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# Offshore Field Measurement Campaign Planning
# Summary of PIRT Workshops and Initial Experiment Conceptualization

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# Multi-lab Team and Organization

- **David Maniaci – Sandia National Laboratories –** Project Lead and Coordinator
- **Jonathan Naughton – University of Wyoming –** Validation Experiment Coordinator
- **Sue Haupt – NCAR –** Air-Mesoscale lead (ABL, Farm-Farm interaction)
- **Matt Churchfield– NREL –** Air-Microscale lead (ABL, Turbine aero., Turbine-Farm interaction)
- **Amy Robertson – NREL –** Water lead (Waves, Current, Tides)
- **Jason Jonkman – NREL –** Structures + Soiling lead

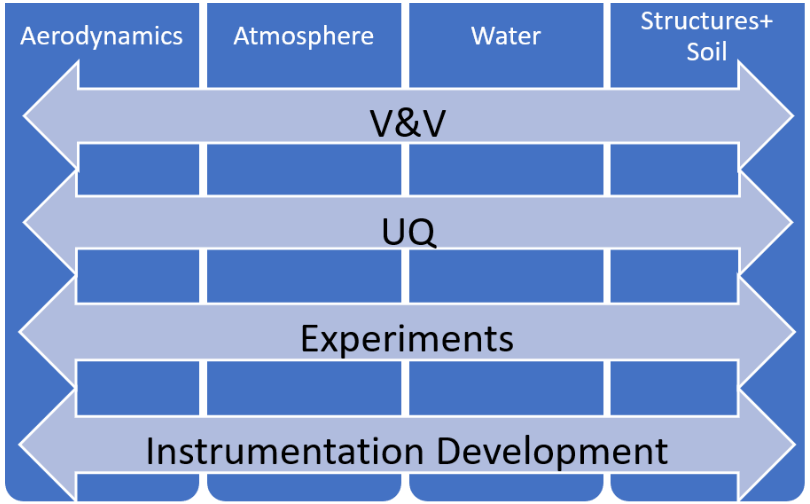
- **Staff at SNL, NREL, PNNL, and NCAR supporting this work directly**
- **Broader lab, research community, and industry input**
  - The A2e PIRT activities last year included input from staff at SNL, NREL, PNNL, LLNL, ANL, and NCAR.

| Phenomena Categories | Group # | Area Lead |
|---|---|---|
| **Air Mesoscale: ABL, Farm-Farm Interaction** | 1a | Sue Haupt |
| **Air Microscale: ABL, Turbine Aero, Turbine-Farm Interaction** | 1b | Matt Churchfield |
| **Water: Waves, Current, Tides** | 2 | Amy Robertson |
| **Structures, Soil** | 3a, 3b | Jason Jonkman |
| **Interfaces:** Water-Structure, Air-Structure, Soil-Structure, Air-Sea, Water-Soil, Water-Soil-Structure, Air-Air, Air-Structure-Control, Water-Structure-Control | | |

# Overview

**Goal: Roadmap for validation of offshore wind design and analysis modeling capabilities**

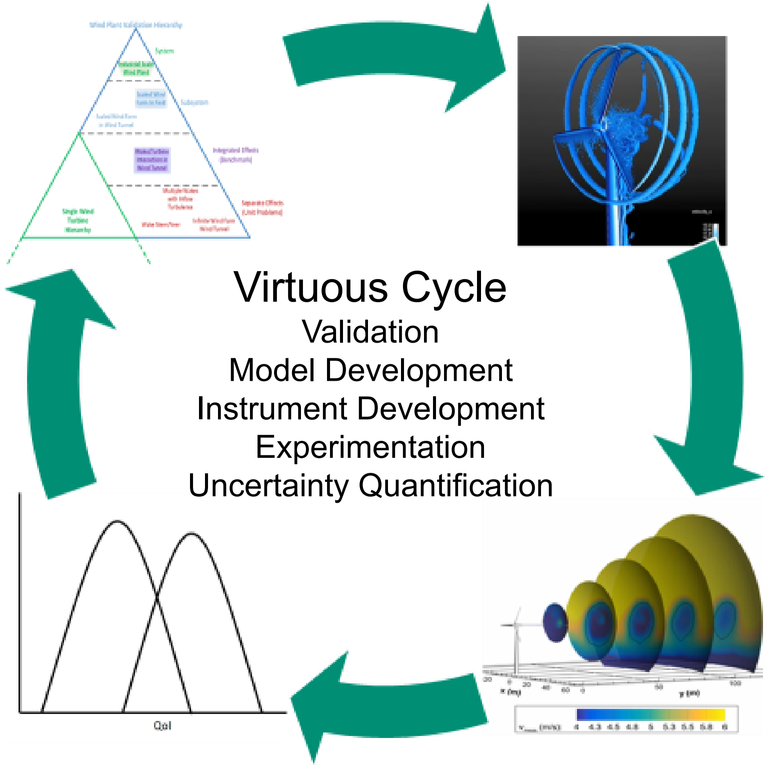
- **Overall Approach:**
  - PIRT – Identify outstanding critical phenomena – areas where we don't understand physics well or are unsure of the accuracy of our tools
  - Develop an organizational structure of the validation needs
    - Define a hierarchy of priorities and dependencies
  - Define an approach to address the prioritized needs
    - Identify available datasets
    - Define needed experiments and required instrumentation and logistics
  - Develop a roadmap that defines approach for organizations to address offshore validation needs
    - Enable structure for international collaboration in tackling needs




- **The validation roadmap developed in this effort will give:**
  - Priorities for model validation campaigns specific to offshore wind energy,
  - Hierarchy of prioritized experiments to meet validation goals,
  - Instrumentation development that will be needed for unique offshore validation needs,
  - Framework for international and cross-institution coordination.

# V&V Coordination Bonds Validation Efforts

- **Directly builds off aspects of the A2e V&V/UQ project and Instrumentation Development Roadmap from AWAKEN**
  - Coordination activities targeting needs for Offshore Wind.
- **Acts as the ‘glue’ between all offshore validation related projects**
  - Depends on multi-year projects and external organizations to cover the time for the contributions of experts.
- **Enables coordination of future offshore wind field experiments and the modeling efforts that will rely on the resultant data for training, calibration, and validation.**
  - Modeling efforts across the program (atmospheric, HFM turbine/plant, systems)
  - Targeted validation experiments
  - Instrumentation development
  - Machine learning and data analysis
  - Uncertainty quantification
- **A focused validation coordination effort has several benefits in preparation for future experimental campaigns:**
  - Synergy between validation focused experimental campaigns.
  - Maximum use of limited funds through careful, integrated planning.
  - Experience gained and instrumentation developed in early campaigns will feed into later campaigns.



# Integrated Verification and Validation (V&V) Methodology

**Integrated Program Planning**
Typically done once (unless program priorities or phenomena ranking change).

**Define Application:** Identify scenarios and response quantities to be predicted by models

**Phenomena Identification:** Physics, model adequacy, and V&V status necessary for accurate model application

**Validation Hierarchy:** Rank phenomena for testing, the scale and hierarchy of experiments, and conceptualize the tests.

**Prioritization:** Rank V&V needs and outline plan based on program priorities and resources

**Integrated Experiment and Model Planning and Execution**
Repeats for each validation experiment.

**Experimentation:** Plan and execute experimental campaigns

**V&V:** Quantitively understand model applicability and accuracy; improve models as needed

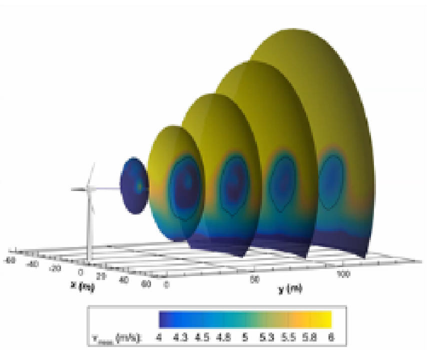
**Advance Technology:** Apply models to advance technology

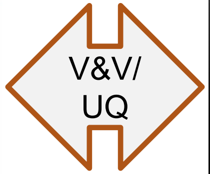
**Outcome of the Planning Process:**

- Prioritized phenomena
- Identification of gaps in existing V&V data and activities
- Hierarchy of prioritized validation experiments and analysis

**Validation Focused Program**

Validation Experiment






Computational Modeling

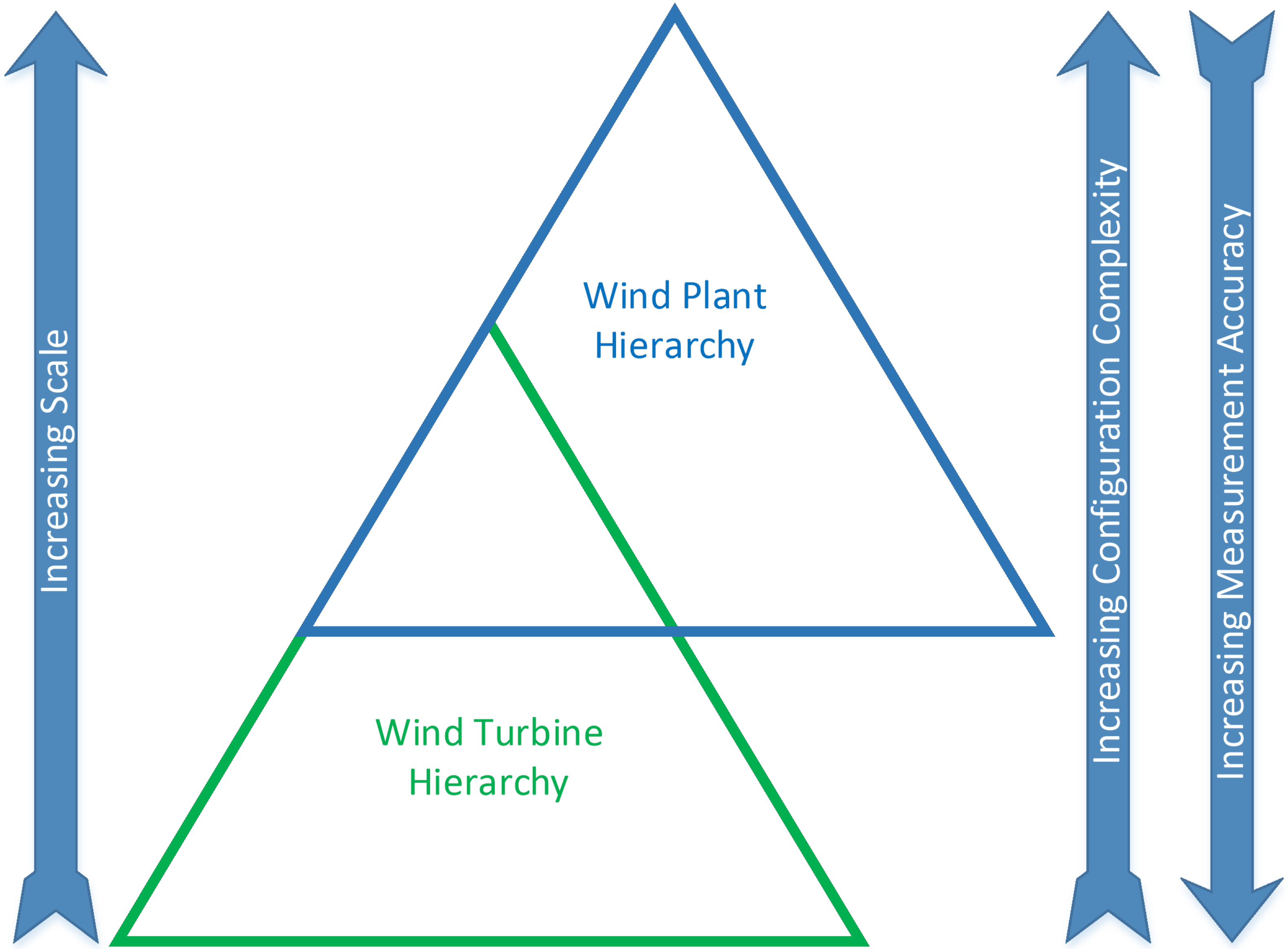
**Prediction** ⇨ **Innovation**

# Backbone of V&V Planning: Phenomenon Identification Ranking Table (PIRT)

| Phenomenon | Importance at Application Level | Model Adequacy | | |
|---|---|---|---|---|
| | | Physics / Code Functionality | Code / Verification | Code / Validation |
| A | H | M | L | L |
| B | H | M | L | L |
| C | M | M | M | L |
| D | H | L | L | L |
| E | Unknown | M | L | L |
| F | H | L | L | L |
| G | L | M | L | L |
| H | H | M | L | L |
| I | H | L | L | L |
| J | H | L | L | L |
| K | H | L | L | L |
| L | M | L | L | L |
| M | H | M | L | L |
| N | L | L | L | L |

- **Specific to application and model**
- **Provides gap analysis regarding ability to model phenomena:**
  - Physics / code functionality gaps
  - Numerical gaps
  - Verification gaps
  - Data gaps
  - Validation gaps
- **Consensus based**
- **Used to prioritize planning, including experimentation needs**
- **Requires reassessment over time as models improve and V&V activities progress**

# Validation Hierarchy




- **PIRT Leads to the Validation Hierarchy**
- **A range of levels of experiments, increasing in scale and complexity:**
  - Simple, laboratory-type experiments at the base
  - Full complex system at the peak

# Phenomena Categories for Application to Offshore Wind

| Phenomena Categories | Group # |
| --- | --- |
| **Air Mesoscale: ABL, Farm-Farm Interaction** | 1a |
| **Air Microscale: ABL, Turbine Aero, Turbine-Farm Interaction** | 1b |
| **Water: Waves, Current, Tides** | 2 |
| **Structures, Soil** | 3a, 3b |
| **Electrical, Grid** | 4 |
| **Interfaces:** | |
| Water-Structure | 2, 3a |
| Air-Structure | 1b, 3a |
| Soil-Structure | 3a, 3b |
| Air-Sea | 1a, 1b, 2 |
| Water-Soil | 2, 3b |
| Water-Soil-Structure | 2, 3a, 3b |
| Air-Air (Terra Incognita) | 1a, 1b |
| Air-Structure-Control | 1b, 3a, 4 |
| Water-Structure-Control | 2, 3a, 4 |

- Fixed and floating
- Performance and loads applications
- Engineering and high fidelity
- Grid (area 4) not addressed at this stage
- Phenomena of high importance shown next

# Group 1a – Mesoscale Air

Mesoscale

Cross-scale Effects

Air-Air, Terra Incognita

ABL

Wind Plant Aero., Wakes (farm-farm)

