document for AWAKEN, RAAW, and the HFM validation roadmap.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
A2e	Atmosphere to Electrons
ABL	atmospheric boundary layer
AERI	Atmospheric Emitted Radiance Interferometer
ARM	Atmospheric Radiation Measurement
ASSIST	Atmospheric Sounder Spectrometer for Infrared Spectral Technology
AWAKEN	American WAKE experimeNt
C	Cost
DIAL	Differential Absorption Lidar
DIC	digital image correlation
DOE	U.S. Department of Energy
DTS	distributed temperature system
DTU	Technical University of Denmark
DU	Development Uncertainty
FSI	fluid structure interaction
HFM	high-fidelity modeling
IDR	Instrumentation Development Roadmap
L	Logistics
LES	large eddy simulation
MMC	mesoscale microscale coupling
MWR	Microwave radiometer
PIV	particle image velocimetry
RAAVEN	Robust Autonomous Airborne Vehicle – Endurant and Nimble
RAAW	Rotor Aerodynamics, Aeroelastics, and Wake
RANS	Reynolds-Averaged Navier Stokes
S	Suitability
SAR	synthetic aperture radar
SCADA	Supervisory Control and Data Acquisition
T	Timeline
TKE	turbulent kinetic energy
TRL	technology readiness level
UAS	unmanned aerial system
V&V	verification and validation
VC	Validation Campaign
W	Weighting

Abbreviation	Definition
WFIP	Wind Forecasting Improvement Project

1. INTRODUCTION

The Instrumentation Development Roadmap identifies those measurements and instruments that are required for future test campaigns to meet both the science goals and validation plans of the wind energy community. The roadmap ensures the measurements are of sufficient accuracy and resolution to meet these goals and needs. The roadmap process includes both instruments that need to be developed and existing instruments that are essential to the test campaigns. The instrumentation development roadmap builds upon the Atmospheric to Electrons validation efforts, science objectives of the American WAKE experimeNt, Rotor Aerodynamics, Aeroelastics, and Wake experiment validation objectives, and near-term high-fidelity models validation requirements. A process was developed for mapping between the (1) instrument measurement categories, (2) physical phenomena important to wind turbines, wind plants, and mesoscale phenomena, (3) wind energy research science objectives, and (4) near-term validation requirements for HFM.

The developed process provides a general mapping from the measurement categories to how well they capture the wind turbine, wind plant, and mesoscale phenomena, independent of experiment goals. A ranking of the phenomena to the test campaign goals then allows the mapping process to identify the measurement categories most important for the goals specific to that campaign. This process can be applied to both past and future test campaigns. Additionally, the measurement categories most important for model validation were identified by ranking the measurement categories relative to the HFM validation needs identified in (Maniaci et al., 2020). The HFM validation needs were included to provide the modeling community perspective in addition to the experimental perspective.

A feasibility score specific to each instrument was defined to convert the measurement category needs to specific instrument recommendations. The feasibility score indicates the suitability of an instrument to capture the measurement needs, its development cost and time, uncertainty in the estimated development and feasibility score, and logistics for deployment. Combining the measurement category with the instrument feasibility score provides a total score prioritizing instruments that are important for development. All instruments included in this process are important for wind energy test campaigns so the exact total score and ranking of a particular instrument are less important than whether it appears near the top or bottom of the ranking, since the rankings are highly dependent on qualitative user input. The results of applying these tools are expected to evolve over time as additional information is gained on the physics and phenomena being observed, the priority of the phenomena change, and as new experiments are designed to observe targeted phenomena in different environments.

The remainder of the document is organized as follows. First, the process used to prioritize instrumentation development is presented in Section 2. The use of this process to identify measurements needed for the AWAKEN and RAAW test campaigns as well as for addressing high fidelity modeling validation and verification needs is discussed in Sections 3–5. In addition to the need for an instrument, the feasibility of its development is important and is discussed in Section 6. Based on the material in Sections 2–6, a discussion of instrumentation development is provided in Section 7 with observations and recommendations provided in Section 8.

2. GENERAL MAPPING PROCESS

Several aspects required for planning and executing a wind energy test study were considered to create the instrumentation development roadmap process. Previous efforts from the AWAKEN planning process, HFM, and verification and validation projects (Maniaci et al., 2020; Maniaci & Naughton, 2019; Moriarty et al., 2024; Moriarty, 2020) were all leveraged for the mapping and ranking process. The mapping dimensions include: the science goals of AWAKEN; physical phenomena important for wind energy; HFM validation needs; and instrumentation or measurement categories, compiled from instrument developer feedback, and known instrument types. Figure 2-1 outlines the mapping process created to develop a prioritized set of observational technologies for development.

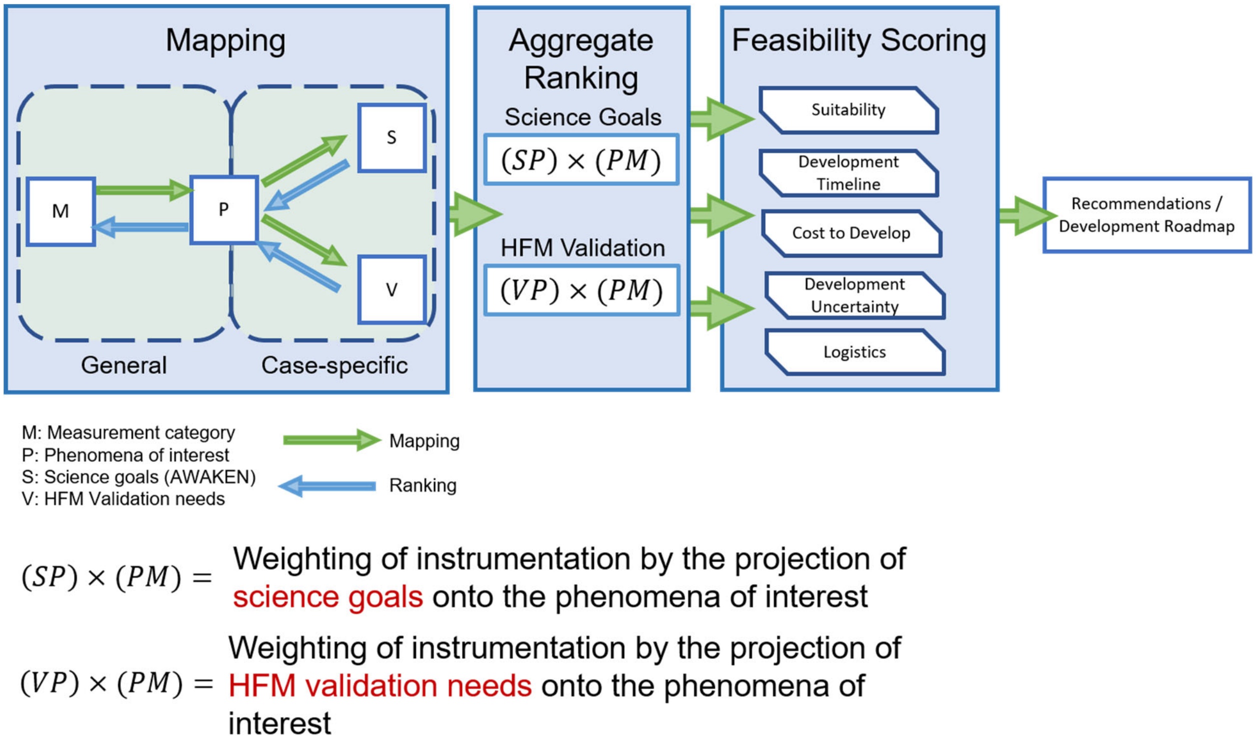


Figure 2-1. Mapping process between measurement needs, wind turbine and wind plant phenomena, AWAKEN science goals, and high-fidelity modeling validation needs.

In Figure 2-1, the "M" represents the measurement or measurement platform category. Appendix A describes the measurement categories and assumptions in greater detail. The measurement category includes the assumption of instruments that exist and that are under development without considering the development time. The "P" denotes the physical phenomena important to wind turbine, wind plant, and mesoscale physics. "S" is the symbol for the AWAKEN science goals, described in Appendix B, while the "V" represents the HFM validation needs, described in Appendix C. Starting from the left of the diagram, the first box describes the mapping process used to classify how well a measurement type or platform captures the known phenomena of interest. Section 3.1 describes this mapping process in greater detail. This step in the mapping process is general and concentrates only on the measurement categories and phenomena important to wind energy. The next step is specific to an experimental campaign's goals or validation requirements. The phenomena are mapped by how strongly they connect with the objectives of the experiment.

Section 3.2 describes this step for AWAKEN, while Sections 4 and 5 describe it for the RAAW experiment and HFM validation needs, respectively. This mapping process can easily be extended to future offshore campaigns once the science and validation goals are fully developed (Maniaci et al., 2024). This future exercise will provide the measurements most important for successful execution of the campaign.

The next step in Figure 2-1, shows an aggregation of the mapping scores by cross multiplying between the measurement to phenomena and the phenomena to experimental goal mappings, providing a single value that indicates the importance (the ranking) of the measurement category to achieving the goals of the campaign. All of the measurement categories are important for wind energy measurements, but this process helps identify the categories grouped near the top to achieve the test goals. This result is one of the primary outcomes of this work. Regardless of specific instrumentation, the measurement category ranking indicates the measurement areas that are most important and indicates if instrument development should be focused on instruments in those categories.

Finally, a rubric was created specific to instruments that exist or are under development to score how feasible the instrument is at capturing the measurements important to each measurement category (Section 6). The rubric includes five categories as shown in Figure 2-1, the suitability of the instrument for making the required observations, the development timeline, the development cost, the uncertainty in the development rubric evaluation, and the logistics of instrument deployment. The scoring rubric provides a score for ranking instruments based on the relative importance of their measurement category and development metrics. The instruments are then sorted by their timelines to better determine which can be developed in time for the planned experimental campaigns and which are generally important for future campaign needs, either validation or scientific, even though they may not be developed in time for planned test campaigns.

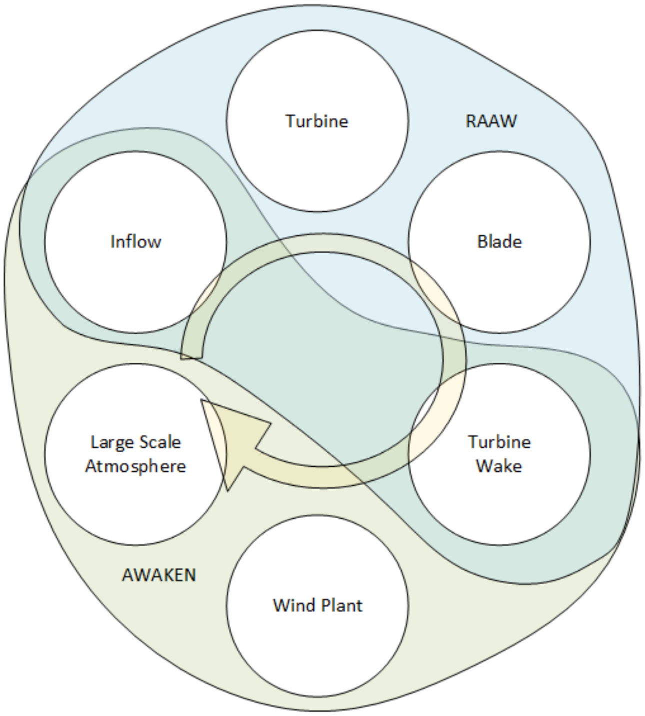


Figure 2-2. Diagram of phenomena, how they interact, and the focus areas of planned field tests.

The mapping process for the RAAW experiment was included as an additional example in Section 4. Figure 2-2 helps to show the connection in phenomena important to the scope of the AWAKEN and RAAW experiments. Inflow and wind turbine wakes are essential phenomena to both campaigns, while the RAAW experiment is focused on the physics of a single turbine with an emphasis on blade phenomena. The turbine wakes propagate through the wind plant flow, while the wind plant affects the large-scale atmospheric phenomena, which also feeds into the wind turbine inflow, completing the cycle of phenomena and the interconnection of the campaigns. Using the phenomenon and focus of both the AWAKEN and RAAW experiments will show the process for determining measurement categories and instrumentation that are important for the respective campaigns and how the recommendations vary based on the needs of the campaign.

3. MAPPING FROM MEASUREMENTS TO AWAKEN SCIENCE GOALS

3.1. Mapping from Measurements to Phenomena

This section describes a step-by-step process of obtaining the measurement needs for the different science goals of the AWAKEN campaign (Moriarty et al., 2024). Appendix A describes the measurement categories and assumptions in greater detail. The measurement categories include both quantities of interest as well as measurement platforms since both aspects of the measurement system can be developed independently. Measurement platforms carry, or support, instruments enabling new measurements. The AWAKEN science goals are described in detail in Appendix B. The first part of the process is a general mapping of the measurement systems to different phenomena. This mapping is independent of the goals of an experiment or campaign. The phenomena are divided into three different categories based on the scale of the problem: a) wind turbine phenomena, b) wind plant phenomena, and c) mesoscale phenomena.

The range of the score used to map different phenomena to a measurement system is between 0 and 2 with an increment of 0.5. The score 0 represents no connection and a score of 2 represents a direct connection (Table 3-1). For example, a score of 2 is provided when a direct connection can be made between the wind turbine phenomena and measurement systems (blade load distribution effects on the rotor and unsteady pressure measurement system in Figure 3-1). And a score of 0 is provided when no possible connection can be established (blade load distribution effects on the rotor and a coarse resolution velocity measurement system).

Table 3-1. Scoring system connecting measurement system to phenomena.

Score	Score Meaning
0	No ability to capture
0.5	Little ability to capture
1	Some ability to capture
1.5	Strong ability to capture
2	Fully able to capture

The mapping of the wind turbine phenomena to the different measurement systems are shown in Figure 3-1. The different measurement systems are presented in the first row of the spreadsheet.

Turbulence length scales in atmospheric flows can span from millimeters to kilometers, as a result the measurement systems or platforms used to capture relevant phenomena are many. Therefore, before moving to the actual mapping, it is important to explain the different categories used to group the wide range of measurement systems. The detailed descriptions of the measurement systems and the reasonings behind the mapping of measurement systems to different phenomena are provided in Appendix A. However, to continue the discussion, the measurement systems, their purposes and commonly considered instruments for the systems are summarized in Table 3-2. The mapping of the wind plant and mesoscale phenomena to the measurement systems are shown in Figures 3-2 and 3-3, respectively.

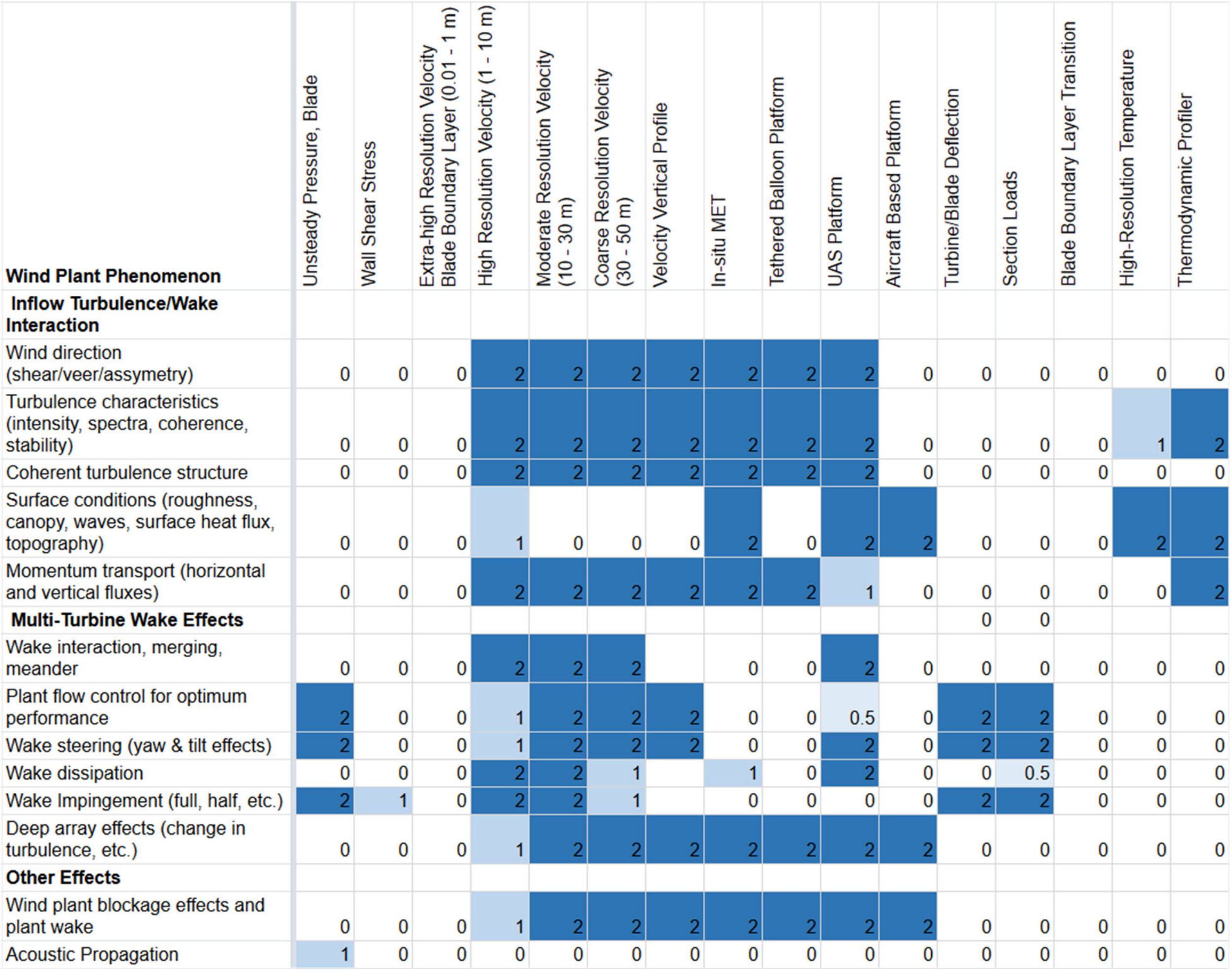
Wind Turbine Phenomenon	Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler
Blade Aero / Wake Generation																
Blade load distribution effects and rotor thrust	2	2	0	2	0	0	0	0	0	0	0	2	2	0	0	0
Tip and root vortex development, evolution and merging	2	1	0	2	0	0	0	0	0	1	0	0	0	0	0	0
Vortex sheet and rollup (in addition to tip/root vortex)	2	1	0	2	0	0	0	0	0	1	0	0	0	0	0	0
Blade generated turbulence characteristics (energetic scales at trailing edge)	2	1	0	2	0	0	0	0	0	1	0	0	0	1	0	0
Root flow acceleration effect ('hub jet')	2	0	0	2	1	0	0	0	0	1	0	0	0	0	0	0
Boundary layer development (transition, separation)	2	2	2	0	0	0	0	0	0	0	0	0	0	2	0	0
Surface roughness effects (roughness, soiling, bugs, erosion)	2	2	2	0	0	0	0	0	0	0	0	0	0	2	0	0
Boundary layer details near leading and trailing edge	2	2	2	0	0	0	0	0	0	0	0	0	0	2	0	0
Rotational augmentation	2	2	2	0	0	0	0	0	0	0	0	1	1	1	0	0
Dynamic stall	2	2	2	0	0	0	0	0	0	0	0	1	1	1	0	0
Unsteady inflow effect (veer, shear, yaw, gusts, atmospheric stability, turbulence intensity, spectra, coherence)	1	1	0	2	2	1	1	2	2	2	1	1	1	0	1	2
Blade flow control	2	2	1	1	0							2	2	2	0	0
Icing	1	1	1	1	0							2	2	0	0	0
Wake Development (growth/recovery)															0	
Skew and meander of aggregate wake	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0
Swirl instability	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0
Vortex merging	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Wake vorticity diffusion and dissipation	1	0	0	2	1	0	0	1	1	2	0	0	0	0	0	0
Asymmetry effects (ground plane, yaw, tilt, cone-angle)	0	0	0	2	2	0	0	1	1	2	0	0	0	0	0	0
Inflow effect (shear, veer, yaw, turb. intensity, turb. spectrum, coherence, gusts, atmos. stab.)	1	1	0	2	2	1	1	2	2	2	1	0	0	0	1	2
Other												0	0	0		
Tower/rotor/nacelle wake interactions	2	1		2	2	0	0	0	0	0	0	0	0	0	0	0
Aeroelasticity	2	1	1	1	0	0	0	0	0	0	0	2	2	0	0	0
Aeroacoustics	2	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0

Figure 3-1. Spreadsheet of different measurement systems and wind turbine phenomena and their mapping scores.

Table 3-2. The different categories of the measurement systems used in the mapping process.

Measurement System / Platform	Purpose and Description	Examples or Commonly Considered Instrument Systems
Unsteady pressure blade measurement system	Systems that measure the unsteady pressure at locations on the blade as well as local blade inflow angle using multi-hole probes	Flush-mounted pressure sensors, pressure tap/tubing/transducer systems, pressure sensitive paint
Shear stress blade measurement system	Measure wall shear stress at locations on the blade	Oil-film interferometry, flush-mounted shear stress sensors
Extra high-resolution blade boundary layer measurement system	Systems that can capture the boundary layer over wind turbine blade surfaces	Particle image velocimetry (PIV) with helium-filled soap bubbles
High resolution velocity measurement system	Measurement systems that capture wind speed with a resolution of around 1 m	These systems are custom built remote sensing instrument like SpinnerLidar or blade inflow measurements or particle image velocimetry
Moderate resolution velocity measurement system	Measurement systems that can cover wind measurements with sufficient resolution (10 m or more)	Commonly referred to as current commercial scanning lidars with wavelength of close to 1.5 µm
Coarse resolution velocity measurement system	Measurement systems that can cover large scale structure	Radar, Satellite Aperture Radar (SAR)
Velocity profile measurement system	Wind speed profiling systems that can measure wind speed at multiple heights covering the wind turbine rotor layer	Radar profiler, lidar, sodar
In-situ meteorological measurement system	Measurements of different atmospheric variables such as wind speed, temperature, humidity, pressure, aerosol concentration etc., at a specific location but at different heights. This system also includes flux measurements near the ground.	Meteorological towers
Tethered balloon platforms	Tethered systems that can capture high frequency data of different atmospheric variables at different heights of a target location	Tethered balloon system at Atmospheric Radiation Measurement (ARM) facilities, University of Colorado Tethered Balloon system, Army Research Laboratory Tethered Balloon system
Thermodynamic profiling system	Thermodynamic vertical profiles at moderate resolution	Atmospheric Emitted Radiance Interferometer (AERI), Atmospheric Sounder Spectrometer for Infrared Spectral Technology (ASSIST)

Measurement System / Platform	Purpose and Description	Examples or Commonly Considered Instrument Systems
Unmanned aerial platforms	The small system that can fly at low altitudes to measure different atmospheric variables such as wind speed, temperature, humidity, pressure, aerosol concentration, etc.	Robust Autonomous Airborne Vehicle – Endurant and Nimble (RAAVEN)
Aircraft-based measurements	Systems that can fly over the wind farms at high speed and can cover the large space, including upstream and downstream of wind farms, and flow phenomena within the wind farms	ArcticShark, Wyoming King Air, DOE ARM Bombardier Challenger 850
Turbine/blade deflection measurement system	Systems that can measure the deflection of the blade, nacelle, and tower; acceleration is also included here as a means for validating the structural model	Image correlation, photogrammetry approaches, integrated blade loads
Section load measurement system	Systems that can measure loads along the blade	Strain gauges, distributed strain fiber, accelerometers
Transition measurement system	Measurements of the transition from laminar to turbulent flow on the blade	IR cameras, tufts, oil flow, temperature sensitive paint, hot-film sensors
High-resolution temperature measurement system	Systems that can measure spatial variability of temperature with probe length less than 1 m	Acoustic tomography
Surface flux measurement system	Turbulent energy flux measured at or near the Earth’s surface	Surface met/surface flux/surface energy balance system, sonic anemometers, hot-wire anemometers, satellites
Terrain and surface roughness measurement systems	Terrain and ground surface roughness can be measured from unmanned aerial system (UAS), Aircraft, Satellites, or directly. Aircraft can uniquely measure roughness as it changes seasonally.	Sentinel-2 Satellite, terrestrial lidar, photogrammetry technology via UAS/aircraft
Supervisory Control and Data Acquisition (SCADA)/Turbine System Information	Turbine system measurements, such as power, rotation rate, control settings, etc. Can include add-on yaw or azimuth sensors that may not be in typical SCADA data. Includes turbine details like blade planform, controls, airfoils, etc.	Onboard sensing system

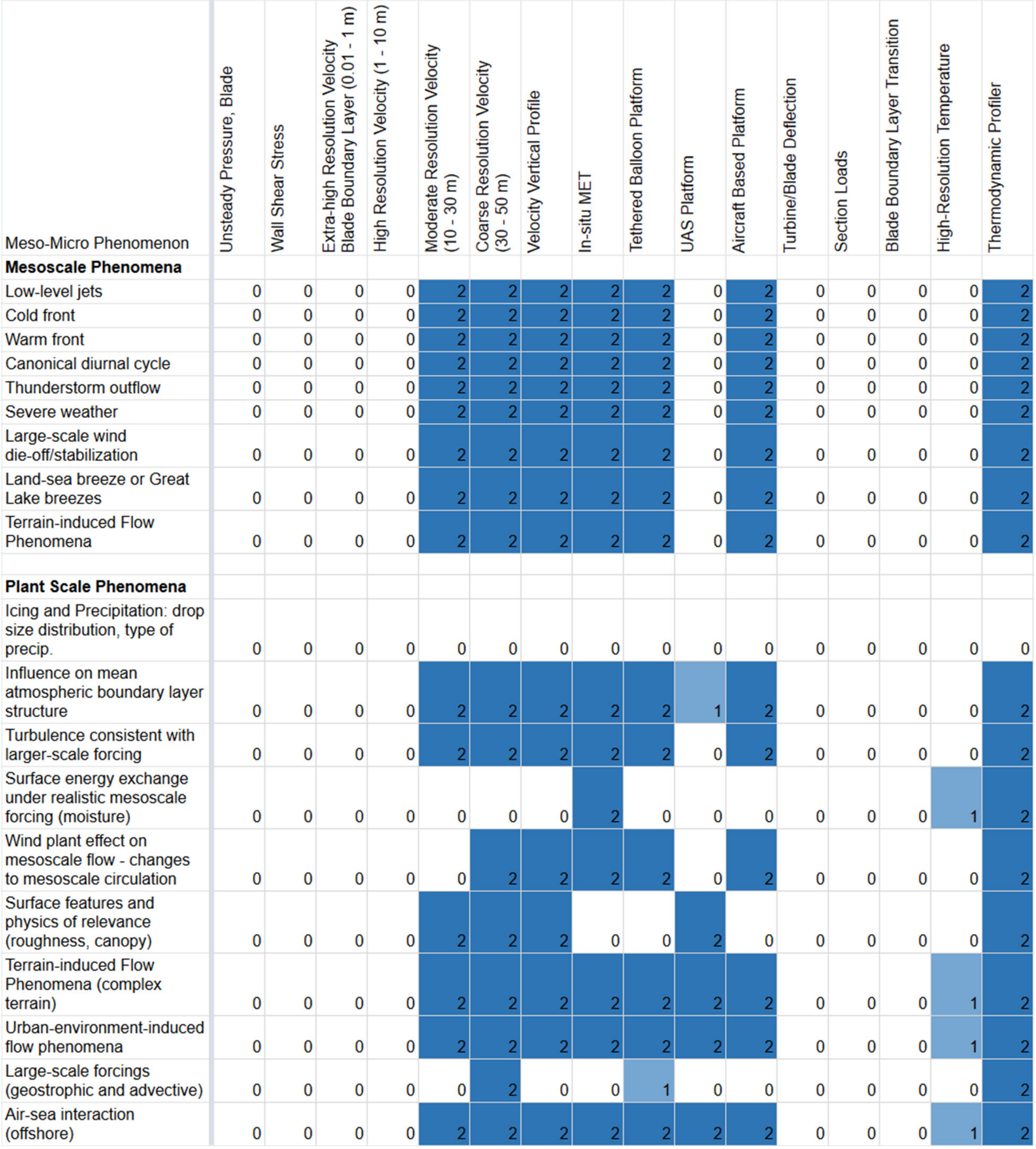


Wind Plant Phenomenon	Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler
Inflow Turbulence/Wake Interaction																
Wind direction (shear/veer/assymetry)	0	0	0	2	2	2	2	2	2	2	0	0	0	0	0	0
Turbulence characteristics (intensity, spectra, coherence, stability)	0	0	0	2	2	2	2	2	2	2	0	0	0	0	1	2
Coherent turbulence structure	0	0	0	2	2	2	2	2	2	2	0	0	0	0	0	0
Surface conditions (roughness, canopy, waves, surface heat flux, topography)	0	0	0	1	0	0	0	2	0	2	2	0	0	0	2	2
Momentum transport (horizontal and vertical fluxes)	0	0	0	2	2	2	2	2	2	1	0	0	0	0	0	2
Multi-Turbine Wake Effects												0	0			
Wake interaction, merging, meander	0	0	0	2	2	2		0	0	2	0	0	0	0	0	0
Plant flow control for optimum performance	2	0	0	1	2	2	2	0	0	0.5	0	2	2	0	0	0
Wake steering (yaw & tilt effects)	2	0	0	1	2	2	2	0	0	2	0	2	2	0	0	0
Wake dissipation	0	0	0	2	2	1		1	0	2	0	0	0.5	0	0	0
Wake Impingement (full, half, etc.)	2	1	0	2	2	1		0	0	0	0	2	2	0	0	0
Deep array effects (change in turbulence, etc.)	0	0	0	1	2	2	2	2	2	2	2	0	0	0	0	0
Other Effects																
Wind plant blockage effects and plant wake	0	0	0	1	2	2	2	2	2	2	2	0	0	0	0	0
Acoustic Propagation	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3-2. Spreadsheet of different wind plant phenomena and their obtained scores with a mapping to different measurement systems.

