Pacific Northwest
NATIONAL LABORATORY

PNNL-30828

Outcomes of the DOE Workshop on Atmospheric Challenges for the Wind Energy Industry

December 2020

SE Haupt
L Berg
A DeCastro
DJ Gagne
P Jimenez
T Juliano
B Kosović
E Quon
W Shaw
M Churchfield
C Draxl
P Hawbecker
A Jonko
C Kaul
J Mirocha
R Rai

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <https://www.ntis.gov/about>
Online ordering: http://www.ntis.gov

PNNL-30828

Outcomes of the DOE Workshop on Atmospheric Challenges for the Wind Energy Industry

December 2020

SE Haupt[1]
L Berg[2]
A DeCastro[1]
DJ Gagne[1]
P Jimenez[1]
T Juliano[1]
B Kosović[1]
E Quon[5]
W Shaw[2]
M Churchfield[5]
C Draxl[5]
P Hawbecker[1]
A Jonko[3]
C Kaul[2]
J Mirocha[4]
R Rai[2]

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99354

[1] National Center for Atmospheric Research (NCAR)
[2] Pacific Northwest National Laboratory (PNNL)
[3] Los Alamos National Laboratory (LANL)
[4] Lawrence Livermore National Laboratory (LLNL)
[5] National Renewable Energy Laboratory (NREL)

Executive Summary

The U.S. Department of Energy (DOE)-funded Mesoscale-to-Microscale Coupling (MMC) project team planned and conducted a virtual Workshop on Atmospheric Challenges for the Wind Energy Industry on October 19 and 20, 2020. The goal of the workshop was to forge a dialog with the community, including industry representatives, on how modeling tools are currently being used, the present active atmospheric modeling research in support of wind energy, and required advancements in capabilities and technology to continue to advance wind energy deployment. The workshop was planned in collaboration with an industry advisory panel that included representatives from wind power plant developers, turbine manufacturers, and companies that provide resource assessment and forecasting services.

The format of the workshop included panels from government research sponsors, visionaries from industry, and mixed panels of researchers discussing research status and needs. A shared keynote presentation from the Technical University of Denmark experts anchored the second day of the workshop. An emphasis was placed on understanding the research needs in the offshore environment. In addition, breakout opportunities were provided each day. On the first day, the breakout discussions addressed predesigned questions configured to elicit participants' thoughts on needed research directions. The second-day breakouts treated three important technical topics through a combination of presentations and group conversations. Each workshop participant chose their breakout preference from among downscaling details, modeling for turbines, and using artificial intelligence for atmospheric modeling. The discussions were robust and productive.

The outcomes of the workshop include archiving a series of recommendations from industry and the research community on research directions required to further advance wind energy deployment. Discussions confirmed the need for high-fidelity modeling but that there are specific areas of applicability and other areas where the time and cost of computation is prohibitive. In those cases, the high-fidelity models can inform low-order models that are more practical for real-time or widely deployed applications. Industry must consider the financial cost of performing more expensive modeling approaches, but industry engineers and researchers are using these approaches where there appears to be a return on investment. An emerging type of low-order model is based on machine learning (ML).

Participants confirmed that there are many atmospheric phenomena that need to be modeled better, including low-level jets, cold air outbreaks, land-sea induced circulations, diurnal variability, thin stable boundary layers, dynamic changes such as from frontal passage, interaction of wakes and blockage, and more. For the offshore environment, there is wide agreement that some level of ocean-wave-atmospheric coupling is necessary to capture variations in rotor-level winds needed to plan and operate offshore wind plants. Another recurring recommendation is that more observations are needed, particularly for the offshore environment. Those observations should consider the needs for model improvement, both for physically based models and for ML models. Observations must capture atmospheric profiles of variables that are important to understanding and modeling atmospheric and oceanic phenomena that impact boundary layer winds. Models must be validated with data and the uncertainty quantified, particularly those that are sensitive to initial and boundary conditions. Finally, a repeated request was to consider the holistic needs of hybrid plants of wind, solar, and storage resources, because those types of plants are likely to be the wave of the future. In addition, industry wishes to understand impacts of the resource under a changing climate for long-term planning.