Air-Sea

# Group 1a – Mesoscale Air – Prioritized Phenomena

- **Highest Priority for Experiments:**
  - Representation of winds and turbulence through the atmospheric boundary layer (ABL) to the top of the rotor – requires profiles of temperature and humidity as well as 3D wind speed and direction. Include cloud impact on ABL
  - Wind plant representation (drag effect of turbines) – include impact of ocean upwelling on stability.
- **Other very high priority**
  - Ramp events – due to mesoscale weather phenomena such as fronts, thunderstorms, …
  - Low level jets
  - Extreme wind events – tropical cyclones, extratropical cyclones, etc. See ANL PIRT.
  - Bridging gap from mesoscale turbulence to microscale turbulence.
  - Impact of plant wake on Mesoscale processes

# Group 1a – Mesoscale Air – Prioritized Phenomena

- **Other very high priority**
  - Stability impacts on the ABL structure.
    - Rolls and cells in convection – surface to above ABL
    - Impact of ABL height on ABL structure – hard to measure when stable.
  - Plant wake – emphasis on the effect of the wind farm on cross-stream downstream regions.
  - Deep array turbulence – within the farm.
  - Lightning – important to structures
  - Precipitation and leading edge erosion – include raindrop size distribution and impact on ocean surface cooling. Important to structures
  - Sea surface conditions – waves, impact of breaking waves. Include upwelling and wind-wave misalignment.
  - Sea surface conditions – temperature (SST) and its gradients at wind plant scales.
  - Swell – larger wave age. Not in mesoscale models

# Group 1a: Mesoscale Air, ABL, Farm-Farm Interaction

| Phenomenon | Importance at Application Level | Relative Importance for experiments | Model Adequacy | | |
|---|---|---|---|---|---|
| | | | Physics | Code | Validation Capability |
| **Mesoscale phenomena** | | | | | |
| Representation of winds and turbulence through the atmos. boundary layer and/or top of rotor | H | *** | M | M | L |
| Wind plant repesentation (i.e., drag effect of turbines) | H | *** | M | M | L |
| Large, persistent high-pressure domes with low wind speeds | H | | M | M | L |
| Terrain influences and Island effects | H | | M | M | L |
| Baroclinicity | H | | M | L | L |
| Cold air outbreaks | H | | M | M | L |
| **Cross-scale effects** | | | | | |
| Low-level jets | H | * | M | M | L |
| West coast synoptically induced high winds | H | | H | H | L |
| Terrain influences and Island effects | H | | M | M | L |
| Gulf stream effects on ABL/mesoscale | H | | M | M | L |
| **Air-Air, Terra Incognita** | | | | | |
| Mesoscale turb. to LES turb. models | H | * | L | M | L |
| Mesoscale to plant inflow | H | | M | M | L |
| Plant wake to mesoscale | H | * | M | M | L |

# Group 1a: Mesoscale Air, ABL, Farm-Farm Interaction

| Phenomenon | Importance at Application Level | Relative Importance for experiments | Model Adequacy | | |
|---|---|---|---|---|---|
| | | | Physics | Code | Validation Capability |
| **ABL** | | | | | |
| Turbine wake interaction within a farm, which is a function of ABL turbulence-(Stability) | H | * | M | M | L |
| Internal boundary layers due to differential advection | H | | M | M | L |
| Low-level jet | H | | M | M | L |
| Impact of clouds on ABL structure | H | | M | L | L |
| Stability impacts on ABL structure | H | * | H | M | L |
| Impact of ABL height on ABL structure | H | * | M | M | L |
| **Wind Plant Aero., Wakes (farm-farm)** | | | | | |
| Plant wake | H | * | M | M | L |
| Heat, moisture and momentum exchange within plant | H | | L | L | L |
| Deep array turbulence | H | * | L | M | M |
| Lightning | H | Sturctures | L | M | M |
| Precipitation and impact on leading edge erosion | H | Structures | M | M | L |
| **Air-Sea** | | | | | |
| Surface conditions - waves, including impact of breaking | H | * | M | L | L |
| Swell - larger wave age | H | * | M | L | L |

# Group 1a – Mesoscale-Microscale Air Crossovers

- **Having correct profiles of thermodynamic variables as well as wind data.**
- **Offshore specific items critical, such as**
  - Land / sea interface
  - SST gradients
  - Hurricanes
- **Wakes of these large offshore wind turbines and wind farms cannot be scaled up from the land-based farms.**
- **Large wind farm clusters impact the mesoscale.**
- **Understanding and modeling deep array turbulence within the farm requires accurate coupling with the mesoscale.**
- **Stability matters for turbulence at both micro and mesoscale.**

# Group 1a – Mesoscale-Turbine Crossovers

- The description of the ABL is becoming more critical for the large offshore turbines to operate efficiently.
- Timescales for forecasting are rapidly decreasing – need accurate forecasts for control.
- Lightning is a critical phenomena where it is difficult to conduct an experiment.
- Precipitation can cause leading edge erosion. To accurately predict that requires drop size distributions.

# Group 1a – Mesoscale Air

- **Main takeaways**
  - Need to better understand and measure the impact of ABL structure on wind energy harvest.
  - Need to couple from mesoscale to microscale to get correct modeling.
  - Need to include impacts of atmospheric stability, including thermodynamic structure as well as 3D wind profiles, which impact convective cells and rolls, and low level jets.
  - Need to better understand impact of turbines on generating turbulence both within the farm and between farms, both of which impact harvest.

# Group 1a – Mesoscale Air

- **Gaps remaining**
  - Impact of ABL stability on wind farm efficiency and maintenance
  - Understand impact of precipitation on
    - Leading edge erosion
    - Changes in ocean temperature

# Group 1a – Mesoscale Air

- **Conceptual Experiments**
  - The team conceived of a large multi-national experiment that would measure many atmospheric properties (wind and thermodynamic properties) and multiple levels and multiple sites. Focus would be both within farms and between farms. If it is to be within the next 5 years, it would have to be off Europe where multiple closely spaced wind farms already exist. We need to understand wake interactions over multiple stability cases particularly for stable conditions, which are likely a worst-case scenario. Could be less than a year but would need to cover several seasons.
  - Long-term measurements (2-5 years) from a tower or instruments in wind farms to obtain multi-year data that could be used to see extreme events and to train machine-learning models of the future.

# Group 1a – Mesoscale Air

- **Instrumentation needs**
  - Multiple lidars to see across wakes and between farms.
  - Doppler radar – perhaps see to longer ranges
  - Synthetic aperture radar from satellite to get SST
  - Radiometer or something that can be deployed offshore to measure temperature profiles
  - Potentially a microwave radiometer on turbine spinners (like forward-looking lidars)
  - Sonics that are easier to maintain in the offshore environment
  - Better measurement of ocean skin temperature and fluxes

# Group 1b – Microscale Air

Microscale Atmosphere

Offshore-Specific Microscale Atmosphere

Air-Sea Interface

Air-Air Gray Zone (Terra Incognita)

Wind Plant Aerodynamics/Wakes

Turbine Aerodynamics – Rotor, Blade

Turbine Aerodynamics – Airfoil

# Group 1b: Microscale Air - Prioritized Phenomena

- **Scoring System:**
  - Phenomenon importance at application level is ranked values of H, M, L
    - H/M/L = high/medium/low importance
  - Physical understanding is ranked values of H, M, L
    - H/M/L = high/medium/low-level of physical understanding
  - Code implementation/verification
    - H/M/L = well/adequately/poorly implemented/verified code
  - Code/Physics validation
    - H/M/L = well/adequately/poorly validated code/physics

# Group 1b: Microscale Air - Prioritized Phenomena

- **Overall Priority:**
  - We then look for disparity between phenomenon importance compared with physical understanding, code implementation/verification, validation.
    - If the disparity is high, there is a high priority.
    - Example, high phenomena importance but poor physics understanding/code/validation means that there should be high priority to do research/model development on this topic
  - These scores are converted to numeric values
    - H = 2, M = 1, L = 0
  - Assign a numerical priority score:
    - $\text{score} = \frac{\text{phenomena importance} - mean(\text{physics, code, validation}) + 2}{2}$
    - The +2 and /2 simply ensure the score is on a range of 0 to 2.
    - Priority level: 2 = high, 1 = medium, 0 = low

# Group 1b: Microscale Air - Prioritized Phenomena

- Prioritized phenomena

| Phenomenon | Planning Priority | | |
|---|---|---|---|
| | High Fidelity | Engineering Tools | Overall |
| General Microscale Atmospheric Phenomena | 1.40 | 1.68 | 1.54 |
| Offshore-Specific Microscale Atmospheric Phenomena | 1.55 | 1.67 | 1.61 |
| Air-Sea Interface Phenomena | 1.65 | 1.73 | 1.69 |
| Air-Air Gray Zone (*Terra Incognita*) | 0.83 | 1.00 | 0.92 |
| Wind Plant Aerodynamics / Wakes | 1.30 | 1.63 | 1.46 |
| Turbine Aerorodynamics -- Rotor, Blade | 1.44 | 1.58 | 1.51 |
| Turbine Aerodynamics -- Airfoil | 1.57 | 1.51 | 1.54 |

Least Important — Most Important

# Group 1b: Microscale Air - Prioritized Phenomena

- **Highest priority rankings naturally had to do with offshore but were atmospheric focused.**
  - #1 Air-Sea Interface – 1.69
  - #2 Offshore specific atmospheric flow – 1.61
  - #3 General atmospheric flow – 1.54
- **Next batch of priority comes from wind turbine and blade aerodynamics**
  - #4 Turbine Aerodynamics – Airfoil – 1.54
  - #5 Turbine Aerodynamics – Rotor – 1.51
- **Wind Plant/Wakes close follower**
  - #6 Wind Plant and Wake Flow – 1.46
- **Gray Zone (Terra Incognita) much lower**
  - #7 Gray Zone – 0.92

# Group 1b: Microscale Air - Prioritized Phenomena

- **Rankings reflect the fact that the offshore atmospheric environment is less studied/modeled and that validation data is harder to obtain**
  - However, we must remember that work has been done
    - Peter Sullivan et al. and high-fidelity wind/wave LES
    - MMC group began offshore work before task ended
    - ORACLE and TREXO projects are offshore focused
    - Significant data: FINO 1, ASIT, California buoys
    - Can we draw from oil and gas industry?
- **Microscale flow continues to be a difficult problem**
  - We have made huge advances in canonical ABL microscale modeling at high-fidelity since the 1970s, so that is great progress
  - However, the range of atmospheric conditions, situations, surface effect is nearly infinite
  - Interaction with mesoscale and surface is complex

# Group 1b: Microscale Air - Prioritized Phenomena

- **Rotor and Airfoil flows rose above plant/wake flow**
  - This is likely explained because offshore rotors are different than current land-based technology with which we have more experience
  - Higher Reynolds number and Mach number, thick airfoils, possible active control devices make this relatively new and higher priority
  - Also, we devoted a lot of work over the last decade to plant/wake flows, so we understand those flows better than before
- **Gray Zone ranks low**
  - Gray zone (terra incognita) refers to the range of scales between mesoscale and microscale
  - The low priority is likely because most mesoscale-microscale coupling methods simply jump directly from mesoscale to microscale without explicitly modeling the gray zone

# Group 1b: Microscale Air - Prioritized PIRT

| Phenomenon | Is it different offshore vs. onshore? | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy (High Fidelity) | | | | Model Adequacy (Engineering Tools) | | | | Planning Priority | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | High Fidelity | Engineering Tools | Overall |
| **General Microscale Atmospheric Phenomena** | | | | | | | | | | | | 1.40 | 1.68 | 1.54 |
| Mean vertical profile (shear/veer/asymmetry) | Yes | both | H | H | M | M | M | M | M | M | L | 1.33 | 1.67 | 1.50 |
| Mean vertical profile, not of just wind, but also temperature and moisture | Yes | both | H | M | L | L | M | L | L | L | L | 1.67 | 2.00 | 1.83 |
| Turbulence Spectrum | Yes | both | H | H | M | L | M | M | M | L | M | 1.33 | 1.50 | 1.42 |
| Turbulence Coherence/Correlation | Yes | both | H | H | M | L | L | M | M | L | L | 1.50 | 1.67 | 1.58 |
| Turbulence Structure (space-time structure) | Yes | both | H | H | L | L | L | H | L | L | L | 1.67 | 1.67 | 1.67 |
| Boundary Layer Height | Yes | both | H | H | M | M | L | L | L | M | L | 1.50 | 2.00 | 1.75 |
| Surface conditions (roughness, canopy, waves, surface heat flux, topography) | Yes | both | H | M | L | M | L | L | M | M | L | 1.83 | 1.83 | 1.83 |

# Group 1b: Microscale Air - Prioritized PIRT

| Phenomenon | Is it different offshore vs. onshore? | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy (High Fidelity): Physics Model | Model Adequacy (High Fidelity): Code + Verification | Model Adequacy (High Fidelity): Do We Have Validation Data? | Model Adequacy (High Fidelity): Have We Validated? | Model Adequacy (Engineering Tools): Physics Model | Model Adequacy (Engineering Tools): Code + Verification | Model Adequacy (Engineering Tools): Do We Have Validation Data? | Model Adequacy (Engineering Tools): Have We Validated? | Planning Priority: High Fidelity | Planning Priority: Engineering Tools | Planning Priority: Overall |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Offshore-Specific Microscale Atmospheric Phenomena** | | | | | | | | | | | | 1.55 | 1.67 | 1.61 |
| Horizontal Heterogeneity | | | H | L | L | M | L | L | L | M | L | 2.00 | 2.00 | 2.00 |
| Coastal Low-Level Jet | Yes | both | H | M | M | M | M | L | L | M | L | 1.50 | 2.00 | 1.75 |
| Transitional Nature of ABL at Land-Sea Interface, and SST Gradients | | | H | M | M | L | L | L | L | L | L | 1.67 | 2.00 | 1.83 |
| Site-Specific-ness (not really a phenomenon) | | | H | M | M | M | M | M | M | M | L | 1.50 | 1.67 | 1.58 |
| ABL within Tropical / ExtraTropical Cyclones | | | H | L | L | L | L | L | L | L | L | 2.00 | 2.00 | 2.00 |
| Design Standard Gust Cases Specific for Offshore and Floating Turbines (not really a phenomenon) | | fixed (same as land) / floating (new) | H | L | L | L | L | M | M | L | L | 2.00 | 1.67 | 1.83 |
| **Air-Sea Interface Phenomena** | | | | | | | | | | | | 1.65 | 1.73 | 1.69 |
| Wave-Driven Mechanical Turbulence | Yes | both | H | L | L | L | L | L | L | L | L | 2.00 | 2.00 | 2.00 |
| Wave-Driven Modification of Mean Profile | | | H | L | L | L | L | L | L | L | L | 2.00 | 2.00 | 2.00 |
| Current | | | H | M | L | M | L | L | L | M | L | 1.83 | 2.00 | 1.92 |
| Flow Modification Due to Thermodynamic Effects | | | H | L | L | M | L | L | L | M | L | 2.00 | 2.00 | 2.00 |
| **Air-Air Gray Zone (*Terra Incognita*)** | | | | | | | | | | | | 0.83 | 1.00 | 0.92 |

