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Offshore Wind Energy Validation Experiment Hierarchy

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Offshore Wind Energy Validation Experiment Hierarchy

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Abstract. This paper provides a summary of planning work for experiments that will be necessary to address the long-term model validation needs required to meet offshore wind energy deployment goals. Conceptual experiments are identified and laid out in a validation hierarchy for both wind turbine and wind plant applications. Instrumentation needs that will be required for the offshore validation experiments to be impactful are then listed. The document concludes with a nominal vision for how these experiments can be accomplished.

1. Introduction

The reliance of offshore wind energy applications on computational modeling is expected to grow considerably with their likely high impact on risk-based investment decisions. The present work aims to coordinate the validation needs of the suite of computational physics-based models that will be developed and applied across offshore wind research and development programs, identifying validation experiments that target the unique needs for offshore wind energy. This effort has been organized into five phenomena areas: mesoscale air (atmospheric physics and dynamics), microscale air (wind turbine and wind plant aerodynamics), water (hydrodynamics and oceanography), structures, and soil (ocean floor). Environmental impact and grid are also areas where model validation gaps exist but were beyond the scope of this effort; however, experiments in these areas could benefit from co-location with experiments described here. These phenomena areas must all address four fundamental needs to assess model adequacy for the intended applications: verification and validation, uncertainty quantification, validation experiments, and instrumentation development. The organization of this effort is shown in Figure 1.

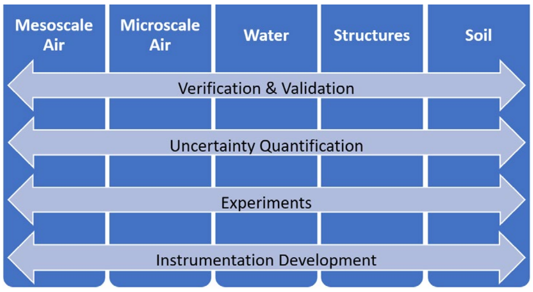

Figure 1. Organization of the offshore validation experiment planning effort

2. Methods

The Verification and Validation Framework provides a process to define the conditions where model predictions can be trusted for a given application [1]. The validation process has been divided into two main sections: Integrated Program Planning, and Integrated Experiment and Model Planning and Execution, as shown in Figure 2. The integrated program planning process has four main parts: application definition, Phenomenon Identification and Ranking Table (PIRT), validation hierarchy, and prioritized phenomenon and experiment mapping [2]. The present work covers the integrated program planning process for offshore wind floating and fixed-bottom applications, ending with concepts for experiments to address the highest priority validation needs along with the instruments that these experiments will depend on. A similar process was used to identify computational model validation needs for onshore wind energy as part of the U.S. Department of Energy Atmosphere to Electrons (A2e) program [2, 3].

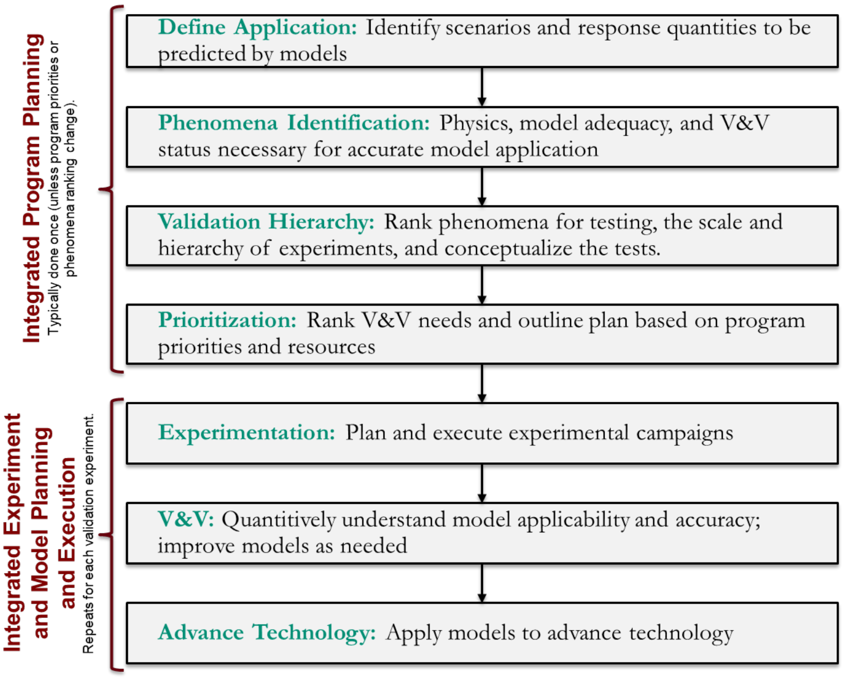

Figure 2. Framework for computational model verification and validation.