While the wind turbine phenomena only consider the phenomena relevant to a single turbine, wind plant phenomena consider physics relevant to multiple wind turbines. Wind plant phenomena include interaction of the atmospheric boundary layer with wind plants, wake interactions among multiple turbines, interactions between wind plants, and deep array effects. As the scale of the problem is large, measurement systems that can cover a large area with an acceptable probe volume (10 m or more) get a higher score for their ability to better capture the wind plant phenomena, as described in Table 3-1. Figure 3-2 shows that moderate or coarse resolution measurement systems received a score of 2 in most of the categories due to their capabilities to cover a larger area. For example, an unmanned aerial system can fly over an area quickly and can capture different physics needed to describe the wind plant wake or interactions of multiple turbines with atmospheric flows. On the other hand, measurement systems like shear stress do not get high scores due to their concentrations in smaller areas more relevant to blade physics.

The mesoscale phenomena and their mapping to different measurement systems are provided in Figure 3-3. In this section different mesoscale phenomena like cold front, mesoscale convective system, severe weather, and their impacts on the wind plant phenomena are considered. The aircraft system can capture these large-scale phenomena and their interactions with wind plants quite well, receiving a score of 2. Note that in-situ instruments (e.g., meteorological tower), tethered balloon systems, and velocity and thermodynamic profiling systems are important both for microscale and mesoscale phenomena, as they can capture the time evolution of vertical profiles of wind speed and different thermodynamic states of the atmospheric boundary layer.



Meso-Micro Phenomenon	Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler
Mesoscale Phenomena																
Low-level jets	0	0	0	0	2	2	2	2	2	0	2	0	0	0	0	2
Cold front	0	0	0	0	2	2	2	2	2	0	2	0	0	0	0	2
Warm front	0	0	0	0	2	2	2	2	2	0	2	0	0	0	0	2
Canonical diurnal cycle	0	0	0	0	2	2	2	2	2	0	2	0	0	0	0	2
Thunderstorm outflow	0	0	0	0	2	2	2	2	2	0	2	0	0	0	0	2
Severe weather	0	0	0	0	2	2	2	2	2	0	2	0	0	0	0	2
Large-scale wind die-off/stabilization	0	0	0	0	2	2	2	2	2	0	2	0	0	0	0	2
Land-sea breeze or Great Lake breezes	0	0	0	0	2	2	2	2	2	0	2	0	0	0	0	2
Terrain-induced Flow Phenomena	0	0	0	0	2	2	2	2	2	0	2	0	0	0	0	2
Plant Scale Phenomena																
Icing and Precipitation: drop size distribution, type of precip.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Influence on mean atmospheric boundary layer structure	0	0	0	0	2	2	2	2	2	1	2	0	0	0	0	2
Turbulence consistent with larger-scale forcing	0	0	0	0	2	2	2	2	2	0	2	0	0	0	0	2
Surface energy exchange under realistic mesoscale forcing (moisture)	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	2
Wind plant effect on mesoscale flow - changes to mesoscale circulation	0	0	0	0	0	2	2	2	2	0	2	0	0	0	0	2
Surface features and physics of relevance (roughness, canopy)	0	0	0	0	2	2	2	0	0	2	0	0	0	0	0	2
Terrain-induced Flow Phenomena (complex terrain)	0	0	0	0	2	2	2	2	2	2	2	0	0	0	1	2
Urban-environment-induced flow phenomena	0	0	0	0	2	2	2	2	2	2	2	0	0	0	1	2
Large-scale forcings (geostrophic and advective)	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	2
Air-sea interaction (offshore)	0	0	0	0	2	2	2	2	2	2	2	0	0	0	1	2

Figure 3-3. Spreadsheet of different mesoscale phenomena and their obtained scores with a mapping to different measurement systems.

3.2. Mapping from Phenomena to Science Goals

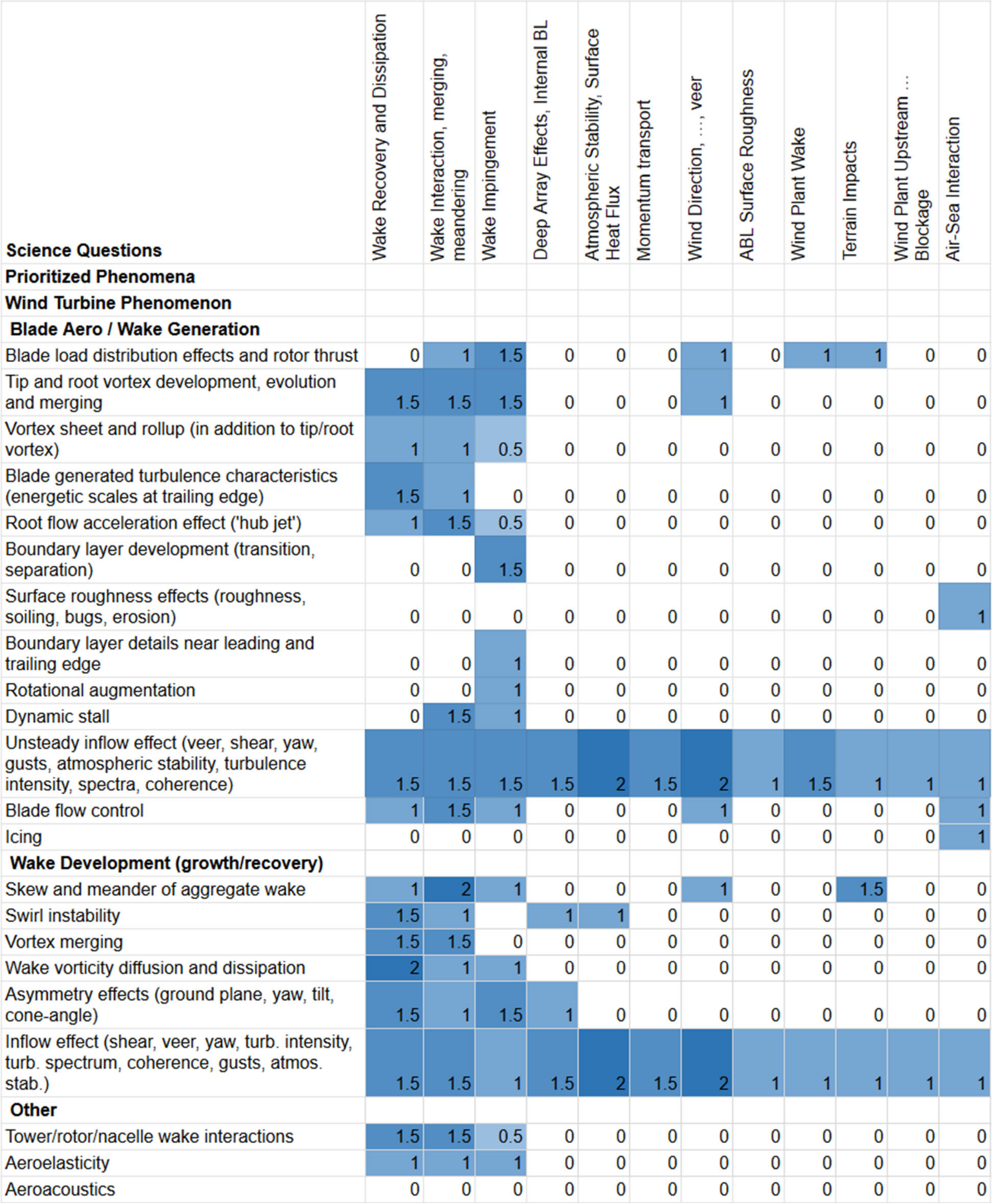
The purpose of the phenomena to science goal mapping is to bridge the gap between instrumentation that best measures a phenomenon and the science questions that are important to the wind energy community. This exercise is focused on the AWAKEN science goals (Moriarty et al., 2024; Moriarty, 2020). Since the completion of the phenomena to science goal mapping, the AWAKEN team has refined the science questions of interest into seven testable hypotheses. Appendix D links the new testable hypotheses to the original science goals and describes instrument groups best suited to address each hypothesis. Other science questions and validation needs beyond the scope of AWAKEN were considered in the measurement to validation campaign mapping (Section 5). Each AWAKEN science goal encompasses many science questions that require the observations of numerous atmospheric, wind plant, and wind turbine phenomena at various resolutions. This section will discuss the process that was taken to determine which phenomena need to be observed and characterized to meet each science goal.

The phenomena were broken down into three categories: wind turbine (Figure 3-4), wind plant (Figure 3-5), and mesoscale-microscale coupling (Figure 3-6) based on the scale and primary impact of the phenomena. As an example, this document will discuss the process of mapping for the wind plant phenomena, but similar processes and logic were applied to the other two mappings. Each phenomenon to science goal mapping was given a score between 0-2, indicating how important the phenomenon is to answer the science question. Table 3-3 describes the meaning of each score.

Table 3-3. Phenomena to science goal mapping scores.

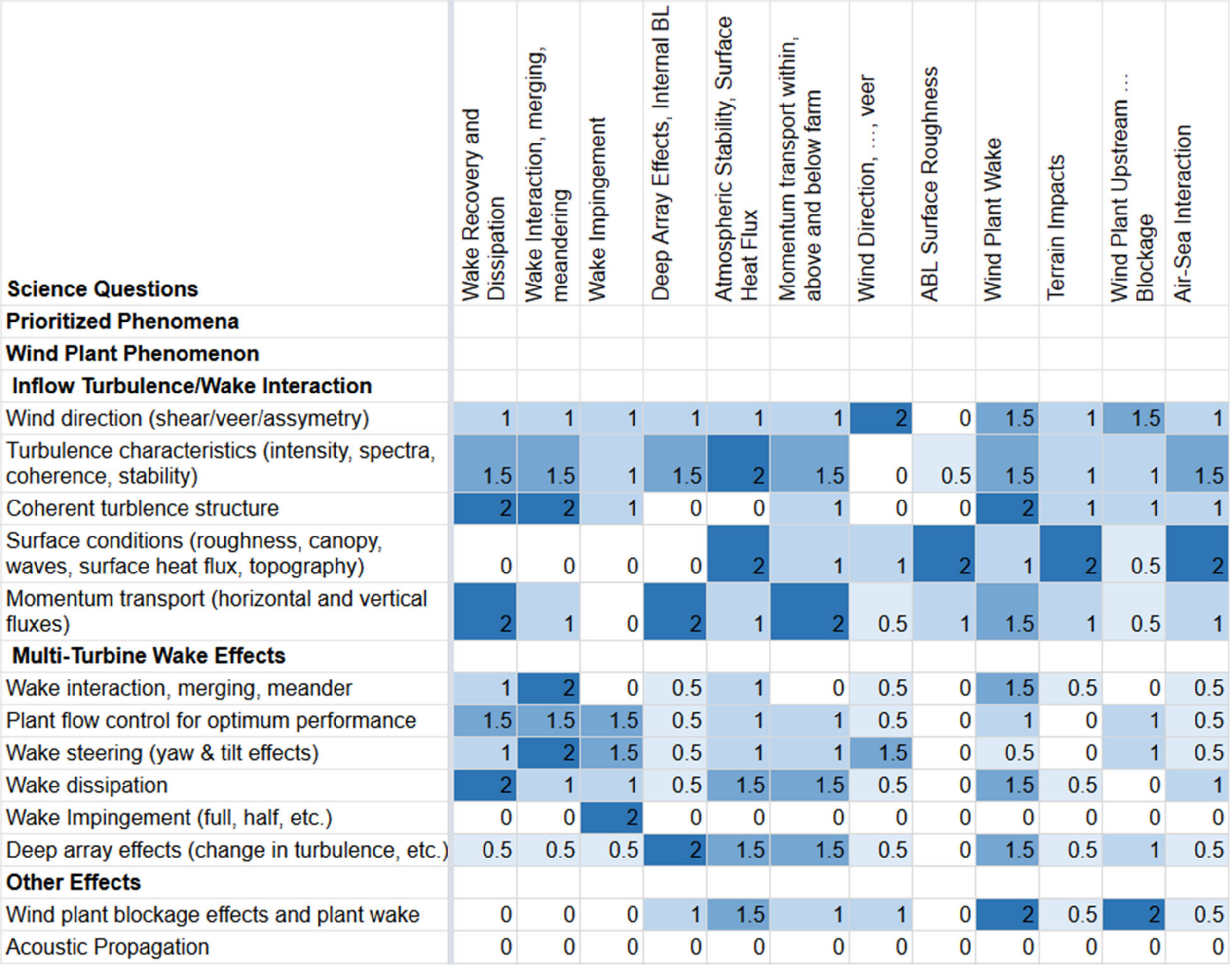
Score	Score Meaning
0	No connection
0.5	Little connection
1	Some connection
1.5	Strong connection
2	Direct connection

For example, a score of 2 indicates a direct mapping between the phenomena and the science goal. The phenomenon “momentum transport” was given a score of 2 for its mapping to the science goal “momentum transport within, above, and below farm” because characterizing the phenomenon of momentum transport is the key component of the science goal. To illustrate a score of 1.5, consider the phenomenon “wake dissipation,” which was given this score in its mapping to “atmospheric stability, surface heat flux” because one of the key questions in this science goal is to understand how atmospheric stability impacts the wind plant wake lifespan and dissipation, making the connection between the phenomena and science goal very strong.



Science Questions	Wake Recovery and Dissipation	Wake Interaction, merging, meandering	Wake Impingement	Deep Array Effects, Internal BL	Atmospheric Stability, Surface Heat Flux	Momentum transport	Wind Direction, …, veer	ABL Surface Roughness	Wind Plant Wake	Terrain Impacts	Wind Plant Upstream … Blockage	Air-Sea Interaction
Prioritized Phenomena												
Wind Turbine Phenomenon												
Blade Aero / Wake Generation												
Blade load distribution effects and rotor thrust	0	1	1.5	0	0	0	1	0	1	1	0	0
Tip and root vortex development, evolution and merging	1.5	1.5	1.5	0	0	0	1	0	0	0	0	0
Vortex sheet and rollup (in addition to tip/root vortex)	1	1	0.5	0	0	0	0	0	0	0	0	0
Blade generated turbulence characteristics (energetic scales at trailing edge)	1.5	1	0	0	0	0	0	0	0	0	0	0
Root flow acceleration effect ('hub jet')	1	1.5	0.5	0	0	0	0	0	0	0	0	0
Boundary layer development (transition, separation)	0	0	1.5	0	0	0	0	0	0	0	0	0
Surface roughness effects (roughness, soiling, bugs, erosion)	0	0	0	0	0	0	0	0	0	0	0	1
Boundary layer details near leading and trailing edge	0	0	1	0	0	0	0	0	0	0	0	0
Rotational augmentation	0	0	1	0	0	0	0	0	0	0	0	0
Dynamic stall	0	1.5	1	0	0	0	0	0	0	0	0	0
Unsteady inflow effect (veer, shear, yaw, gusts, atmospheric stability, turbulence intensity, spectra, coherence)	1.5	1.5	1.5	1.5	2	1.5	2	1	1.5	1	1	1
Blade flow control	1	1.5	1	0	0	0	1	0	0	0	0	1
Icing	0	0	0	0	0	0	0	0	0	0	0	1
Wake Development (growth/recovery)												
Skew and meander of aggregate wake	1	2	1	0	0	0	1	0	0	1.5	0	0
Swirl instability	1.5	1		1	1	0	0	0	0	0	0	0
Vortex merging	1.5	1.5	0	0	0	0	0	0	0	0	0	0
Wake vorticity diffusion and dissipation	2	1	1	0	0	0	0	0	0	0	0	0
Asymmetry effects (ground plane, yaw, tilt, cone-angle)	1.5	1	1.5	1	0	0	0	0	0	0	0	0
Inflow effect (shear, veer, yaw, turb. intensity, turb. spectrum, coherence, gusts, atmos. stab.)	1.5	1.5	1	1.5	2	1.5	2	1	1	1	1	1
Other												
Tower/rotor/nacelle wake interactions	1.5	1.5	0.5	0	0	0	0	0	0	0	0	0
Aeroelasticity	1	1	1	0	0	0	0	0	0	0	0	0
Aeroacoustics	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3-4. Spreadsheet showing the mapping between wind turbine phenomena and AWAKEN science goals.



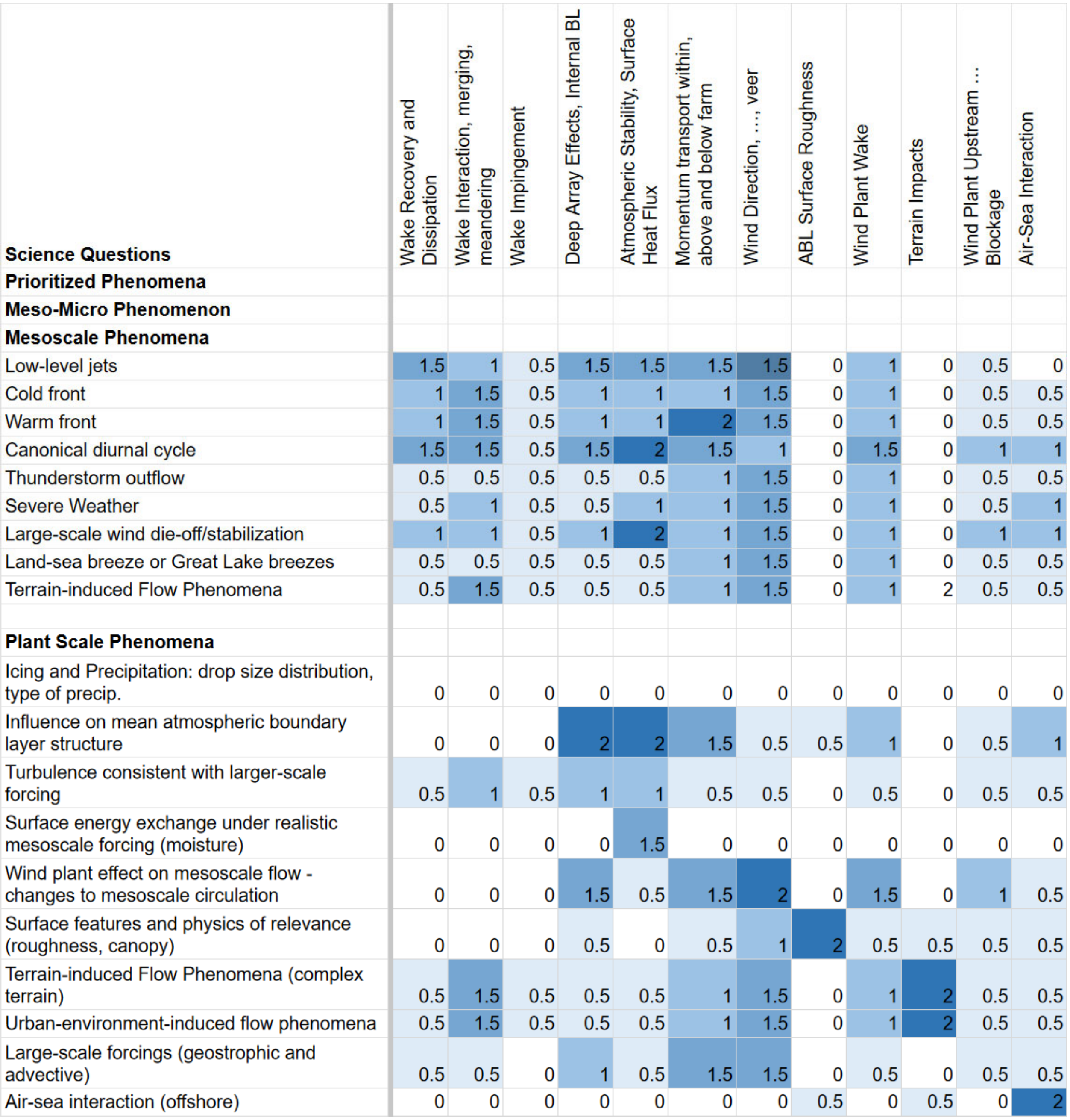
Science Questions	Wake Recovery and Dissipation	Wake Interaction, merging, meandering	Wake Impingement	Deep Array Effects, Internal BL	Atmospheric Stability, Surface Heat Flux	Momentum transport within, above and below farm	Wind Direction, …, veer	ABL Surface Roughness	Wind Plant Wake	Terrain Impacts	Wind Plant Upstream … Blockage	Air-Sea Interaction
Prioritized Phenomena												
Wind Plant Phenomenon												
Inflow Turbulence/Wake Interaction												
Wind direction (shear/veer/assymetry)	1	1	1	1	1	1	2	0	1.5	1	1.5	1
Turbulence characteristics (intensity, spectra, coherence, stability)	1.5	1.5	1	1.5	2	1.5	0	0.5	1.5	1	1	1.5
Coherent turblence structure	2	2	1	0	0	1	0	0	2	1	1	1
Surface conditions (roughness, canopy, waves, surface heat flux, topography)	0	0	0	0	2	1	1	2	1	2	0.5	2
Momentum transport (horizontal and vertical fluxes)	2	1	0	2	1	2	0.5	1	1.5	1	0.5	1
Multi-Turbine Wake Effects												
Wake interaction, merging, meander	1	2	0	0.5	1	0	0.5	0	1.5	0.5	0	0.5
Plant flow control for optimum performance	1.5	1.5	1.5	0.5	1	1	0.5	0	1	0	1	0.5
Wake steering (yaw & tilt effects)	1	2	1.5	0.5	1	1	1.5	0	0.5	0	1	0.5
Wake dissipation	2	1	1	0.5	1.5	1.5	0.5	0	1.5	0.5	0	1
Wake Impingement (full, half, etc.)	0	0	2	0	0	0	0	0	0	0	0	0
Deep array effects (change in turbulence, etc.)	0.5	0.5	0.5	2	1.5	1.5	0.5	0	1.5	0.5	1	0.5
Other Effects												
Wind plant blockage effects and plant wake	0	0	0	1	1.5	1	1	0	2	0.5	2	0.5
Acoustic Propagation	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3-5. Spreadsheet showing the mapping between wind plant phenomena and AWAKEN science goals.

A score of 1 indicates that the phenomena is important to the science goal, but not the primary phenomena that is relevant to answering the science questions. For example, the phenomenon inflow wind direction (sheer/veer/asymmetry) is important to measure for characterizing other phenomena more directly related to science goals. Therefore, it received a score of 1 for wake recovery and dissipation, wake interaction, merging, and meandering, wake impingement, deep array effects, and internal boundary layer, atmospheric stability and surface heat flux, and momentum transport within, above, and below farms.

A "loose connection score" of 0.5 is applied when there is a secondary relationship linking the phenomena to answering the science question, or in situations where it is unknown if the phenomena is important to the science goal. An example of this is the relationship between many phenomena and air-sea interactions. Since offshore wind is still a newer area of research, there are still many unknowns as to how air-sea interactions will impact wind plant phenomena, or vice-versa. A score of 0 is given where a phenomenon has no relevance to the science goal.

Overall, in looking at the phenomena to science goal mappings, a pattern emerges where one can see which phenomena are poorly studied in the AWAKEN science goals (e.g., acoustic propagation from wind plants). It is acknowledged that this will weigh instrumentation importance in favor of phenomena captured by the AWAKEN science goals, but this effect is offset by the measurements to modeling validation needs exercise (Section 5). In looking at all three phenomena to science goal mappings, a pattern also emerges as to which science goals are focused on each scale of phenomena (small-scale wind turbine, larger wind plant, or mesoscale phenomena). Overall, the majority of AWAKEN science goals are focused on wind plant phenomena. These patterns are important to recognize and consider when looking at the final instrumentation roadmap.



Science Questions	Wake Recovery and Dissipation	Wake Interaction, merging, meandering	Wake Impingement	Deep Array Effects, Internal BL	Atmospheric Stability, Surface Heat Flux	Momentum transport within, above and below farm	Wind Direction, …, veer	ABL Surface Roughness	Wind Plant Wake	Terrain Impacts	Wind Plant Upstream … Blockage	Air-Sea Interaction
Prioritized Phenomena												
Meso-Micro Phenomenon												
Mesoscale Phenomena												
Low-level jets	1.5	1	0.5	1.5	1.5	1.5	1.5	0	1	0	0.5	0
Cold front	1	1.5	0.5	1	1	1	1.5	0	1	0	0.5	0.5
Warm front	1	1.5	0.5	1	1	2	1.5	0	1	0	0.5	0.5
Canonical diurnal cycle	1.5	1.5	0.5	1.5	2	1.5	1	0	1.5	0	1	1
Thunderstorm outflow	0.5	0.5	0.5	0.5	0.5	1	1.5	0	1	0	0.5	0.5
Severe Weather	0.5	1	0.5	0.5	1	1	1.5	0	1	0	0.5	1
Large-scale wind die-off/stabilization	1	1	0.5	1	2	1	1.5	0	1	0	1	1
Land-sea breeze or Great Lake breezes	0.5	0.5	0.5	0.5	0.5	1	1.5	0	1	0	0.5	0.5
Terrain-induced Flow Phenomena	0.5	1.5	0.5	0.5	0.5	1	1.5	0	1	2	0.5	0.5
Plant Scale Phenomena												
Icing and Precipitation: drop size distribution, type of precip.	0	0	0	0	0	0	0	0	0	0	0	0
Influence on mean atmospheric boundary layer structure	0	0	0	2	2	1.5	0.5	0.5	1	0	0.5	1
Turbulence consistent with larger-scale forcing	0.5	1	0.5	1	1	0.5	0.5	0	0.5	0	0.5	0.5
Surface energy exchange under realistic mesoscale forcing (moisture)	0	0	0	0	1.5	0	0	0	0	0	0	0
Wind plant effect on mesoscale flow - changes to mesoscale circulation	0	0	0	1.5	0.5	1.5	2	0	1.5	0	1	0.5
Surface features and physics of relevance (roughness, canopy)	0	0	0	0.5	0	0.5	1	2	0.5	0.5	0.5	0.5
Terrain-induced Flow Phenomena (complex terrain)	0.5	1.5	0.5	0.5	0.5	1	1.5	0	1	2	0.5	0.5
Urban-environment-induced flow phenomena	0.5	1.5	0.5	0.5	0.5	1	1.5	0	1	2	0.5	0.5
Large-scale forcings (geostrophic and advective)	0.5	0.5	0	1	0.5	1.5	1.5	0	0.5	0	0.5	0.5
Air-sea interaction (offshore)	0	0	0	0	0	0	0	0.5	0	0.5	0	2

Figure 3-6. Spreadsheet showing the mapping between mesoscale-microscale coupling phenomena and AWAKEN science goals.

3.3. Summary of Science Goal Measurements

The previous sections have identified the ability of different instrumentation systems to capture different phenomena and the importance of capturing those phenomena to addressing the science objectives of the AWAKEN project. This section couples the two together to determine the instrumentation most important for addressing the science goals.

To determine the relative importance of each of the instruments, the importance of each phenomena to a specific science question (ranked 0-2) (Figures 3-4 through 3-6) was multiplied by the ability of an instrument to capture that phenomena (ranked 0-2) (Figures 3-1 through 3-3) resulting in a numerical value of 0-4. For each measurement category of instruments or measurement platforms, these numerical values were summed over all phenomena resulting in a score for each science question/instrument combination, shown in the columns of Figure 3-7. Finally, summing over all science objectives yields an overall ranking for that measurement category, which are the numbers in the green shading at the bottom.