# Group 1b: Microscale Air - Prioritized PIRT

| Phenomenon | Is it different offshore vs. onshore? | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy (High Fidelity) | | | | Model Adequacy (Engineering Tools) | | | | Planning Priority | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | High Fidelity | Engineering Tools | Overall |
| **Wind Plant Aerodynamics / Wakes** | | | | | | | | | | | | 1.30 | 1.63 | 1.46 |
| Momentum Transport (horizontal and vertical fluxes) | Possibly, see notes | both | H | H | H | L | L | M | M | L | L | 1.33 | 1.67 | 1.50 |
| Skew and Meander of Aggregate Wake | | | H | H | H | M | M | M | M | M | L | 1.17 | 1.67 | 1.42 |
| Vortex Merging | | | H | H | H | M | L | L | L | M | L | 1.33 | 2.00 | 1.67 |
| Asymmetry Effects (ground plane, yaw, tilt, cone-angle) | | | H | M | M | M | M | M | M | M | L | 1.50 | 1.67 | 1.58 |
| Wake Impingement (full, half, etc.) | | | H | H | H | L | L | M | M | L | L | 1.33 | 1.67 | 1.50 |
| Floater Motion And Impact on Other Phenomena | | | H | M | M | M | L | M | M | M | L | 1.67 | 1.67 | 1.67 |
| Gravity Waves And Wind Plant Blockage | | | H | M | M | L | L | L | L | L | L | 1.67 | 2.00 | 1.83 |
| Deep Array Effects (change in turbulence, etc.) | | | H | M | M | L | L | L | L | L | L | 1.67 | 2.00 | 1.83 |
| Wind Plant Wake (Interarray waking) | | | H | M | M | M | L | L | L | M | L | 1.67 | 2.00 | 1.83 |

# Group 1b: Microscale Air - Prioritized PIRT

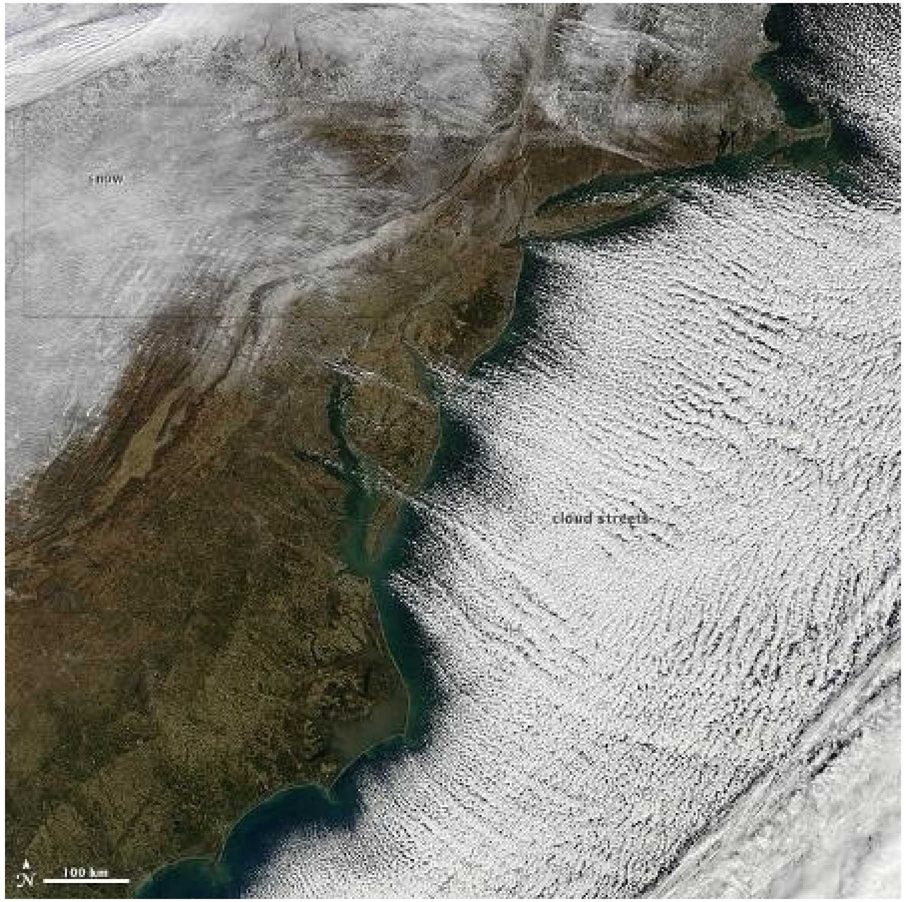
| Phenomenon | Is it different offshore vs. onshore? | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy (High Fidelity) | | | | Model Adequacy (Engineering Tools) | | | | Planning Priority | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | High Fidelity | Engineering Tools | Overall |
| **Turbine Aerodynamics -- Rotor, Blade** | | | | | | | | | | | | 1.44 | 1.58 | 1.51 |
| Blade Load Distribution Effects and Rotor Thrust | Possibly, see notes. | both | H | M | M | M | M | L | L | M | L | 1.50 | 2.00 | 1.75 |
| Tip and Root Vortex Development, Evolution and Merging | | | H | M | M | L | L | M | M | L | L | 1.67 | 1.67 | 1.67 |
| Vortex Sheet and Rollup (in addition to tip/root vortex) | | | H | M | M | L | L | M | M | L | L | 1.67 | 1.67 | 1.67 |
| Distributed Active Aerodynamic Flow Control | | | H | M | M | L | L | M | M | L | L | 1.67 | 1.67 | 1.67 |
| Vortex-Generator Flow | | | H | M | M | M | M | M | M | M | L | 1.50 | 1.67 | 1.58 |
| Unsteady Inflow Effect (veer, shear, yaw, gusts, atmospheric stability, turbulence intensity, spectra, coherence) | | | H | M | M | L | L | M | M | L | L | 1.67 | 1.67 | 1.67 |
| Hydrometeor Erosion/Damage | | | H | L | L | L | L | L | L | L | L | 2.00 | 2.00 | 2.00 |
| **Turbine Aerodynamics -- Airfoil** | | | | | | | | | | | | 1.57 | 1.51 | 1.54 |
| High Reynolds Number Aerodynamics | Possibly, see notes. | both | H | M | M | M | L | M | M | M | M | 1.67 | 1.50 | 1.58 |
| Blade Surface Effects (roughness, soiling, bugs, erosion) | | | H | L | L | M | L | M | M | M | M | 2.00 | 1.50 | 1.75 |
| Boundary Layer Development (transition, separation) | | | H | M | M | M | M | M | M | M | M | 1.50 | 1.50 | 1.50 |
| Dynamic Stall | | | H | M | M | M | L | M | M | M | M | 1.67 | 1.50 | 1.58 |
| Icing - effect on boundary layer | | | H | L | L | L | L | L | L | L | L | 2.00 | 2.00 | 2.00 |
| Unsteady inflow effect (turbulence intensity, spectra, coherence) | | | H | M | M | L | L | L | L | L | L | 1.67 | 2.00 | 1.83 |

# Group 1b: Microscale Air - Takeaways

- **Main Takeaways**
  - Turbines are getting bigger; offshore ABL often shallower. Ratio of turbine scale to ABL scale shrinks
  - Need for atmospheric measurement with detailed profiles to at least top of ABL
  - Turbulence structure is very important – need to take advantage of measurement devices that capture structure (X-Band radar, etc.)
  - We should not assume that phenomena like wake meandering will simply scale up, nor that it should be constant from top to bottom
  - Land-sea interaction needs to be better quantified, but translated to simpler models (like those for land) for surface momentum/heat/moisture exchanges
  - ABL state is site specific: ex. U.S. Atlantic coast very different than U.S. Pacific
  - Should our models include moisture? If yes, we need to measure this.
  - Research had shifted from turbine to plant, but renewed interest in turbine because of
    - Higher Re/MA airfoil effects
    - Thicker airfoils
    - More structural flexibility
    - Floating substructures
  - "Wind plant blockage" is sort of a catch-all phrase that is likely caused by various phenomena in combination. Need to better understand this.
  - Working together with Europeans is key.
  - Distinct differences in model adequacy between high-fidelity and engineering tools. More effort is necessary to create symbiosis between the two classes of models.

# Group 1b: Microscale Air - Takeaways

- **Gaps Remaining**
  - Need more understanding of air-sea interface.
  - Need more understanding of marine-specific ABL.
  - Land-sea “history”/”memory” effects (i.e., internal boundary layer, transitional boundary layer state) likely important given that wind farms are relatively close to shore. Many of the conditions of interest require mesoscale-microscale coupling in simulations; does that mean we need mesoscale measurements, too?
  - Wake behavior at long distances within very large wind farms.
  - Wind plant wake behavior. We do not understand what all causes “wind-plant blockage”.
  - Effect of floater motion on wind farm waking.
  - Better understanding of higher Re/Ma airfoil behavior on more flexible structures




Cloud streets indicating transitional boundary layer at land-sea interface along U.S. Atlantic coast. This caused by air over cold land (stable stratification) transitioning to warm sea (unstable stratification).

# Group 1b: Microscale Air - Conceptual Experiments and Instruments

- **Conceptual Experiments**
  - A few “unit” level experiments to test subsets of phenomena (ex. turbine, airfoil)
    - Many would not require measurements in wind farm
    - Data may partially exist
  - One “system level” experiment in an existing wind farm
    - The offshore version of AWAKEN
    - However, we should leverage existing offshore wind farm data
      - Alpha Ventus, Egmond aan Zee (OWEZ), Lillgrund, Dudgeon, Hywind Scotland

# Group 1b: Microscale Air - Conceptual Experiments and Instruments

- **Instrumentation Needs:**
  - Measurement devices that measure wind, temperature, moisture through entire ABL, but with detail near surface where gradients are steepest
  - Mesoscale measurements (existing daily soundings, meso-net)
  - How to measure wind plant wakes?
  - Can we make more use of scanning radar (e.g., TTU X-Band radar) to quantify ABL turbulence structure for validation of LES and informing synthetic turbulence methods?
  - Can we make use of existing and emerging satellite data? Collaborate with NASA.
  - Critically need measurements of wind-farm-induced atmospheric gravity waves? Do they exist or not?
  - How to measure wind plant blockage when its effect is relatively small?
  - Measurement on buoys have to be measurement compensated and have to deal with marine environment.
  - How do we test airfoils at higher Re or Ma?
  - What can be measured without a plant/what needs a plant?
  - Can we make use of drones with measurement devices?

# Group 2 - Water

**Mesoscale Water**

**Microscale Water**

**Water-Structure**

**Water-Structure-Control**

**Air-Sea**

# Group 2 – Water - Prioritized Phenomena

- **No Mesoscale Water phenomena were prioritized as High**
- **For Microscale Water (defined as the farm level), these were of High planning priority:**

| Phenomena | Application: Floating, Fixed, or Both | Importance | Model Adequacy/Confidence | | | Planning Priority |
|---|---|---|---|---|---|---|
| | | | Physics | Code/Verif | Code/Valid | |
| Freak/rogue wave | Both | H | M | M | L | H |
| Steep/breaking waves | Both | H | M | M | L | H |
| Wave nonlinearity | Both | H | M | M | M | H |
| Waves + current | Both | H | M | L | L | H |

- **Notes from discussion:**
  - *Steep/breaking waves* - Henrik Bredmose (DTU) has done a lot of work in this area, but not well characterized in many tools; many experiments at model scale
  - *Wave nonlinearity* - Need better ways of capturing combined irregularity / nonlinearity of waves
  - *Wave plus current* - the important focus is wave kinematics in the presence of nonuniform current; dispersion relationship

# Group 2 – Water-Structure Prioritized Phenomena

| Phenomena | Application: Floating, Fixed, or Both | Importance | Model Adequacy/Confidence | | | Planning Priority | Comments |
|---|---|---|---|---|---|---|---|
| | | | Physics | Code/ Verif | Code/ Valid | | |
| Viscous loading - Member in isolation, current vs wave | Both | H | M | M | M | H | How to scale up viscous loads from experiment? Not easy |
| Viscous loading - Shadowing effects | Both | H | M | L | M | H | Results are likely case specific; not predictive to new concepts |
| Viscous loading - frequency dependency | Floating | H | M | L | M | H | How to model viscous loads when motion/wave at multiple freqs? |
| VIM - substructure | Floating | H | M | M | L | H | Low validation on floating wind; important for tow-out; important at low frequencies |
| VIV - stationkeeping | Floating | H | M | M | L | H | Important for fatigue in some cases. Not in our models. |
| Floater flexibility | Floating | H | M | M | L | H | |
| Multi-body support structures | Floating | H | M | M | L | H | Designs like Tetraspar where two bodies may move independently. |
| Wave/current–body interaction | Both | H | M | L | L | H | |
| Breaking/steep/slam wave loads | Both | H | M | M | L | H | Decent for fixed monopiles, much less for floating substructures |
| Water-Heave Plate interaction | Floating | H | M | M | L | H | Lower confidence in our models for shallow drafts |
| Marine Growth and Surface roughness | Both | H | M | M | L | H | Important for mooring/cabling loads; limited data - likely overconservative |
| Corrosion | Both | H | M | M | L | H | Modeling capability low, but an existing solution that negates the issue of corrosion. |

# Group 2 – Water – Gaps Remaining / Takeaways

- **Gaps Remaining:**
  - Better understanding of joint probability across metocean parameters
  - Does the power cable influence the motion of the platform, thus requiring coupled analysis?
  - How to most effectively use multiple fidelities of tools
  - How to tune hydro coefficients for mid-fidelity tools
  - What does model-scale validation imply for full-scale simulations?
  - Need guidelines on offshore wind testing and validation
  - Need to streamline design process
  - Cannot predict damping well in offshore wind systems

- **Takeaways:**
  - Many of the topics may not adequately address specific needs for towing, installation, and maintenance
  - Evaluate the suitability of our existing modeling tools for digital-twins application
  - Did we adequately address damage cases (e.g., mooring line loss?)