The backbone of the validation experiment planning effort is the PIRT [1]. The PIRT is a tool for collecting expert input on the physical phenomena that are most important to model for a given application and to rank the current state of adequacy regarding whether the correct physics are present, the state of verification, and the state of validation. Top modeling gaps are identified along with whether those gaps need to be addressed through model development, model verification, and/or model validation. The physical phenomena are ranked by their importance at the application level and then assessed for model adequacy. Only phenomena with the largest discrepancy between importance and model adequacy have been prioritized to be the focus of future offshore wind energy validation experiments. A process of expert elicitation was used to identify and rank the physical phenomena necessary to model offshore wind turbines and wind farms, with over 140 international subject matter experts participating [4]. The elicitation process incorporated experts from around the world through series of virtual meetings, including a full-day in-person workshop. Experiments to address these prioritized phenomena were then conceptualized as stand-alone experiments to target specific physical phenomena and then, where applicable, were combined into more complex combined experiments. The validation hierarchy is used to show how experiments of different scales and levels of complexity can be used to build confidence in the capability of a model to simulate offshore wind energy at the full scale and system complexity.

3. Hierarchy of Offshore Validation Experiments

For the initial validation experiment roadmap, experiments were targeted in the following areas: Mesoscale Air (1a), Microscale Air (1b), Water (2), and Structures (3), (Soil will be considered in the future). Experiments were developed by a team of subject matter experts to address the validation gaps identified in the preceding PIRT analysis [4]. Many individual experiments were developed that were joined into Combined Experiments. Combined Experiments tend to be larger-scale experiments, although some intermediate-scale experiments are included as well. The more targeted experiments of each of the phenomena areas are included below in the master experiment list and the validation hierarchies. The Combined Experiments cross-cut many phenomena areas and include a large number of phenomena and their interactions, but with less detail and higher uncertainty than the more targeted experiments in each phenomena area. They also are at the top of the validation hierarchy, capturing aspects of wind system physics at the wind turbine and wind plant application system levels. The resulting master experiment list for offshore wind plant model applications is shown in Table 1.

Table 1. Master experiment list of offshore validation experiments. Combined experiments address the validation needs of multiple physics areas; targeted physics experiments focus on one area.

Combined Experiments
MetOcean: Wind, Ocean, and Thermodynamic Experiment[a]
Offshore Wind Plant Flow and Multi-Farm Study of Impact of Mesoscale on Farm and Farm on Mesoscale Flow[a]
Offshore Aero/Hydro/Structure System, Fixed Bottom
Offshore Aero/Hydro/Structure System, Floating
Intermediate Scale Offshore Single Turbine Experiments

Targeted Physics Experiments	
1 Mesoscale and Microscale Air	**3 Structures[b]**
High Reynolds Number Airfoil Aerodynamics	Damping in a Vacuum Chamber
Unsteady and 3D Aerodynamics, Airfoil & Blade	Full Scale Validation of Wind Blade Lightning Protection Systems
Leading Edge Erosion	High Current Testing on Glass and Carbon Blades
2 Water	Blade Subscale Testing
Extreme Waves and Impact Loads	Full Scale Modal Validation of Highly Flexible Blades
Waves + Current	Subscale Jointed Connection Validation
Vortex Induced Motion	Elastic Response and Fatigue of Synthetic Fiber Subropes
Water-Heave Plate Interaction	Mechanical Response, Limits, and Fatigue of Dynamic Power Cables
Viscous Loading	Elastic and Fatigue Characterization of Synthetic Fiber Rope Mooring Lines
Floater Flexibility	

[a] *Mesoscale experiments are covered in the Combined Experiments*
[b] *Soils experiments will be added in the future.*