PDFs of the presentations and videos of many of them are archived at https://ral.ucar.edu/events/2020/atmospheric-challenges-for-the-wind-energy-industry-workshop.

The MMC team expects to use the recommendations in planning for future research and to disseminate it widely throughout the research and sponsoring community.

Acronyms and Abbreviations

A2e	Atmosphere to Electrons
AI	artificial intelligence
CFD	computational fluid dynamics
DOE	Department of Energy
DTU	Technical University of Denmark
GPU	graphics processing unit
HPC	high-performance computing
km	kilometers
LANL	Los Alamos National Laboratory
LCOE	levelized cost of energy
LES	large-eddy simulation
LLNL	Lawrence Livermore National Laboratory
m	meter
ML	machine learning
MMC	Mesoscale-to-Microscale Coupling
MOST	Monin-Obukhov similarity theory
NCAR	National Center for Atmospheric Research
NREL	National Renewable Energy Laboratory
NWP	numerical weather prediction
PBL	planetary boundary-layer
PNNL	Pacific Northwest National Laboratory
RANS	Reynolds-averaged Navier-Stokes
SAR	synthetic aperture radar
SST	sea surface temperature
SWAN	Simulating Waves Nearshore
U.S.	United States
WETO	Wind Energy Technologies Office
WRF	Weather Research and Forecasting

Contents

Figures

1.0 Introduction

The United States (U.S.) Department of Energy (DOE) Workshop on Atmospheric Challenges for the Wind Energy Industry was sponsored by the DOE Wind Energy Technologies Office (WETO) and organized by the multi-laboratory Mesoscale-to-Microscale Coupling (MMC) project within the Atmosphere to Electrons (A2e) program. A2e seeks to improve wind plant performance, ultimately reducing the cost of wind energy production. Within A2e, MMC oversees the development and validation of coupled mesoscale-to-microscale modeling. Figure 1, from WETO Director Dr. Robert Marlay's presentation, summarizes WETO's program.

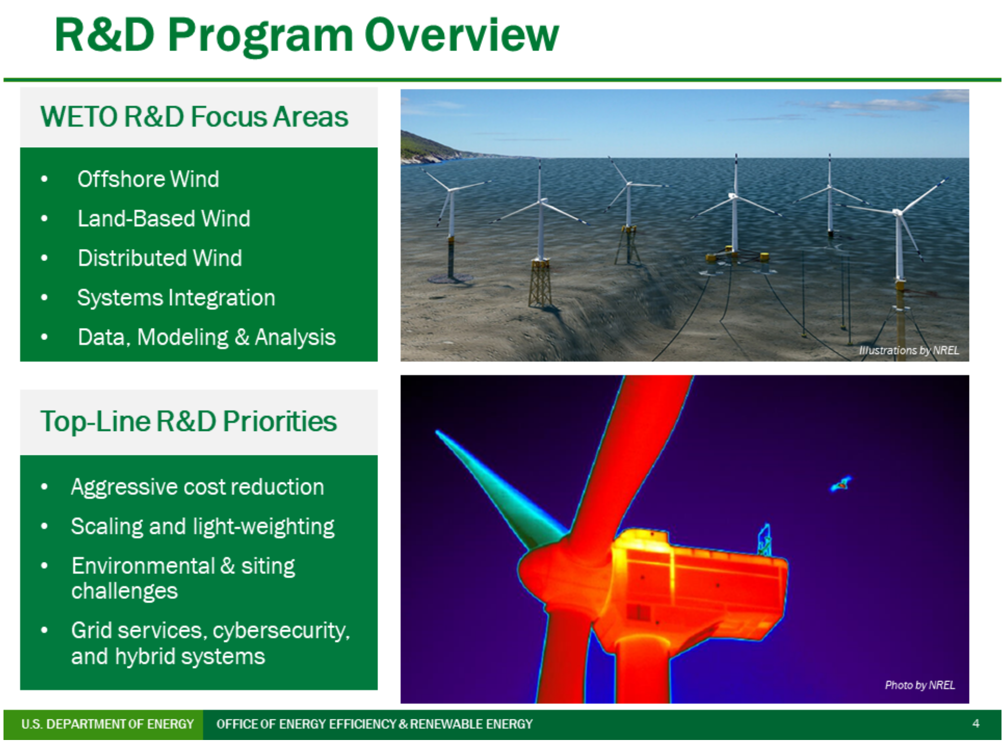

Figure 1. Dr. Robert Marlay's overview of WETO research and development focus areas and top-line research and development priorities.