# Group 2 – Water – Experiments

- **Highest Priorities**
  - Public full-scale validation dataset (floating) (5 yr)
    - Scaled validation lacks complexity of real metocean conditions
    - How to focus on specific phenomena?
    - Significant uncertainty in full-scale datasets
    - Difficulty to achieve under-water measurements
  - Measurement of full set of metocean parameters (2 yr)
    - East Coast, West Coast, Gulf of Mexico, Great Lakes
  - Viscous loading at full scale (2 yr)

- **Additional Considerations:**
  - Measurements of hurricane conditions (including waves)
  - Need focus on moorings / cabling
  - Consideration of different floating platform design types

- **Existing Datasets:**
  - Model-scale measurements available from other organizations, but data quality (and uncertainty) may be difficult to assess
  - Roadmap can enhance the clarity of out data request to industry, thereby increasing the likelihood of successful outcomes and better identification of industry value

# Group 2 – Water – Instruments

- **Model Scale (outstanding needs)**
  - Distributed pressure on the substructure
  - Internal loads in the substructure

- **Full Scale**
  - High-resolution time measurements of wind and waves concurrently, including wind/wave misalignment
  - (Wind) – how do we get good offshore measurements of shear, turbulence, veer, and coherence?
  - Difficult to get below the waterline measurements
    - Problems with installation damaging
    - Difficult to deploy below the waterline after installation
    - Difficult to keep measurements calibrated in offshore environment

# Group 2 – Water - Data Availability

- **Model-scale dataset**
  - Breaking waves – Sintef
  - Member-level flexibility: Experiments at DHI on two columns with heave plates. The columns are bridged together at the top by a beam with a flexible joint in the middle.
  - Controls and member-level loads in the platform – from the FOCAL project
  - Component-level offshore wind/structure measurements, including distributed pressure load (NREL)
  - Spar / semi-sub from the EU/H2020 COREWIND project will become available. The experiment was performed by IHCantabria.

- **Testing facility opportunities**
  - Plymouth Univ. has a wave tank which might be used to perform experiments. Recently installed fans.

- **Full-scale datasets**
  - HUTT have worked with Ideol on their design prototype in the FloatGen project and had good data from turbine.
    - Only had one wave buoy of data that was 1km away, so no way to correlate time series of waves at platform.

# Group 3a – Structures

Rotors,

Sensors and Actuators,

Nacelle and Drivetrain,

Tower and Substructure,

Stationkeeping and Dynamic Power Cable Systems,

Air-Structure

# Group 3a – Structures: Prioritized Structural Phenomena

- **Rotors**
  - Structural damping – Lack of data; difficulty going from coupon to full scale; models not predictive
  - Fracture mechanics, crack growth, and damage propagation of composite materials – Low cycle fatigue; sequence effects beyond Miner's sum; lack of predictive capability; holy grail of material science
  - Blade shear and torsion – Getting from 3D FEA to beams and back
  - Interface between spar and skin/shell and LE/TE – Adhesives
  - Lightning protection – Especially for carbon blades
- **Sensors and Actuators**
  - Effect of sensor integration within the structure – Strain; load cells; pressure taps; cable bundle
  - Effect of actuator integration within the structure – Reliability

# Group 3a – Structures: Prioritized Structural Phenomena

- **Tower and Substructure**
  - Joint performance, flexibility and stress concentrations, load transfer, bolted connections – Impact of welding; steel-concrete connections; bolts; grouted connections; slip joints
  - Member-level loads in multi-member structures
  - Damage stability load cases
  - Structural damping – Lack of data; models not predictive
- **Stationkeeping and Dynamic Power Cable Systems**
  - Hysteresis of synthetic lines
  - Bending of dynamic power cable
  - Mooring line loss
  - Creep of tendons
  - Structural loading of chains

# Group 3a – Structures: Prioritized Air-Structure Phenomena

- **Air-Structure**
  - Aeroelasticity/loads – Ability to predict lifetime ultimate loads and fatigue loads; less data for large slender rotors and floating systems
  - Aeroelasticity/stability during operation
  - Vortex-induced vibration (VIV) – Stall induced vibration when idling in high winds
  - Passive load reduction – Bend-twist coupling
  - Wind farm control -- Wake steering; induction; wake mixing
  - Individual turbine control response to waked inflow
  - Aerodynamics under large floater motion – Rotor effects; wake effects; near-to-far wake transition
  - Extreme events – Tropical cyclones; thunderstorm downburst; ride through
  - Flutter
  - Soiling – Impact of droplets and salt
  - Idling case with fault – Edgewise instability
  - Impacts of large inflow nonheterogeneity – Unique large rotor effects

# Group 3a – Structures: Prioritized Structural PIRT

| Phenomenon | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy - Focused on beam-type | | | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|
| | | | Physics | Code | Val - Industry | | |
| **Rotor - Long, flexible blades** | Both | H/M/L | H/M/L | H/M/L | H/M/L | H/M/L | |
| Structural damping | | H | M | M | L | H | Big issue is lack of data to set inputs; can you extend from coupon or small scale level to full scale? |
| Fracture mechanics, crack growth, damage propagation | | H | L | L | L | H | Low-cycle fatigue, fatigue damage of composite materials; sequence effects beyond Miner's sum |
| Shear and torsion | | H | M | M | L | H | Getting from 3D FEA to beams and back |
| Interfaces between spar and skin/shell and LE/TE | | H | L | L | L | H | Adhesives |
| Lightning protection | | H | L | L | L | H | Need other experts to comment; don't really test lightning protection; bigger problem in carbon blades |
| **Sensors and Actuators** | Both | | | | | | |
| Effect of the sensors integration within the structure | | H | M | L | L | H | Strain, load, acceleration, load cells, pressure taps; important in the valiation application; cable bundle |
| Effect of the actuators integration within the structure | | H | M | L | L | H | Reliability |
| **Tower and Substructure** | Both | | | | | | |
| Joint performance: flexibility and stress concentrations and load transfer; bolted connections | | H | M | L | L | H | Impact of welding; steel-concrete connections, bolts, grouted connections, slip joints |
| Member-level loads | Floating | H | M | M | L | H | |
| Damage stability | Floating | H | M | M | L | H | Damage stability load cases |
| Structural damping | | H | M | M | L | H | Very little data for floating substructures |
| **Stationkeeping and Dynamic Power Cable Systems** | Floating | | | | | | |
| Hysteresis of synthetic lines | | H | M | M | L | H | |
| Bending of dynamic power cable | | H | M | M | L | H | |
| Mooring line loss | | H | M | L | L | H | |
| Creep | | H | L | L | L | H | Important for tendons |
| Structural loading of chains | | H | M | L | L | H | Industry likely has much more data than DOE WETO |

# Group 3a – Structures: Prioritized Air-Structure PIRT

| Phenomenon | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy - Focused on beam-type | | | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|
| | | | Physics | Code | Val - Industry | | |
| **Air-Structure** | Both | | | | | | |
| Aeroelasticity - Loads | Floating | H | M | M | L | H | Ultimate; fatigue loads prediction; good data for smaller, fixed systems; less data for very large, slender rotors and for floating systems; load cases |
| Aeroelasticity - Stability - Operation | | H | M | M | L | H | |
| VIV - Stall induced vibration | | H | L | L | L | H | Idling situation in high winds |
| Passive load reduction | | H | M | M | L | H | Bend-twist coupling |
| Wind farm control (wake steering, induction, wake mixing) | | H | M | M | L | H | |
| Individual turbine control response to waked inflow | | H | M | M | L | H | |
| Aerodynamics under large motion | Floating | H | M | M | L | H | Aerodynamic loads, near-to-far wake; perrhaps split out betwewen local/rotor effects and wake effects |
| Extreme events | | H | M | M | L | H | Tropical cyclones, thunderstorm downbursts; ride through |
| Flutter | | H | M | M | L | H | |
| Soiling | | H | M | M | L | H | Salt |
| Idling case with fault | | H | M | M | L | H | Edgewise instability |
| Impacts of large inflow nonheterogeniety | | H | M | M | L | H | Unique large wind turbine rotor effects |

# Group 3a – Structures: Takeaways

- **Main takeaways**
  - Structures not covered in prior DOE WETO PIRTs, but there are many important phenomena, both structures in isolation and structure-air/water/soil interaction
  - Main overall challenge is ability to predict lifetime ultimate and fatigue loads for all components, which depends on combined effect of all phenomena
  - Large scale offshore = large cost for experiments
    - Likely need for international collaboration
    - Importance of intermediate scale structural tests
    - Necessity of building block approach for structures from coupon to subsection to full component
- **Gaps remaining**
  - Structural experimental planning more high level so far
  - Little discussion of structural instrumentation needs so far
  - Related topics mentioned, but not covered in detail so far: installation scenarios, O&M, digital twins

# Group 3a – Structures: Conceptual Experiments and Instruments

- **Conceptual Experiments**
  - Clear need for offshore-specific RAAW and AWAKEN experiments
    - Need for component-level tests in coordination with large field experiments

    NOTE: OEMs don't own turbines; need to coordinate with owners/operators as well
  - Value of intermediate scale due to large costs of, and lack of test facilities at, full scale
  - Necessity of building block approach for structures from coupon to subsection to full component
  - Structural damping measurements require use of vacuum chamber
  - Lightning protection experiments should be solvable at lab scale

  NOTE: Industry likely has more data than labs/academia – Sharing data incurs cost to industry, so, need to show clear benefits of data sharing
- **Instrumentation needs**
  - Can we instrument turbines while being built in anticipation of data needs?
    - Important to identify sensors and install at design/development stage
  - Tip vortex measurement
  - Pressure distribution measurement on blades and support structure

# Group 3b – Soil

**Soil,**

**Soil-Structure,**

**Water-Soil-Structure**

# Group 3b – Soil: Prioritized Soil Phenomena

- **Soil**
  - Geotechnical characterization – Fundamental challenge do to importance, but with high costs and risks and limited reliability involved
  - Integrated geophysical/geotechnical characterization – Link between geophysical data and geotechnical characterization; need for reduced uncertainty
  - Glauconite sand – U.S.-specific issue for pile driving
- **Soil-Structure**
  - Soil damping – High uncertainty; industry too conservative
  - Lateral monopile-soil interaction – Models good for small diameter and deep penetration, but lacking for large diameter and shallow penetration
  - Soil static and dynamic stiffness, including hysteresis, strain hardening/softening – Especially changes in properties over time
  - Pile/suction anchor pull-out capacity
  - Buried power cable from wind farm to substation – Block Island failure example; importance of temperature effects

# Group 3b – Soil: Prioritized Soil Phenomena

- **Water-Soil-Structure**
  - Scouring – How good are scour protection systems?
  - Sand wave migration – Impact on boundary conditions for cables and burial depth
  - Liquification – Soil strength/stiffness reduced by seismic or wave loading; concern for U.S. West coast

# Group 3b – Soil : Prioritized PIRT

| Phenomenon | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy - Focused on beam-type: Physics | Code | Val - Industry | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|
| **Soil** | Both | | | | | | |
| Geotechnical characteristization | Both | H | M | M | M | H | High planning priority because it is the key fundamental problem; including multi-layered soil profiles; industry knows how to do it, but requires time and money, risk and reliability; statistical map across site; link geophysical data to geotech |
| Integrated geophysical/geotechnical characterization | Both | H | M | L | L | H | Focus on statistical links between datapoints; synthetic soil profiles; reducing uncertainty |
| Glauconite Sand | Both | H | L | L | L | H | US-specific issue; issue with pile driving; frictional resistance; features of behaviour challenging to capture in engineering numerical models |
| **Soil-Structure** | Both | | | | | | |
| Soil damping | Fixed | H | M | M | L | H | Lots of uncertainty; industry is usually too conservative, e.g. 5% damping is applied universally; could also be applied through hysteretic behavior of plastic soils |
| Lateral monopile pile-soil interaction | Fixed | H | M | M | L | H | Good physical models, limited validation data, diameters keep increasing; probably most crucial aspect of monopile performance; more validation needed for realistically inhomogeneous soil profiles |
| Soil static and dynamic stiffness, including hysteresis, strain hardening/softening | Fixed | H | M | M | L | H | Limitations of p-y and t-z curves; change in soil-structure properties over time; difficulties in quantifying energy dissipation properties from sight investigation data |
| Pile/suction anchors - pull out capacity | Floating | H | M | L | L | H | Could perhaps be combined with axial pile-soil interaction; need to look at drainage and time scale of cyclic loading; rely on partial suction for semi-taut and catenary moorings |
| Burried power cable from wind farm to substation | Both | H | M | L | L | H | Critical zone of uncertainty; example Block Island failure; temperature effects in soil response |
| **Water-Soil-Structure** | Both | | | | | | |
| Scouring | Fixed | H | M | L | L | H | See UWA recent research; physics much better understood; how good are scour protection systems? They work but can damage cables as seen from Orsted EU projects |
| Sand wave migration | Both | H | M | L | L | H | Impact on boundary conditions for cables and burial depth considerations |
| Liquification | Both | H | M | L | L | H | Phenomenon in which the strength/stiffness of soil is reduced by earthquake or wave loading; affects foundation capacity, displacements, and cable burial - may become very relevant for West Coast projects |

# Group 3b – Soil: Takeaways

- **Main takeaways**
  - Soil not covered in prior DOE WETO PIRTs, but there are many important phenomena, both soil in isolation and structure/water/soil interaction
  - Soil was originally a subset of structures, but separated out due to distinction of soil SMEs and high number of important phenomena
- **Gaps remaining**
  - Soils group only formed recently; has not yet discussed experimental planning or instrumentation
  - May not have strong national lab soil SMEs

# Offshore PIRT – PIRT Overlaps

**In many cases, phenomena may occur in one or more area**

### Air Meso - Air Micro Overlap

- Icing
  - Air Meso
    - Under what conditions do icing conditions occur?
  - Air Micro
    - What is the impact of icing on wind turbine aerodynamics?

### Air Micro – Structure Overlap

- Aeroelastics
  - Air Micro
    - What is the impact of fluid/structure coupling on aerodynamics loads?
  - Structure
    - What is the impact of unsteady aerodynamic loading on structure lifetime?