3.1. Wind Turbine and Wind Plant Combined Experiment Hierarchies

The validation hierarchy is used to show how experiments of different scales and levels of complexity can be used to build confidence in a model for simulations at full scale and system complexity. The experiments are mapped into the offshore single wind turbine validation experiment hierarchy (Figure 3) and the offshore wind plant validation hierarchy (Figure 4). Many additional experiments were identified in each phenomena area that started as separate experiments but were then merged with other experiment concepts to form the Combined Experiments at the top of the hierarchy. Some experiments cannot be merged or carried out in the field but are critical for model validation as they tend to have significantly reduced uncertainty and more targeted measurements of individual phenomena than those of the Combined Experiments [5]. These experiments are present in the hierarchies, but they are not captured in this paper for brevity, the Combined Experiments are summarized in the next section.

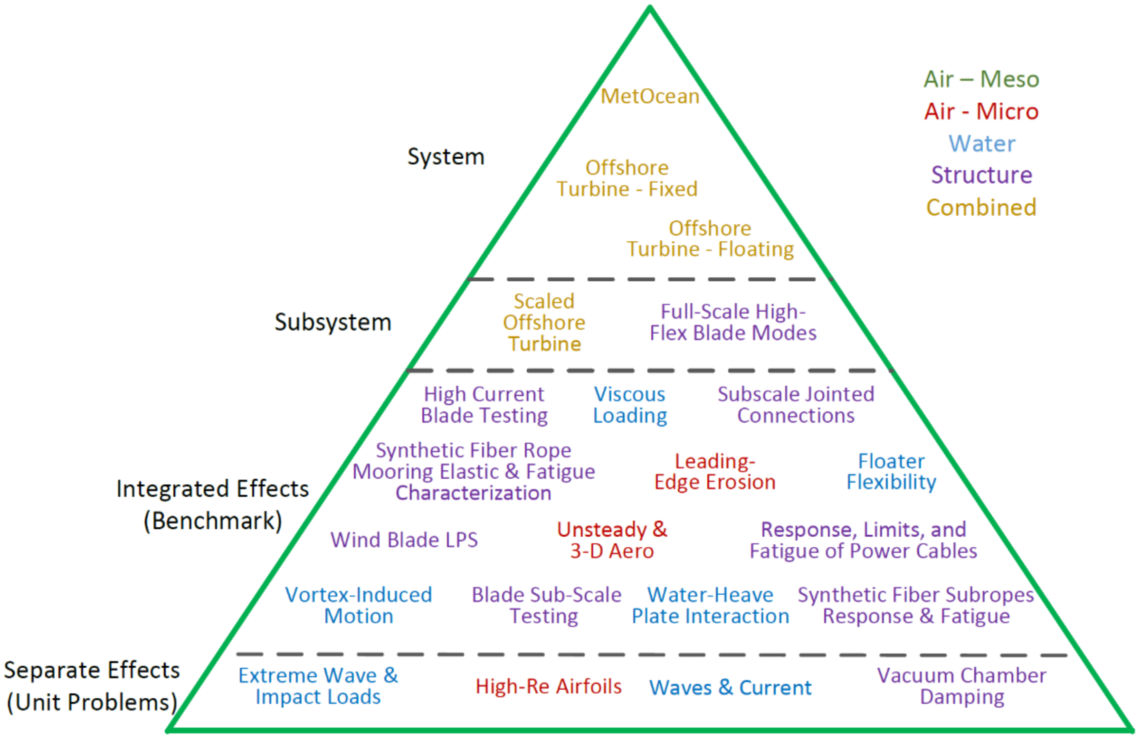

Figure 3. Offshore Single Turbine Validation Hierarchy.