Science Questions	Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler
Wake Recovery and Dissipation	27	11.5	2	58	62.5	46	41	28.5	43	40.75	23	10.5	11.5	3.5	48.5	33
Wake Interaction, merging, meandering	34	17	5.5	57.5	71.5	56	50	36	48.5	42.75	32	17	17.5	5.5	44	40
Wake Impingement	35.5	22	11	38.5	43.5	30.5	27.5	23.5	26.5	27.25	15.5	20.5	21	9	27	19
Deep Array Effects, Internal BL	5	3	0	25	53	51.5	48	34	50	29.25	36	3.5	3.75	0	21.5	43
Atmospheric Stability, Surface Heat Flux	8	4	0	30	60	55.5	51	40	51.5	36.5	43	6	6.75	0	26	51
Momentum transport within, above and below farm	7	3	0	25.5	60	61.5	57	39	56.5	34	43	5.5	6.25	0	23	52
Wind Direction, …, veer	14	9	1	26.5	60	60.5	56	46	55.5	32.25	47	10	10.25	2	20.5	54
ABL Surface Roughness	2	2	0	9	13	11	11	6	9	15.5	8	1	1	0	11	17
Wind Plant Wake	7.5	4.5	0	32	61	61	55.5	34	54.5	39	40.5	6.5	7.25	0	24	44
Terrain Impacts	4	4	0	22	33	27.5	26	17	27	29	21	3	3.25	0	17.5	26
Wind Plant Upstream … Blockage	6	2	0	17.5	38	39	38	21	35.5	24.5	26	5	5	0	14	27
Air-Sea Interaction	9	7	4	22	41	40	37	25	36.5	30.25	29	7	7.5	4	19	36
Total	159.0	89.0	23.5	363.5	596.5	540.0	498.0	350.0	494.0	381.0	364.0	95.5	101.0	24.0	296.0	442.0
Rank	11	14	16	8	1	2	3	9	4	6	7	13	12	15	10	5

Figure 3-7. Numerical value representing the importance of each instrument class to each science objective.

The highest ranked instrumentation classes for the AWAKEN campaign determined from this ranking are the moderate (1) and coarse (2) resolution velocity measurements, which can provide detailed measurements of the inflow and wake (moderate) as well as wind plant behavior (coarse). These instruments were followed by instruments that could characterize the atmospheric conditions and inflow: velocity profile (3), tethered balloon (4), and thermodynamic profiler (5). Next in the rankings were UAS (6) and aircraft (7) measurements that have the possibility of measuring inflow, turbine wakes, and wind plant wake.

High-resolution velocity measurements (8) are next, with applications to both inflow and near-wake measurements as well as flows near the blade. In-situ measurements such as met towers (9) and high-resolution thermodynamic profilers (10) were next since such measurements are necessary to provide long-term monitoring of wind conditions. Last in priority were measurements of the blades including unsteady pressure (11), section loads (12), blade deflection (13), and wall shear stress (14). These measurements are lower priority in this test as the blade flows are not a focus of the AWAKEN campaign's science objectives. To this point, instrumentation has only been provided as classes. In some cases, there are many specific instruments that can provide the types of measurements indicated. Specific instruments that can address measurement needs identified by a specific class are listed in Table 3-2.

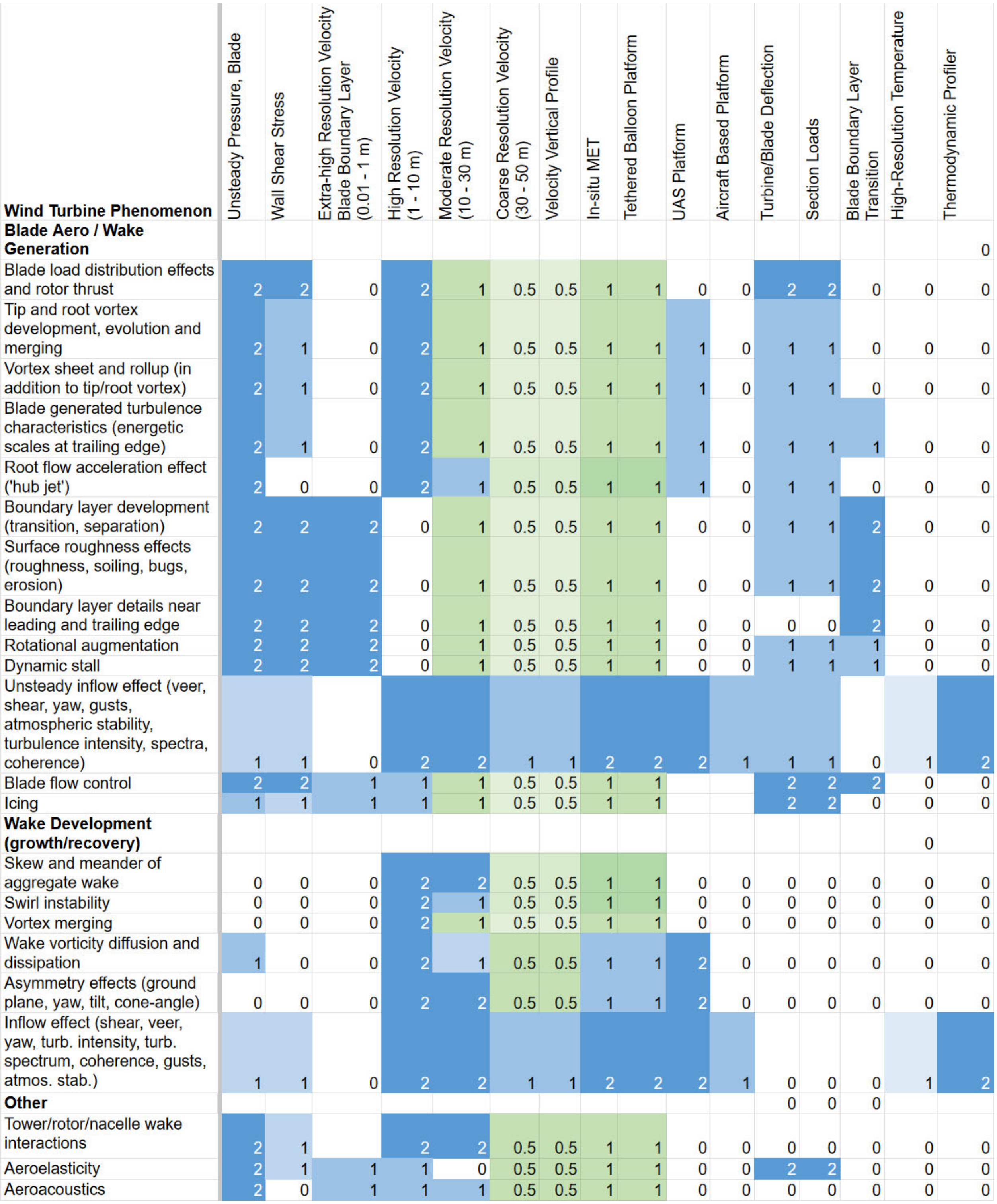
4. MAPPING FROM MEASUREMENTS TO RAAW EXPERIMENTAL GOALS

To provide another example of applying the instrumentation mappings discussed above, the approach is applied to the validation activities conducted during the Rotor Aerodynamic, Aeroelastics, and Wake experiment (Brown et al., 2024; Doubrawa et al., 2024). Figure 4-1 is a modication of Figure 3-1 to reflect the focus of the RAAW experiment on the inflow, turbine response, and the resulting wake in scoring the connection between the measurement categories and platforms to wind turbine phenomena. The differences between Figure 3-1 are highlighted in green. The goals of the RAAW project are referred to as experimental goals because they are a combination of both science goals and validation goals.

The second column (in blue shading) in Figure 4-2 shows the importance of the connection of each of the wind turbine phenomena to the experimental goals of the RAAW project. The phenomena are scored as 0-not relevant, 1-relevant, and 2-highly relevant to the RAAW experiment. For example, aeroelasticity is highly weighted since this experiment is concerned with the interaction of the inflow, blade response, and the resulting wake. Similarly, surface roughness effects are weighted low, not because they are not important, but because this is not a focus of the RAAW effort. These scores are then multiplied by the ability of the instrument/measurement category to capture the phenomena listed in Figure 4-1. The cross-multiplied results (displayed in green) were summed over the phenomena resulting in an overall score and ranking for each measurement category for the RAAW experiment. Both the summed score and the rank of each instrument is provided at the top of the table.

The results of the mapping are not surprising considering the focus of the RAAW experiment. High and moderate resolution velocity measurements rank highly as do pressure and shear stress measurements on the blade. These rankings reflect the interest in the coupled inflow/blade/wake measurements that are needed for validation of models of highly flexible wind turbine blades. Measurements of the atmospheric conditions also rank highly as they are needed for interpreting the turbine response and wake behavior. The blade deflection and section loads also rank in the top half of categories. These measurements are critical for monitoring the blade response and understanding that impact on wake development to ensure proper model comparisons. Note that the feasibility of having the instrumentation available for RAAW was not considered in this analysis. Feasibility scoring is discussed in a later section and will have an important impact on what instrumentation is deployed for a follow-on experiment to RAAW.

It should also be noted that these rankings are highly sensitive to the weighting that is applied. Small changes in the weighting or in the importance of an instrument to capturing a phenomenon can produce notable effects in the ranking. Since all the instruments were selected based on their promise of providing useful measurements in wind-energy-focused measurement campaigns, it is important to stress that the exact ranking should not be considered as the only factor for deciding which measurement systems to focus on.



Wind Turbine Phenomenon	Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler
Blade Aero / Wake Generation																0
Blade load distribution effects and rotor thrust	2	2	0	2	1	0.5	0.5	1	1	0	0	2	2	0	0	0
Tip and root vortex development, evolution and merging	2	1	0	2	1	0.5	0.5	1	1	1	0	1	1	0	0	0
Vortex sheet and rollup (in addition to tip/root vortex)	2	1	0	2	1	0.5	0.5	1	1	1	0	1	1	0	0	0
Blade generated turbulence characteristics (energetic scales at trailing edge)	2	1	0	2	1	0.5	0.5	1	1	1	0	1	1	1	0	0
Root flow acceleration effect ('hub jet')	2	0	0	2	1	0.5	0.5	1	1	1	0	1	1	0	0	0
Boundary layer development (transition, separation)	2	2	2	0	1	0.5	0.5	1	1	0	0	1	1	2	0	0
Surface roughness effects (roughness, soiling, bugs, erosion)	2	2	2	0	1	0.5	0.5	1	1	0	0	1	1	2	0	0
Boundary layer details near leading and trailing edge	2	2	2	0	1	0.5	0.5	1	1	0	0	0	0	2	0	0
Rotational augmentation	2	2	2	0	1	0.5	0.5	1	1	0	0	1	1	1	0	0
Dynamic stall	2	2	2	0	1	0.5	0.5	1	1	0	0	1	1	1	0	0
Unsteady inflow effect (veer, shear, yaw, gusts, atmospheric stability, turbulence intensity, spectra, coherence)	1	1	0	2	2	1	1	2	2	2	1	1	1	0	1	2
Blade flow control	2	2	1	1	1	0.5	0.5	1	1			2	2	2	0	0
Icing	1	1	1	1	1	0.5	0.5	1	1			2	2	0	0	0
Wake Development (growth/recovery)															0	
Skew and meander of aggregate wake	0	0	0	2	2	0.5	0.5	1	1	0	0	0	0	0	0	0
Swirl instability	0	0	0	2	1	0.5	0.5	1	1	0	0	0	0	0	0	0
Vortex merging	0	0	0	2	1	0.5	0.5	1	1	0	0	0	0	0	0	0
Wake vorticity diffusion and dissipation	1	0	0	2	1	0.5	0.5	1	1	2	0	0	0	0	0	0
Asymmetry effects (ground plane, yaw, tilt, cone-angle)	0	0	0	2	2	0.5	0.5	1	1	2	0	0	0	0	0	0
Inflow effect (shear, veer, yaw, turb. intensity, turb. spectrum, coherence, gusts, atmos. stab.)	1	1	0	2	2	1	1	2	2	2	1	0	0	0	1	2
Other												0	0	0		
Tower/rotor/nacelle wake interactions	2	1		2	2	0.5	0.5	1	1	0	0	0	0	0	0	0
Aeroelasticity	2	1	1	1	0	0.5	0.5	1	1	0	0	2	2	0	0	0
Aeroacoustics	2	0	1	1	1	0.5	0.5	1	1	0	0	0	0	0	0	0

Figure 4-1. Mapping scores of measurement systems and wind turbine phenomena to include inflow and turbine response weighting.

	Phenomena Measured by RAAW	Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler
Sum		35.5	23	10	45	33.5	15.75	15.75	31.5	31.5	19	4	19.5	19.5	6.5	4	8
Rank		2	6	12	1	3	10	10	4	4	9	15	7	7	14	15	13
Wind Turbine Phenomenon																	
Blade Aero / Wake Generation																	
Blade load distribution effects and rotor thrust	2	4	4	0	4	2	1	1	2	2	0	0	4	4	0	0	0
Tip and root vortex development, evolution and merging	2	4	2	0	4	2	1	1	2	2	2	0	2	2	0	0	0
Vortex sheet and rollup (in addition to tip/root vortex)	1	2	1	0	2	1	0.5	0.5	1	1	1	0	1	1	0	0	0
Blade generated turbulence characteristics (energetic scales at trailing edge)	1	2	1	0	2	1	0.5	0.5	1	1	1	0	1	1	1	0	0
Root flow acceleration effect ('hub jet')	2	4	0	0	4	2	1	1	2	2	2	0	2	2	0	0	0
Boundary layer development (transition, separation)	1	2	2	2	0	1	0.5	0.5	1	1	0	0	1	1	2	0	0
Surface roughness effects (roughness, soiling, bugs, erosion)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Boundary layer details near leading and trailing edge	0.5	1	1	1	0	0.5	0.25	0.25	0.5	0.5	0	0	0	0	1	0	0
Rotational augmentation	1.5	3	3	3	0	1.5	0.75	0.75	1.5	1.5	0	0	1.5	1.5	1.5	0	0
Dynamic stall	1	2	2	2	0	1	0.5	0.5	1	1	0	0	1	1	1	0	0
Unsteady inflow effect (veer, shear, yaw, gusts, atmospheric stability, turbulence intensity, spectra, coherence)	2	2	2	0	4	4	2	2	4	4	4	2	2	2	0	2	4
Blade flow control	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Icing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wake Development (growth/recovery)																	
Skew and meander of	2	0	0	0	4	4	1	1	2	2	0	0	0	0	0	0	0
Swirl instability	2	0	0	0	4	2	1	1	2	2	0	0	0	0	0	0	0
Vortex merging	2	0	0	0	4	2	1	1	2	2	0	0	0	0	0	0	0
Wake vorticity diffusion and	1.5	1.5	0	0	3	1.5	0.75	0.75	1.5	1.5	3	0	0	0	0	0	0
Asymmetry effects (ground	1	0	0	0	2	2	0.5	0.5	1	1	2	0	0	0	0	0	0
Inflow effect (shear, veer, yaw, turb. intensity, turb. spectrum, coherence, gusts, atmos. stab.)	2	2	2	0	4	4	2	2	4	4	4	2	0	0	0	2	4
Other																	
Tower/rotor/nacelle wake	1	2	1	0	2	2	0.5	0.5	1	1	0	0	0	0	0	0	0
Aeroelasticity	2	4	2	2	2	0	1	1	2	2	0	0	4	4	0	0	0
Aeroacoustics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wake vorticity diffusion and dissipation	1.5	1.5	0	0	3	1.5	0.75	0.75	1.5	1.5	3	0	0	0	0	0	0
Asymmetry effects (ground plane, yaw, tilt, cone-angle)	1	0	0	0	2	2	0.5	0.5	1	1	2	0	0	0	0	0	0
Inflow effect (shear, veer, yaw, turb. intensity, turb. spectrum, coherence, gusts, atmos. stab.)	2	2	2	0	4	4	2	2	4	4	4	2	0	0	0	2	4
Other																	
Tower/rotor/nacelle wake	1	2	1	0	2	2	0.5	0.5	1	1	0	0	0	0	0	0	0
Aeroelasticity	2	4	2	2	2	0	1	1	2	2	0	0	4	4	0	0	0
Aeroacoustics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 4-2. RAAW phenomena to instrumentation mapping.

5. MAPPING FROM MEASUREMENTS TO HIGH-FIDELITY MODELING VERIFICATION AND VALIDATION NEEDS

5.1. Mapping Measurements to Needed Validation Campaigns

As wind energy research and observational needs extend beyond the AWAKEN and RAAW projects, the High-Fidelity Modeling Validation and Verification Roadmap was introduced to the instrumentation development effort (Maniaci et al., 2020). The V&V roadmap aggregates outstanding observational needs required to quantify the accuracy and uncertainty associated with high-fidelity modeling codes for wind plant modeling applications. The report specifies in great detail which observations are needed to support validation efforts for particular quantities of interest within the high-fidelity modeling codes, making it a valuable resource for prioritizing measurement and observations in field research. The V&V roadmap considered current wind HFM model platforms, or code bases, as well as the vision for future modeling capabilities, focusing on what is needed to capture dominant physical phenomena for wind plant modeling applications.

The V&V roadmap organizes needed observations into 9 validation campaigns, each aimed at validating a particular uncertainty in the HFM code, including:

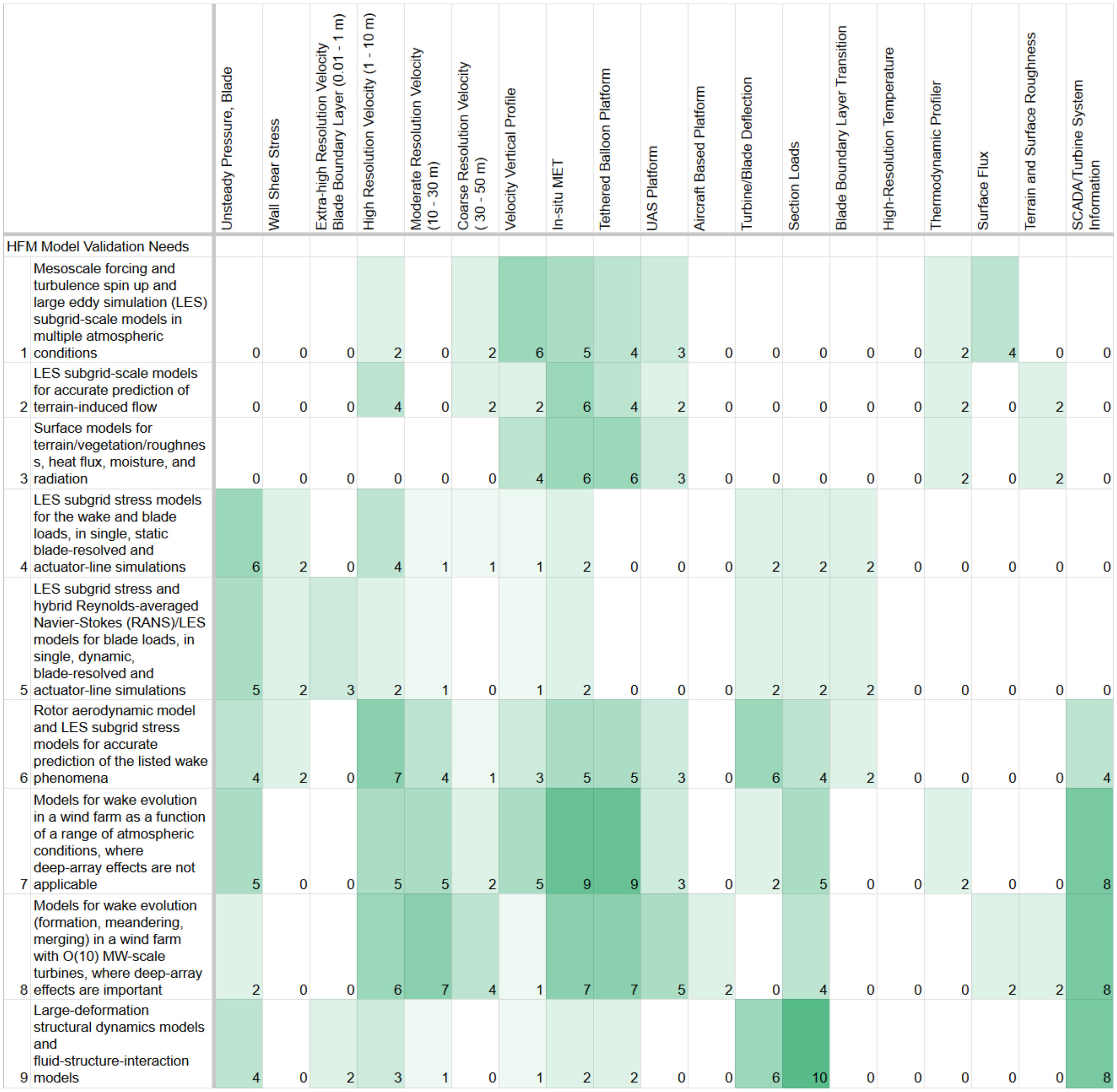
1. Mesoscale forcing and turbulence spin up and large eddy simulation (LES) subgrid-scale models in multiple atmospheric conditions
2. LES subgrid-scale models for accurate prediction of terrain-induced flow
3. Surface models for terrain/vegetation/roughness, heat flux, moisture, and radiation
4. LES subgrid stress models for the wake 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 blade loads, in single, dynamic, blade-resolved, and actuator-line simulations
6. Rotor aerodynamic model and LES subgrid stress models for accurate prediction of the listed wake phenomena
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
8. Models for wake evolution (formation, meandering, merging) in a wind farm with 10 MW-scale turbines, where deep-array effects are important
9. Large-deformation structural dynamics models and fluid-structure-interaction models

These 9 validation campaigns can each utilize multiple experiments to meet their individual objectives, and likewise validation experiments can meet the needs of multiple validation campaigns. Each of the campaigns are defined through a validation objective, dominant physical phenomena, quantities of interest, turbine geometry and flow condition requirements, and measurement requirements. The measurement requirements include varying levels of detail, of spatial and temporal resolution, giving direct input to instrumentation needs to meet the validation campaign objectives. An example of a validation campaign and the identification of measurement requirements can be found in Appendix C.

The observational needs in the V&V roadmap have now been remapped onto the categories discussed above with respect to the AWAKEN and RAAW projects since the V&V roadmap was previously developed (Maniaci et al., 2020). In so doing, known measurement platforms, both commercially available and in development, were connected to each of the physical phenomena addressed in the measurement needs of the campaigns listed above. A similar ranking scheme was adopted for the mapping of instrumentation to V&V needs as in Section 2, ranging from 0–2, where

0 indicates that an instrument is not suitable to measure a particular physical phenomenon, 1 indicates that an instrument may contribute some insight to the campaign, and 2 indicates that an instrument is capable of delivering the needed observation directly. In addition to indicating each instrument's suitability for observing the specified phenomena, the development timeline was also specified.

The suitability of each instrument to capture the quantities of interest within the validation measurement requirement subcategory were mapped onto the measurement categories specified in Section 3 and summed across the measurement requirement categories associated with each campaign. The table in Figure 5-1 indicates how well each of the measurement categories meets the



		Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler	Surface Flux	Terrain and Surface Roughness	SCADA/Turbine System Information
	HFM Model Validation Needs																			
1	Mesoscale forcing and turbulence spin up and large eddy simulation (LES) subgrid-scale models in multiple atmospheric conditions	0	0	0	2	0	2	6	5	4	3	0	0	0	0	0	2	4	0	0
2	LES subgrid-scale models for accurate prediction of terrain-induced flow	0	0	0	4	0	2	2	6	4	2	0	0	0	0	0	2	0	2	0
3	Surface models for terrain/vegetation/roughness, heat flux, moisture, and radiation	0	0	0	0	0	0	4	6	6	3	0	0	0	0	0	2	0	2	0
4	LES subgrid stress models for the wake and blade loads, in single, static blade-resolved and actuator-line simulations	6	2	0	4	1	1	1	2	0	0	0	2	2	2	0	0	0	0	0
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	5	2	3	2	1	0	1	2	0	0	0	2	2	2	0	0	0	0	0
6	Rotor aerodynamic model and LES subgrid stress models for accurate prediction of the listed wake phenomena	4	2	0	7	4	1	3	5	5	3	0	6	4	2	0	0	0	0	4
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	5	0	0	5	5	2	5	9	9	3	0	2	5	0	0	2	0	0	8
8	Models for wake evolution (formation, meandering, merging) in a wind farm with O(10) MW-scale turbines, where deep-array effects are important	2	0	0	6	7	4	1	7	7	5	2	0	4	0	0	0	2	2	8
9	Large-deformation structural dynamics models and fluid-structure-interaction models	4	0	2	3	1	0	1	2	2	0	0	6	10	0	0	0	0	0	8

Figure 5-1. Mapping of V&V campaigns to measurements.

designed measurement requirements for each of the validation campaigns. Cells for which the suitability is 0 (white coloring) indicates that the measurement category (column) is not needed for a particular validation campaign (row). Appendix C supplies the measurement category score for each of the validation campaign quantity of interest or measurement requirement subcategory.

As an example, within the first validation campaign, focused on "Mesoscale forcing and turbulence spin up and large eddy simulation subgrid-scale models in multiple atmospheric conditions," one of the specified measurement needs is in Table 5-1 with a list of instruments and a score of how well the instrument meets the measurement need.

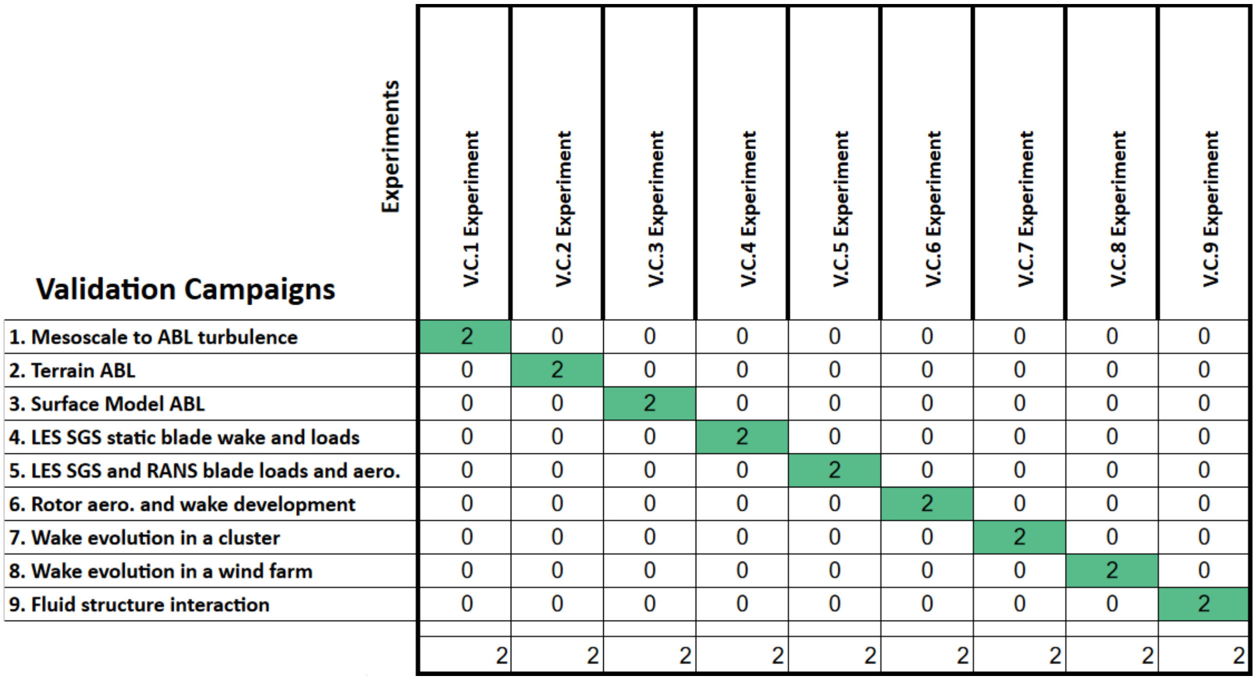
Table 5-1. Vertical profiles of wind velocity and temperature at a 1 Hz minimum frequency at least to 160 m

Instrument	Score
Met tower – ideally sonics with temp	2
Distributed temperature balloon with sonics	2
Profiling lidars could get velocity profiles	2
Radiosondes	1
UAS	1

As listed, met towers, distributed measurements on tethered balloon systems, and profiling lidars are all well suited to providing the needed observations. Radiosondes and UAS-based measurements may contribute to the characterization of velocity and temperature profiles, but do not have the temporal resolution to achieve robust statistical estimates. Each instrument was mapped to the respective measurement category in the table, averaged across campaign subcategories, and then summed across all campaign subcategories, providing the listed values.