As A2e and the MMC project head toward program/project culmination, MMC researchers and DOE program managers recognized a need to communicate the results of this atmospheric science research to the community and to solicit feedback, particularly from those involved in the wind industry, on the usefulness of the outcomes and the next most important research needs.

The meeting was initially planned to be held in person in June 2020 in Boulder, Colorado; however, the COVID-19 pandemic shut down travel in 2020, so the meeting was moved to a virtual platform and scheduled for October 19 and 20, 2020, with sessions held in the morning (8:00 a.m. to noon Mountain Daylight Time; 14:00 to 18:00 Coordinated Universal Time) to encourage attendance from time zones across the United States and Europe.

1.1 Purpose

As DOE moves toward closing out the A2e program and determining the most important directions for the next projects, it seemed important to discuss with industry the future of atmospheric modeling research for wind energy. Specifically, the workshop was configured to promote conversation between the research community and industry regarding wind energy modeling research needs, including to

- Hear from industry regarding their current modeling applications, future plans, and perception of research needs
- Present the current state of atmospheric modeling research
- Forge a dialog that will inform future research in atmospheric/oceanic modeling for wind energy.

1.2 Preparation

Planning for the DOE industry workshop was led primarily by the MMC multi-laboratory team, particularly the executive committee of project leadership. But to ensure that the workshop would meet the needs of industry, the team initiated an industry advisory board. This board included representatives from wind turbine manufacturers, wind plant developers and operators, and a company that specializes in wind resource assessment and wind power forecasting. Working with this team of experts from industry greatly enhanced the relevance of the workshop.

The MMC team advertised the conference in several ways. A flyer was developed (see Figure 2) and sent widely to wind energy professionals included on a mailing list that was enhanced for the workshop. In addition, MMC leadership worked to advertise the workshop through professional organizations, including the American Wind Energy Association, Energy Systems Integration Group, World Energy & Meteorology Council, and International Energy Agency Task 36 on Forecasting for Wind Energy. A website was set up to display the agenda and information regarding the workshop as well as for registration (https://ral.ucar.edu/events/2020/atmospheric-challenges-for-the-wind-energy-industry-workshop). Despite the very specialized nature of the workshop, it drew a total of 218 registrants.

1.3 Agenda

The agenda for the workshop was configured to allow for both passing information via keynote talks and panels, as well as to promote conversation between the private sector and the research community (see Figure 3). The first day was planned to focus on a big picture vision for atmospheric science research to benefit the wind industry, and it began with a welcome from WETO Director Dr. Robert Marlay, then moved to a DOE panel to describe the vision for DOE's wind program, the vision for atmospheric science research, and a short review of research being accomplished by the MMC team. That was followed by a panel of industry visionaries who presented their thoughts on what is needed in atmospheric science research to advance the state of the science. That panel was followed by a set of four breakout sessions led by MMC leaders who guided focused conversations around a series of predetermined questions. A short report-out session summarized key points made during the breakout sessions, and it allowed for some large group reflection.