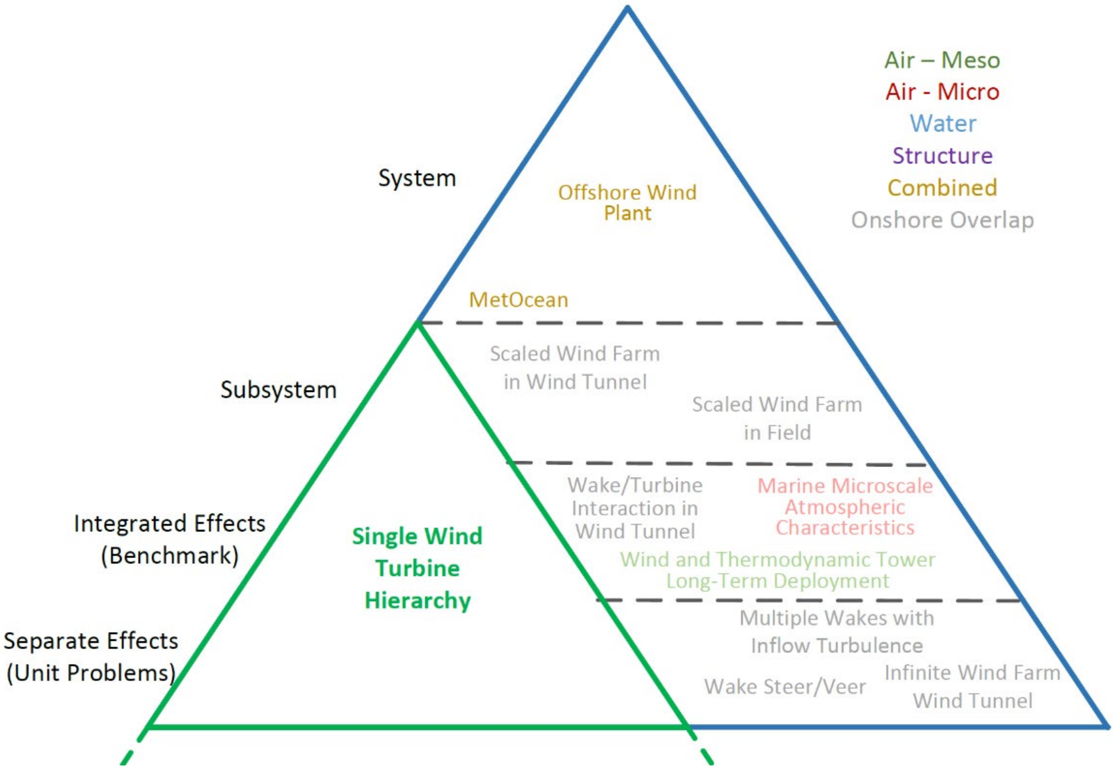

Figure 4. Offshore Wind Plant Validation Hierarchy.

4. Combined Experiments

This section includes proposed concepts for experiments that cross-cut multiple phenomena areas, termed Combined Experiments. These tend to be larger-scale experiments, although an intermediate scale experiment is included as well. The cross-cutting experiments will include all of the phenomena and their interactions for the target application but with a lower level of detail and higher uncertainty than the more targeted experiments. They also are at the top of validation hierarchy, capturing aspects of wind system physics at the system level.

4.1. *MetOcean: Wind, Ocean, and Thermodynamic Experiment*

The focus of the MetOcean: Wind, Ocean, and Thermodynamic Experiment is to gain the necessary information to validate the offshore meso- and micro-scale atmospheric and oceanographic models and to identify the unique MetOcean characteristics in different geographic locations, as summarized in Table 2. The focus is long-term measurements of atmospheric and oceanographic phenomena for the characterization of the offshore environment where wind plants are likely to be developed. No turbines are needed for this experiment, but associated load measurements would be valuable; thus, this experiment could be coupled with those planned with the turbine itself. Similar concepts should be developed for coastal sites around the world.

Table 2. MetOcean: Wind, Ocean, and Thermodynamic Experiment summary.