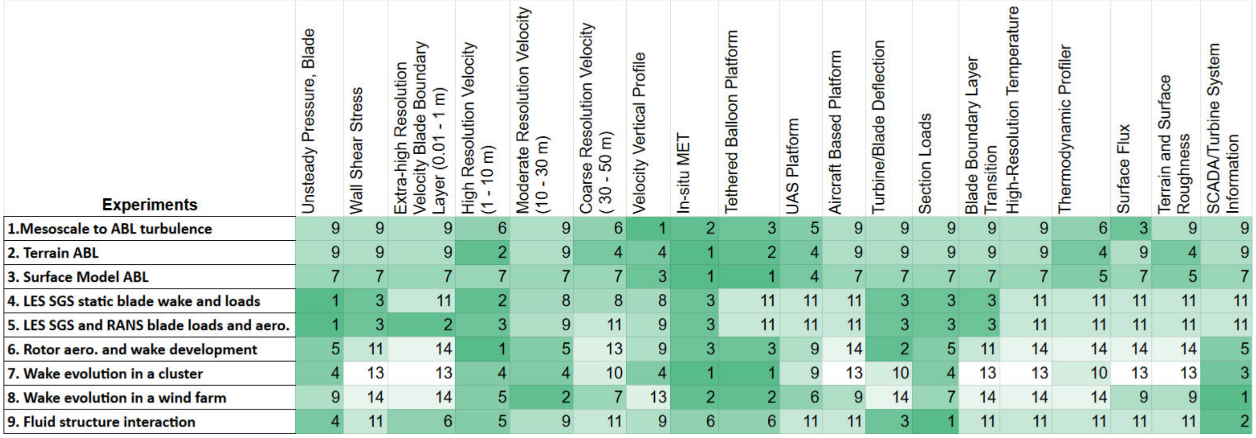
5.2. Example Validation Campaign to Instrument Mapping

The validation campaign to instrument mapping process is first demonstrated to show the instrument priorities for example experiments that each target an individual validation campaign. Actual experiments target multiple validation campaigns, and the associated overlapping physical phenomena relevant to each campaign. By looking at the prioritized instruments for each campaign separately, one can more clearly see how addressing multiple validation campaigns can shift the relative priority of each instrument. The validation campaign to the theoretical experiment weighting table is shown in Figure 5-2. The resulting prioritized ranking for each instrument measurement category is shown for each validation campaign experiment in Figure 5-3.



Validation Campaigns / Experiments	V.C.1 Experiment	V.C.2 Experiment	V.C.3 Experiment	V.C.4 Experiment	V.C.5 Experiment	V.C.6 Experiment	V.C.7 Experiment	V.C.8 Experiment	V.C.9 Experiment
1. Mesoscale to ABL turbulence	2	0	0	0	0	0	0	0	0
2. Terrain ABL	0	2	0	0	0	0	0	0	0
3. Surface Model ABL	0	0	2	0	0	0	0	0	0
4. LES SGS static blade wake and loads	0	0	0	2	0	0	0	0	0
5. LES SGS and RANS blade loads and aero.	0	0	0	0	2	0	0	0	0
6. Rotor aero. and wake development	0	0	0	0	0	2	0	0	0
7. Wake evolution in a cluster	0	0	0	0	0	0	2	0	0
8. Wake evolution in a wind farm	0	0	0	0	0	0	0	2	0
9. Fluid structure interaction	0	0	0	0	0	0	0	0	2
	2	2	2	2	2	2	2	2	2

Figure 5-2. Validation campaign (VC) weighting for theoretical experiments targeting each validation campaign separately.



Experiments	Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler	Surface Flux	Terrain and Surface Roughness	SCADA/Turbine System Information
1.Mesoscale to ABL turbulence	9	9	9	6	9	6	1	2	3	5	9	9	9	9	9	6	3	9	9
2. Terrain ABL	9	9	9	2	9	4	4	1	2	4	9	9	9	9	9	4	9	4	9
3. Surface Model ABL	7	7	7	7	7	7	3	1	1	4	7	7	7	7	7	5	7	5	7
4. LES SGS static blade wake and loads	1	3	11	2	8	8	8	3	11	11	11	3	3	3	11	11	11	11	11
5. LES SGS and RANS blade loads and aero.	1	3	2	3	9	11	9	3	11	11	11	3	3	3	11	11	11	11	11
6. Rotor aero. and wake development	5	11	14	1	5	13	9	3	3	9	14	2	5	11	14	14	14	14	5
7. Wake evolution in a cluster	4	13	13	4	4	10	4	1	1	9	13	10	4	13	13	10	13	13	3
8. Wake evolution in a wind farm	9	14	14	5	2	7	13	2	2	6	9	14	7	14	14	14	9	9	1
9. Fluid structure interaction	4	11	6	5	9	11	9	6	6	11	11	3	1	11	11	11	11	11	2

Figure 5-3. Prioritized ranking of each instrument measurement category for each theoretical validation campaign targeted experiment.

The measurement categories can then be listed in prioritized order for each theoretical validation campaign targeted experiment, as shown in Figure 5-4. In Figure 5-4 some of the highest ranked instruments are color coded so that their position across the different prioritizations can be easily tracked. As expected, validation campaigns focused on atmospheric phenomena (1, 2, 3) tend to

	1.Mesoscale to ABL turbulence		2. Terrain ABL		3. Surface Model ABL		4. LES SGS static blade wake and loads		5. LES SGS and RANS blade loads and aero.		6. Rotor aero. and wake development		7. Wake evolution in a cluster		8. Wake evolution in a wind farm		9. Fluid structure interaction
1	Velocity Profile	1	In-situ Met	1	In-situ Met	1	Unsteady Pressure	1	Unsteady Pressure	1	High Res. Vel.	1	In-situ Met	1	SCADA/Turbine Info.	1	Section Loads
2	In-situ Met	2	High Res. Vel.	1	Tethered Balloon	2	High Res. Vel.	2	Extra-high Res. Vel.	2	Turbine/Blade Defl.	1	Tethered Balloon	2	Moderate Res. Vel.	2	SCADA/Turbine Info.
3	Tethered Balloon	2	Tethered Balloon	3	Velocity Profile	3	Shear Stress	3	Shear Stress	3	In-situ Met	3	SCADA/Turbine Info.	2	In-situ Met	3	Turbine/Blade Defl.
3	Surface flux	4	Coarse Res. Vel.	4	UAS	3	In-situ Met	3	High Res. Vel.	3	Tethered Balloon	4	Unsteady Pressure	2	Tethered Balloon	4	Unsteady Pressure
5	UAS	4	Velocity Profile	5	Thermo. Profiler	3	Turbine/Blade Defl.	3	In-situ Met	5	Unsteady Pressure	4	High Res. Vel.	5	High Res. Vel.	5	High Res. Vel.
6	High Res. Vel.	4	UAS	5	Terrain/Roughness	3	Section Loads	3	Turbine/Blade Defl.	5	Moderate Res. Vel.	4	Moderate Res. Vel.	6	UAS	6	Extra-high Res. Vel.
6	Coarse Res. Vel.	4	Thermo. Profiler	7	Unsteady Pressure	3	Blade B.L. Transition	3	Section Loads	5	Section Loads	4	Velocity Profile	7	Coarse Res. Vel.	6	In-situ Met
6	Thermo. Profiler	4	Terrain/Roughness	7	Shear Stress	8	Moderate Res. Vel.	3	Blade B.L. Transition	5	SCADA/Turbine Info.	4	Section Loads	7	Section Loads	6	Tethered Balloon
9	Unsteady Pressure	9	Unsteady Pressure	7	Extra-high Res. Vel.	8	Coarse Res. Vel.	9	Moderate Res. Vel.	9	Velocity Profile	9	UAS	9	Unsteady Pressure	9	Moderate Res. Vel.
9	Shear Stress	9	Shear Stress	7	High Res. Vel.	8	Velocity Profile	9	Velocity Profile	9	UAS	10	Coarse Res. Vel.	9	Aircraft Based	9	Velocity Profile
9	Extra-high Res. Vel.	9	Extra-high Res. Vel.	7	Moderate Res. Vel.	11	Extra-high Res. Vel.	11	Coarse Res. Vel.	11	Shear Stress	10	Turbine/Blade Defl.	9	Surface flux	11	Shear Stress
9	Moderate Res. Vel.	9	Moderate Res. Vel.	7	Coarse Res. Vel.	11	Tethered Balloon	11	Tethered Balloon	11	Blade B.L. Transition	10	Thermo. Profiler	9	Terrain/Roughness	11	Coarse Res. Vel.
9	Aircraft Based	9	Aircraft Based	7	Aircraft Based	11	UAS	11	UAS	13	Coarse Res. Vel.	13	Shear Stress	13	Velocity Profile	11	UAS
9	Turbine/Blade Defl.	9	Turbine/Blade Defl.	7	Turbine/Blade Defl.	11	Aircraft Based	11	Aircraft Based	14	Extra-high Res. Vel.	13	Extra-high Res. Vel.	14	Shear Stress	11	Aircraft Based
9	Section Loads	9	Section Loads	7	Section Loads	11	High Res. Temp.	11	High Res. Temp.	14	Aircraft Based	13	Aircraft Based	14	Extra-high Res. Vel.	11	Blade B.L. Transition
9	Blade B.L. Transition	9	Blade B.L. Transition	7	Blade B.L. Transition	11	Thermo. Profiler	11	Thermo. Profiler	14	High Res. Temp.	13	Blade B.L. Transition	14	Turbine/Blade Defl.	11	High Res. Temp.
9	High Res. Temp.	9	High Res. Temp.	7	High Res. Temp.	11	Surface flux	11	Surface flux	14	Thermo. Profiler	13	High Res. Temp.	14	Blade B.L. Transition	11	Thermo. Profiler
9	Terrain/Roughness	9	Surface flux	7	Surface flux	11	Terrain/Roughness	11	Terrain/Roughness	14	Surface flux	13	Surface flux	14	High Res. Temp.	11	Surface flux
9	SCADA/Turbine Info.	9	SCADA/Turbine Info.	7	SCADA/Turbine Info.	11	SCADA/Turbine Info.	11	SCADA/Turbine Info.	14	Terrain/Roughness	13	Terrain/Roughness	14	Thermo. Profiler	11	Terrain/Roughness

Figure 5-4. Measurement categories listed in prioritized order for each validation campaign targeted experiment.

prioritize measurements of velocity and temperature over large areas. Validation campaigns focused on rotor aerodynamic and wake physics tend to prioritize more detailed velocity measurements and measurements of the loading effects across each rotor blade. Unsteady pressure measurements on the rotor blade also move up in priority for the campaigns that concern detailed blade aerodynamics and structural interaction (4, 5, 9), whereas the overall blade loading and turbine system integrated load measurements, are more important for campaigns focused on broader interactions of the atmosphere, rotor, and wake (6, 7, 8). When multiple validation campaigns are targeted by the actual experiments, as in the next section, these competing measurement priorities combine to give a different set of instrument priorities that are sometimes less intuitive than the rankings for the individual validation campaigns. In addition to competing measurement priorities, actual experiments are also affected by the availability of instruments and knowledge of the turbine systems, due to logistical, budget, or legal constraints.

5.3. Weighting of Validation Campaigns

The validation campaigns were weighted relative to each considered experiment to prioritize the instruments for validation needs. The results of the weighting process are summarized in a list of instrumentation in relative order to how important they are to meet the needs of the envisioned experiments. An idealized weighting is shown as well as a weighting for the actual experiments, with the difference between them showing how future instrumentation development can improve the capture of physical phenomena relevant to each validation campaign. For instrumentation mapping, this process isn't a weighting of the experiments against each other, rather it is a weighting of instrumentation importance for each experiment to meet the needs of the validation campaigns. The weighting considers the impact of the presence and knowledge of atmospheric conditions, terrain, turbine physical properties (type, size, arrangement), and instrumentation.

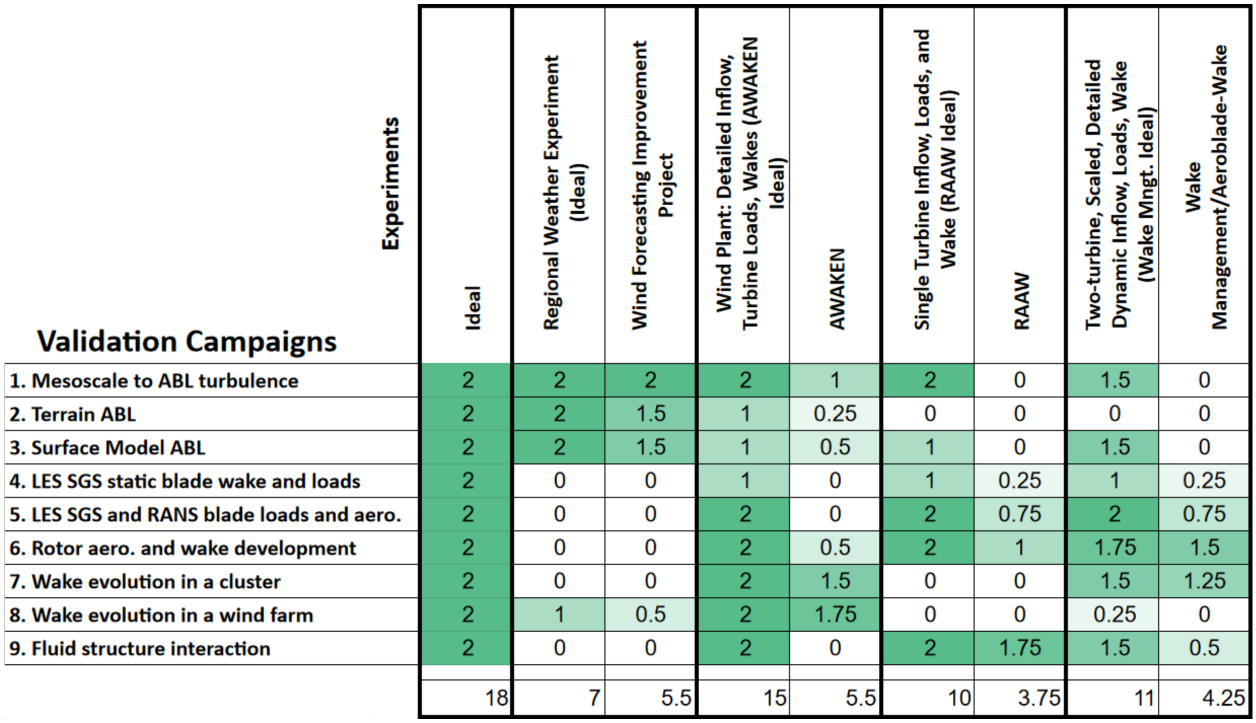
Four categories of validation experiments were considered to give coverage across the wind program proximal experimental campaigns. The first is an experiment focused on atmospheric physics and processes. The Wind Forecasting Improvement Project (WFIP) is an example of this type of experiment. The second category of experiment is a wind plant wake experiment, such as AWAKEN. The third category of experiment is focused on the interaction of wind turbine structural dynamics with the rotor and wake aerodynamics, such as the RAAW experiment, and the fourth type of experiment is focused on detailed wake interaction and control in a cluster of turbines, which the Wake Management experiment targets.

Two types of instrument mappings were explored for each category of validation experiment, ideal and actual. The ideal set focused on which physical phenomena are present in an experiment, whereas the actual set is focused on which phenomena can be captured given limitations on instrumentation and knowledge of the test conditions. These two processes answer two different questions regarding instrumentation:

1. Ideal: For a set of validation campaigns, what are the idealized set of instruments to capture all possible phenomena present in an experiment?
2. Actual: Given the limitations on instrumentation and knowledge of the test conditions, how well is an actual experiment able to capture the physical phenomena present in an experiment?

For the weighting of validation campaigns, both processes were used to show the difference between how they affect the instrument prioritization. The difference in instrument priority has some relationship to where instrument development can help capture additional phenomena in a validation experiment. Capturing additional phenomena will allow for more detailed validation of our computational models, ideally building additional trust in the models and increasing the technical innovations and advances they can help realize.

The mapping of validation campaigns to experiments considered input from the experiment, validation, and modeling communities. For each experiment, a weight was assigned for how well the proposed experiment will cover each validation campaign's needs, as defined in the High Fidelity Modeling Validation Roadmap (Maniaci et al., 2020). The resulting weightings are shown in Figure 5-5.



Validation Campaigns \ Experiments	Ideal	Regional Weather Experiment (Ideal)	Wind Forecasting Improvement Project	Wind Plant: Detailed Inflow, Turbine Loads, Wakes (AWAKEN Ideal)	AWAKEN	Single Turbine Inflow, Loads, and Wake (RAAW Ideal)	RAAW	Two-turbine, Scaled, Detailed Dynamic Inflow, Loads, Wake (Wake Mngt. Ideal)	Wake Management/Aeroblade-Wake
1. Mesoscale to ABL turbulence	2	2	2	2	1	2	0	1.5	0
2. Terrain ABL	2	2	1.5	1	0.25	0	0	0	0
3. Surface Model ABL	2	2	1.5	1	0.5	1	0	1.5	0
4. LES SGS static blade wake and loads	2	0	0	1	0	1	0.25	1	0.25
5. LES SGS and RANS blade loads and aero.	2	0	0	2	0	2	0.75	2	0.75
6. Rotor aero. and wake development	2	0	0	2	0.5	2	1	1.75	1.5
7. Wake evolution in a cluster	2	0	0	2	1.5	0	0	1.5	1.25
8. Wake evolution in a wind farm	2	1	0.5	2	1.75	0	0	0.25	0
9. Fluid structure interaction	2	0	0	2	0	2	1.75	1.5	0.5
	18	7	5.5	15	5.5	10	3.75	11	4.25

Figure 5-5. Experiment to validation campaign weighting, showing ideal weightings (whether physics are present in the experiment) and actual weightings (accounting for instrumentation and experiment condition knowledge limitations).

These weightings are a combination of whether the required physics, the required instrumentation, and the required test article and environmental conditions can be met by the experiment. A weighting of 0 means that the experiment provides no coverage for the validation campaign, 1 means that there is useful coverage for most of the requirements, and 2 indicates an experiment targeted to meet the specific validation needs of the given campaign.

5.3.1. Weighting Process for Each Experiment

The idealized regional weather experiment focuses on the mesoscale, terrain, and surface model validation campaigns, requiring coverage over wind farm areas with a wide range of terrain. Coarse lidar or radar scans could provide some relevant wind farm wake data, as well for validation, if combined with turbine SCADA data. In an actual wind forecasting experiment, there are limitations on the range of terrain and surface conditions included, as well as limitations on the wake and turbine measurements within the included wind farms.

The AWAKEN experiment is primarily focused on mesoscale inflow, wind farm wake development within a large wind farm, and farm-to-farm interaction. It will not focus on fluid structure interaction, detailed wake development, or detailed blade aerodynamics, as are covered by other experiments. Instead, it will focus on larger scale phenomena and how they are influenced by the atmosphere. The mesoscale to atmospheric boundary layer (ABL) turbulence validation campaign is covered sufficiently by the AWAKEN experiment, as the primary quantities of interest are mainly covered, and the supplemental quantities could be covered through additional instrumentation. The coverage of the primary quantities of interest assumes that a tethered balloon can be an adequate replacement for a tall (>160 m) MET tower with development.

The ideal weighting for AWAKEN was only reduced for terrain, as the experiment is focused on sites with minimal terrain influence to focus on wake and atmospheric interaction effects within and around wind plants. The weighting for the actual envisioned AWAKEN experiment will be limited due to the focus on large-scale interactions between atmosphere and wind plants rather than terrain and surface effects on ABL, detailed blade aerodynamic measurements, near wake measurements, and potential limitations on sharing some turbine design and controller information with all validation parties. The experiment focuses on atmospheric measurements around and within the wind farm, inflow measurements around the farm, wake measurements of each turbine in the farm, wake measurements behind the farm, the tower and blade root loads of a selection of turbines in the farm, and the power of each turbine. This selection of instruments and test condition knowledge resulted in AWAKEN primarily focusing on addressing validation campaign 8, mostly addressing campaigns 7 and 1, and partially addressing campaigns 6 and 5, as shown by the score rankings in Figure 5-5.

The RAAW experiment primarily focused on fluid structure interaction, and so received a rating above 1 for validation campaign 9 as represented in the Figure 5-5 scoring. It is likely that there will be some limits on data of the aerodynamic and structural properties of the blades, which limited the score of the validation campaign. This experiment also provided blade aerodynamic measurements and some wake development measurements, allowing it to address campaigns 4, 5, and 6 to varying levels (Figure 5-5). Campaign 4 is ideally for a static blade with very detailed inflow, blade, and wake measurements, more suitable for a wind tunnel or with instrumentation beyond current capabilities, such as field PIV. Campaign 5 also requires detailed inflow, blade, and wake aerodynamic measurements on an ideally relatively rigid blade to limit uncertainty due to blade torsion and flexibility. The wind turbine blades in the RAAW experiment are large and flexible to meet the campaign 9 requirements. However, these flexible blades limit the RAAW experiments application toward the campaign 5 objectives on detailed wake measurement for specific flow phenomena such as the tip vortex. RAAW addresses campaign 6 sufficiently by combining a high-resolution scanning lidar system with detailed blade surface pressure measurements at 5 spanwise stations and detailed, synchronized inflow measurements. Campaigns 7 and 8 are not addressed due to the lack of wake interaction.

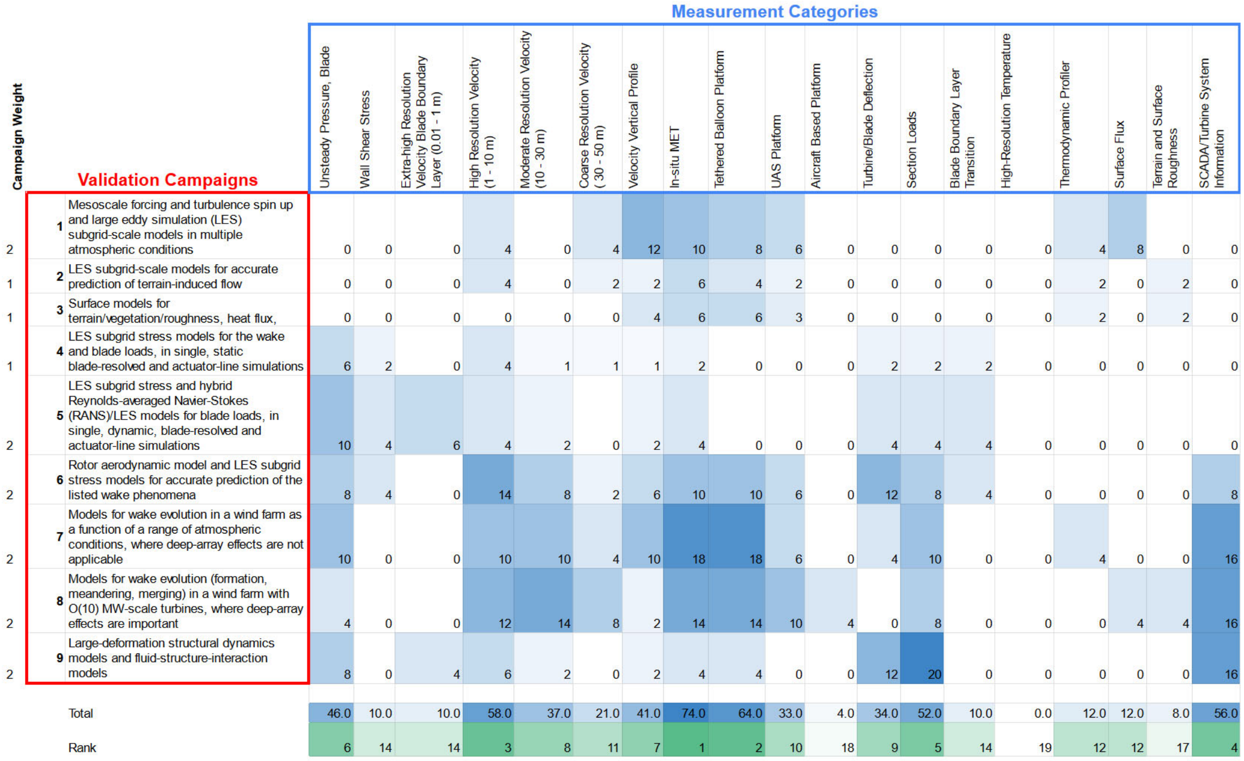
The Wake Management experiment has been proposed for an experimental facility with multiple turbines and involves two or three scaled (~30-m diameter) heavily instrumented rotors, with detailed blade aerodynamic and structural measurements, and detailed wake instrumentation. The experiment would involve taking data over several months to capture the effect of atmospheric stability, intentional yaw offset, blade static and dynamic pitching, and possibly other factors on the development of the wake and its dynamics and effects on downstream rotors. This experiment was weighted in Figure 5-5 to primarily focus on rotor aerodynamic modeling, near-wake modeling, and turbine-to-turbine interaction. Some weight was also given for fluid structure interaction, as the detailed open-source aeroelastic model and measurements of the blades would be useful as a public aeroelastic reference model. For wake evolution in a cluster, this experiment was rated a 1.25 (Figure 5-5), as it would meet the wake interaction requirements with either 2 or 3 turbines operating together to capture a range of wake interactions that occur in a turbine cluster. A turbine cluster is typically defined as 3 to 5 turbines, although the range of wake interactions defined in the HFM validation roadmap could be captured by a minimum of two turbines with three having complete coverage. Validation campaigns 6 and 7 received scores greater than 1 due to the wake measurements exceeding the basic requirements of the campaigns, but the scores were limited below 2 due to scaling effects limiting some of the physics present for atmosphere to turbine interaction.

5.3.2. Validation Campaign to Measurement Category Mapping Results

The prioritization of the validation campaign focus for each experiment (Figure 5-5) was then combined with the mapping of V&V campaigns to measurements (Figure 5-1) to give the prioritized measurement category map for each idealized and actual experiment. Examples of the combination process are displayed in Figures 5-6 and 5-7. These measurement category to validation campaign maps are then summed to give a final relative measurement category ranking for each experiment. This final ranking is then explored in relative priority order of each experiment.

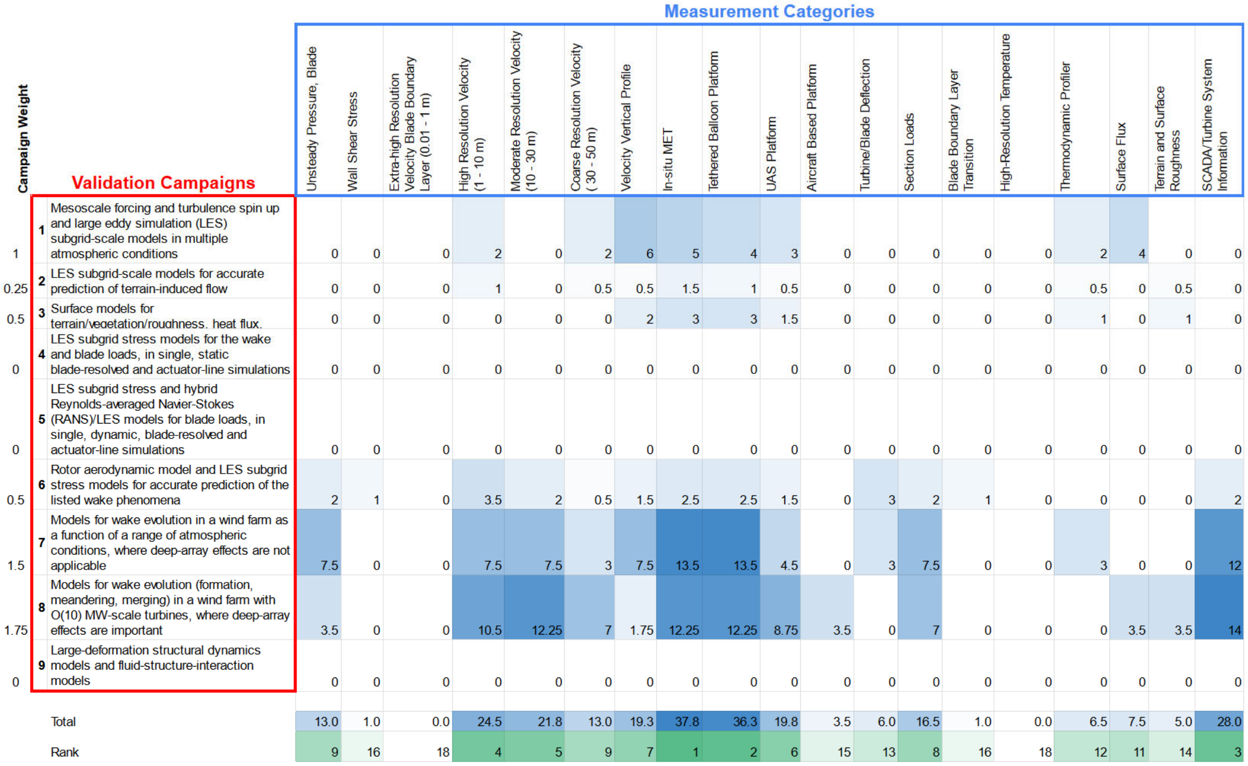
The final row in each of the validation-campaign to measurement category maps (labeled “Rank”) were then combined to give relative measurement category rankings for all the experiments, shown in Figure 5-8. The AWAKEN science goal (Section 3) and RAAW experimental goal (Section 4) mappings are also included here for comparison with those separate instrument prioritization processes.

The relative measurement category rankings are shown in order for each experiment in Figure 5-9 and represent the prioritized measurement categories (and the associated instruments) for each experiment (Figure 5-5). Each measurement category has the same color coding for the top ten instruments in each experiment category.