# Area Specific Takeaways

- **Group 1a – Mesoscale Air**
  - Need to better understand and measure the impact of ABL structure on wind energy harvest.
  - Need to couple from mesoscale to microscale to get correct modeling.
  - Need to include impacts of atmospheric stability, including thermodynamic structure as well as 3D wind profiles, which impact convective cells and rolls, low level jets, and
  - Need to better understand impact of turbines on generating turbulence both within the farm and between farms, both of which impact harvest.
- **Group 1b – Microscale Air**
  - Turbines are getting bigger; offshore ABL often shallower. Ratio of turbine scale to ABL scale shrinks
  - Need for atmospheric measurement with detailed profiles to at least top of ABL
  - Turbulence structure is very important – need to take advantage of measurement devices that capture structure (X-Band radar, etc.)
  - We should not assume that phenomena like wake meandering will simply scale up, nor that it should be constant from top to bottom
  - Land-sea interaction needs to be better quantified, but translated to simpler models (like those for land) for surface momentum/heat/moisture exchanges
  - ABL state is site specific: ex. U.S. Atlantic coast very different than U.S. Pacific
  - Should our models include moisture? If yes, we need to measure this.
  - Research had shifted from turbine to plant, but renewed interest in turbine because of: Higher Re/MA airfoil effects, Thicker airfoils, More structural flexibility, and Floating substructures.
  - "Wind plant blockage" is sort of a catch-all phrase that is likely caused by various phenomena in combination. Need to better understand this.
  - Distinct differences in model adequacy between high-fidelity and engineering tools. More effort is necessary to create symbiosis between the two classes of models.
- **Group 2 – Water**
  - Many of the topics may not adequately address specific needs for towing, installation, and maintenance
  - Evaluate the suitability of our existing modeling tools for digital-twins application
  - Did we adequately address damage cases (e.g., mooring line loss?)
- **Group 3a – Structures**
  - Structures not covered in prior DOE WETO PIRTs, but there are many important phenomena, both structures in isolation and structure-air/water/soil interaction
  - Main overall challenge is ability to predict lifetime ultimate and fatigue loads for all components, which depends on combined effect of all phenomena
  - Large scale offshore = large cost for experiments
- **Group 3b – Soil**
  - Soil not covered in prior DOE WETO PIRTs, but there are many important phenomena, both soil in isolation and structure/water/soil interaction
  - Soil was originally a subset of structures, but separated out due to distinction of soil SMEs and high number of important phenomena

# Area Specific Gaps

- **Group 1a – Mesoscale Air**
  - Impact of ABL stability on wind farm efficiency and maintenance
  - Understand impact of precipitation on leading edge erosion and changes in ocean temperature
- **Group 1b – Microscale Air**
  - Need more understanding of air-sea interface.
  - Need more understanding of marine-specific ABL.
  - Land-sea “history”/”memory” effects (i.e., internal boundary layer, transitional boundary layer state) likely important given that wind farms are relatively close to shore. Many of the conditions of interest require mesoscale-microscale coupling in simulations; does that mean we need mesoscale measurements, too?
  - Wake behavior at long distances within very large wind farms.
  - Wind plant wake behavior. We do not understand what all causes “wind-plant blockage”.
  - Effect of floater motion on wind farm waking.
  - Better understanding of higher Re/Ma airfoil behavior on more flexible structures
- **Group 2 – Water**
  - Better understanding of joint probability across metocean parameters
  - Does the power cable influence the motion of the platform, thus requiring coupled analysis?
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  - What does model-scale validation imply for full-scale simulations?
  - Need guidelines on offshore wind testing and validation
  - Need to streamline design process
  - Cannot predict damping well in offshore wind systems
- **Group 3a – Structures**
  - Structural experimental planning more high level so far
  - Little discussion of structural instrumentation needs so far
  - Related topics mentioned, but not covered in detail so far: installation scenarios, O&M, digital twins
- **Group 3b – Soil**
  - Soils group only formed recently; has not yet discussed experimental planning or instrumentation
  - May not have strong national lab soil SMEs

# Area Specific Conceptual Experiments

- **Group 1a – Mesoscale Air**
  - The team conceived of a large multi-national experiment that would measure many atmospheric properties (wind and thermodynamic properties) and multiple levels and multiple sites. Focus would be both within farms and between farms. If it is to be within the next 5 years, it would have to be off Europe where multiple closely spaced wind farms already exist. We need to understand wake interactions over multiple stability cases particularly for stable conditions, which are likely a worst-case scenario.
  - Long-term measurements from a tower or instruments in wind farms to obtain multi-year data that could be used to see extreme events and to train machine-learning models of the future.
- **Group 1b – Microscale Air**
  - A few "unit" level experiments to test subsets of phenomena
    - Many would not require measurements in wind farm
    - Data may partially exist
  - One "system level" experiment in an existing wind farm
    - The offshore version of AWAKEN.
    - However, we should leverage existing offshore wind farm data
    - Alpha Ventus, Egmond aan Zee (OWEZ), Lillgrund, Dudgeon, Hywind Scotland
- **Group 2 – Water**
  - Public full-scale validation dataset (floating). Scaled validation lacks complexity of real metocean conditions
  - Significant uncertainty in full-scale datasets, and difficulty to achieve under-water measurements
  - Measurement of full set of metocean parameters (East Coast, West Coast, Gulf of Mexico, Great Lakes)
  - Viscous loading at full scale
  - Measurements of hurricane conditions (including waves)
  - Need focus on moorings / cabling
  - Consideration of different floating platform design types
- **Group 3a – Structures**
  - Clear need for offshore-specific RAAW and AWAKEN experiments
  - Need for component-level tests in coordination with large field experiments
  - Value of intermediate scale due to large costs of, and lack of test facilities at, full scale
  - Necessity of building block approach for structures from coupon to subsection to full component
  - Structural damping measurements require use of vacuum chamber
  - Lightning protection experiments should be solvable at lab scale

***Note: Group 3b – Soil has not addressed experiments yet.**

# Area Specific Conceptual Instrumentation Needs

- **Group 1a – Mesoscale Air**
  - Multiple lidars to see across wakes and between farms.
  - Doppler radar – perhaps see to longer ranges
  - Synthetic aperture radar from satellite to get SST
  - Radiometer or something that can be deployed offshore to measure temperature profiles
  - Potentially a microwave radiometer on turbine spinners (like forward-looking lidars)
  - Sonics that are easier to maintain in the offshore environment
  - Better measurement of ocean skin temperature and fluxes
- **Group 1b – Microscale Air**
  - Measurement devices that measure wind, temperature, moisture through entire ABL, but with detail near surface where gradients are steepest
  - Mesoscale measurements (existing daily soundings, meso-net)
  - How to measure wind plant wakes?
  - Can we make more use of scanning radar (e.g., TTU X-Band radar) to quantify ABL turbulence structure for validation of LES and informing synthetic turbulence methods?
  - Can we make use of existing and emerging satellite data? Collaborate with NASA.
  - Critically need measurements of wind-farm-induced atmospheric gravity waves? Do they exist or not?
  - How to measure wind plant blockage when its effect is relatively small?
  - Measurement on buoys have to be measurement compensated and have to deal with marine environment.
  - How do we test airfoils at higher Re or Ma?
  - What can be measured without a plant/what needs a plant?
  - Can we make use of drones with measurement devices?
- **Group 2 – Water**
  - Distributed pressure on the substructure
  - Internal loads in the substructure
  - High-resolution time measurements of wind and waves concurrently, including wind/wave misalignment
  - (Wind) – how do we get good offshore measurements of shear, turbulence, veer, and coherence?
  - Difficult to get below the waterline measurements
- **Group 3a – Structures**
  - Can we instrument turbines while being built in anticipation of data needs?
  - Important to identify sensors and install at design/development stage
  - Tip vortex measurement
  - Pressure distribution measurement on blades and support structure

***Note: Group 3b – Soil has not addressed instruments yet.**

# Conclusions: Common Takeaways and Themes

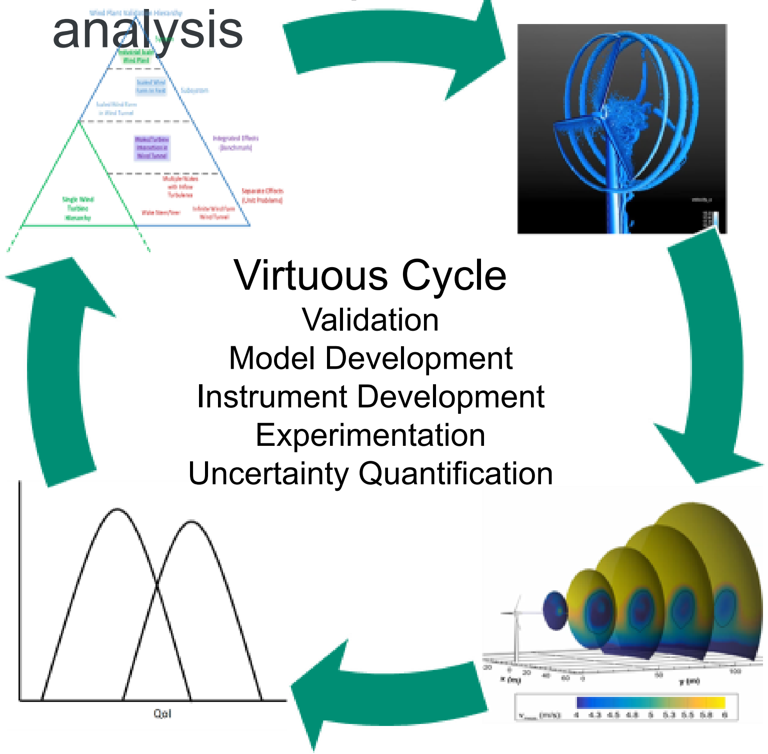
- **Offshore wind energy validation planning is more complex than onshore due to additional physics, the coupling between physics, and more unknowns**
- **Industry likely has more data than labs/academia – Sharing data incurs cost to industry, so, need to show clear benefits of data sharing**
  – OEMs don't own turbines; need to coordinate with owners/operators as well
- **Necessity of building block approach**
  – 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 validation (ex. LLJ shear across rotor diameter).
  – Some phenomena can be tested scaled, some cannot, some we are not sure of > requires testing at a range of scales (ex. nonlinear wave-structure interaction).
  – Some phenomena cannot be adequately measured at full scale for validation (ex. some atmos. phenomena that impact the turbines).
- **Need for international collaboration**
  – Some atmospheric phenomena are site specific but can be measured without a farm in place
  – Some phenomena are not site specific, but require a farm or farms offshore (wind plant wakes)
  – Large scale offshore = large cost for experiments
- **Joint-probability distributions and high-frequency synchronized time measurements required for many areas**
  – Metocean parameters and ABL profiles at actual locations/coasts
  – Time-accurate microscale ABL joint with turbine aerodynamics, loads, and wakes
  – Micro- and Mesoscale ABL measurements joint with turbine and wind-plant wakes

# Expected Outcomes and Impact

- **The validation roadmap developed in this effort will give:**
  - Priorities for model validation campaigns specific to offshore wind energy,
  - Hierarchy of prioritized experiments to meet validation goals,
  - Instrumentation development that will be needed for unique offshore validation needs,
  - Framework for international and cross-institution coordination.
- **A focused validation coordination effort has several benefits in preparation for future experimental campaigns:**
  - Synergy between validation focused experimental campaigns.
  - Maximum use of limited funds through careful, integrated planning.
  - Experience gained and instrumentation developed in early

**Outcome of the Planning Process:**

- Prioritized phenomena
- Identification of gaps in existing V&V data and activities
- Hierarchy of prioritized validation experiments and analysis



# Next Steps

- Continue to develop conceptual experiments and instrumentation requirements
- Present work to WETO and collaborate on program prioritization
- This work will help inform the Instrumentation Development TEM that will occur later this year
- Develop framework for and begin work on draft report, including cross-phenomena
- Develop the validation roadmap, laying out conceptual experiments
- Obtain feedback on the final report
- Release final report

# Group 1a: Mesoscale Air, ABL, Farm-Farm Interaction

| Phenomenon | Importance at Application Level | Relative Importance for experiments | Model Adequacy | | | Issues/Comments |
|---|---|---|---|---|---|---|
| | | | Physics | Code | Validation Capability | |
| **Mesoscale phenomena** | | | | | | Mesoscale codes |
| Representation of winds and turbulence through the atmos. boundary layer and/or top of rotor | H | *** | M | M | L | Include profiles of other relevant variables, such as temperature, humidity, ...Include cloud and impact on BL |
| Wind plant repesentation (i.e., drag effect of turbines) | H | *** | M | M | L | Impact on ocean upwelling and stability, some datasets out there, not all are accessible commonly.mpact on upwelling |
| Ramp events (due to mesoscale weather phenomena such as fronts, thunderstorms) | H | * | H | H | M | Satellite data available, holes in thermodynamics. Include veer. |
| Large, persistent high-pressure domes with low wind spe | H | | M | M | L | Stilling - well characteried for resouce assessment, but less so for forecasting.. more important in changing climate. Some ridges get more persisent. |
| High-altiture wind resource for airborne wind energy | L | | M | M | L | up to 300-600 m |
| Cloud and rain macro-physical properties like coverage, type (e.g. liquid, or ice), and condensate loading | M | | M | M | M | |
| Coastal influences such as land-sea breezes | M | | H | M | L | In certain places this is more important, add example areas that would be a 3. extent of breeze not modeled as well. Buoy data, satellite data coarse but can see structure |
| Terrain influences and Island effects | H | | M | M | L | Santa Ana winds, Coastal jet, Coastally trapped flow reversersals |
| Large scale advection of air masses | M | | H | H | H | |
| Baroclinicity | H | | M | L | L | Impact on ABL structure that can lead to LLJ and veer |
| Cold air outbreaks | H | | M | M | L | Large scale intrusion of cold polar air toward mid latitudes resulting in development of mesoscale convective structures, convective rolls and associated cloud streets and eventually convective cells. |

# Group 1a: Mesoscale Air, ABL, Farm-Farm Interaction

| Phenomenon | Importance at Application Level | Relative Importance for experiments | Model Adequacy | | | Issues/Comments |
|---|---|---|---|---|---|---|
| | | | Physics | Code | Validation Capability | |
| **Cross-scale effects** | | | | | | |
| Turbine scale icing | M | | M | L | L | In some places very important, but not important at all in other locations; however, there is some uceratinty as to where this transition happens. |
| Low-level jets | H | * | M | M | L | Lidar data captures this, but there is a sparsity of data; turbulence information would be helpful in improving understanding and modeling. |
| Atmos. waves (gravity) | M | | H | M | L | |
| Extreme wind events (details in ANL PIRT, including TCs, ETCs, nor'easters, etc) | H | * | M | M | M | Discuss interfaces, but there will be a project focused on developing an extreme weather/hurricane PIRT next year. Adequacy depends on scale of models |
| Precipitation and impact on leading edge erosion | M | | M | L | L | Precipitation is very important for leading edge erosion potential, highly variable region to region |
| Convective structures | M | | H | M | L | |
| West coast synoptically induced high winds | H | | H | H | L | Can get hurrican force winds on west coast, considered extreme wind events |
| Impact of coastal or island urban heat islands | M | | H | M | L | |
| Terrain influences and Island effects | H | | M | M | L | Santa Ana winds, Coastal jet, Coastally trapped flow reversersals, von Karman vortices |
| Gulf stream effects on ABL/mesoscale | H | | M | M | L | Include coastal wind gradient |
| Land use change due to Climate Change, and its representation in products | M | | L | L | L | |