Experiment Summary:	• Validate offshore meso- and micro-scale atmospheric and oceanographic models • Identify the unique MetOcean characteristics in different geographic locations. • Perform long-term measurements of atmospheric and oceanographic phenomena • Target where wind plants are likely to be developed.
Phenomena Targeted:	• Winds and turbulence through the atmospheric boundary layer (ABL) and the top of rotor for a variety of conditions – including profile (shear and veer), turbulence spectra in u/v/w, spatial coherence in u/v/w, component correlations (Reynolds stresses), and even instantaneous 2D/3D turbulent field measurements. • Ramping and extreme events, including large persistent high pressure systems • Terrain and island effects • Baroclinicity • Low level jets • Gulf Stream effects • Cascade of energy from mesoscale to large-eddy simulations (LES) scales • Sea surface conditions, waves, breaking waves • Swell • Water depth variation from tides and storm • Air and water temperatures profiles and variations • Wave nonlinearity • Wave directional spreading • Coupled wind/wave characteristics – including wind/wave misalignment • Wave/current interaction • Precipitation and sea ice
Measurements and Instrumentation Needed:	• Met mast with at least five (prefer more) levels of high-frequency 3D anemometers to get wind speed (3D) and turbulence measurement, including shear and veer. • Vertically pointed lidar • Radiometer to provide temperature profiles • Flux sensors for heat, momentum, moisture flux • Instruments for wave height, direction, spreading, run-up, and kinematics with sea surface temperature (SST) • Downward looking acoustic Doppler current profiler (ADCP) for current measurement • Measurement devices that can capture 2D/3D turbulent fields such as scanning lidar or radar, or novel ideas like vertical profiling radar moved along a path on a boat or aircraft, unmanned aerial vehicles, dropsonde gliders, or satellites.
Duration:	7+ yr. total (1 yr. planning, 5 yr. execution, 1 yr. data analysis, 2 yr. model validation).

4.2. *Offshore Wind Plant and Mesoscale Flow Experiment*

The Offshore Wind Plant Flow and Multi-Farm Study of Impact of Mesoscale on Farm and Farm on Mesoscale Flow Experiment will be a large-scale international field campaign to measure atmospheric variables within and between several wind plants, as summarized in Table 3. The goals span the microscale and mesoscale: 1) mesoscale) to define the impact of the atmosphere on the wind plant and of the wind plant on the atmosphere, including downwind plants. 2) microscale) to understand wind-plant flows (e.g. wake impacts, impact of marine ABL on wakes/turbines, impacts of turbines on marine ABL) in the offshore environment. This major field campaign will require various atmospheric measurements and wind turbine wake measurements, much like the American WAKE experimeNt (AWAKEN) campaign in the United States, but also marine-specific instrumentation including ocean state and fluxes between ocean and atmosphere [6]. Because it will happen after AWAKEN, measurement technology should reflect the technology innovations. Additionally, it was recommended that this experiment would be best accomplished through collaboration with European partners.

Table 3. Offshore Wind Plant Flow and Multi-Farm Study of Impact of Mesoscale on Farm and Farm on Mesoscale Flow Experiment summary.

Experiment Summary:	Measure atmospheric variables within and between several wind plants. 1. (Mesoscale) to define the impact of the atmosphere on the wind plant and of the wind plant on the atmosphere, including downwind plants. 2. (Microscale) to understand wind-plant flows (e.g. wake impacts, impact of marine ABL on wakes/turbines, impacts of turbines on marine ABL) in the offshore environment.
Phenomena Targeted:	• Wake behavior • Wind plant blockage effects, including atmospheric gravity waves induced by the wind farm • Wind plant control • Impact of marine-specific ABLs on wind plant/turbine performance (e.g., coastal low-level jet) • Wind plant wake impact on downwind wind plants • Impact of plant wake on mesoscale • Heat, momentum, and moisture exchange within plant • Impact of precipitation on leading edge erosion • Impact of surface conditions, wave state, on plant. • Lightning physics interactions with wind turbine generators
Measurements and Instrumentation Needed:	• Scanning lidars to measure wind within and between wind plants • Radiometer to provide temperature profiles • Flux sensors for heat, momentum, moisture flux • Wave motion sensors and sea surface temperature sensor • Inertial measurements unit on multiple wind turbines for floater motion • Blade surface condition measurements and repair history • Loads instrumentation for some of the turbines • “Instantaneous cut planes” of velocity field, (horizontal to capture full farm wakes) and vertical to capture wind plant impact of atmosphere well above wind farm (gravity waves, ABL top displacement) • Instrumentation to provide high-resolution wake cut planes of wind speed • Wind plant wake measurements (possibly from satellite) • Upstream measurements to see blockage • Farm or turbine lightning detection system.
Duration:	1+ years for the experiment, 6.5+ years total (2 years planning, 1+ years execution, 1 year data analysis, 2 years validation, 6 months data archive).