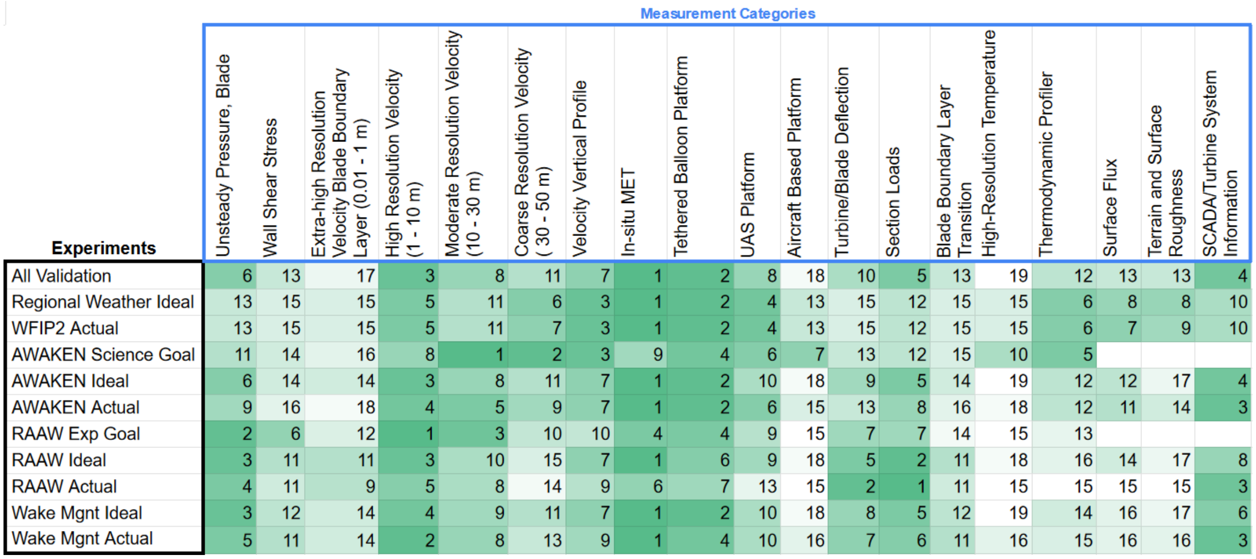
Campaign Weight		Validation Campaigns	Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler	Surface Flux	Terrain and Surface Roughness	SCADA/Turbine System Information
2	1	Mesoscale forcing and turbulence spin up and large eddy simulation (LES) subgrid-scale models in multiple atmospheric conditions	0	0	0	4	0	4	12	10	8	6	0	0	0	0	0	4	8	0	0
1	2	LES subgrid-scale models for accurate prediction of terrain-induced flow	0	0	0	4	0	2	2	6	4	2	0	0	0	0	0	2	0	2	0
1	3	Surface models for terrain/vegetation/roughness, heat flux,	0	0	0	0	0	0	4	6	6	3	0	0	0	0	0	2	0	2	0
1	4	LES subgrid stress models for the wake and blade loads, in single, static blade-resolved and actuator-line simulations	6	2	0	4	1	1	1	2	0	0	0	2	2	2	0	0	0	0	0
2	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	10	4	6	4	2	0	2	4	0	0	0	4	4	4	0	0	0	0	0
2	6	Rotor aerodynamic model and LES subgrid stress models for accurate prediction of the listed wake phenomena	8	4	0	14	8	2	6	10	10	6	0	12	8	4	0	0	0	0	8
2	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	10	0	0	10	10	4	10	18	18	6	0	4	10	0	0	4	0	0	16
2	8	Models for wake evolution (formation, meandering, merging) in a wind farm with O(10) MW-scale turbines, where deep-array effects are important	4	0	0	12	14	8	2	14	14	10	4	0	8	0	0	0	4	4	16
2	9	Large-deformation structural dynamics models and fluid-structure-interaction models	8	0	4	6	2	0	2	4	4	0	0	12	20	0	0	0	0	0	16
		Total	46.0	10.0	10.0	58.0	37.0	21.0	41.0	74.0	64.0	33.0	4.0	34.0	52.0	10.0	0.0	12.0	12.0	8.0	56.0
		Rank	6	14	14	3	8	11	7	1	2	10	18	9	5	14	19	12	12	17	4

Figure 5-6. Validation campaign needs to measurement category mapping: AWAKEN Ideal.



Campaign Weight		Validation Campaigns	Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler	Surface Flux	Terrain and Surface Roughness	SCADA/Turbine System Information
1	1	Mesoscale forcing and turbulence spin up and large eddy simulation (LES) subgrid-scale models in multiple atmospheric conditions	0	0	0	2	0	2	6	5	4	3	0	0	0	0	0	2	4	0	0
0.25	2	LES subgrid-scale models for accurate prediction of terrain-induced flow	0	0	0	1	0	0.5	0.5	1.5	1	0.5	0	0	0	0	0	0.5	0	0.5	0
0.5	3	Surface models for terrain/vegetation/roughness, heat flux,	0	0	0	0	0	0	2	3	3	1.5	0	0	0	0	0	1	0	1	0
0	4	LES subgrid stress models for the wake and blade loads, in single, static blade-resolved and actuator-line simulations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	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	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	6	Rotor aerodynamic model and LES subgrid stress models for accurate prediction of the listed wake phenomena	2	1	0	3.5	2	0.5	1.5	2.5	2.5	1.5	0	3	2	1	0	0	0	0	2
1.5	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	7.5	0	0	7.5	7.5	3	7.5	13.5	13.5	4.5	0	3	7.5	0	0	3	0	0	12
1.75	8	Models for wake evolution (formation, meandering, merging) in a wind farm with O(10) MW-scale turbines, where deep-array effects are important	3.5	0	0	10.5	12.25	7	1.75	12.25	12.25	8.75	3.5	0	7	0	0	0	3.5	3.5	14
0	9	Large-deformation structural dynamics models and fluid-structure-interaction models	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Total	13.0	1.0	0.0	24.5	21.8	13.0	19.3	37.8	36.3	19.8	3.5	6.0	16.5	1.0	0.0	6.5	7.5	5.0	28.0
		Rank	9	16	18	4	5	9	7	1	2	6	15	13	8	16	18	12	11	14	3

Figure 5-7. Validation campaign needs to measurement category mapping: AWAKEN Actual.



Experiments	Measurement Categories																		
	Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler	Surface Flux	Terrain and Surface Roughness	SCADA/Turbine System Information
All Validation	6	13	17	3	8	11	7	1	2	8	18	10	5	13	19	12	13	13	4
Regional Weather Ideal	13	15	15	5	11	6	3	1	2	4	13	15	12	15	15	6	8	8	10
WFIP2 Actual	13	15	15	5	11	7	3	1	2	4	13	15	12	15	15	6	7	9	10
AWAKEN Science Goal	11	14	16	8	1	2	3	9	4	6	7	13	12	15	10	5			
AWAKEN Ideal	6	14	14	3	8	11	7	1	2	10	18	9	5	14	19	12	12	17	4
AWAKEN Actual	9	16	18	4	5	9	7	1	2	6	15	13	8	16	18	12	11	14	3
RAAW Exp Goal	2	6	12	1	3	10	10	4	4	9	15	7	7	14	15	13			
RAAW Ideal	3	11	11	3	10	15	7	1	6	9	18	5	2	11	18	16	14	17	8
RAAW Actual	4	11	9	5	8	14	9	6	7	13	15	2	1	11	15	15	15	15	3
Wake Mgnt Ideal	3	12	14	4	9	11	7	1	2	10	18	8	5	12	19	14	16	17	6
Wake Mgnt Actual	5	11	14	2	8	13	9	1	4	10	16	7	6	11	16	15	16	16	3

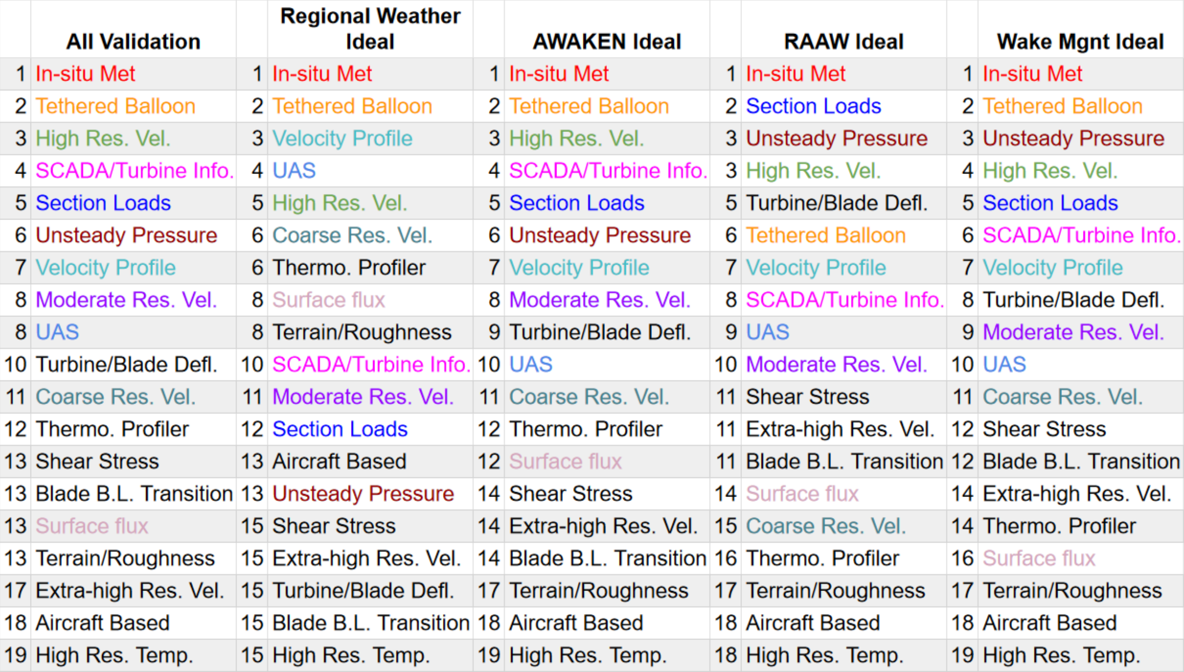
Figure 5-8. Final measurement category ranking for each experiment.

	All Validation		Regional Weather Ideal		WFIP2 Actual		AWAKEN Science Goal		AWAKEN Ideal		AWAKEN Actual		RAAW Exp Goal		RAAW Ideal		RAAW Actual		Wake Mgnt Ideal		Wake Mgnt Actual
1	In-situ Met	1	In-situ Met	1	In-situ Met	1	Moderate Res. Vel.	1	In-situ Met	1	In-situ Met	1	High Res. Vel.	1	In-situ Met	1	Section Loads	1	In-situ Met	1	In-situ Met
2	Tethered Balloon	2	Tethered Balloon	2	Tethered Balloon	2	Coarse Res. Vel.	2	Tethered Balloon	2	Tethered Balloon	2	Unsteady Pressure	2	Section Loads	2	Turbine/Blade Defl.	2	Tethered Balloon	2	High Res. Vel.
3	High Res. Vel.	3	Velocity Profile	3	Velocity Profile	3	Velocity Profile	3	High Res. Vel.	3	SCADA and Turbine Info.	3	Moderate Res. Vel.	3	Unsteady Pressure	3	SCADA and Turbine Info.	3	Unsteady Pressure	3	SCADA and Turbine Info.
4	SCADA and Turbine Info.	4	UAS	4	UAS	4	Tethered Balloon	4	SCADA and Turbine Info.	4	High Res. Vel.	4	In-situ Met	3	High Res. Vel.	4	Unsteady Pressure	4	High Res. Vel.	4	Tethered Balloon
5	Section Loads	5	High Res. Vel.	5	High Res. Vel.	5	Thermo. Profiler	5	Section Loads	5	Moderate Res. Vel.	4	Tethered Balloon	5	Turbine/Blade Defl.	5	High Res. Vel.	5	Section Loads	5	Unsteady Pressure
6	Unsteady Pressure	6	Coarse Res. Vel.	6	Thermo. Profiler	6	UAS	6	Unsteady Pressure	6	UAS	6	Shear Stress	6	Tethered Balloon	6	In-situ Met	6	SCADA and Turbine Info.	6	Section Loads
7	Velocity Profile	6	Thermo. Profiler	7	Coarse Res. Vel.	7	Aircraft Based	7	Velocity Profile	7	Velocity Profile	7	Turbine/Blade Defl.	7	Velocity Profile	7	Tethered Balloon	7	Velocity Profile	7	Turbine/Blade Defl.
8	Moderate Res. Vel.	8	Surface flux	7	Surface flux	8	High Res. Vel.	8	Moderate Res. Vel.	8	Section Loads	7	Section Loads	8	SCADA and Turbine Info.	8	Moderate Res. Vel.	8	Turbine/Blade Defl.	8	Moderate Res. Vel.
8	UAS	8	Terrain and Roughness	9	Terrain and Roughness	9	In-situ Met	9	Turbine/Blade Defl.	9	Unsteady Pressure	9	UAS	9	UAS	9	Extra-high Res. Vel.	9	Moderate Res. Vel.	9	Velocity Profile
10	Turbine/Blade Defl.	10	SCADA and Turbine Info.	10	SCADA and Turbine Info.	10	High Res. Temp.	10	UAS	9	Coarse Res. Vel.	10	Coarse Res. Vel.	10	Moderate Res. Vel.	9	Velocity Profile	10	UAS	10	UAS
11	Coarse Res. Vel.	11	Moderate Res. Vel.	11	Moderate Res. Vel.	11	Unsteady Pressure	11	Coarse Res. Vel.	11	Surface flux	10	Velocity Profile	11	Shear Stress	11	Shear Stress	11	Coarse Res. Vel.	11	Shear Stress
12	Thermo. Profiler	12	Section Loads	12	Section Loads	12	Section Loads	12	Thermo. Profiler	12	Thermo. Profiler	12	Extra-high Res. Vel.	11	Extra-high Res. Vel.	11	Blade B.L. Transition	12	Shear Stress	11	Blade B.L. Transition
13	Shear Stress	13	Aircraft Based	13	Unsteady Pressure	13	Turbine/Blade Defl.	12	Surface flux	13	Turbine/Blade Defl.	13	Thermo. Profiler	11	Blade B.L. Transition	13	UAS	12	Blade B.L. Transition	13	Coarse Res. Vel.
13	Blade B.L. Transition	13	Unsteady Pressure	13	Aircraft Based	14	Shear Stress	14	Shear Stress	14	Terrain and Roughness	14	Blade B.L. Transition	14	Surface flux	14	Coarse Res. Vel.	14	Extra-high Res. Vel.	14	Extra-high Res. Vel.
13	Surface flux	15	Shear Stress	15	Shear Stress	15	Blade B.L. Transition	14	Extra-high Res. Vel.	15	Aircraft Based	15	Aircraft Based	15	Coarse Res. Vel.	15	Aircraft Based	14	Thermo. Profiler	15	Thermo. Profiler
13	Terrain and Roughness	15	Extra-high Res. Vel.	15	Extra-high Res. Vel.	16	Extra-high Res. Vel.	14	Blade B.L. Transition	16	Shear Stress	15	High Res. Temp.	16	Thermo. Profiler	15	High Res. Temp.	16	Surface flux	16	Aircraft Based
17	Extra-high Res. Vel.	15	Turbine/Blade Defl.	15	Turbine/Blade Defl.		Surface flux	17	Terrain and Roughness	16	Blade B.L. Transition		Surface flux	17	Terrain and Roughness	15	Thermo. Profiler	17	Terrain and Roughness	16	High Res. Temp.
18	Aircraft Based	15	Blade B.L. Transition	15	Blade B.L. Transition		Terrain and Roughness	18	Aircraft Based	18	Extra-high Res. Vel.		Terrain and Roughness	18	Aircraft Based	15	Surface flux	18	Aircraft Based	16	Surface flux
19	High Res. Temp.	15	High Res. Temp.	15	High Res. Temp.		SCADA and Turbine Info.	19	High Res. Temp.	18	High Res. Temp.		SCADA and Turbine Info.	18	High Res. Temp.	15	Terrain and Roughness	19	High Res. Temp.	16	Terrain and Roughness

Figure 5-9. Measurement category relative priority for each experiment.

5.4. Interpretation of Validation Measurement Needs

The results of the prioritized measurement system ranking process (see Figure 5-9) are examined in this section. The ‘All Validation’ category is compared to the idealized experiments in Figure 5-10. The ‘Regional Weather Ideal’ and ‘All Validation’ experiments have similar results for the first 5 measurement categories due to the importance of inflow to all validation campaigns. For the other idealized experiments, measurements related to turbine loads, blade aerodynamics, and wake measurements come next. The main distinction of the ‘Regional Weather Ideal’ experiment is the relative higher importance of atmospheric measurements, as is expected. The high-resolution velocity measurements are within the top five of the ‘Regional Weather Ideal’ experiment because of the emphasis on subgrid-scale velocity measurement requirements in campaign 1.

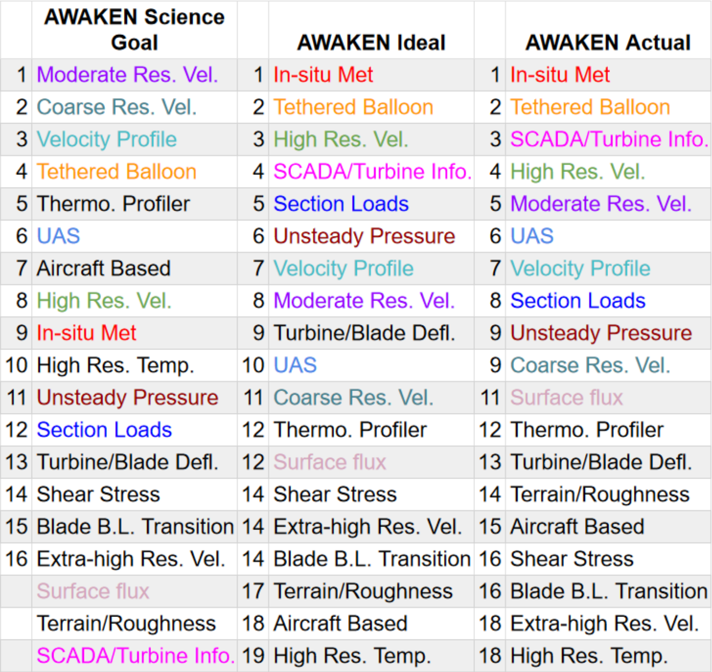


	All Validation		Regional Weather Ideal		AWAKEN Ideal		RAAW Ideal		Wake Mgnt Ideal
1	In-situ Met	1	In-situ Met	1	In-situ Met	1	In-situ Met	1	In-situ Met
2	Tethered Balloon	2	Tethered Balloon	2	Tethered Balloon	2	Section Loads	2	Tethered Balloon
3	High Res. Vel.	3	Velocity Profile	3	High Res. Vel.	3	Unsteady Pressure	3	Unsteady Pressure
4	SCADA/Turbine Info.	4	UAS	4	SCADA/Turbine Info.	3	High Res. Vel.	4	High Res. Vel.
5	Section Loads	5	High Res. Vel.	5	Section Loads	5	Turbine/Blade Defl.	5	Section Loads
6	Unsteady Pressure	6	Coarse Res. Vel.	6	Unsteady Pressure	6	Tethered Balloon	6	SCADA/Turbine Info.
7	Velocity Profile	6	Thermo. Profiler	7	Velocity Profile	7	Velocity Profile	7	Velocity Profile
8	Moderate Res. Vel.	8	Surface flux	8	Moderate Res. Vel.	8	SCADA/Turbine Info.	8	Turbine/Blade Defl.
8	UAS	8	Terrain/Roughness	9	Turbine/Blade Defl.	9	UAS	9	Moderate Res. Vel.
10	Turbine/Blade Defl.	10	SCADA/Turbine Info.	10	UAS	10	Moderate Res. Vel.	10	UAS
11	Coarse Res. Vel.	11	Moderate Res. Vel.	11	Coarse Res. Vel.	11	Shear Stress	11	Coarse Res. Vel.
12	Thermo. Profiler	12	Section Loads	12	Thermo. Profiler	11	Extra-high Res. Vel.	12	Shear Stress
13	Shear Stress	13	Aircraft Based	12	Surface flux	11	Blade B.L. Transition	12	Blade B.L. Transition
13	Blade B.L. Transition	13	Unsteady Pressure	14	Shear Stress	14	Surface flux	14	Extra-high Res. Vel.
13	Surface flux	15	Shear Stress	14	Extra-high Res. Vel.	15	Coarse Res. Vel.	14	Thermo. Profiler
13	Terrain/Roughness	15	Extra-high Res. Vel.	14	Blade B.L. Transition	16	Thermo. Profiler	16	Surface flux
17	Extra-high Res. Vel.	15	Turbine/Blade Defl.	17	Terrain/Roughness	17	Terrain/Roughness	17	Terrain/Roughness
18	Aircraft Based	15	Blade B.L. Transition	18	Aircraft Based	18	Aircraft Based	18	Aircraft Based
19	High Res. Temp.	15	High Res. Temp.	19	High Res. Temp.	18	High Res. Temp.	19	High Res. Temp.

Figure 5-10. Measurement category relative priority for each experiment: Ideal.

The three mappings for AWAKEN are shown in Figure 5-11. The ‘AWAKEN Science Goal’ mapping comes from the process outlined in Section 3, while the ‘AWAKEN Ideal’ and ‘AWAKEN Actual’ mappings come from the validation campaign mapping process described previously in this section. In the envisioned actual AWAKEN experiment, the blade load, aerodynamic, and high-resolution wake measurements have moved lower in priority relative to the idealized experiment due to limitations and availability of systems to measure these quantities at a full wind turbine scale. Development of measurement technology for these areas would allow an experiment like AWAKEN to capture the measurements listed in the idealized experiment in the future.

The science goal mapping process resulted in generally less emphasis on blade and turbine load measurements, on high resolution wake measurements, and in situ met measurements. In exchange, it placed greater emphasis on moderate and coarse resolution flow field measurements. This difference is likely due to the validation process placing emphasis on the importance of inflow measurements to correlate with turbine and wake measurements as being critical to enable model validation. This result underpins the fact that initial and boundary conditions are critical for model validation, whereas these measurements are less important for meeting science goals.

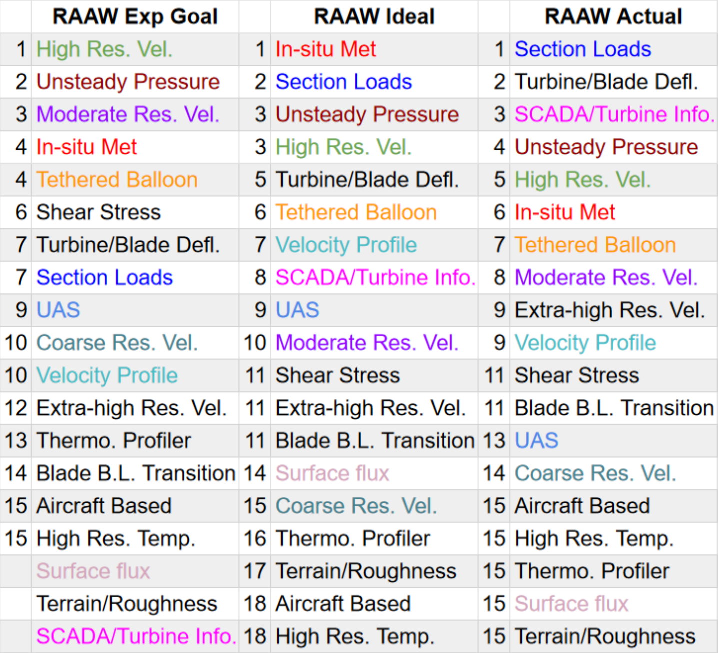


	AWAKEN Science Goal		AWAKEN Ideal		AWAKEN Actual
1	Moderate Res. Vel.	1	In-situ Met	1	In-situ Met
2	Coarse Res. Vel.	2	Tethered Balloon	2	Tethered Balloon
3	Velocity Profile	3	High Res. Vel.	3	SCADA/Turbine Info.
4	Tethered Balloon	4	SCADA/Turbine Info.	4	High Res. Vel.
5	Thermo. Profiler	5	Section Loads	5	Moderate Res. Vel.
6	UAS	6	Unsteady Pressure	6	UAS
7	Aircraft Based	7	Velocity Profile	7	Velocity Profile
8	High Res. Vel.	8	Moderate Res. Vel.	8	Section Loads
9	In-situ Met	9	Turbine/Blade Defl.	9	Unsteady Pressure
10	High Res. Temp.	10	UAS	9	Coarse Res. Vel.
11	Unsteady Pressure	11	Coarse Res. Vel.	11	Surface flux
12	Section Loads	12	Thermo. Profiler	12	Thermo. Profiler
13	Turbine/Blade Defl.	12	Surface flux	13	Turbine/Blade Defl.
14	Shear Stress	14	Shear Stress	14	Terrain/Roughness
15	Blade B.L. Transition	14	Extra-high Res. Vel.	15	Aircraft Based
16	Extra-high Res. Vel.	14	Blade B.L. Transition	16	Shear Stress
	Surface flux	17	Terrain/Roughness	16	Blade B.L. Transition
	Terrain/Roughness	18	Aircraft Based	18	Extra-high Res. Vel.
	SCADA/Turbine Info.	19	High Res. Temp.	18	High Res. Temp.

Figure 5-11. Measurement category relative priority for each experiment: AWAKEN.

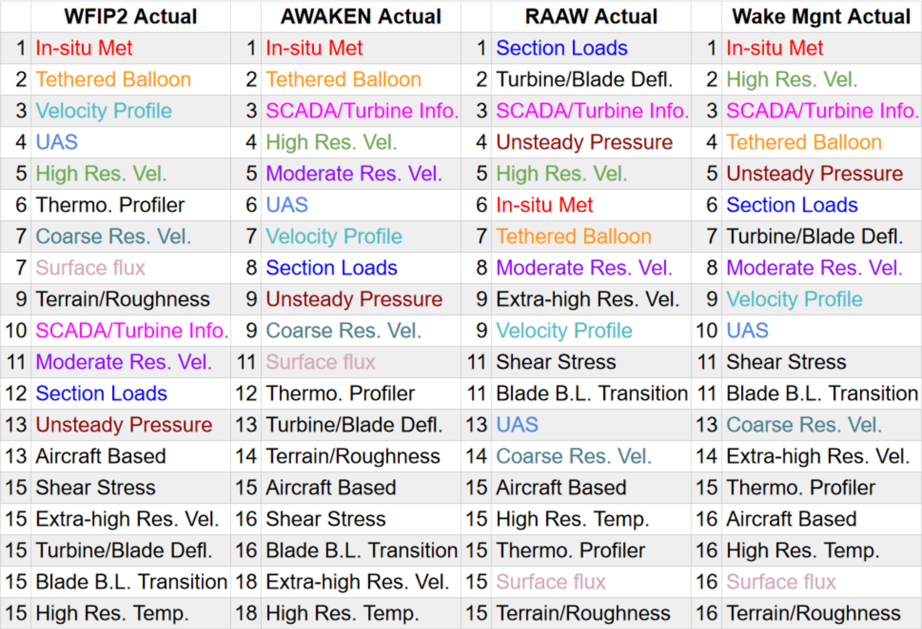
Figure 5-12 shows the same three different measurement category rankings for the RAAW experiment as was compiled for the AWAKEN experiment. High-resolution wake measurements are shown to be important for this experiment due to the emphasis on capturing the effect of blade aerodynamics on wake dynamics. Inflow measurements are shown to be important, as the inflow conditions can dominate the effects of other physical phenomena. Blade deflection was also ranked relatively high in the ideal and actual experiment validation rankings due to its strong presence in validation campaign 9; as shown in the experiment goals, this is a critical measurement for the RAAW experiment to meet its fluid structure interaction (FSI) focus. The unsteady pressure and section loads are also critical measurements for the RAAW experiment, as they appear near the top of the ranking for each of the categorizing methods. This result matches the primary focus and need of RAAW, focusing on FSI, blade aerodynamics, and near-wake measurements.

The envisioned actual experiments are compared in Figure 5-13. The WFIP2 and AWAKEN experiments place emphasis on met measurements and high-altitude atmospheric measurements, as well as large field velocity scans with UAS systems. The AWAKEN experiment places increased emphasis on high-resolution velocity measurements due to the need to capture the detailed inflow and wake interaction between turbines. SCADA measurements and turbine information are also very important for AWAKEN due to the need for turbine load, power production statistics, and system response information for wake validation studies. Section loads are important to AWAKEN, showing an area where additional instrument development could help bring such measurements to utility turbine validation studies. Section loads are critical for the RAAW experiment, as well as very important for the Wake Management experiment to meet detailed wake model validation goals. High-resolution velocity measurements of the wake are very important for AWAKEN, RAAW, and the Wake Management projects, as is inflow, with ABL velocity profiles being more important for Wake Management due to the increased focus on wake interaction campaigns. Unsteady blade surface pressure measurements are also relatively important for both the RAAW and Wake Management experiments, with increased importance being placed on RAAW due to the importance of this measurement for fluid structure interaction and blade aerodynamics model validation campaigns.