# Group 1a: Mesoscale Air, ABL, Farm-Farm Interaction

| Phenomenon | Importance at Application Level | Relative Importance for experiments | Model Adequacy | | | Issues/Comments |
|---|---|---|---|---|---|---|
| | | | Physics | Code | Validation Capability | |
| **Air-Air, Terra Incognita** | | | | | | Mesoscale/plant scale |
| Mesoscale turb. to LES turb. models | H | * | L | M | L | Terra incognita and turbulence generation |
| Mesoscale to plant inflow | H | | M | M | L | Don't understand fetch well enough yet. both turbulence and mean. |
| Plant wake to mesoscale | H | * | M | M | L | |
| Full plant-scale vertical energy transfer (plant/atmos.). vertical momentum flux | M | | M | M | L | |
| Waterspouts | L | | L | L | L | Seen more frequently than expected. |
| **ABL** | | | | | | |
| Turbine wake interaction within a farm, which is a function of ABL turbulence-(Stability) | H | * | M | M | L | |
| Internal boundary layers due to differential advection | H | | M | M | L | Critical in some areas. integrated with stability impacts. |
| Thermodynamically decoupled boundary layers | M | | M | L | L | Stand-alone microscale models don't handle clouds well. WRF does. |
| Impact of clouds on ABL structure | H | | M | L | L | Destabilization from above due to cloud top cooling. depends on location - critically important some places, but not all. microscale codes don't handle this yet. |
| Stability impacts on ABL structure | H | * | H | M | L | |
| Rolls and cells - convections | H | * | M | M | M | part of stability - surface to above ABL |
| Impact of ABL height on ABL structure | H | * | M | M | L | part of stability - hard to measure when stable. Adequacy depends on meso, vs micro |
| Subsidence, enhanced entrainment | M | | L | L | L | part of stability |

# Group 1a: Mesoscale Air, ABL, Farm-Farm Interaction

| Phenomenon | Importance at Application Level | Relative Importance for experiments | Model Adequacy | | | Issues/Comments |
|---|---|---|---|---|---|---|
| | | | Physics | Code | Validation Capability | |
| **Wind Plant Aero., Wakes (farm-farm)** | | | | | | All physics dependent on plant scale and operating conditions |
| Wind plant blockage effects and wind plant boundary layer growth (above plant) | M | | L | L | L | |
| Plant wake | H | * | M | M | L | Emphasis on the effect of the wind farm on cross-stream downstream regions. Wind theft. |
| Acoustic propagation | L | | L | L | L | Noise generation and propagation through a wind plant. |
| Heat, moisture and momentum exchange around plant | M | | L | L | L | Could become a legal issue impacting downwind plants. |
| Heat, moisture and momentum exchange within plant | H | | L | L | L | |
| Upscaling effect of wind farm control | M | | L | L | L | Including wake steering |
| Deep array turbulence | H | * | L | M | M | Models haven't been verified |
| Lightning | H | Sturctures | L | M | M | Global lightning detection system helpful. Individual hits hard to predict |
| Precipitation and impact on leading edge erosion | H | Structures | M | M | L | Include Raindrop size distribution, and impact on ocean surface cooling |
| Fog | L | | L | L | | Impacts when can do maintenance |
| **Air-Sea** | | | | | | (How are waves impacting the air) |
| Surface conditions - waves, including impact of breaking | H | * | M | L | L | include upwelling. Ecosystem impacts. Wind-wave misalignment |
| Surface Conditions - Sea Surface Temperature and their gradients at wind plant scales (SST) | H | * | M | M | M | |
| Swell - larger wave age | H | * | M | L | L | Not in WRF |
| Currents | M | | M | L | L | Important but second order to top 3 |
| Ocean mixed layer depth | M | | M | L | L | Important for tropical cyclones - that will be in TC PIRT |
| Depth of ocean and impact on wind | M | | M | L | L | need to parameterize more than depth itself. don't know impact on wind resource. |
| Sea Spray - salt erosion | M | | L | L | L | Potential impact on stability |
| Freezing seaspray | M | | L | L | L | Operation & Maintenance |
| Sea-ice impact | L | | | L | | surface roughness. Depends on location - great lakes |

# Group 1b: Microscale Air - Prioritized PIRT

1b complete PIRT available at: https://docs.google.com/spreadsheets/d/1zL-Tn2JTgEUVm_u6RgjGhgk7k7L2oAU1bQ3yyeQcxCE/edit#gid=1293763345

| Phenomenon | Is it different offshore vs. onshore? | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy (High Fidelity) | | | | Model Adequacy (Engineering Tools) | | | | Planning Priority | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | High Fidelity | Engineering Tools | Overall |
| **General Microscale Atmospheric Phenomena** | | | | | | | | | | | | 1.40 | 1.68 | 1.54 |
| Mean vertical profile (shear/veer/asymmetry) | Yes | both | H | H | M | M | M | M | M | M | L | 1.33 | 1.67 | 1.50 |
| Mean vertical profile, not of just wind, but also temperature and moisture | | | H | M | L | L | M | L | L | L | L | 1.67 | 2.00 | 1.83 |
| Turbulence Intensity | | | H | H | M | M | M | M | M | M | M | 1.33 | 1.50 | 1.42 |
| Turbulence Spectrum | | | H | H | M | L | M | M | M | L | M | 1.33 | 1.50 | 1.42 |
| Turbulence Coherence/Correlation | | | H | H | M | L | L | M | M | L | L | 1.50 | 1.67 | 1.58 |
| Turbulence Structure (space-time structure) | | | H | H | L | L | L | H | L | L | L | 1.67 | 1.67 | 1.67 |
| Evolution of Turbulence vs. Frozen Turbulence | | | M | H | H | L | L | L | L | L | L | 0.83 | 1.50 | 1.17 |
| Boundary Layer Height | | | H | H | M | M | L | L | L | M | L | 1.50 | 2.00 | 1.75 |
| Inversion Strength | | | M | H | M | L | L | L | L | L | L | 1.00 | 1.50 | 1.25 |
| Surface conditions (roughness, canopy, waves, surface heat flux, topography) | | | H | M | L | M | L | L | M | M | L | 1.83 | 1.83 | 1.83 |

# Group 1b: Microscale Air - Prioritized PIRT

| Phenomenon | Is it different offshore vs. onshore? | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy (High Fidelity) | | | | Model Adequacy (Engineering Tools) | | | | Planning Priority | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | High Fidelity | Engineering Tools | Overall |
| **Offshore-Specific Microscale Atmospheric Phenomena** | | | | | | | | | | | | 1.55 | 1.67 | 1.61 |
| Horizontal Heterogeneity | | | H | L | L | M | L | L | L | M | L | 2.00 | 2.00 | 2.00 |
| Coastal Low-Level Jet | | | H | M | M | M | M | L | L | M | L | 1.50 | 2.00 | 1.75 |
| Land-Sea Breeze | | | M | L | L | L | L | L | L | L | L | 1.50 | 1.50 | 1.50 |
| Transitional Nature of ABL at Land-Sea Interface, and SST Gradients | | | H | M | M | L | L | L | L | L | L | 1.67 | 2.00 | 1.83 |
| Absense of Strong Diurnal Cycle/Persistent Conditions | | | M | H | H | M | M | H | H | M | L | 0.67 | 0.83 | 0.75 |
| Persistent Cloud-Topped ABL | | | M | L | L | M | L | L | L | M | L | 1.50 | 1.50 | 1.50 |
| Shallow, Very Stable Layers | | both | M | M | M | L | L | L | L | L | L | 1.17 | 1.50 | 1.33 |
| Site-Specific-ness (not really a phenomenon) | Yes | | H | M | M | M | M | M | M | M | L | 1.50 | 1.67 | 1.58 |
| ABL within Tropical / ExtraTropical Cyclones | | | H | L | L | L | L | L | L | L | L | 2.00 | 2.00 | 2.00 |
| Design Standard Gust Cases Specific for Offshore and Floating Turbines (not really a phenomenon) | | fixed (same as land) / floating (new) | H | L | L | L | L | M | M | L | L | 2.00 | 1.67 | 1.83 |

# Group 1b: Microscale Air - Prioritized PIRT

| Phenomenon | Is it different offshore vs. onshore? | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy (High Fidelity) | | | | Model Adequacy (Engineering Tools) | | | | Planning Priority | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | High Fidelity | Engineering Tools | Overall |
| **Air-Sea Interface Phenomena** | | | | | | | | | | | | 1.65 | 1.73 | 1.69 |
| Wave-Driven Mechanical Turbulence | Yes | both | H | L | L | L | L | L | L | L | L | 2.00 | 2.00 | 2.00 |
| Wave-Driven Modification of Mean Profile | Yes | both | H | L | L | L | L | L | L | L | L | 2.00 | 2.00 | 2.00 |
| Water Depth/Fetch | Yes | both | M | M | M | H | L | L | L | H | M | 1.17 | 1.33 | 1.25 |
| Current | Yes | both | H | M | L | M | L | L | L | M | L | 1.83 | 2.00 | 1.92 |
| Microscale-variability of sea-surface temperature | Yes | both | M | M | M | M | L | L | L | M | L | 1.17 | 1.50 | 1.33 |
| Flow Modification Due to Thermodynamic Effects | Yes | both | H | L | L | M | L | L | L | M | L | 2.00 | 2.00 | 2.00 |
| Salt-Water Spray | Yes | both | M | L | L | L | L | L | L | L | L | 1.50 | 1.50 | 1.50 |
| Blade/Structure Icing | Yes | both | M | L | L | L | L | L | L | L | L | 1.50 | 1.50 | 1.50 |
| **Air-Air Gray Zone (*Terra Incognita*)** | | | | | | | | | | | | 0.83 | 1.00 | 0.92 |
| Gray Zone | No | both | L | L | L | M | M | L | L | M | L | 0.83 | 1.00 | 0.92 |

# Group 1b: Microscale Air - Prioritized PIRT

| Phenomenon | Is it different offshore vs. onshore? | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy (High Fidelity) | | | | Model Adequacy (Engineering Tools) | | | | Planning Priority | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | High Fidelity | Engineering Tools | Overall |
| **Wind Plant Aerodynamics / Wakes** | | | | | | | | | | | | 1.30 | 1.63 | 1.46 |
| Momentum Transport (horizontal and vertical fluxes) | Possibly, see notes | both | H | H | H | L | L | M | M | L | L | 1.33 | 1.67 | 1.50 |
| Skew and Meander of Aggregate Wake | | | H | H | H | M | M | M | M | M | L | 1.17 | 1.67 | 1.42 |
| Swirl Instability | | | L | M | M | L | L | L | L | L | L | 0.67 | 1.00 | 0.83 |
| Vortex Merging | | | H | H | H | M | L | L | L | M | L | 1.33 | 2.00 | 1.67 |
| Wake Vorticity Diffusion and Dissipation | | | H | H | H | M | M | M | M | M | M | 1.17 | 1.50 | 1.33 |
| Asymmetry Effects (ground plane, yaw, tilt, cone-angle) | | | H | M | M | M | M | M | M | M | L | 1.50 | 1.67 | 1.58 |
| Inflow Effect (shear, veer, yaw, turb. intensity, turb. spectrum, coherence, gusts, atmos. stab.) | | | H | H | H | M | M | M | M | M | M | 1.17 | 1.50 | 1.33 |
| Wake Interaction, Merging, Meander, Evolution, Recovery | | | H | H | H | M | M | M | M | M | M | 1.17 | 1.50 | 1.33 |
| Plant Flow Control for Optimal Performance | | | H | H | H | M | M | M | M | M | M | 1.17 | 1.50 | 1.33 |
| Wake Steering (yaw & tilt effects) | | | H | H | H | M | M | M | M | M | M | 1.17 | 1.50 | 1.33 |
| Wake Dissipation | | | H | H | H | M | M | M | M | M | M | 1.17 | 1.50 | 1.33 |
| Wake Impingement (full, half, etc.) | | | H | H | H | L | L | M | M | L | L | 1.33 | 1.67 | 1.50 |
| Impact of Smaller Air Gap | | | M | H | H | L | L | L | L | L | L | 0.83 | 1.50 | 1.17 |
| Floater Motion And Impact on Other Phenomena | | | H | M | M | M | L | M | M | M | L | 1.67 | 1.67 | 1.67 |
| Gravity Waves And Wind Plant Blockage | | | H | M | M | L | L | L | L | L | L | 1.67 | 2.00 | 1.83 |
| Deep Array Effects (change in turbulence, etc.) | | | H | M | M | L | L | L | L | L | L | 1.67 | 2.00 | 1.83 |
| Wind Plant Wake (Interarray waking) | | | H | M | M | M | L | L | L | M | L | 1.67 | 2.00 | 1.83 |
| Localized Flow withing Wind Farm | | | M | L | L | L | L | L | L | L | L | 1.50 | 1.50 | 1.50 |