4.3. *Offshore Aero/Hydro/Structure System, Fixed Bottom Experiment*

The Offshore Aero/Hydro/Structure System, Fixed Bottom Experiment will collect validation data from a highly instrumented fixed-bottom offshore wind system to validate numerical models for atmospheric inflows, turbine performance and loads, wakes, incident waves, and hydrodynamic loads, for the offshore environment, as summarized in Table 4. This experiment expands on the onshore Rotor Aerodynamics Aeroelastics and Wake (RAAW) experiment to enable validation of marine atmospheric boundary layers affecting larger offshore turbines considering the aeroelastic response and performance of wind turbines, as well as on full-scale hydroelastic response [7]. This experiment is focused on collecting data to better model the aeroelastic and hydroelastic response of a turbine atop a fixed support structure in the offshore environment. A monopile or jacket substructure is anticipated, depending on the water depth. This experiment also requires instrumentation development. For example, a meteorological tower may not be available to measure inflow, but inflow measurements are likely a requirement. Also, aerodynamic blade forces will be more difficult to measure due to clogging from water in the marine environment. Blade deflection measurements are more difficult to measure due to the lack of a fixed ground to install stationary instruments. Robustness of sensors in the presence of salt water is paramount. An impact of this experiment is validating the wide range of offshore wind computational models, including engineering tools and high-fidelity tools. At the end of the project, participating laboratories will have new offshore wind turbine instrumentation to measure blade aerodynamic forces, blade elastic deformations, and hydrodynamic loads.

Table 4. Offshore Aero/Hydro/Structure System, Fixed Bottom Experiment summary.

Experiment Summary:	• Collect validation data from a highly instrumented, fixed-bottom, offshore wind system • Validate wind energy codes for: − Atmospheric inflows − Turbine performance and loads − Wakes − Incident waves and hydrodynamic loads. • Expands upon the onshore RAAW experiment to enable validation of marine atmospheric boundary layer effects and full-scale offshore turbine scale effects on the aeroelastic response and performance of wind turbines, as well as on full-scale hydroelastic response
Phenomena Targeted:	• Marine atmospheric boundary layer physics • Aeroelastic response of offshore scale turbines and blades • Wake physics in marine atmospheric boundary layer • Unsteady aerodynamic blade forces • Hydrodynamic loads on the substructure • Full-scale structural damping • Shear and torsion (support structure, tower, blades) • Jointed connections • Member-level loads • Air-water-structure interaction • Ocean floor soil
Measurements and Instrumentation Needed:	• Atmospheric inflow beyond 3D upstream, inflow coherence and structures • Aerodynamic blade forces, distributed blade strain, blade deflection in flap/edge/torsion, turbine supervisory control and data acquisition (SCADA), blade surface condition, blade sectional surface pressure and local inflow • Wake velocity cross sections and downstream planes • Wave height and direction, current speed/direction/profile, water run-up, green water • Tower top and bottom strains/forces, substructure distributed loads/strains • Soil conditions (ocean floor) • All measurements should be time correlated at the location of the wind system. • Attention on the impact of the measurement and sensors on the system response.
Duration:	5 years total (1 yr. experiment planning, 1 yr. instrumentation dev., 1 yr. instrumentation deployment, 1 yr. experiment execution, 1yr. data processing and model validation)

4.4. *Offshore Floating Aero/Hydro/Structure System Experiment*

The Offshore Floating Aero/Hydro/Structure System Experiment will collect validation data from a highly instrumented floating offshore wind turbine (FOWT) to validate the DOE codes for atmospheric inflows, turbine performance and loads, wakes, as well as incident waves and current, hydrodynamic loads, and floater response, for the offshore environment, as summarized in Table 5. This experiment is focused on collecting data to better model the aeroelastic and hydroelastic response of a turbine atop a floating support structure in the offshore environment. A semisubmersible is anticipated, but a spar or tension-leg platform (TLP) could also be considered. Two campaigns on different structure types would be valuable. This dataset expands on onshore and fixed-bottom offshore RAAW-like experiments to enable validation with the added complexity of floater motion (impacting aerodynamics and hydrodynamics) and the stationkeeping and dynamic power cable systems on the aeroelastic response and performance of wind turbines, as well as on full-scale hydroelastic response. This experiment also requires instrumentation development. Additional instruments needed would include mooring tension and dynamic power cable bending sensors. An impact of this experiment is validating offshore wind codes, including engineering tools and high-fidelity tools, using the data collected in this experiment. At the end of the project, there will be new offshore wind turbine instrumentation to measure the full-scale incident wind and wave inflow, FOWT response, and outflow in the offshore environment.