	RAAW Exp Goal		RAAW Ideal		RAAW Actual
1	High Res. Vel.	1	In-situ Met	1	Section Loads
2	Unsteady Pressure	2	Section Loads	2	Turbine/Blade Defl.
3	Moderate Res. Vel.	3	Unsteady Pressure	3	SCADA/Turbine Info.
4	In-situ Met	3	High Res. Vel.	4	Unsteady Pressure
4	Tethered Balloon	5	Turbine/Blade Defl.	5	High Res. Vel.
6	Shear Stress	6	Tethered Balloon	6	In-situ Met
7	Turbine/Blade Defl.	7	Velocity Profile	7	Tethered Balloon
7	Section Loads	8	SCADA/Turbine Info.	8	Moderate Res. Vel.
9	UAS	9	UAS	9	Extra-high Res. Vel.
10	Coarse Res. Vel.	10	Moderate Res. Vel.	9	Velocity Profile
10	Velocity Profile	11	Shear Stress	11	Shear Stress
12	Extra-high Res. Vel.	11	Extra-high Res. Vel.	11	Blade B.L. Transition
13	Thermo. Profiler	11	Blade B.L. Transition	13	UAS
14	Blade B.L. Transition	14	Surface flux	14	Coarse Res. Vel.
15	Aircraft Based	15	Coarse Res. Vel.	15	Aircraft Based
15	High Res. Temp.	16	Thermo. Profiler	15	High Res. Temp.
	Surface flux	17	Terrain/Roughness	15	Thermo. Profiler
	Terrain/Roughness	18	Aircraft Based	15	Surface flux
	SCADA/Turbine Info.	18	High Res. Temp.	15	Terrain/Roughness

Figure 5-12. Measurement category relative priority for each experiment: RAAW.



	WFIP2 Actual		AWAKEN Actual		RAAW Actual		Wake Mgnt Actual
1	In-situ Met	1	In-situ Met	1	Section Loads	1	In-situ Met
2	Tethered Balloon	2	Tethered Balloon	2	Turbine/Blade Defl.	2	High Res. Vel.
3	Velocity Profile	3	SCADA/Turbine Info.	3	SCADA/Turbine Info.	3	SCADA/Turbine Info.
4	UAS	4	High Res. Vel.	4	Unsteady Pressure	4	Tethered Balloon
5	High Res. Vel.	5	Moderate Res. Vel.	5	High Res. Vel.	5	Unsteady Pressure
6	Thermo. Profiler	6	UAS	6	In-situ Met	6	Section Loads
7	Coarse Res. Vel.	7	Velocity Profile	7	Tethered Balloon	7	Turbine/Blade Defl.
7	Surface flux	8	Section Loads	8	Moderate Res. Vel.	8	Moderate Res. Vel.
9	Terrain/Roughness	9	Unsteady Pressure	9	Extra-high Res. Vel.	9	Velocity Profile
10	SCADA/Turbine Info.	9	Coarse Res. Vel.	9	Velocity Profile	10	UAS
11	Moderate Res. Vel.	11	Surface flux	11	Shear Stress	11	Shear Stress
12	Section Loads	12	Thermo. Profiler	11	Blade B.L. Transition	11	Blade B.L. Transition
13	Unsteady Pressure	13	Turbine/Blade Defl.	13	UAS	13	Coarse Res. Vel.
13	Aircraft Based	14	Terrain/Roughness	14	Coarse Res. Vel.	14	Extra-high Res. Vel.
15	Shear Stress	15	Aircraft Based	15	Aircraft Based	15	Thermo. Profiler
15	Extra-high Res. Vel.	16	Shear Stress	15	High Res. Temp.	16	Aircraft Based
15	Turbine/Blade Defl.	16	Blade B.L. Transition	15	Thermo. Profiler	16	High Res. Temp.
15	Blade B.L. Transition	18	Extra-high Res. Vel.	15	Surface flux	16	Surface flux
15	High Res. Temp.	18	High Res. Temp.	15	Terrain/Roughness	16	Terrain/Roughness

Figure 5-13. Relative ranking in measurement categories for the envisioned actual experiments.

6. INSTRUMENT FEASIBILITY SCORING

To create a uniform metric, considering the feasibility of a given measurement category or a measurement platform for a project, an instrument feasibility scoring metric was defined. The instrument feasibility scoring method explained below provides a methodology to calculate a total score (the overall feasibility score for an instrument) metric for each instrument that is planned to be deployed for a given test campaign. Based on the overall feasibility scoring, the principal investigators can assess if a given instrument is more suitable than others to meet their research objectives.

6.1. Instrument Feasibility Categories

Five instrument feasibility categories are defined to rank each instrument for a given project. The categories are: a) Suitability, b) Timeline, c) Development Cost, d) Development Uncertainty, and e) Logistics. Below we define each category and provide scoring metrics for each category.

The Suitability of an instrument meeting the research needs of a given project is key for deploying the instrument. Based on the science goals for a given project, the suitability of a given instrument can be determined. For example, does the instrument meet the spatial and temporal resolution needed for the science objectives? Is it sufficiently easy to use in the field? How well does the instrument capture the phenomenon of interest? The scoring metric for the Suitability of a given instrument is given below:

Score 0 - Doesn't capture quantities of interest with sufficient resolution or accuracy

Score 1 - Makes notional contribution to observational capability, e.g., more than one of the following:

- measurements have high uncertainty
- resolution requirements not met
- indirect observation of quantities of interest

Score 2 - Instrument makes observations that partially contribute to understanding phenomena of interest, but does not significantly progress measurement capability

Score 3 - Makes significant (but incomplete) contribution to observational capability, e.g., meets requirements except for one of the following:

- measurements have high uncertainty
- resolution requirements not met
- indirect observation of quantities of interest

Score 4 - Can measure multiple phenomena of interest at required resolution and accuracy

Secondly, the Timeline of a given instrument that can support the needs of the research project is considered. For example, if a new instrument takes 4 years for development, it would not be appropriate for a field deployment in 2 years. The scoring metric for the Timeline category is defined below:

Score 0 - Ready to go any time

Score 1 - Development to an acceptable technology readiness level (TRL) level (generally TRL 7) before the field deployment

Score 2 - Development timeline not suitable to deployment for a given project

The Development Cost for an instrument in any project depends on availability of funding to advance the instrument TRL to an acceptable level (generally TRL 7), and if experts have time/personnel to advance the technology. Therefore, the necessary cost and time needed to advance a key instrument for the project should be considered. The scoring metric for the Development Cost is defined below:

Score 0 - Instrument already developed, or funding already secured, personnel and resources available

Score 1 - Some external funding available or project team limited

Score 2 - Project currently unfunded, personnel and resources not available

For wind energy research projects, it is critical to understand the uncertainty of producing and deploying a given instrument. The Development Uncertainty category provides the possibility of a non-cost development risk to advancing a technology to the point of use for wind energy field research. For example, if sources of development uncertainty for an instrument are known, the feasibility of that instrument to be used in the field is higher. The scoring metric for the Development Uncertainty category is defined below:

Score 0 - Path forward is clear, parts/components are widely available, operating principles are clear and tested, instrument has made field observations already

Score 1 - Instrument/principles tested in controlled conditions but not in the final environment, assumptions require continued investigation, parts identified but not acquired, may require moderate fabrication, modification, or assembly

Score 2 - Assumptions remain untested, operation not fully validated, requires sourcing or fabrication of new components

Finally, the Logistics of a test campaign play a crucial role in the feasibility of an instrument to be deployed during a test campaign. For example, onsite power availability, onsite deployability, operability, additional infrastructure needed for an instrument, turbine downtime, safety (electrical, chemical, etc.), or any approval/permitting/licensing requirements. Logistics play a vital role in any test campaign and need to be addressed for feasibility of an instrument to be deployed for prolonged durations. The scoring metric for the Logistics category is defined below:

Score 0 - Easy to deploy and operate, minimal additional infrastructure or equipment required, infrequent calibration or maintenance requirements, safe to operate autonomously without supervision, no turbine downtime (e.g., scanning lidar, thermodynamic profiler, ceilometer)

Score 1 - May require moderate or periodic maintenance or calibration, impose brief or limited turbine downtime, requires moderate support structures or external equipment

Score 2 - Requires significant oversight to operate, difficult or expensive to place on location, calibration sensitive to disturbances or operating environment, contains potentially hazardous components

6.2. Instrument Feasibility Weighting

In this section, we discuss how the individual scores are combined to provide a total feasibility scoring for a given instrument. Each category is weighted depending on the importance of a given category for a test campaign. The importance for each category was defined by the authors below, based on their collective experience in numerous test campaigns. These weights can be adjusted for each research project.

Table 6-1. Weights for each feasibility category.

Category	Weighting (W)*
Suitability (S)	1.25
Timeline (T)	-0.125
Cost (C)	-0.125
Development Uncertainty (DU)	-0.5
Logistics (L)	-0.25

*Negative weightings are to account for the scoring differences between each category.

Instruments with highest Suitability for a test campaign are given the highest priority, as they match the research objectives. The Development Uncertainty is the second highest category because wind energy-related instruments with an unknown development pathway have a higher risk in achieving the estimated suitability for capturing the phenomenon/research objective. Logistics plays a key role in a field deployment campaign and is especially important for long-term deployments. Logistics would impact the placement of certain instruments (e.g., power restrictions) and can impact research objectives. The Timeline and Cost categories are equally weighted, as they are related in several ways. Therefore, the total score for an instrument is given by:

$$Total\ Score = \sum \xi_{score} \times W$$

where ξ_{score} is the score for each feasibility category and W is the weight for each feasibility category shown in Table 6-1. The weights do not sum to 1 and were determined based on relative importance by the authors.

An example calculation for the total score is shown in Table 6-2 for a hypothetical list of 11 instruments. Each feasibility category score (listed in Section 6.1) is multiplied with their corresponding feasibility weighting to calculate the total score. If the total score for a given instrument is high, then the feasibility of using that instrument to attain the objectives of the test campaign are high. In Table 6-2, for instrument 1, the suitability of that instrument for the test campaign is high and also the timeline, cost and development uncertainty matches with the test campaign objective (with the instrument ready for deployment, no additional cost to achieve TRL 7 and the uncertainty framework already known).

Table 6-2. Sample instrument total score calculation.

Instrument	Suitability Score	Timeline Score	Cost Score	Dev Unc. Score	Logistics Score	Total Score
1	3	0	0	0	0	**3.75**
2	2.5	0	0	0	0	**3.125**
3	3	1	1	1	1	**2.75**
4	3	1	1	1	1	**2.75**
5	3.5	2	2	2	1	**2.625**
6	3	1	2	1	1	**2.625**
7	2.5	1	0	1	0	**2.5**
8	2.5	1	0	1	1	**2.25**
9	2.5	1	1	1	2	**1.875**
10	2.5	2	1	2	2	**1.25**
11	2	2	1	2	0	**1.125**

6.3. Feasibility Score Results

The feasibility scoring system was applied to the instrumentation listed in Table 6-3. These scores were compiled from questionnaires provided by developers using the rubric in Section 6.1. Each author applied their scoring interpretation using the rubric and questionnaire answers with the average score listing in Table 6-3. The rankings show that instruments that capture the measurement category needs well have a low development uncertainty, are easy to deploy, and have the highest feasibility score.

Table 6-3. Average instrument feasibility scores.

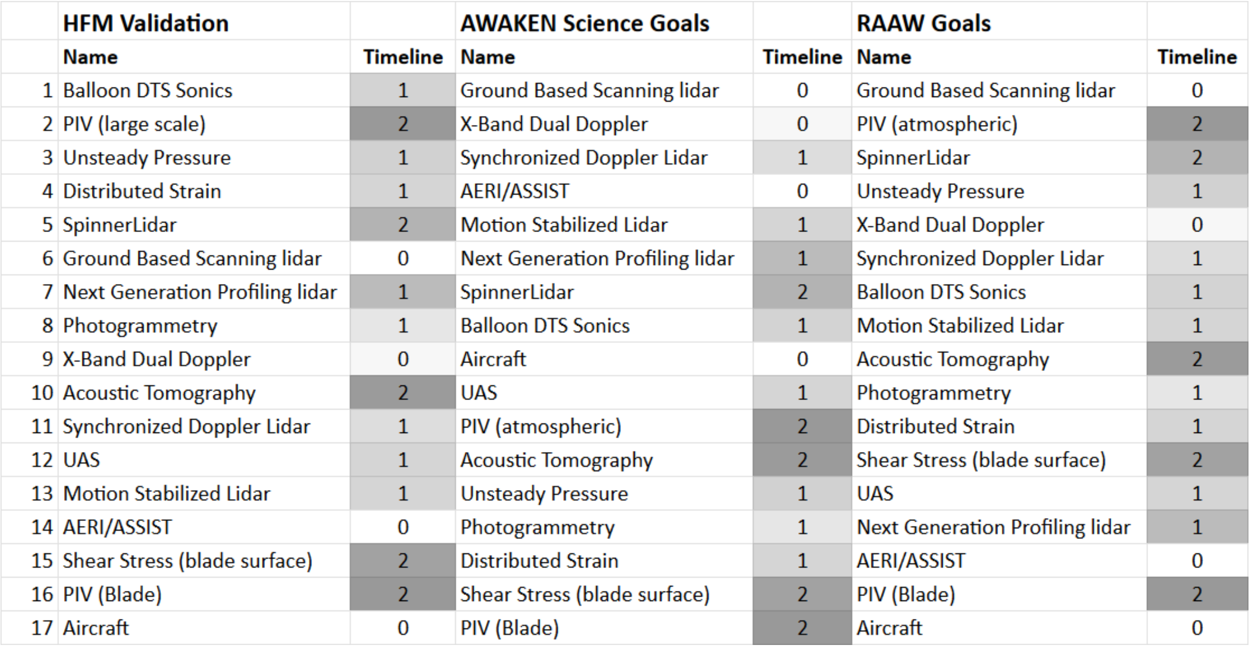
	Instrument	Suitability Score	Timeline Score	Cost Score	Dev Unc. Score	Logistics Score	Total Score
1	Ground Based Scanning Lidar	3.13	0.00	0.25	0.00	0.50	3.75
2	AERI/ASSIST	3.00	0.00	0.25	0.25	0.13	3.56
3	Photogrammetry	3.37	0.50	0.83	0.67	0.83	3.50
4	Aircraft	2.83	0.00	0.33	0.00	0.58	3.35
5	X-Band Dual Doppler	3.21	0.17	0.50	0.50	1.58	3.28
6	Unsteady Pressure	3.17	0.92	0.92	0.67	1.25	3.08
7	Synchronized Doppler Lidar	3.00	0.67	1.00	0.67	0.83	3.00
8	SpinnerLidar	3.23	1.50	2.00	0.98	1.00	2.86
9	Next Generation Profiling Lidar	3.17	1.33	1.00	1.50	0.50	2.79
10	Distributed Strain	3.00	0.83	0.92	0.98	1.08	2.77
11	Balloon DTS Sonics	3.00	0.88	1.00	1.00	1.00	2.77
12	UAS	3.00	0.83	0.75	1.17	1.33	2.64

	Instrument	Suitability Score	Timeline Score	Cost Score	Dev Unc. Score	Logistics Score	Total Score
13	PIV (Large-Scale)	3.38	2.00	1.50	1.63	1.75	2.53
14	Motion Stabilized Lidar	2.83	0.83	1.17	1.00	1.33	2.46
15	PIV (Blade)	3.50	2.00	2.00	2.00	2.00	2.38
16	Shear Stress (Blade Surface)	2.83	1.83	1.33	1.33	1.33	2.15
17	Acoustic Tomography	2.75	1.97	1.00	1.71	1.86	1.74

7. INSTRUMENTATION DEVELOPMENT DISCUSSION

7.1. Instrumentation Total Mapping Score

Recommendations on instrument prioritization for development and utilization can be made based on a total score of the feasibility and measurement category prioritization. The total score for recommendations for developing instruments used to meet a planned science or validation need was calculated by multiplying the feasibility score (Table 6-3) and the corresponding instrument measurement category score (Figures 5-10 through 5-12). Figure 7-1 shows the rankings of instruments for the All HFM Validation Campaign case (Figure 5-10), the AWAKEN Science Goal (Figure 5-10), and RAAW Experimental Goals (Figure 5-12). Using the AWAKEN, RAAW, and all HFM validation measurement categories provides a ranking of instrumentation across the near-term experimental needs.



	HFM Validation		**AWAKEN Science Goals**		**RAAW Goals**	
	Name	**Timeline**	**Name**	**Timeline**	**Name**	**Timeline**
1	Balloon DTS Sonics	1	Ground Based Scanning lidar	0	Ground Based Scanning lidar	0
2	PIV (large scale)	2	X-Band Dual Doppler	0	PIV (atmospheric)	2
3	Unsteady Pressure	1	Synchronized Doppler Lidar	1	SpinnerLidar	2
4	Distributed Strain	1	AERI/ASSIST	0	Unsteady Pressure	1
5	SpinnerLidar	2	Motion Stabilized Lidar	1	X-Band Dual Doppler	0
6	Ground Based Scanning lidar	0	Next Generation Profiling lidar	1	Synchronized Doppler Lidar	1
7	Next Generation Profiling lidar	1	SpinnerLidar	2	Balloon DTS Sonics	1
8	Photogrammetry	1	Balloon DTS Sonics	1	Motion Stabilized Lidar	1
9	X-Band Dual Doppler	0	Aircraft	0	Acoustic Tomography	2
10	Acoustic Tomography	2	UAS	1	Photogrammetry	1
11	Synchronized Doppler Lidar	1	PIV (atmospheric)	2	Distributed Strain	1
12	UAS	1	Acoustic Tomography	2	Shear Stress (blade surface)	2
13	Motion Stabilized Lidar	1	Unsteady Pressure	1	UAS	1
14	AERI/ASSIST	0	Photogrammetry	1	Next Generation Profiling lidar	1
15	Shear Stress (blade surface)	2	Distributed Strain	1	AERI/ASSIST	0
16	PIV (Blade)	2	Shear Stress (blade surface)	2	PIV (Blade)	2
17	Aircraft	0	PIV (Blade)	2	Aircraft	0

Figure 7-1. Measurement category relative priority for each experiment; A timeline score of 0, 1, or 2 means the instrument is ready, requires 1 – 3 years of development, or requires 4 – 10 years of development, respectively.

Table 7-1 groups the instruments near the top of each of these test categories by their development time category to identify those critical instruments that might be prioritized so they may be deployed in future campaigns. Table 7-1 shows the instruments that already exist that are important for all of the HFM V&V campaigns, the AWAKEN science goals, and the RAAW Experimental Goals, while the tethered balloon system with distributed temperature and sonic anemometers, unsteady pressure measurement system, advanced lidar development, next-generation profiling lidar, and distributed strain or photogrammetry of wind turbine blade deformation are all important and could be developed in time for near-term experiments. Large-scale particle image velocimetry, long-range SpinnerLidar, and acoustic tomography will all be valuable for future tests, but their development should start soon to be available in the mid-term. The long-term high-resolution velocity measurements are very important to meet future validation needs but will require investment now for field tests that are not yet planned. Table 7-2 shows the same grouping as Table 7-1 but with slightly less priority of need. This grouping of instrumentation based on timeline shows the instrumentation important for development and when they could be ready to contribute to the field tests.

Table 7-1. Top ranked instrumentation grouped by development time.

Already Developed	1. Ground Based Scanning Lidar 2. X-Band Dual Doppler 3. AERI/ASSIST Profilers
Near Term (1 – 3 years)	1. Balloon DTS w/ Sonics 2. Unsteady Pressure 3. Synchronized Doppler Lidar 4. Motion Stabilized Lidar 5. Next Generation Profiling Lidar 6. Distributed Strain/Photogrammetry
Long Term (4 – 10 years)	1. PIV (Atmospheric, Ground Based) 2. SpinnerLidar (Long-Range) 3. Acoustic Tomography

Table 7-2. Lower ranked instruments that are still important, grouped by development time.

Already Developed	Aircraft
Near Term (1 – 3 years)	UAS
Long Term (4 – 10 years)	Shear Stress

7.2. Instrumentation Gaps Analysis

An additional analysis of gaps within the measurement categories was conducted to provide a recommended roadmap of instrumentation development beyond the grouping of important instrumentation based on their timeline of development shown in Table 7-1. An analysis of gaps in existing instrumentation options was done using a combination of the top ranked measurement categories from Section 5 and the feasibility scores of instruments to determine where instrumentation development can be most impactful for upcoming experiments. Figure 5-10 shows the top ranked measurement categories important for capturing the necessary phenomena for all nine validation campaigns. The top ten measurement categories can be grouped as shown in Table 7-3 to help evaluate development needs.

Table 7-3. Grouping of measurement categories important for all validation campaigns.

Group Number	Group Description	Measurement Categories
1.	Velocity profile measurements across the wind turbine inflow or wake with turbulence spectra measurements	In-situ met, tethered balloon, velocity profile
2.	High-spatial resolution velocity measurements capturing the rotor inflow and/or near wake formation as well as subgrid-scale atmospheric turbulence	High-resolution velocity
3.	Wind turbine information and SCADA measurements to know the wind turbine state during experiments	SCADA/turbine info
4.	Wind turbine blade section loads and deflection	Section loads, blade/deflection
5.	Unsteady pressure measurements along the blade	Unsteady pressure
6.	Moderate-spatial resolution velocity measurements and unmanned aerial system measurements capturing a larger area of wind turbine and wind plant phenomena	Moderate resolution velocity
7.	Velocity, pressure, and temperature measurements across a large area capturing wind turbine and wind plant phenomena	UAS

The in-situ met, tethered balloon, and velocity profiler (such as sodar or lidar profilers) categories can be grouped as a velocity profile measurement spanning the wind turbine rotor in height with sufficient turbulence characterization, either for inflow measurements or wake measurements. During experiments, these inflow measurements are required but installing a met mast of sufficient height (wind turbine hub-height and above) is usually prohibitively expensive and difficult to install in suitable quantity for the goals of the experiment. This grouping of measurement categories becomes a more cost-effective method for replacing met masts with adequately similar measurements. A tethered balloon system or profiling lidar could be sufficiently developed to meet this measurement gap.

The high spatial resolution velocity measurements stay as their own group requiring instruments that can capture an area of velocity at 1–10 m resolution. These measurements include inflow, near wake formation, and subgrid-scale atmospheric turbulence. The upper end (coarser resolutions) of the resolution requirements could be met with development of a long range continuous-wave scanning lidar, such as the Technical University of Denmark (DTU) SpinnerLidar, capable of measuring the inflow of a large rotor to correlate with blade loading and wake measurements within one diameter downstream. Near wake measurements near the smaller end (finer resolution) of the resolution requirements would require the longer-term development of a large-scale PIV or acoustic tomography system to meet the spatial resolution needs within this measurement category.

Wind turbine information and SCADA data are necessary for logging the state of the wind turbine during experiments. The necessary sensors within this category already exist but additional development could be done to create more robust sensors with better logistics for installing, data connection, and widespread implementation. An example is a differential GPS system that provides yaw heading with low uncertainty without the need to install a yaw encoder. Multiple sensors providing redundant measurements are also helpful as sensors invariably cease to operate during testing. The wind turbine blade section loads and blade deflection measurement categories were included in the same grouping to provide the strain and distributed forces on the wind turbine rotor. Distributed strain instruments already exist, such as foil or fiber Bragg grating sensors, though the logistics of installation are cumbersome. Ground-based photogrammetry and digital image correlation (DIC) systems exist but are not yet widely used at the scale of modern wind turbines. Additional development could increase the prevalence of these types of blade measurements. Blade-mounted systems have also been used in the past but development of a ground-based system, with similar effectiveness, would help with deployment logistics. Unsteady pressure measurements exist as their own grouping to provide the aerodynamic pressure distribution measurements at various stations on the blade for comparisons with models. The unsteady pressure measurement category currently has a gap in instrumentation to meet its requirements. Instrumentation development is needed to capture pressure measurements on modern utility-scale wind turbines.

The moderate-spatial resolution velocity measurement category is an important category for the near-term and planned experiments and validation needs for HFM. Many instruments are already developed to meet a lot of the requirements of this measurement category. Both ground-based and nacelle mounted scanning lidars meet many of the measurement criteria for this category in addition to the X-band dual Doppler radars. Additional development on lidar such as synchronization and motion stabilization would provide additional accuracy and spatial variability in these measurements. Further into the future, additional lidar and radar developments to improve turbulence measurements that require higher spatial and temporal resolution will also contribute to the development needs of this category. Thus, this measurement category can be improved upon with instrumentation development but overall has fewer gaps than the previously mentioned groups. The UAS platform can also further be developed to capture velocity, pressure, and temperature throughout the wind plant observing both the effects of single turbines as well as wind plant effects.

7.3. Recommended Development Path

Table 7-4 lists the instruments with feasibility scores from Table 6-3 that fit into each measurement category group. The corresponding average development timeline and total score are included for each grouping. The timeline score indicates the average development time left for the grouping, whereas the total score provides a guide for prioritizing instrumentation development. Remember that the timeline score is based on the rubric in Section 6 and is not listed as years in Table 7-4. Based on the timeline and total score of the groupings, the instrumentation development roadmap timeline in Figure 7-2 is recommended as a guide for the development of instrumentation. The measurement category groupings with gaps, the shortest timeline, and highest score are recommended first. Thus, group 4 (strain and deflection measurements) is recommended first to help with development of this technology for use during the near-term experiments. The blade strain and deflection measurements are important for turbine-focused campaigns, and additional instrumentation development will help meet the goals of the experiment. Following that, the unsteady pressure measurement group (group 5) is important to develop. The system is important for turbine-focused campaigns and could potentially be ready to contribute to near-term experimental campaigns with appropriate prioritization and funding. Following that, the inflow measurement development (group 1) is important for all test campaigns. With development investment next year, the technology could be ready for near-term experiments. Next it is recommended to start on the development of the high-resolution measurement category (group 2). The category is very important for future experiments but could take 4 to 10 years to develop. Following that, the upgraded moderate resolution velocity and UAS systems (groups 6 and 7) are important for development. These are the systems that are recommended for development along the Figure 7-2 roadmap to help with the present gaps in measurement technology for both the current and future validation campaigns.

Table 7-4. Instruments under development fitting within each measurement category grouping. The total score and timeline score are based on the rubric in Section 6. The timeline score does not have units of years, but an approximate window of years is provided.

Group Number	Instruments Being Developed	Timeline	Total Score
1.	Balloon DTS Sonics, Next Generation Profiling Lidar	1.1 ~(2 – 4 years)	2.8
2.	PIV, Acoustic Tomography, Long Range Continuous-Wave Scanning Lidar	1.8 ~(4 – 10 years)	2.3
3.	Turbine Information		
4.	Distributed Strain, Photogrammetry	0.7 ~(1 – 3 years)	3.1
5.	Unsteady Pressure	0.9 ~(2 – 4 years)	3.1
6.	Ground Based Scanning Lidar, X-Band Dual Doppler Radar, Synchronized Doppler Lidar, Motion Stabilized Lidar	0.4 ~(1 – 2 years)	3.1
7.	UAS	0.8 ~(2 – 4 years)	2.6

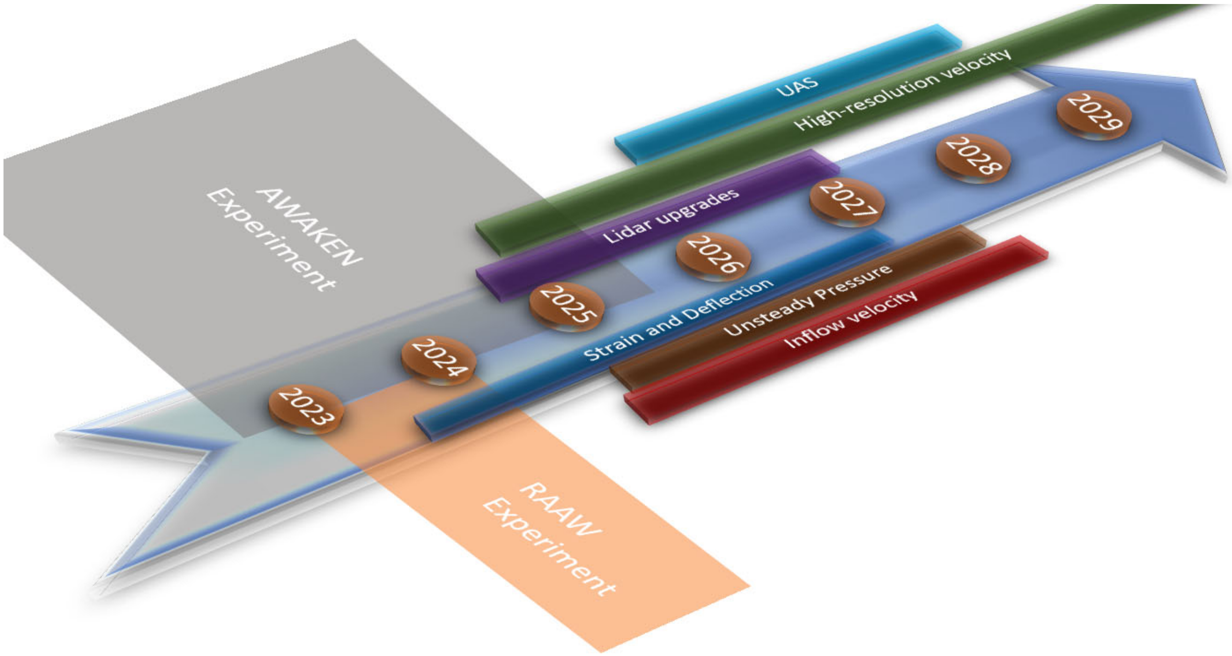


Figure 7-2. Recommended development path to meet gaps within measurement categories.