# Group 1b: Microscale Air - Prioritized PIRT

| Phenomenon | Is it different offshore vs. onshore? | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy (High Fidelity) | | | | Model Adequacy (Engineering Tools) | | | | Planning Priority | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | High Fidelity | Engineering Tools | Overall |
| **Turbine Aerodynamics -- Rotor, Blade** | | | | | | | | | | | | 1.44 | 1.58 | 1.51 |
| Blade Load Distribution Effects and Rotor Thrust | Possibly, see notes. | both | H | M | M | M | M | L | L | M | L | 1.50 | 2.00 | 1.75 |
| Tip and Root Vortex Development, Evolution and Merging | | | H | M | M | L | L | M | M | L | L | 1.67 | 1.67 | 1.67 |
| Vortex Sheet and Rollup (in addition to tip/root vortex) | | | H | M | M | L | L | M | M | L | L | 1.67 | 1.67 | 1.67 |
| Blade-Generated Turbulence (energetic scales at trailing edge) | | | M | M | M | L | L | L | L | L | L | 1.17 | 1.50 | 1.33 |
| Root Rlow Acceleration Effect ('hub jet') | | | M | H | H | L | L | L | L | L | L | 0.83 | 1.50 | 1.17 |
| Flow Acceleration Under Rotor | | | M | H | H | L | L | L | L | L | L | 0.83 | 1.50 | 1.17 |
| Boundary Layer Development (transition, separation) | | | H | M | M | M | M | M | M | M | M | 1.50 | 1.50 | 1.50 |
| Boundary Layer Details Near Leading and Trailing Edge | | | H | M | M | M | L | M | M | M | M | 1.67 | 1.50 | 1.58 |
| Rotational Augmentation | | | H | M | M | M | M | M | M | M | M | 1.50 | 1.50 | 1.50 |
| Dynamic Stall | | | H | M | M | M | M | M | M | M | M | 1.50 | 1.50 | 1.50 |
| Distributed Active Aerodynamic Flow Control | | | H | M | M | L | L | M | M | L | L | 1.67 | 1.67 | 1.67 |
| Vortex-Generator Flow | | | H | M | M | M | M | M | M | M | L | 1.50 | 1.67 | 1.58 |
| Unsteady Inflow Effect (veer, shear, yaw, gusts, atmospheric stability, turbulence intensity, spectra, coherence) | | | H | M | M | L | L | M | M | L | L | 1.67 | 1.67 | 1.67 |
| Blade Flow Control | | | M | M | M | L | L | L | L | L | L | 1.17 | 1.50 | 1.33 |
| Icing | | | M | L | L | M | L | L | L | M | L | 1.50 | 1.50 | 1.50 |
| Hydrometeor Erosion/Damage | | | H | L | L | L | L | L | L | L | L | 2.00 | 2.00 | 2.00 |
| Tower/Rotor/Nacelle Wake Interactions | | | M | M | M | L | L | M | M | L | L | 1.17 | 1.17 | 1.17 |
| Mooring Lines Piercing Water Surface | | | M | L | L | L | L | L | L | L | L | 1.50 | 1.50 | 1.50 |

# Group 1b: Microscale Air - Prioritized PIRT

| Phenomenon | Is it different offshore vs. onshore? | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy (High Fidelity) | | | | Model Adequacy (Engineering Tools) | | | | Planning Priority | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | Physics Model | Code + Verification | Do We Have Validation Data? | Have We Validated? | High Fidelity | Engineering Tools | Overall |
| **Turbine Aerodynamics -- Airfoil** | | | | | | | | | | | | 1.57 | 1.51 | 1.54 |
| High Reynolds Number Aerodynamics | Possibly, see notes. | both | H | M | M | M | L | M | M | M | M | 1.67 | 1.50 | 1.58 |
| Higher Mach Number Aerodynamics | | | M | M | M | L | L | M | M | L | L | 1.17 | 1.17 | 1.17 |
| Thick Airfoils | | | H | M | M | M | M | M | M | M | M | 1.50 | 1.50 | 1.50 |
| Aeroacoustics | | | M | L | L | M | L | M | M | M | M | 1.50 | 1.00 | 1.25 |
| Blade Surface Effects (roughness, soiling, bugs, erosion) | | | H | L | L | M | L | M | M | M | M | 2.00 | 1.50 | 1.75 |
| Boundary Layer Development (transition, separation) | | | H | M | M | M | M | M | M | M | M | 1.50 | 1.50 | 1.50 |
| Boundary Layer Details Near Leading and Trailing Edge | | | H | M | M | M | M | M | M | M | M | 1.50 | 1.50 | 1.50 |
| Dynamic Stall | | | H | M | M | M | L | M | M | M | M | 1.67 | 1.50 | 1.58 |
| Vortex-Generator Flow | | | H | M | M | M | M | M | M | M | M | 1.50 | 1.50 | 1.50 |
| Blade Flow Control | | | M | M | M | L | L | L | L | L | L | 1.17 | 1.50 | 1.33 |
| Icing - effect on boundary layer | | | H | L | L | L | L | L | L | L | L | 2.00 | 2.00 | 2.00 |
| Unsteady inflow effect (turbulence intensity, spectra, coherence) | | | H | M | M | L | L | L | L | L | L | 1.67 | 2.00 | 1.83 |

# Group 2 – Full Water PIRT

| Phenomena | Application: Floating, Fixed, or Both | Importance | Model Adequacy/ Confidence | | | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|
| | | | Physics | Code/ Verif | Code/ Valid | | |
| **Mesoscale Water** | | | | | | | |
| Tides | Both | M | M | H | H | L | |
| Ocean circulation / currents | Both | M | H | L | L | L | If trying to redo standards and replace measurements |
| Sea surface temperature | Both | H | H | M | M | L | Important for formation of tropical cyclones; determines the atmospheric stability |
| Seabed bathymetry | Both | L | L | L | L | L | |
| Coastal effects | Both | M | M | M | M | M | Coastal gradients; likely covered by air-mesoscale PIRT |
| Salinity | Both | L | H | L | L | L | |
| **Microscale Water** | | | | | | | |
| Freak/rogue wave | Both | H | M | M | L | H | Focused wave |
| Steep/breaking waves | Both | H | M | M | L | H | Including intermittent; Henrik Bredmose has done a lot of work in this area; not well characterized in many tools; many experiments at model scale |
| Wave nonlinearity | Both | H | M | M | M | H | Higher-order wave theory |
| Waves + current | Both | H | M | L | L | H | Wave kinematics in the presence of nonuniform current; dispersion relationship |
| Bi-modal | Both | M | M | M | L | M | Including bi-directionality, At mid-fidelity, can easily model, but not sure at high-fidelity |
| Wave propagation through farm | Both | H | M | M | L | M | Important for shared moorings |
| Short-crested / wave directionality | Both | H | M | M | L | M | Straightforward when linear; much more difficult with nonlinearity |
| Non-stationary waves (non-equilibrium) - not same over hour | Both | L | M | L | L | L | Industry cares about statics; relevant to controls? Perhaps is issue for installation and O&M? Solved by short-term forecasting. |
| Salinity | Both | L | L | M | M | L | |
| Tsunami | Both | M | H | L | L | L | Only important in small number of areas |
| Seabed bathymetry | Both | M | H | L | L | L | Most analyses consider flat seabed; more important in shallow water |
| Spectral properties | Both | M | M | M | L | L | Typically use standard spectrum, might be regions where other spectrum are needed. |
| Shallow-water turbulence | Fixed | L | L | L | L | L | |
| Surface tension | Both | L | L | L | L | L | |

# Group 2 – Full Water-Structure PIRT – Part 1

| Phenomena | Application: Floating, Fixed, or Both | Application Area of Highest Imp | Importance | Model Adequacy/Confidence Physics | Code/ Verif | Code/ Valid | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|---|
| **Water-Structure** | | | | | | | | |
| Viscous loading - Member in isolation, current vs wave | Both | Low data/conf at scale | H | M | M | M | H | How to scale up viscous loads from exp? Not easy |
| Viscous loading - Shadowing effects | Both | | H | M | L | M | H | Results are likely case specific; results are not predictive to new concepts |
| Viscous loading - frequency dependency | Floating | | H | M | L | M | H | How to model viscous loads when motion/wave at multiple frequencies (multiple KC number) coexist? |
| VIM - substructure | Floating | OW – low conf. | H | M | M | L | H | Low validation on floating wind; importance depends on the substructure; important for tow-out; important at low frequencies |
| VIV - stationkeeping | Floating | | H | M | M | L | H | Important for fatigue in some cases. Not currently in our models. |
| Floater flexibility | Floating | | H | M | M | L | H | |
| Multi-body support structures | Floating | | H | M | M | L | H | Designs like Tetraspar where two bodies may move independently. |
| Wave/current–body interaction | Both | | H | M | L | L | H | |
| Slap / Slam loads | Both | | H | M | M | L | H | Understand what the load is and what the effect is on the structure; merge with breaking/steep wave loads |
| Breaking/steep wave loads | Both | | H | M | M | L | H | Decent for fixed monopiles, much less for floating substructures |
| Water-Heave Plate interaction | Floating | | H | M | M | L | H | Lower confidence in our models for shallow drafts |
| Marine Growth and Surface roughness | Both | | H | M | M | L | H | Marine growth important for mooring/cabling loads; limited data we have is likely overconservative |
| Corrosion | Both | | H | M | M | L | H | Modeling capability is low, but there is an existing solution that negates the issue of corrosion. |
| Pressure mapping | Floating | | H | M | M | L | M/H | |
| Vessel impact | Both | | H | M | M | L | M/H | More of an industry problem; customized tools for this application |
| VIV - substructure | Fixed | Low conf for OW | M | M | M | M | M | Low validation on floating wind; importance depends on the substructure; important for tow-out; important at low frequencies |
| Hydrodynamic forcing on station keeping and power system | Floating | | M | M | M | L | M | Mooring lines and power cables; Important for loads especially on cables in shallow water or high currents; perhaps split into stationkeeping and dynamic power cable separately |
| Acoustic waves from piling | Fixed | High imp for wildlife | H | M | M | M | M | Maybe not the focus of the tools we're addressing in this PIRT |
| Wave Run-up | Both | | H | M | M | M | M | Wave stretching - applicability across different sizes and motion |
| Nonlinear excitation – diff/sum/mean | Both | | H | M | M | M | M | Drift loads important for moorings. We don't currently have good low-fidelity models for it. |
| Springing - higher-order wave loading response | Floating | TLPs only | H | M | M | M | M | |
| Floating ice - salt water | Both | | H | M | M | M | M | Region specific: Maine for floating sea ice. |
| Floating ice - fresh water | Both | Great Lakes only? | H | L | L | L | M | Region specific: Great Lakes for fresh-water ice |
| Hydrostatics | Floating | Low confidence for some designs | H | H | M | M | M | including nonlinearities; especially for unique substructures |
| Water egress for damping | Fixed | | H | M | M | M | M | Monopiles; passive damping |

# Group 2 – Full Water-Structure PIRT – Part 2

| Phenomena | Application: Floating, Fixed, or Both | Application Area of Highest Imp | Importance | Model Adequacy/Confidence Physics | Code/ Verif | Code/ Valid | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|---|
| **Water-Structure** | | | | | | | | |
| Hybrid platforms | Both | | L | M | L | L | L | |
| Lifting from hydrofoil | Both | | L | M | M | L | L | |
| Magnus effect | Floating | Only rotating spars | L | M | L | L | L | |
| Wave variation in farm from structure interaction | Both | | L | L | L | L | L | Wave radiation and diffraction |
| Diffraction loads | Both | | H | H | H | H | L | Structure induced wave nonlinearity / breaking |
| Radiation damping | Floating | | H | H | H | H | L | |
| Added Mass | Floating | | H | H | H | M | L | Modification by viscous effects |
| OWT + vessel hydrodynamic interactions | Both | | M | M | M | M | M | |
| Water-Strake interaction | Floating | Few designs | L | M | L | L | L | |
| Sloshing | Floating | | L | M | L | L | L | |
| Hydrodynamic loading on appurtenances | Both | | L | L | L | L | L | Appurtenances = secondary structures = j-tubes/ladders |
| Ringing - impulsive loading response | Both | | M | M | M | L | L | |
| Green water | Both | | M | M | M | M | L | |
| Fast ice | Fixed | Great Lakes only? | L | M | L | L | L | Ice stuck to structure |
| Moonpool | Floating | | M | M | M | L | L | |
| Cavitation | Floating | | L | M | L | L | L | |
| **Water-Structure-Control** | | | | | | | | |
| Active ballast system | Floating | Some uniqu techn | H | M | M | M | M | |
| Thrusters | Floating | Roaming turbines | L | M | L | L | L | |
| **Air-Sea (how wind impacts waves)** | | | | | | | | |
| Swells | Both | How do you do it? | H | M | M | L | H | |
| Tropical cyclones | Both | | H | L | L | L | H | Both temparatue and air aspects |
| Air/sea temperature effects | Both | Mesoscale processes | H | M | L | L | H | |
| Surface roughess | Both | | H | H | H | M | H | |
| Storm surge | Fixed | | H | M | M | L | H | |
| Wind-driven waves | Both | | H | M | L | M | M | Non-swells - more localized |
| Joint probability across metocean parameters | Both | Big meas campaign | H | M | L | L | M | |
| Wind/wave misalignment | Both | | H | L | L | L | L | |
| Air entrainment from breaking waves | Both | | L | M | L | L | L | |
| Air-induced currents (surface currents) | Both | | L | M | L | L | L | |

# Group 3a – Structures: Full Rotor PIRT

| Phenomenon | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy - Focused on beam-type | | | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|
| | | | Physics | Code | Val - Industry | | |
| **Rotor - Long, flexible blades** | Both | H/M/L | H/M/L | H/M/L | H/M/L | H/M/L | |
| Elasticity and stress recovery of composite materials | | H | H | M | M | M | |
| Loads and displacements | | H | M | M | M | M | Representing blades as beams/solids; issue with loads is aerodynamic related, not structural |
| Structural damping | | H | M | M | L | H | Big issue is lack of data to set inputs; can you extend from coupon or small scale level to full scale? |
| Buckling | | H | H | M | M | M | |
| Sectional warping | | M | M | M | L | M | |
| Geometric nonlinearities in displacement | | H | H | H | M | M | |
| Fracture mechanics, crack growth, damage propagation | | H | L | L | L | H | Low-cycle fatigue, fatigue damage of composite materials; sequence effects beyond Miner's sum |
| Bending | | H | H | H | M | M | |
| Shear and torsion | | H | M | M | L | H | Getting from 3D FEA to beams and back |
| Natural frequencies and mode shapes | | H | H | M | L | M | The effects of aerodynamics are not well validated, coupled effects |
| Resonance | | H | H | M | M | M | |
| Interfaces between spar and skin/shell and LE/TE | | H | L | L | L | H | Adhesives |
| Root joint to hub - composite/bolt connection | | M | M | M | M | L | |
| Joints / segmented / hinged components | | L | L | L | L | L | Probably not relevant for offshore wind turbines, at least now |
| Reponse flatback airfoils | | M | M | M | L | M | Prediction of failure modes |
| Material characterization | | M | M | H | L | M | Especially for new materials that are recyclable or using advanced manufacturing / 3D printing; only the inputs is needed in HFM and OpenFAST |
| Material properties impact on structural response | | H | M | M | M | M | Limited testing of actual blade failures |
| Lightning protection | | H | L | L | L | H | Need other experts to comment; don't really test lightning protection; bigger problem in carbon blades |
| VAWT phenomena | | M | M | M | L | L | May be important in the future |
| Multi-rotor phenomena | Floating | M | L | L | L | M | Up and coming technology |