Table 5. Offshore Floating Aero/Hydro/Structure System Experiment summary.

Experiment Summary:	This experiment is focused on collecting data to better model the aeroelastic and hydroelastic response of a turbine atop a floating support structure in the offshore environment. It will collect validation data from a highly instrumented full-scale FOWT to validate numerical simulations for: • Atmospheric inflows, • Turbine performance and loads, • Wakes, • Incident waves and current, • Hydrodynamic loads, • Floater response
Phenomena Targeted:	Same phenomena as Fixed Bottom Experiment with additional phenomena: • Floater-motion induced effects, • Phenomena associated with the station keeping and dynamic power cable system, including those driven by vortex-induced vibration of the lines and vortex-induced motion of the floater. • Tests to validate damage stability load cases would also be valuable.
Measurements and Instrumentation Needed:	Same as Fixed Bottom Experiment with additional needs: • Tower top and bottom strains/forces, nacelle acceleration, substructure distributed loads/strains, inclinometer/motion response • Mooring line fairlead loads, anchor loads, and loads along the length of the mooring lines and dynamic power cable including bending of the power cable.
Duration:	5-7 years total: 1-2 years planning, 1-2 year execution, 1 year data analysis, 2 years validation and data archive).

4.5. *Intermediate Scale Turbine Experiment*

The Intermediate Scale Turbine Experiment will collect validation data from a highly instrumented FOWT at intermediate scale (<1 MW) to validate codes (e.g. OpenFAST, ExaWind) for atmospheric inflows, turbine performance and loads, and wakes, as well as incident waves and current, hydrodynamic loads, and floater response, for the offshore environment, as summarized in Table 6. The term ‘intermediate scale’ refers to using a turbine that is smaller in size than modern offshore turbine but would still be of significant scale to capture a majority of the physics interactions. This experiment is focused on collecting data to better model the aeroelastic and hydroelastic response of a turbine atop a floating support structure in the offshore environment. This experiment is a compromise of scale and cost, as the interaction of aerodynamics, hydrodynamics, and structural dynamics will not be equal to commercial, floating, offshore wind turbines. This experiment values collecting data for validation of models over modeling the special interactions of unsteady forces unique to larger scale wind turbines. At intermediate scale, this experiment has an advantage over full scale in that the experiment is less expensive, there is more possibility of obtaining system properties (lower impact of proprietary data limits), and the (scaled) extreme wind conditions and (scaled) severe sea states are more likely to occur at intermediate scale. Therefore, further work to design this experiment includes identifying which physics within wind turbine models would have the greatest uncertainty and hence benefit most from an intermediate scale, floating wind turbine experiment.

Table 6. Intermediate Scale Turbine Experiment summary

Experiment Summary:	• Collect validation data from a highly instrumented FOWT at intermediate scale (< 1 MW) • Validate coupled models for atmospheric inflows, turbine performance and loads, wakes, as well as incident waves and current, hydrodynamic loads, and floater response. • Intermediate scale has advantages over full scale: – Less expensive and fewer intellectual property limitations – Extreme wind conditions and severe sea states are more likely to occur at intermediate scale, relative to the turbine size/scale.
Phenomena Targeted:	Same as the full-scale floating experiment, but with more focus on extreme wind conditions and severe sea states, relative to the turbine size/scale.
Measurements and Instrumentation Needed:	Same as the full-scale floating experiment.
Duration:	1 year for the experiment, 3 years total (1 year planning, 1 year execution, 1 year data analysis+validation+data archive).

5. Instrumentation Development Needs

Instruments that were identified as being critical to the success of the experiments identified above are listed in Table 7. An International Energy Agency (IEA) Wind Topical Experts Meeting (TEM110) recently focused on international and commercial collaboration to address the instrumentation development needs.

Table 7. Critical instruments for offshore wind validation.