8. SUMMARY, OBSERVATIONS, AND RECOMMENDATIONS

The primary goal of this effort was to provide an instrumentation roadmap that clarified measurement needs and gaps in instrumentation technology. A process was created for determining instrumentation that could capture the important phenomena at the resolution necessary for both the science goals and validation needs of a particular experiment. The effort began to identify instrumentation for the AWAKEN experimental campaign, but it evolved into a roadmap for instrumentation development relevant to current and future campaigns that are part of the larger effort to improve the ability to capture the many scales of phenomena important for wind energy.

In the process of developing the roadmap, a group of tools have been developed to identify suitable instrumentation for known research and validation needs. The tools provide a general mapping of measurement categories to phenomena important for wind turbines, wind plants, and mesoscale forcing and will be available as spreadsheets for others to use in experimental planning. The tools will be distributed as part of a future IEA Wind TCP task on instrumentation development. This mapping can be used by future experimental planning efforts once the ranking or mapping of the importance of the phenomena to the experiment are determined. The prioritization of measurement categories is demonstrated here by mapping phenomena to the AWAKEN and RAAW experimental goals and coupling this with the instrumentation-to-phenomena ranking. These tools are expected to evolve over time as additional information is gained on the physics and phenomena being observed, the priority of the phenomena change, and as new experiments are designed to observe targeted phenomenon in different environments. For example, offshore wind or marine atmospheric boundary layer phenomena are not included in the current process, but these phenomena can be incorporated in the future to identify the instrumentation relevant for offshore wind energy.

These tools were also applied to the campaigns specified in the HFM V&V roadmap to determine measurement categories that are most critical for future validation efforts. The results reveal the importance of considering both the instrumentation limits, as well as scale, environment, and turbine system knowledge limits when planning an experiment and determining its research objectives. These aspects are important as the focus of an experiment determines how limited resources should be allocated, including which instruments to employ. The experiment can be limited by knowledge of the test article and the test conditions as much as by the available instrumentation. Future model validation prioritization could include test conditions, test article knowledge, and instrumentation in a common prioritization framework, since each can be influenced by future research investments.

A feasibility scoring rubric was created to help categorize instruments into stages of development. The time necessary to mature an instrument to the point where it can be effectively used in an experiment affects its usefulness for a particular study. In addition, those instruments with the capability to measure important phenomena but requiring significant development efforts are identified so that their development can be prioritized.

Observations:

- A multi-discipline team including instrumentation, wind energy, and atmospheric science experts was critical to ensure that both science and validation goals are met by identifying critical instrumentation needs. This effort provided guidance for future instrumentation development efforts by weighing the capability enhancement gained against the investment made.
- A key outcome of this effort is the identification of measurement needs of a particular phenomenon observed in a wind farm and linking that phenomenon with the ability of various

instruments (existing and yet-to-be developed) to capture it. This step informs whether an existing instrument can meet the measurement need or identifies where gaps exist for novel instrumentation development.

- Another key outcome of this effort is the identification of the need to link the ability of various instruments (existing and yet-to-be developed) to a given scientific project based on the phenomena important to that project and how well potential instruments capture those phenomena.
- The feasibility of deploying a given instrument for a project is critical to consider both for selecting instrumentation for a near-term project and considering what instrumentation requires further investment prior to deployment. The interpretation of instrument ranking results should be considered with care. All instruments discussed in this work are relevant to wind energy experimental campaigns to various degrees. Applying the mapping and feasibility framework to a given application separates critically important instruments from those that may provide extra value but are not strictly required to achieve a specific science goal.
- Limitations of the instrument's capability, scale of the measurement, the environment in which the experiment occurs, and knowledge of the turbine system are all important to consider when developing a test campaign and choosing which instrumentation to use.
- Identification of instrumentation development priorities for validation is facilitated by comparing idealized experiments with what is currently possible for an actual experiment. In addition to competing measurement priorities, actual experiments are affected by the availability of instruments and ability to share turbine system information, due to logistical, budget, or legal constraints.

Recommendations

- Based on applying the instrumentation ranking process to the AWAKEN, RAAW, and HFM validation campaigns, research efforts should be prioritized to developing those instruments that can provide measurements of critical phenomena but are not yet fully deployable. For some instruments, the development time will be 1 to 3 years, while others may take 4 to 10 years. Without investment, these instruments will not be available when needed for future measurement campaigns. This ranking is a relative ranking because all the instruments listed here are considered important.
    - Specific instruments for development in the short term:
        - Highest priority: measurement systems that can capture the inflow with adequate resolution and turbulent spectra: tethered balloon with distributed temperature sensing and sonic anemometers, or next generation profiling lidar; blade measurements: unsteady blade pressure measurements systems, distributed strain/photogrammetry systems; and improvements to moderate-resolution velocity measurements: synchronized Doppler lidar and motion stabilized lidar
        - Lower priority: unmanned aerial systems
    - Specific instruments for development in the long term:
        - Highest priority: high-resolution velocity measurements: ground-based, large-scale particle image velocimetry, long-range continuous wave lidar, and acoustic tomography
        - Lower priority: blade surface shear stress

- The process and tools developed here need to be updated regularly as new phenomena are identified for emerging applications. The scoring and weighting used in this effort may not be universal to all projects. However, the framework developed here should be useful for many future experiments by providing guidance in the selection of instrumentation, much like what has been realized in this document for AWAKEN, RAAW, and the HFM validation roadmap.
- Development of instruments, the expertise of personnel to deploy them, and the analysis methods necessary to make the result useful for validation and scientific discovery will benefit from a sustained focus. Much like developing and maintaining computational models, obtaining key instruments and developing the expertise to use them for a series of experimental campaigns will increase efficiency and capability.

The instrumentation ranking process documented here is expected to be applied to future campaigns to determine instruments capable of measuring important phenomena as discerned from both validation and science goal perspectives. This approach prompts investigators to perform much needed analysis and to discuss the feasibility of using specific instrumentation for a project. The analysis and discussion should define the measurement systems, quantities of interest and phenomena relevant to wind energy research and inform the instrumentation to select with the required spatial and temporal resolution. This will avoid selecting instruments that are currently available but insufficient to meet the project objectives. The ranking process also allows for the justification of the use (or development) of a given instrument based on the project's scientific and validation objectives.

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APPENDIX A. DETAILED MEASUREMENT ASSUMPTIONS

A.1. Unsteady Pressure Measurements

The unsteady pressure measurement categories includes measurements such as flush-mounted transducers, such as Kulites, tap/tubing/transducer systems, and microphones. This measurement platform measures unsteady pressure, which is important and connected to the physics occurring within the individual wind turbine blades or close to the blades. Therefore, phenomena such as rotor thrust, blade load, and blade boundary layer development received a score of 2 since unsteady pressure measurements capture these phenomena well. Most of the wind plant phenomena are not captured well with unsteady pressure measurements and thus received a 0. However, wind plant flows are controlled through the individual wind turbine, and the controlled physics are directly connected to the unsteady pressure variable receiving a score of 2.

A.2. Wall Shear Stress Measurements

The wall shear stress measurements consist primarily of miniature floating elements. Shear stress measurements capture the wall shear stress along the blade boundary layer indicating where the boundary layer is laminar or turbulent and if boundary layer separation occurs on the blade. As a result, the blade boundary layer, surface roughness, blade load distribution, dynamic stall, and blade flow control are wind turbine phenomena all impacted by changes in shear stress and thus are important for being captured by shear stress measurements. Shear stress is somewhat connected with the tip and root vortex development, vortex sheet and rollup and blade generated turbulence receiving a score of 1. Wind plant and mesoscale phenomena have little to no connection with blade shear stress.

A.3. Section Loads Measurements

The section load measurement category includes foil and fiber optic strain gauges, distributed fiber strain measurements, and accelerometers. Section load measurements capture the wind turbine blade load distribution, blade flow control, aeroelasticity, and icing well receiving a score of 2. The section load measurements also capture wind plant control, wake steering, and wake impingement with a score of 2.

A.4. Blade Deflection Measurements

The blade deflection measurement category includes photogrammetry and fiber optic sensors. The mapping of the blade deflection measurements in how well they capture wind turbine, wind plant, and mesoscale phenomena matches the section load measurements.

A.5. Blade Boundary Layer Laminar to Turbulent Transition

The blade laminar to turbulent boundary layer transition category contains infrared thermography, temperature sensitive pain, hot film, oil flow, hot wire anemometers, and noise measurements.

A.6. Extra-High Spatial Resolution Velocity Remote Sensing Measurements

The extra-high spatial resolution velocity remote sensing measurement category includes measurements with a spatial resolution between 0.01 to 0.1 m and includes acoustic tomography and particle image velocimetry on a blade.

The boundary layer developed over the blade surface can be captured with an extra-high resolution velocity measurement system. The boundary layer, effect of blade surface on the boundary layer, and unsteady inflow effect on the flow physics near to the blades are relevant here, and they have received a score of 2. The target area is too close to the wind turbine blades, and wake development and growth phenomena are out of scope for this measurement system.

A.7. High Spatial Resolution Velocity Remote Sensing Measurements

The high spatial resolution velocity remote sensing measurement category includes particle image velocimetry, acoustic tomography, and custom made Doppler lidar systems. The velocity measurements are targeted with a spatial resolution between 1 and 10 m. The high spatial resolution velocity measurements are important for capturing blade load distributions, tip and root vortex development, vortex sheet and rollup, blade generated turbulence, root flow acceleration, unsteady inflow effects, skew and meandering, swirl instability, vortex merging, wake vorticity, asymmetry effects of rotor alignment and inflow effects on wake development and recovery. These measurements also capture the wind plant wind direction, turbulence characteristics, coherent turbulence, momentum transport, wake interaction, wake dissipation, and wake impingement. High resolution velocity also somewhat captures the wind plant surface conditions, plant flow control, dep array effects, and wind plant blockage effects.

A.8. Moderate Spatial Resolution Velocity Remote Sensing Measurements

The moderate spatial resolution velocity remote sensing measurement category includes long-range scanning Doppler lidar and X-band radar. Moderate resolution velocity measurements include velocity measurements with a spatial resolution between 10 to 30 m. The assumptions for mapping in this category include all velocity measurements within this spatial range using both ground-based and nacelle mounted lidar. The unsteady inflow, wake skew and meandering, yaw, tilt, and shear effects on wake development can be captured with this system. With some cautions, this system also can be used for the wind plant wind direction, turbulence characteristics, coherent turbulence, momentum transport, wake interaction, plant flow control, wake steering, wake dissipation, wake impingement, deep array effects, and wind plant blockage. This velocity measurement also captures all of the mesoscale phenomena except icing and precipitation, surface energy, wind plant effect, and large-scale forcing.

A.9. Coarse Spatial Resolution Velocity Remote Sensing Measurements

The coarse spatial resolution velocity remote sensing measurements include radar and long-range scanning Doppler lidar. This platform targets large-scale flow physics relevant to wind plant phenomena or a cluster of wind turbines. The X-band radar can measure 30–40 km with resolution of 15–30 m, and the long range lidar can measure up to 12–15 km with a spatial resolution of 100–200 m. This coarse resolution is meant for the plant-level physics but not to the individual turbine or blade phenomena. Therefore, swirl instability, vortex merging, wake vorticity received score 0, and inflow to the wind plant, multi-turbine wake effects received score 2. The satellite data, particularly the synthetic aperture radar data, has been recently used to visualize the wind plant wakes and their interactions. These coarse resolution velocity remote sensing instruments cover a large area to visualize the large-scale flow phenomena with a compromise to the small-scale flow structures.

A.10. Velocity Vertical Profilers

The velocity vertical profiler category includes pulsed and continuous wave profiling lidars, spidars, and radar profilers. This system provides wind speed profiles with a sufficient vertical resolution (i.e., 20 m) to capture wind shear and veer of the atmospheric boundary layer. This vertical profiler system can measure wind speed with high temporal frequency (i.e., 1–5 Hz) and therefore it can be used for turbulence measurement considering the limitations. The coherent turbulent structure, wind shear/veer/asymmetry, turbulence characteristics received score 2. In addition, as this system can measure wind speed components with high temporal frequency, derived quantities like momentum flux can be achieved by this system. Due to its reasonable spatial (5–20 m) and temporal resolution (1–5 Hz), this system possibly can be used to observe the wind turbine wake within the plant and different downstream locations. Therefore, deep array effects, wind plant wake, steered wake, flow upstream of wind plants receive score 2.

A.11. In-Situ Met Measurements

The in-situ met measurements include sensors located on met towers to acquire high-fidelity velocity and atmospheric condition measurements. The commonly used sensors are sonic and cup anemometers, temperature, pressure and relative humidity probes, and hot wire anemometers. The in-situ met measurement system provides highly accurate measurements and can be used to measure the turbulence statistics of the targeted variables. The inflow measurements, coherent structure turbulent structures, momentum transport receive score 2. A set of in-situ met systems can be placed at different locations to observe the impact of mesoscale and different turbulence structures on the wind plant. Therefore, mesoscale phenomena, terrain induced flow phenomena, influence of mean atmospheric boundary layer receive score 2. An important purpose of the in-situ met system is to capture the near surface measurements, which can be used to retrieve friction velocity, moisture, heat flux, roughness, etc. Any in-situ instruments can be added to this system based on the target physics, and due to its measurement capabilities, surface conditions (roughness, surface heat flux, topography) receive score 2.

A.12. Tethered Balloon Platforms

The tethered balloon platform includes development of the platform for sensors such as hot wire anemometers motion compensated sonic anemometers, distributed temperature fiber optic sensors, aerosol concentration, and temperature, pressure, and relative humidity probes. The mapping for the tethered balloon assumed that the balloons would be able to operate at winds up to 20 m/s, with an FAA license that allowed lower altitude (~300 m) day and night operations within 3 diameters of a wind turbine, including the waked condition. Additionally, mapping assumed another high-altitude deployment further from obstructions that could measure the temperature and velocity up to 1.5 km altitude. The mappings assumed with development the directionally tracked sonics could capture 3-component velocity and turbulence at 7 to 8 locations along the tethered balloon. With these assumptions, the tethered balloon captures the unsteady inflow, wake vorticity diffusion and dissipation, wake asymmetries, and inflow effects on the wake phenomena. For wake plant phenomena, the tethered balloon captures wind direction, turbulence characteristics, coherent turbulence structure, momentum transport, deep array effects, and wind plant blockage effects. The tethered balloon also captures all of the mesoscale phenomena except icing and precipitation, surface energy exchange under realistic mesoscale forcing, and only partially captures large-scale forcing.

A.13. High-Resolution Temperature Measurements

The high-resolution temperature measurements category primarily includes acoustic tomography. Acoustic tomography can capture high-resolution velocity measurements in addition to high spatial resolution temperature measurements. This category of measurements partially captures wind turbine inflow effects and inflow effects on wake development, wind plant inflow turbulence characteristics, and fully captures the wind plant inflow surface conditions. Additionally, the surface energy, terrain-induced flow and air-sea interactions mesoscale phenomena are partially captured.

A.14. Thermodynamic Remote Sensing Profilers

The thermodynamic remote sensing profiler includes Raman lidar, Differential Absorption Lidar (DIAL), AERI, and ASSIST profilers and microwave radiometer (MWR) measurements. This category assumes a moderate resolution vertical profile of thermodynamic properties and fully captures temperature, moisture, pressure, etc., which are needed to characterize the inflow and atmospheric conditions. The atmospheric stability profiles at and around the wind plant can be achieved with this system. The energy balance and transport of energy require different atmospheric variables, and this system is useful to characterize the energy transport and balance at different heights due to its ability to measure different atmospheric variables at upper altitudes of the atmospheric boundary layer.

A.15. Unmanned Aerial System Platforms

The UAS platform development includes hot wire anemometers, motion-compensated sonic anemometers, aerosol measurements, and temperature, pressure, and relative humidity probes on a fixed wind UAS system. This category also includes velocity measurements using quadcopter like systems. This category partially captures the wind turbine tip and root vortex development, vortex rollup, blade generated turbulence, root flow acceleration, and fully captures the unsteady inflow and wake vorticity diffusion and dissipation, asymmetry, and inflow effects on the wind turbine wake. The UAS platform also fully captures all of the wind plant phenomena except partially capturing the momentum transport and minimally capturing plant flow control. The platform also fully captures the mesoscale surface features, terrain-induced flow, urban-environment, and air-sea interaction, and partially captures the influence on plant influence on the mean atmospheric boundary layer. UAS platforms are also capable of measuring surface roughness and terrain through lidar or photogrammetry techniques, but the importance of these measurements were captured under the 'Terrain/Surface Roughness' measurement category.

A.16. Aircraft-Based Platforms

The aircraft-based platform measurements include downward and upward looking lidar including aerosol, Raman, and Doppler lidar, radars, dropsondes, basic instruments such as PWD, pitot tubes, and temperature and humidity sensors. This measurement category partially captures the wind turbine unsteady inflow and inflow effects on wind turbine wakes. The aircraft also fully captures the wind plant surface conditions, deep array effects, and wind plant blockage. The aircraft platform also fully captures all of the mesoscale phenomena except for icing and precipitation, surface energy exchange, surface features, and large-scale forcings. Aircraft platforms are also capable of measuring surface roughness and terrain through lidar or photogrammetry techniques, but the importance of these measurements were captured under the 'Terrain/Surface Roughness' measurement category.

APPENDIX B. DETAILED SCIENCE GOAL ASSUMPTIONS

B.1. Wake Recovery and Dissipation

This science goal was largely focused on two general topics, the first being the impacts atmospheric phenomena have on wake recovery and dissipation. These atmospheric phenomena include atmospheric stability, wind stratification and shear, momentum above the wind farm, and freestream turbulent dissipation. Given this first focus, many of the phenomena mapped to this science goal are the inflow and general atmospheric phenomena. Examples of these include the atmospheric boundary layer structure, mesoscale phenomena such as fronts and low-level jets, inflow conditions such as turbulence characteristics, the diurnal cycle, and momentum transport (horizontal and vertical fluxes).

The second broader focus of this science goal is on characterizing how other turbine characteristics and phenomena and wake recovery and dissipation are impacted by each other. Examples of this are characterizing how wake recovery is related to wake meandering, and how yaw influences wake recovery. This second focus led to mapping this science goal to turbine wake effects phenomena like plant flow control, and wake interaction, merging, and meander. There were also many strong connections to turbine phenomena like tower/rotor/nacelle wake interactions, blade-generated turbulence characteristics (energetic scales at trailing edge), and asymmetry effects.

B.2. Wake Interaction, Merging, and Meandering

This science goal was once again assumed to have two primary focuses. The first focus was on how wake interaction, merging, and meander changes based on turbine controls and farm layout/location i.e., terrain within and surrounding the farm. This focus of the science goal resulted in a mapping with strong connections to wind plant controls, blade flow control, and terrain impacts.

The second focus for this science goal was based on the background atmospheric conditions and inflow and how these conditions will change the behavior of wakes. As a result, phenomena like unsteady inflow, turbulence characteristics, fronts, and the diurnal cycle were given scores of 1.5, or strong connection.

Acknowledging that there are connections between how wakes behave in general, other wake characteristics and effects like swirl instability and wake vorticity diffusion and dissipation were given scores of 1. Likewise, to acknowledge the impact general inflow conditions like wind direction, shear, veer, and momentum transport have on wake behavior, these phenomena were also given scores of 1.

B.3. Wake Impingement

The wake impingement science goal was largely focused on the impacts wakes have on blade loads and associated turbine blade phenomena. Examples of such phenomena that were given scores of 1.5 are blade load distribution, tip and root vortex, and blade boundary layer development. Other blade effects such as rotational augmentation and dynamic stall were given scores of 1 to indicate their connection to wake impingement but were not a primary focus for this science goal.

Additionally, controls were assumed to be a primary focus of this science goal due to the effort within wake controls to minimize the impacts of wake impingement. Therefore, plant flow control and wake steering were given high scores. Blade flow controls were given a score of 1 because, while related, these not a primary control focus for minimizing impingement on downstream turbines.

Additional phenomena were given scores of 1 to acknowledge their impact on wake development/dissipation and therefore impingement. Examples of these phenomena are inflow effects, wake vorticity diffusion and dissipation, turbulence characteristics, and coherent turbulence structure.

B.4. Deep Array Effects, Internal Boundary Layer

This science goal was assumed to be largely focused on the inflow and larger atmospheric phenomena that impact deep array effects and the internal boundary layer. Examples of phenomena given a score of 1.5 are the low-level jet, the diurnal cycle, turbulence characteristics, and inflow effects. Additionally, the impacts the wind plant itself has on the mesoscale circulation and flow was also mapped to have a strong connection.

B.5. Atmospheric Stability, Surface Heat Flux

Atmospheric stability and surface heat flux was interpreted as focusing on how stability and heat fluxes impact wind plant effects. As a result, phenomena like blockage, deep array effects, and wake dissipation were given scores of 1.5. The impacts stability and heat flux have on wake behavior, and therefore controls, was also acknowledged but as a secondary focus for this science goal. Phenomena such as wake interaction, merging, meander, plant flow control, and wake steering were given scores of 1.

B.6. Momentum Transport

The main focus of the momentum transport science goal was interpreted as being focused on the effects momentum transport has on wind farm phenomena, and on the impacts momentum transport has on atmospheric structure and the broader mesoscale flow. As such, phenomena like deep array effects, wind farm wake dissipation, wind plant wakes effect on mesoscale flow, and influence on mean boundary layer structure were given scores of 1.5.

Because momentum transport is related to most, if not all atmospheric phenomena, many of the mesoscale-microscale coupling (MMC) were given a score of 1 for this mapping, including severe weather and large-scale wind die off/stabilization. Additionally, due to the connection between momentum transport and impacts on wakes, plant flow control and wake steering were also given scores of 1.

B.7. Wind Direction, Shear, and Veer

The key assumption in the mapping of this science goal was looking at what phenomena impact the overall wind direction, shear, and veer. This assumption was made largely because the impacts wind direction etc., have on wakes and other phenomena were captured in other science goals (i.e., B.1 and B.2). As a result, this mapping was focused on what phenomena will need to be understood in order to understand the impacts of wind direction, shear, and veer on wind turbines and wind farms. As a result, many of the mesoscale phenomena scored highly due to their impact on the wind inflow.

B.8. Atmospheric Boundary Layer Surface Roughness

Atmospheric boundary layer surface roughness was assumed to deal with land surface changes and their effects on wind plant power performance. As a result, it was poorly represented in the phenomena list. Some of the phenomena were direct matches like surface features and physics of relevance, while others were loose connections at best.

B.9. Wind Plant Wake

The wind plant wake science goal was again assumed to have two primary focuses. The first is the focus on what atmospheric phenomena impact the wind plant wake. Many of the inflow and stability characteristics were given high scores to highlight their importance on the development of a wind plant wake.

The second focus of this science goal is understanding the effects within the wake that need to be studied and characterized. Characteristics like wake dissipation, wake interaction, merging, meander, and deep array effects were scored highly as a result.

B.10. Terrain Impacts

The terrain impacts science goal was overall poorly represented in the phenomena, but the impact terrain was acknowledged through scores of 1 for several phenomena. In the wind plant phenomena, inflow conditions, turbulence, and momentum transport are all impacted by terrain.

B.11. Wind Plant Upstream Blockage

Because the blockage effect is relatively poorly understood, it was assumed that many phenomena may have a connection to this science goal. Many phenomena were given scores of 1 or 0.5 to acknowledge that these phenomena may be important to blockage, but the level of their importance is not yet known. Additionally, the extent to which blockage impacts phenomena like plant wakes and their behavior is also not well known, so these wake phenomena were also scored with a connection to wind plant blockage.

B.12. Air-Sea Interaction

This topic has many unknowns. The mapping was conducted considering that for some phenomena it is unknown how important they are (at least by the team creating this roadmap). In future offshore focused mapping exercises, this topic should be more fully fleshed out with relevant experts lending their input.

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APPENDIX C. MEASUREMENT TO VALIDATION NEED MAPPING

The identification of measurements needs for each validation campaign was accomplished by going through the Wind Energy High-Fidelity Model Verification and Validation Roadmap report and identifying required measurements (Maniaci et al., 2020). The required measurements for each validation campaign were then mapped to instruments and measurement categories and given scores for the importance to meet the needs of the measurement campaigns. An example validation campaign summary is shown below with the measurement needs underlined.

Validation Campaign 8: Models for wake evolution (formation, meandering, merging) in a wind farm with 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.

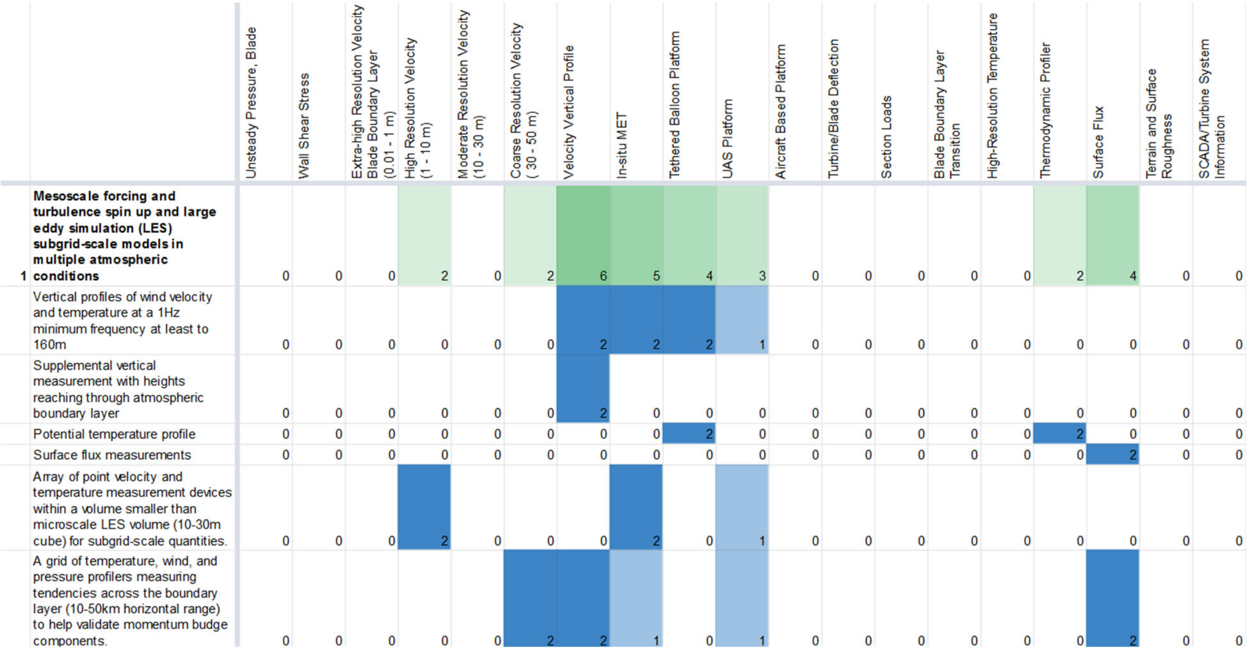
Quantities of Interest: The phenomena at play include wake formation, merging, meandering, and deep array effects.

- **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.