# Group 3a – Structures: Full Sensors and Actuators PIRT

| Phenomenon | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy - Focused on beam-type | | | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|
| | | | Physics | Code | Val - Industry | | |
| **Sensors and Actuators** | Both | | | | | | |
| Tuned mass dampers (TMDs) | | H | M | M | M | M | Floating is where the gap is; industry has good data for land-based systems |
| Tuned liquid column dampers (TLCDs) | | M | M | L | L | M | |
| Bearings in pitch and yaw drivers | | M | M | M | M | L | |
| Active cable tensioners | | M | M | M | L | L | Substructure, blades, tendons |
| Airfoil flow control | | M | M | M | L | M | TE actuation, e.g., plasma, developing technology |
| Actuator limits | | H | M | M | L | M | E.g., max pitch or yaw rates; industry has more experience than DOE WETO |
| Hybrid model testing representations | | M | M | M | M | L | |
| Ailerons | | L | L | L | L | L | Mechanical devices |
| Other actuators | | L | L | L | L | L | Power screw; rack and pinion |
| Faults / Failures | | H | M | M | M | M | E.g., pitch actuator, loss of grid; modeling of aerodynamics during start-up/shutdown could be improved; industry has data that R&D may not have |
| Impact of feed-forward control on system response | | M | H | H | M | L | E.g., LiDAR: Enabling technology for floating |
| Effect of the sensors integration within the structure | | H | M | L | L | H | Strain, load, acceleration, load cells, pressure taps; important in the valiation application; cable bundle |
| Effect of the actuators integration within the structure | | H | M | L | L | H | Reliability |
| Impact of feedback control on system response | | H | M | M | M | M | Operators disable controllers because they have issues; likely more of an issue for floater feedback control |
| Impact of feedback control on system response -- Floater feedback control | Floating | H | M | M | M | M | Floater feedback control; industry has likely done great work with full-scale data that is not publicly available |
| Partial span pitch | | L | L | L | L | L | |

# Group 3a – Structures: Full Nacelle and Drivetrain PIRT

| Phenomenon | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy - Focused on beam-type | | | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|
| | | | Physics | Code | Val - Industry | | |
| **Nacelle and Drivetrain** | Both | | | | | | |
| Bearings (dynamics) | | M | L | L | M | M | DOE WETO codes are limited, industry codes (SIMPACK) are better |
| Gears | | M | L | L | M | M | DOE WETO codes are limited, industry codes (SIMPACK) are better; Direct drive becoming more common offshore, negating importance of gears. |
| Bedplate flexibility | | H | M | M | M | M | DOE WETO codes are limited, industry codes (SIMPACK) are better |
| Permenant magnet direct drive | | M | M | M | L | M | Industry has more data than DOE WETO |
| Hydrualic drives | | M | L | L | L | M | |
| Fracture mechanics | | M | L | L | L | M | white etching / cracks, stray currents from generator |
| Lubrication | | M | L | L | M | M | |
| Superconducting generators | | M | L | L | L | M | Proof of concept and reliability |
| Resonance of the drive system | | M | L | L | L | M | Amplification with the tower |
| Whirling of the shaft (boundary condition of the rotor/drivetain) | | H | M | M | M | M | |
| Effect of non torque loading of the gearbox | | M | L | L | M | M | Impact of stochastic excitation to the drivetrain |
| Impact of floater motion on mechanical components | Floating | H | M | M | L | M | |

# Group 3a – Structures: Full Tower and Substructure PIRT

| Phenomenon | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy - Focused on beam-type | | | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|
| | | | Physics | Code | Val - Industry | | |
| **Tower and Substructure** | Both | | | | | | |
| Elasticity and stress recovery of composite and concrete materials | | H | H | M | M | M | |
| Joint performance: flexibility and stress concentrations and load transfer; bolted connections | | H | M | L | L | H | Impact of welding; steel-concrete connections, bolts, grouted connections, slip joints |
| Member-level loads | Floating | H | M | M | L | H | |
| Lattice tower effects | | M | M | M | L | L | |
| Impact of marine growth on structural response | | M | M | M | L | M | |
| Response of unique structure types | | M | M | M | L | L | Lattice towers, compliant towers |
| Impact of pile driving on fatigue life of pile | Fixed | H | M | M | M | M | Also noise mitigation |
| Loading of secondary structures | | L | M | M | L | L | |
| Damage stability | Floating | H | M | M | L | H | Damage stability load cases |
| Fatigue demand capacity and utilization | | H | M | M | M | M | Especially important for components of high thickness |
| Buckling | | H | H | M | M | M | |
| Buoyancy cans | Floating | M | M | M | L | L | Move to water PIRT? |
| Prestressed cable influence on response and loading | | H | H | H | L | M | |
| Structural damping | | H | M | M | L | H | Very little data for floating substructures |
| Loading of scantling from global structural response | | M | L | L | L | M | |
| Geometric nonlinearities | | H | H | H | M | M | E.g., p-delta effect |

# Group 3a – Structures: Full Stationkeeping and Dynamic Power Cable Systems PIRT

| Phenomenon | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy - Focused on beam-type | | | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|
| | | | Physics | Code | Val - Industry | | |
| **Stationkeeping and Dynamic Power Cable Systems** | Floating | | | | | | |
| Hysteresis of synthetic lines | | H | M | M | L | H | |
| Bending of dynamic power cable | | H | M | M | L | H | |
| Mooring line loss | | H | M | L | L | H | |
| Tension-torsion coupling | | M | L | L | L | M | More important in very deep water |
| Wear and fatigue of mooring components | | M | L | L | L | M | Important for chain |
| Clashing | | M | L | L | L | M | line-line impact |
| Above-water station-keeping systems | | M | M | M | L | L | |
| Structural damping | | M | M | M | L | M | Most important for tendons |
| Creep | | H | L | L | L | H | Important for tendons |
| Slack events (onset and dynamic response) | | H | M | M | M | M | Important for tendons |
| Geometric nonlinearities | | H | H | H | H | L | |
| Response of floats and clump weights | | M | M | M | L | M | |
| Loading of shackles and linkages | | M | L | L | L | M | |
| Buoyancy modules for dynamic power cables | | M | M | M | L | M | |
| Bend stiffners and bend restrictors of dynamic power cables | | M | L | L | L | M | |
| Shared mooring effects | | M | M | M | L | M | |
| Structural loading of chains | | H | M | L | L | H | Industry likely has much more data than DOE WETO |

# Group 3a – Structures: Full Air-Structure PIRT

| Phenomenon | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy - Focused on beam-type | | | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|
| | | | Physics | Code | Val - Industry | | |
| **Air-Structure** | Both | | | | | | |
| Aeroelasticity - Loads | Floating | H | M | M | L | H | Ultimate; fatigue loads prediction; good data for smaller, fixed systems; less data for very large, slender rotors and for floating systems; load cases |
| Aeroelasticity - Stability - Operation | | H | M | M | L | H | |
| VIV - Stall induced vibration | | H | L | L | L | H | Idling situation in high winds |
| Passive load reduction | | H | M | M | L | H | Bend-twist coupling |
| Wind farm control (wake steering, induction, wake mixing) | | H | M | M | L | H | |
| Individual turbine control response to waked inflow | | H | M | M | L | H | |
| Wake impacts on downstream rotors | | H | M | M | M | M | Important for larger turbines, floating, and deep into the array |
| Aerodynamics under large motion | Floating | H | M | M | L | H | Aerodynamic loads, near-to-far wake; perrhaps split out betwewen local/rotor effects and wake effects |
| Downwind rotor effects (rotors downwind of the tower) | | M | M | M | L | L | |
| Water egress in composites | | M | L | L | L | M | |
| Extreme events | | H | M | M | L | H | Tropical cyclones, thunderstorm downbursts; ride through |
| Climatological changes | | M | L | L | L | M | Should be covered by Air group |
| Pressure mapping | | M | L | L | L | M | Getting from an actuator line to a shell or solid; a modeling issue, but not a phenomena |
| Icing | | M | M | M | L | M | |
| Flutter | | H | M | M | L | H | |
| Soiling | | H | M | M | L | H | Salt |
| Aeroacoustics | | M | M | M | M | L | Less of an issue offshore |
| Idling case with fault | | H | M | M | L | H | Edgewise instability |
| Erosion | | H | M | M | M | M | Industry is addressing this; less need for DOE WETO to address |
| Add-ons | | H | M | M | M | M | Wind tunnel validation, but not at scale |
| Drag on nacelle and support structure | | H | M | M | M | M | Important for parked/idling conditions; industry has a lead over R&D |
| Impacts of large inflow nonheterogeniety | | H | M | M | L | H | Unique large wind turbine rotor effects |

# Group 3b – Soil: Full Soil PIRT

| Phenomenon | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy - Focused on beam-type | | | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|
| | | | Physics | Code | Val - Industry | | |
| **Soil** | Both | | | | | | |
| Geotechnical characteristization | Both | H | M | M | M | H | High planning priority because it is the key fundamental problem; including multi-layered soil profiles; industry knows how to do it, but requires time and money, risk and reliability; statistical map across site; link geophysical data to geotech |
| Innovation in sight investigation testing procedures | Both | M | M | L | M | L | Explore/remedy possible lack of sight investigation procedures for offshore wind (e.g., obtaining from in-situ data reliable soil damping values for fatigue analyses) |
| Integrated geophysical/geotechnical characterization | Both | H | M | L | L | H | Focus on statistical links between datapoints; synthetic soil profiles; reducing uncertainty |
| Soil characterization -- from samples to full scale | Both | H | M | M | M | M | |
| Constitutive soil modeling | Both | M | M | M | L | M | Gap is between the soil characterization and (advanced) constitutive models, particularly with regard to parameter calibration - stronger link to typical sight investigation data needed |
| Geohazards | Both | H | H | M | M | M | Regional seismicity, landslands (West coast), setiment mobility/scour (regional), boulders, glacial soil conditions, carbonates (East coast/South atlantic) |
| Soft soils | Both | M | H | H | M | M | Issue for concrete gravity base for sliding along weak layers or settlement over thicker layers |
| Glauconite Sand | Both | H | L | L | L | H | US-specific issue; issue with pile driving; frictional resistance; features of behaviour challenging to capture in engineering numerical models |
| Boulders | Both | M | M | L | L | M | Relevance is pile diameter/thickness specific; can move or drive through in many cases; boulders typically close to shore in US |
| Micas | Both | L | M | L | L | L | Probably not issue for US east coast since mica length to sand diameter ratios are too small to create high void ratio |
| Carbonates | Both | L | M | L | L | L | limited to Sout Atlantic regions, increasing carbonate content with reducing latitude (rock in S FL and islands) |
| Lithification | Both | L | M | L | L | L | Process where freshly deposited loose grains of sediments are converted into rock; long time scale |

# Group 3b – Soil: Full Soil-Structure PIRT

| Phenomenon | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy - Focused on beam-type | | | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|
| | | | Physics | Code | Val - Industry | | |
| **Soil-Structure** | Both | | | | | | |
| Seabed friction – mooring | Floating | M | M | M | L | M | Need to understand axial response of different mooring line materials (chain, rope, fiber) |
| Soil damping | Fixed | H | M | M | L | H | Lots of uncertainty; industry is usually too conservative, e.g. 5% damping is applied universally; could also be applied through hysteretic behavior of plastic soils |
| Lateral jacket pile-soil interaction | Fixed | M | M | M | M | L | Physical models historic, based on small D piles, limited soil conditions; usually not governing for jackets |
| Lateral monopile pile-soil interaction | Fixed | H | M | M | L | H | Good physical models, limited validation data, diameters keep increasing; probably most crucial aspect of monopile performance; more validation needed for realistically inhomogeneous soil profiles |
| Axial pile-soil interaction | Fixed | H | H | M | M | M | Focus on cyclic axial response of jackets |
| Soil static and dynamic stiffness, including hysteresis, strain hardening/softening | Fixed | H | M | M | L | H | Limitations of p-y and t-z curves; change in soil-structure properties over time; difficulties in quantifying energy dissipation properties from sight investigation data |
| Shared anchor effects | Floating | M | M | M | L | M | Can help or hinder |
| Drag-embeddment anchors | Floating | M | M | M | L | L | Limited to specific soil conditions, e.g. deep clay deposits; industry moving away from these |
| Pile/suction anchors - pull out capacity | Floating | H | M | L | L | H | Could perhaps be combined with axial pile-soil interaction; need to look at drainage and time scale of cyclic loading; rely on partial suction for semi-taut and catenary moorings |
| DIrectional anchor capacity | Floating | M | L | L | L | M | Could perhaps be combined with shared anchor effects; problem arising from anchor sharing and multiple directions of loading |
| Reverse catenary | Floating | M | L | L | L | M | Often ignored; trenching effects |
| Dynamic power cable-soil interaction | Floating | M | M | L | L | M | Cables are flexible so more resiliant than rigid pipelines e.g. - unknown extent of interaction with soil |
| Burried power cable from wind farm to substation | Both | H | M | L | L | H | Critical zone of uncertainty; example Block Island failure; temperature effects in soil response |
| Foundations and anchors in rock | Both | M | M | L | L | M | Mostly relevant to highly cemented carbonates in FL and surface bedrock in ME - very little amount of available data for validation of advanced and simplified calculation models |
| Export cable-soil interaction | Both | M | M | L | L | M | Could perhaps combine with dynamic power cable-soil interaction; temperature plays a role |
| Trenching of mooring lines in soil | Floating | M | L | L | L | M | Big holes can develop but only under specific metocean and soil conditions; analysis shows a 25% capacity reduction at most |
| Gap between structure and soil | Fixed | M | L | L | L | M | Impact loads; is this for assessing potential for gap to occur or effect of gap on foundation capacity? |

# Group 3b – Soil: Full Water-Soil-Structure PIRT

| Phenomenon | Offshore Application: Floating, Fixed, or Both | Importance at Application Level | Model Adequacy | | | Planning Priority | Issue/Comments |
|---|---|---|---|---|---|---|---|
| | | | Physics | Code Verification | Val | | |
| **Water-Soil-Structure** | Both | | | | | | |
| Scouring | Fixed | H | M | L | L | H | See UWA recent research; physics much better understood; how good are scour protection systems? They work but can damage cables as seen from Orsted EU projects |
| Sand wave migration | Both | H | M | L | L | H | Impact on boundary conditions for cables and burial depth considerations |
| Backfilling | Both | M | M | M | L | M | Monitoring can be employed, but uncertainty in temporal conditions due to sediment mobility; need to protect cables |
| Liquification | Both | H | M | L | L | H | Phenomenon in which the strength/stiffness of soil is reduced by earthquake or wave loading; affects foundation capacity, displacements, and cable burial - may become very relevant for West Coast projects |
| Submarine landslides | Both | M | M | L | L | M | Part of "Geohazard", requires understanding of soil-water-structure interaction; potentially harmful to export cable routes or WTG foundations/anchors within run-out distances from landslide triggering area |