Group 1a – Mesoscale Air • Multiple lidars to see across wakes and between farms, built for long-term offshore deployment • Doppler radar for longer ranges • Synthetic aperture radar from satellite to get sea surface temperature • Radiometer or similar that can be deployed offshore to measure temperature profiles • Microwave radiometer on turbine spinners (like forward-looking lidars) • Sonic anemometers that are easier to maintain in the offshore environment • Improved instrumentation for measurement of ocean skin temperature and fluxes
Group 1b – Microscale Air • Instruments to measure wind, temperature, moisture through entire ABL, but with detail of steepest gradients near surface. • Instruments to measure mesoscale phenomena (existing daily soundings, meso-net). • Instruments to measure wind plant wakes • Instrument(s) to quantify ABL turbulence structure for validation of large-eddy simulation and informing synthetic turbulence methods such as scanning radar (e.g., TTU X-Band radar). • Utilize existing and emerging satellite data through collaboration with NASA. • Instruments to measure wind-farm-induced atmospheric gravity waves. • Instruments and methods to measure wind plant blockage. • Instrumented buoys: measurement compensation and marine environment reliability.

• Instruments to measure blade surface pressure and inflow for unsteady conditions, lightning safe • Define what can be sufficiently measured by or augmented with drones.
Group 2 – Water • Instruments for high-resolution time measurements of wind and waves concurrently, including wind/wave misalignment and wave run-up • Instrumentation for combined current and wave measurements • Measurement approaches for wave nonlinearity and wave spreading • Instruments for motion and acceleration measurements for floating wind systems • Instrument for distributed load measurements for the moorings and power cables • Instrument for distributed pressure on the substructure • Internal loads in the substructure • Reliable measurements below the waterline
Group 3 – Structures • Instrument turbines while being built in anticipation of data needs • Identify sensors and install at design/development stage • Instruments for tip vortex measurement • Instrument for pressure distribution measurement on blades and support structure

6. Conclusions

A building block approach is necessary to address the wide spectrum of validation needs for offshore wind energy. Some phenomena and coupling must be tested at scale for complete system complexity, but uncertainty of full-scale experiments is too high to be useful for some validation efforts (e.g., low-level jet shear across rotor diameter). Additionally, there is a strong need for collaboration, both internationally as well as between the wind industry and the broader research community. Commercial wind turbines and wind plants will be an integral part of the combined experiments, but sharing data incurs a cost to industry partners, so collaborative agreements must be made early in the experiment development process. The scale and complexity of these experiments prevent a single national entity from adequately addressing them, but international collaboration can require long lead times to mature. In summary, a range of experiments is needed to allow the offshore wind industry to develop; the planning and collaboration required for these experiments to be successful must start now.

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References

[1] Hills R G, Maniaci D C, and Naughton J W, *V&V Framework*. 2015. doi:10.2172/1214246.

[2] Maniaci D C, and Naughton J W, 2019: *V&V Integrated Program Planning for Wind Plant Performance*. Sandia National Laboratories report SAND-2019-6888, doi:10.2172/1762662.

[3] Maniaci D C, Moriarty P J, Barone M F, Churchfield M J, Sprague M A, and Arunajatesan S, 2020: *Wind Energy High-Fidelity Model Verification and Validation Roadmap*. SAND2020-1332, doi:10.2172/1634281.

[4] Maniaci D, Naughton J, Haupt S, Churchfield M, Robertson A, and Jonkman J, 2023: *Offshore Field Measurement Campaign Planning, Summary of PIRT Workshops and Initial Experiment Conceptualization*. Sandia National Laboratories report, SAND2023-02373PE.

[5] Maniaci D, Naughton J, Haupt S, Churchfield M, Robertson A, Jonkman J, Johnson N, et al., 2023: *Offshore Validation Experiment Roadmap Reference PIRTs, Experiments, and Instrumentation Needs*. Sandia National Laboratories, SAND2023-120010PE.

[6] Moriarty P., Hamilton N, Debnath M, et al. 2020. *American WAKE experiment (AWAKEN)*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-75789. https://www.nrel.gov/docs/fy20osti/75789.pdf.

[7] Kelley C, Doubrawa P, Hamilton N, Naughton J, *Rotor Aerodynamics, Aeroelastics, & Wake Project*. NAWEA/WindTech, University of Delaware, 2022.