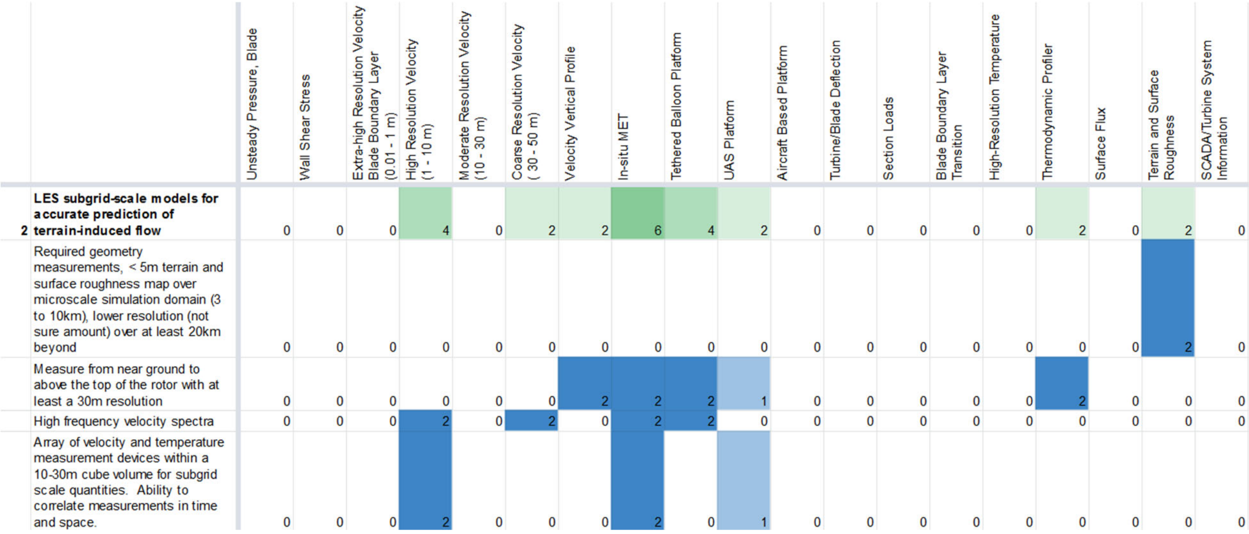
Validation Data Requirements: Data requirements include **vertical velocity profiles** within the wind plant during normal operation and when the wind plant is in a non-uprating state. Measurements of **undisturbed atmospheric inflow on all sides of the wind plant** are also required in at least one 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**.

The identified measurement requirements were then linked to each validation campaign as shown in Figures C-1 through C-9, and the results of which were then used for validation to instrument mapping in Section 5.



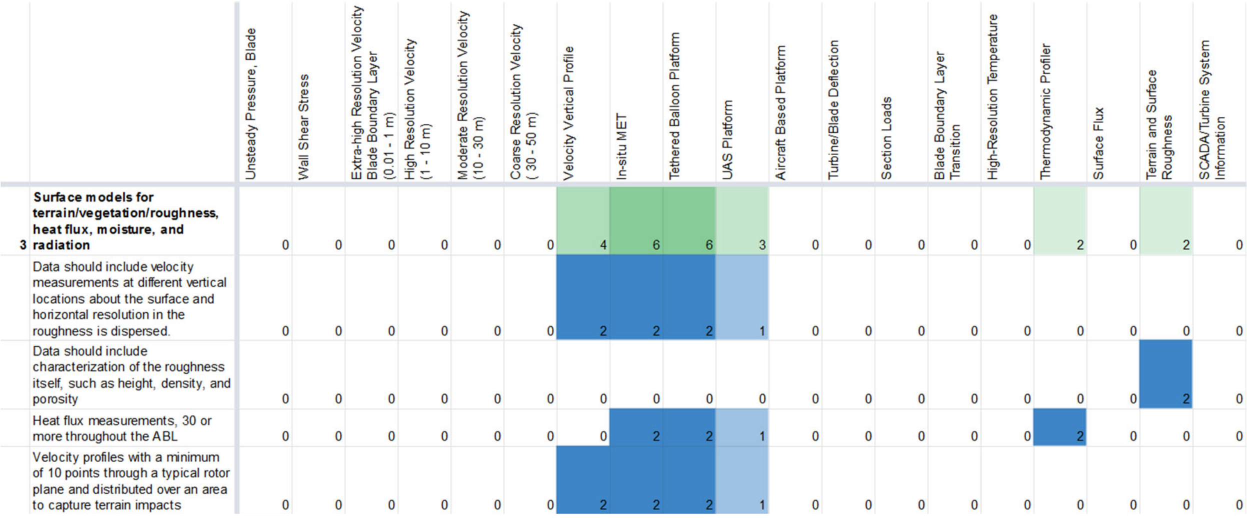
		Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler	Surface Flux	Terrain and Surface Roughness	SCADA/Turbine System Information
1	**Mesoscale forcing and turbulence spin up and large eddy simulation (LES) subgrid-scale models in multiple atmospheric conditions**	0	0	0	2	0	2	6	5	4	3	0	0	0	0	0	2	4	0	0
	Vertical profiles of wind velocity and temperature at a 1Hz minimum frequency at least to 160m	0	0	0	0	0	0	2	2	2	1	0	0	0	0	0	0	0	0	0
	Supplemental vertical measurement with heights reaching through atmospheric boundary layer	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
	Potential temperature profile	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0
	Surface flux measurements	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
	Array of point velocity and temperature measurement devices within a volume smaller than microscale LES volume (10-30m cube) for subgrid-scale quantities.	0	0	0	2	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0
	A grid of temperature, wind, and pressure profilers measuring tendencies across the boundary layer (10-50km horizontal range) to help validate momentum budge components.	0	0	0	0	0	2	2	1	0	1	0	0	0	0	0	0	2	0	0

Figure C-1. Mapping of measurement needs to validation campaign 1.



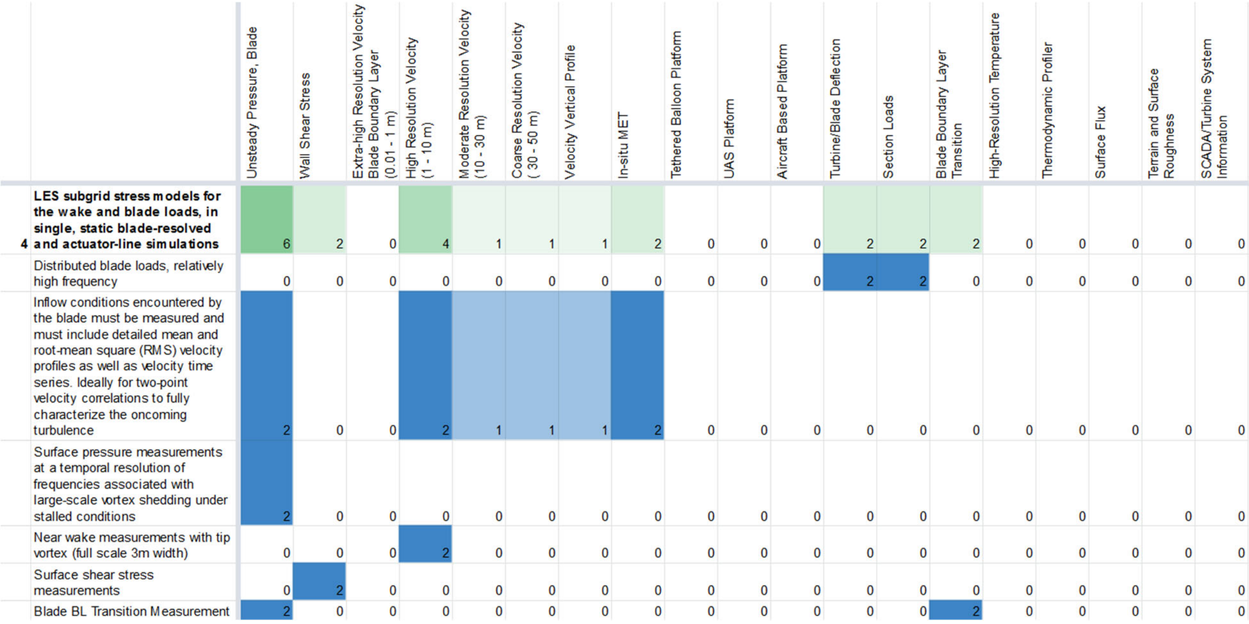
		Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler	Surface Flux	Terrain and Surface Roughness	SCADA/Turbine System Information
2	**LES subgrid-scale models for accurate prediction of terrain-induced flow**	0	0	0	4	0	2	2	6	4	2	0	0	0	0	0	2	0	2	0
	Required geometry measurements, < 5m terrain and surface roughness map over microscale simulation domain (3 to 10km), lower resolution (not sure amount) over at least 20km beyond	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
	Measure from near ground to above the top of the rotor with at least a 30m resolution	0	0	0	0	0	0	2	2	2	1	0	0	0	0	0	2	0	0	0
	High frequency velocity spectra	0	0	0	2	0	2	0	2	2	0	0	0	0	0	0	0	0	0	0
	Array of velocity and temperature measurement devices within a 10-30m cube volume for subgrid scale quantities. Ability to correlate measurements in time and space.	0	0	0	2	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0

Figure C-2. Mapping of measurement needs to validation campaign 2.



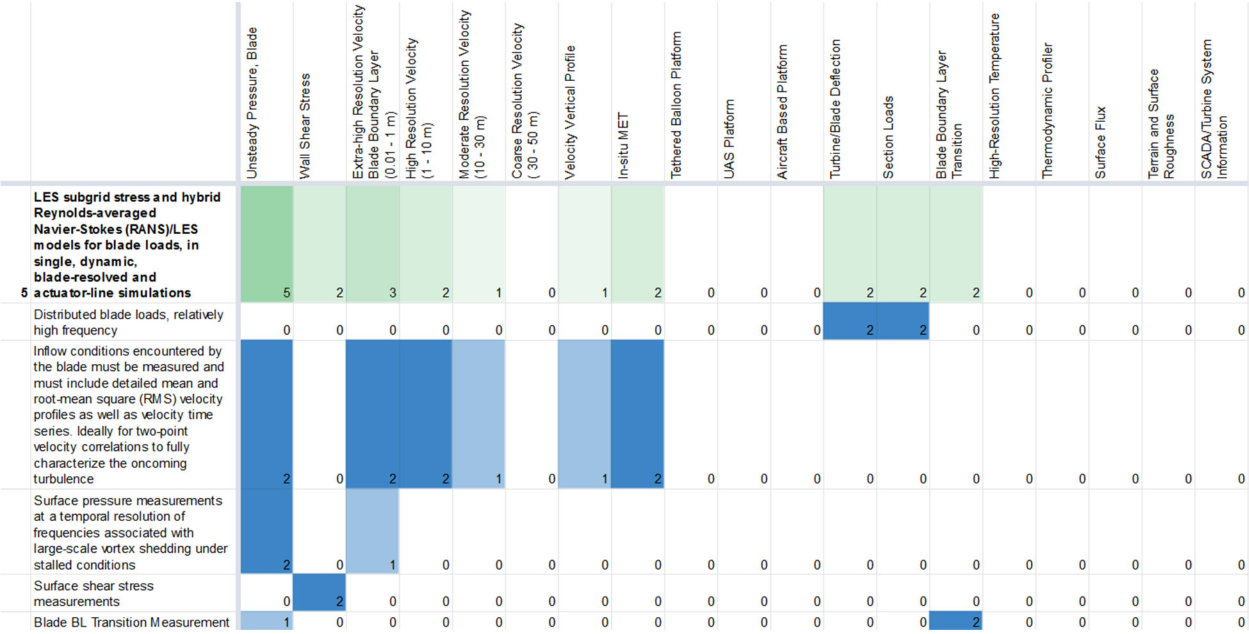
		Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler	Surface Flux	Terrain and Surface Roughness	SCADA/Turbine System Information
3	**Surface models for terrain/vegetation/roughness, heat flux, moisture, and radiation**	0	0	0	0	0	0	4	6	6	3	0	0	0	0	0	2	0	2	0
	Data should include velocity measurements at different vertical locations about the surface and horizontal resolution in the roughness is dispersed.	0	0	0	0	0	0	2	2	2	1	0	0	0	0	0	0	0	0	0
	Data should include characterization of the roughness itself, such as height, density, and porosity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
	Heat flux measurements, 30 or more throughout the ABL	0	0	0	0	0	0	0	2	2	1	0	0	0	0	0	2	0	0	0
	Velocity profiles with a minimum of 10 points through a typical rotor plane and distributed over an area to capture terrain impacts	0	0	0	0	0	0	2	2	2	1	0	0	0	0	0	0	0	0	0

Figure C-3. Mapping of measurement needs to validation campaign 3.



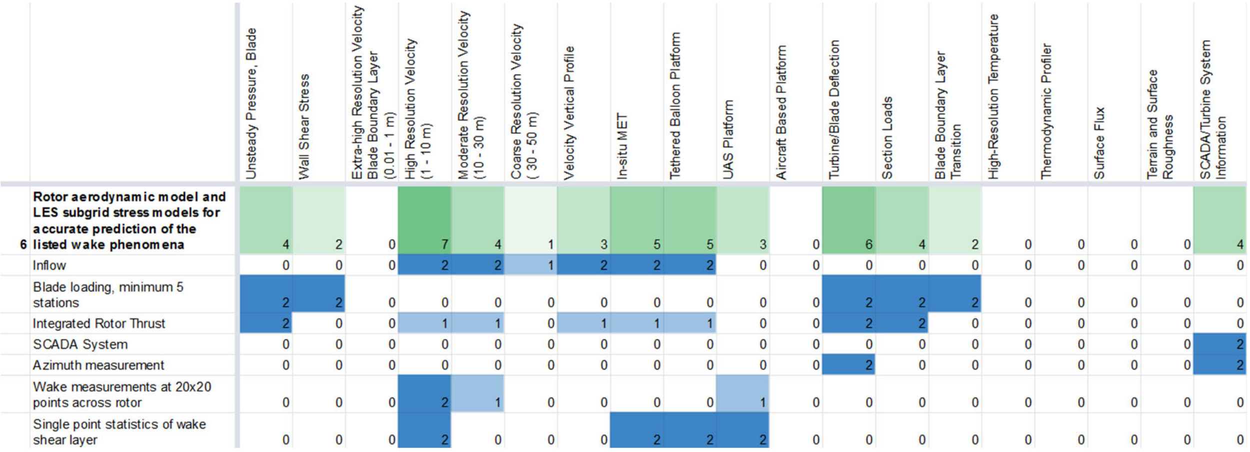
		Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler	Surface Flux	Terrain and Surface Roughness	SCADA/Turbine System Information
4	**LES subgrid stress models for the wake and blade loads, in single, static blade-resolved and actuator-line simulations**	6	2	0	4	1	1	1	2	0	0	0	2	2	2	0	0	0	0	0
	Distributed blade loads, relatively high frequency	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0
	Inflow conditions encountered by the blade must be measured and must include detailed mean and root-mean square (RMS) velocity profiles as well as velocity time series. Ideally for two-point velocity correlations to fully characterize the oncoming turbulence	2	0	0	2	1	1	1	2	0	0	0	0	0	0	0	0	0	0	0
	Surface pressure measurements at a temporal resolution of frequencies associated with large-scale vortex shedding under stalled conditions	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Near wake measurements with tip vortex (full scale 3m width)	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Surface shear stress measurements	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Blade BL Transition Measurement	2	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0

Figure C-4. Mapping of measurement needs to validation campaign 4.



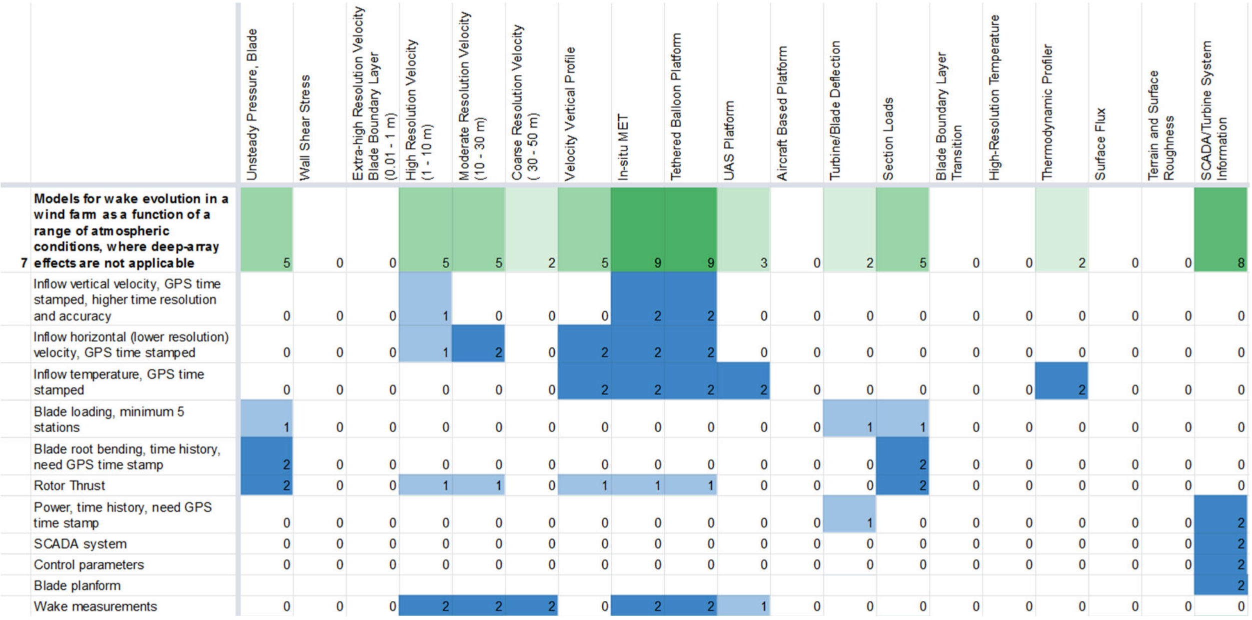
		Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler	Surface Flux	Terrain and Surface Roughness	SCADA/Turbine System Information
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**	5	2	3	2	1	0	1	2	0	0	0	2	2	2	0	0	0	0	0
	Distributed blade loads, relatively high frequency	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0
	Inflow conditions encountered by the blade must be measured and must include detailed mean and root-mean square (RMS) velocity profiles as well as velocity time series. Ideally for two-point velocity correlations to fully characterize the oncoming turbulence	2	0	2	2	1	0	1	2	0	0	0	0	0	0	0	0	0	0	0
	Surface pressure measurements at a temporal resolution of frequencies associated with large-scale vortex shedding under stalled conditions	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Surface shear stress measurements	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Blade BL Transition Measurement	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0

Figure C-5. Mapping of measurement needs to validation campaign 5.



		Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler	Surface Flux	Terrain and Surface Roughness	SCADA/Turbine System Information
6	**Rotor aerodynamic model and LES subgrid stress models for accurate prediction of the listed wake phenomena**	4	2	0	7	4	1	3	5	5	3	0	6	4	2	0	0	0	0	4
	Inflow	0	0	0	2	2	1	2	2	2	0	0	0	0	0	0	0	0	0	0
	Blade loading, minimum 5 stations	2	2	0	0	0	0	0	0	0	0	0	2	2	2	0	0	0	0	0
	Integrated Rotor Thrust	2	0	0	1	1	0	1	1	1	0	0	2	2	0	0	0	0	0	0
	SCADA System	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	Azimuth measurement	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2
	Wake measurements at 20x20 points across rotor	0	0	0	2	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	Single point statistics of wake shear layer	0	0	0	2	0	0	0	2	2	2	0	0	0	0	0	0	0	0	0

Figure C-6. Mapping of measurement needs to validation campaign 6.

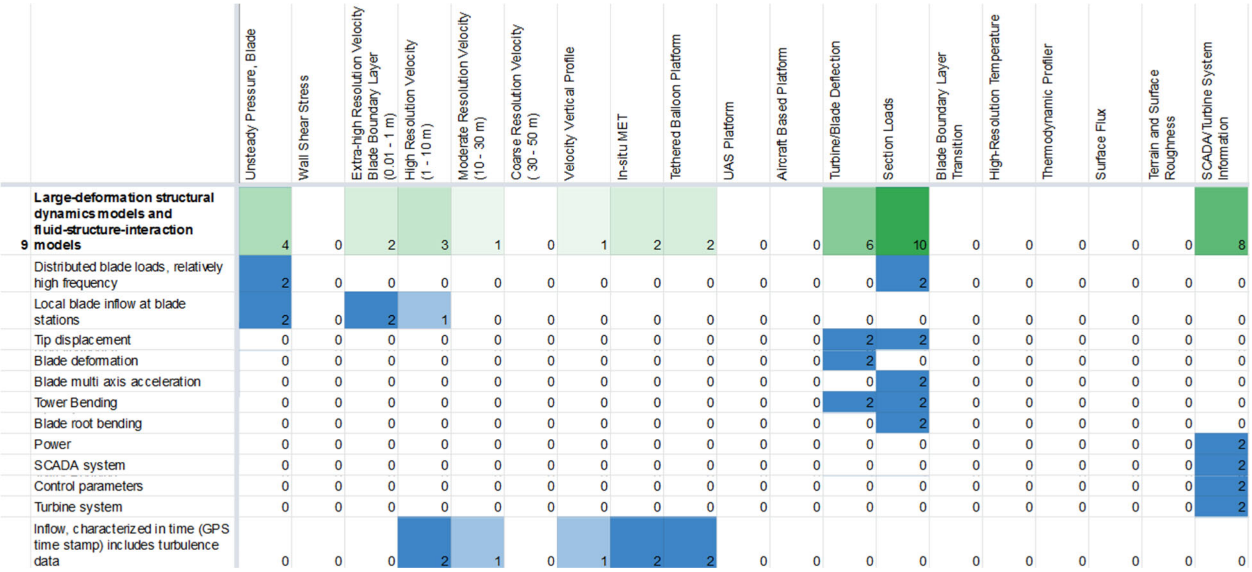


		Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler	Surface Flux	Terrain and Surface Roughness	SCADA/Turbine System Information
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**	5	0	0	5	5	2	5	9	9	3	0	2	5	0	0	2	0	0	8
	Inflow vertical velocity, GPS time stamped, higher time resolution and accuracy	0	0	0	1	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0
	Inflow horizontal (lower resolution) velocity, GPS time stamped	0	0	0	1	2	0	2	2	2	0	0	0	0	0	0	0	0	0	0
	Inflow temperature, GPS time stamped	0	0	0	0	0	0	2	2	2	2	0	0	0	0	0	2	0	0	0
	Blade loading, minimum 5 stations	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
	Blade root bending, time history, need GPS time stamp	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
	Rotor Thrust	2	0	0	1	1	0	1	1	1	0	0	0	2	0	0	0	0	0	0
	Power, time history, need GPS time stamp	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2
	SCADA system	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	Control parameters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	Blade planform																			2
	Wake measurements	0	0	0	2	2	2	0	2	2	1	0	0	0	0	0	0	0	0	0

Figure C-7. Mapping of measurement needs to validation campaign 7.

		Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler	Surface Flux	Terrain and Surface Roughness	SCADA/Turbine System Information
8	**Models for wake evolution (formation, meandering, merging) in a wind farm with O(10) MW-scale turbines, where deep-array effects are important**	2	0	0	6	7	4	1	7	7	5	2	0	4	0	0	0	2	2	8
	Plant Inflow, side, wake, and internal vertical velocity, GPS time stamped, higher time resolution and accuracy	0	0	0	1	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0
	Need temperature two heights (see temperature profiler above). There are already surface flux measurement stations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
	Data should include characterization of the roughness itself, such as height, density, and porosity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
	Rotor Thrust, time history so need GPS time stamp	1	0	0	1	1	0	1	1	1	0	0	0	2	0	0	0	0	0	0
	Blade root bending, time history, need GPS time stamp	1	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
	Power, time history, need GPS time stamp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	SCADA system	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	Control parameters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	Turbine system	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	Vertical velocity profiles extend 1D above rotor 250m to 325m	0	0	0	2	2	0	0	2	2	1	0	0	0	0	0	0	0	0	0
	Vertical planar measurements, extends above the rotor disk of turbines	0	0	0	2	2	2	0	0	0	2	0	0	0	0	0	0	0	0	0
	Plant wake	0	0	0	0	2	2	0	2	2	2	2	0	0	0	0	0	0	0	0

Figure C-8. Mapping of measurement needs to validation campaign 8.



		Unsteady Pressure, Blade	Wall Shear Stress	Extra-high Resolution Velocity Blade Boundary Layer (0.01 - 1 m)	High Resolution Velocity (1 - 10 m)	Moderate Resolution Velocity (10 - 30 m)	Coarse Resolution Velocity (30 - 50 m)	Velocity Vertical Profile	In-situ MET	Tethered Balloon Platform	UAS Platform	Aircraft Based Platform	Turbine/Blade Deflection	Section Loads	Blade Boundary Layer Transition	High-Resolution Temperature	Thermodynamic Profiler	Surface Flux	Terrain and Surface Roughness	SCADA/Turbine System Information
9	**Large-deformation structural dynamics models and fluid-structure-interaction models**	4	0	2	3	1	0	1	2	2	0	0	6	10	0	0	0	0	0	8
	Distributed blade loads, relatively high frequency	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
	Local blade inflow at blade stations	2	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tip displacement	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0
	Blade deformation	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
	Blade multi axis acceleration	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
	Tower Bending	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0
	Blade root bending	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
	Power	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	SCADA system	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	Control parameters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	Turbine system	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	Inflow, characterized in time (GPS time stamp) includes turbulence data	0	0	0	2	1	0	1	2	2	0	0	0	0	0	0	0	0	0	0

Figure C-9. Mapping of measurement needs to validation campaign 9.

APPENDIX D. AWAKEN TESTABLE HYPOTHESES

The AWAKEN project team have identified seven testable hypotheses which will be the primary research questions the project will aim to address. These testable hypotheses were developed from the science goals and home in on testable science questions. The hypotheses were developed after the roadmap mapping exercises were completed and were therefore not directly used in the mapping process. The content below outlines how the AWAKEN science goals used in the mapping process relate to the testable hypothesis and lists what instrument types have been identified as useful for testing each hypothesis.

1. The maximum energy produced by a large (>100 MW) land-based wind farm is constrained by the momentum flux between the surrounding atmosphere and the flow within the wind farm.
    a. Science Goals: Momentum transport within, above, and below farm
    b. Instruments: Moderate and coarse resolution velocity remote sensors, mobile remote sensing (vehicle and aircraft mounted), thermodynamic remote sensing profilers, tethered balloons, and towers with in situ wind measurements (i.e., sonic anemometers)
2. Intermittent turbulent bursting events related to Kelvin-Helmholtz instability, gravity waves, and bores lead to fluctuations in wind farm power production and structural loading of wind turbines.
    a. Science Goals: Blade loading
    b. Instruments: Velocity vertical profilers, tethered balloons, UAS, aircraft with remote sensing (i.e., lidar), thermodynamic profilers, section loads measurements, blade deflection measurements, wall shear stress measurements, unsteady pressure measurements.
3. Wind turbines in the interior of land-based wind farms tend to have more turbulent inflows resulting in higher damage-equivalent loads than those on the exterior. The turbulence levels in land based wind farms asymptote to a fully developed condition after the first three rows of wind turbines.
    a. Science Goals: Deep array effects, internal boundary layer
    b. Instruments: Section loads measurements, high-mid resolution velocity remote sensing, high resolution in situ (i.e., sonic anemometers)
4. Turbine wake morphology, evolution, and wake interactions are affected by a complex interplay of events connected to turbine settings, control, and short-term variability of the incoming wind conditions. Including a stochastic component to wake, turbulence, and turbine models will enable higher accuracy for predictions of wind turbine wakes and their interactions.
    a. Science Goals: Wake recovery and dissipation, wake interaction, merging, meandering
    b. Instruments: Section loads measurements, high, mid, and coarse resolution velocity remote sensing

5. The decrease in hub-height velocity 1-30D upwind of a land based wind farm due to the wind-farm induction zone, which distorts power production and predictions, depends on atmospheric stability, inflow wind speed, boundary-layer height, wind shear and veer (interacting with wind turbine characteristics, wind farm layout, terrain & surface roughness, and operative conditions); the induction zone may create speed-up along the edges of the wind farm.
    a. Science Goals: Wind plant upstream blockage, atmospheric stability, surface heat flux, wind direction, shear, and veer, terrain impacts
    b. Instruments: Moderate to coarse resolution velocity remote sensing, thermodynamic profilers
6. Wake steering and turbine consensus control increase full wind farm power production and reduce structural loads of turbines under a specific range of atmospheric conditions. The overall benefit of wind farm control is primarily dependent upon inflow winds, atmospheric stability, boundary layer height, wind shear and veer, and wind direction variability (interacting with the turbine type, orography, inter-turbine spacing and alignment), with maximum benefit coming when columns of turbines are aligned with wind direction under stable conditions.
    a. Science Goals: Wake impingement, atmospheric stability, surface heat flux, wind direction, shear, and veer, blade loading
    b. Instruments: Section loads measurements, coarse, moderate, and high resolution velocity remote sensing, vertical velocity profilers, thermodynamic profilers

7. Wind farm wakes propagate on land for tens of kilometers and lower the energy production of neighboring wind farms. Characteristics (magnitude and extent of momentum deficits, magnitude and extent of region of increased turbulent kinetic energy (TKE)) of wind plant wakes depend primarily on the spacing of turbines in a wind farm along the primary wind direction, turbine size, individual turbine power level and hub-height turbulent kinetic energy (or turbulence intensity), wind speed at hub height, and atmospheric stability. Wind farm wakes can be steered using coordinated individual turbine yaw control, although topography and yaw-misalignment will also influence wake propagation.
    a. Science Goals: Wind plant wake, atmospheric stability, surface heat flux, wind direction, shear, and veer
    b. Instruments: Aircraft, UAS, coarse and moderate velocity remote sensing , tethered balloons, in situ measurements on towers (sonic anemometers), thermodynamic profilers

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