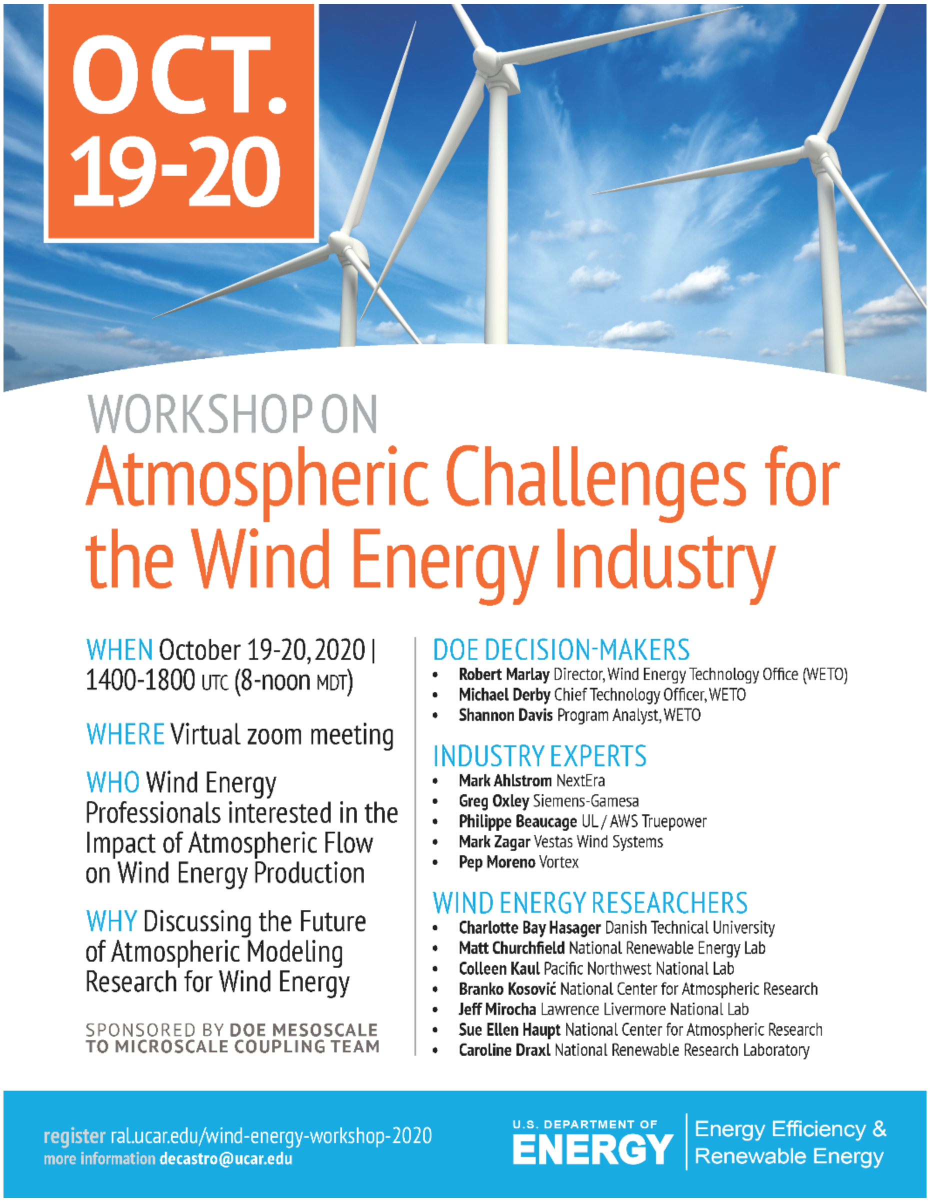

Figure 2. Workshop flyer.

The second day of the workshop focused on the technical details of ongoing research and posited types of research needed to move forward. The day started with a panel on Offshore Wind Research, beginning with two keynotes by researchers from the Technical University of Denmark (DTU). That panel continued with talks by MMC team members, an industry representative, and a laboratory scientist. The second panel on Day 2 described Modeling Challenges for the Wind Industry, including talks by MMC team members and by industry researchers. The theme of that session was dealing with uncertainty in terms of quantifying uncertainty and coping with uncertainty in both measurements and modeling.

Following the second panel, participants could choose from three parallel sessions: The Details of Downscaling, Modeling for Turbines, and the Use of AI in Atmospheric Modeling. After the parallel sessions, participants came back together for a larger group discussion led by the rapporteurs and moderators from each parallel session.

For most sessions, there were about 120 attendees. Discussion in breakouts was at times robust.

Agenda for
MMC-Sponsored Industry Workshop
October 19-20, 8-noon MDT
Atmospheric Challenges for the Wind Energy Industry

Monday, Oct. 19 - Big Picture Vision for Atmospheric Science Research
Join Zoom Meeting

Times in Mountain Daylight Time (0800 MDT = 1400 UTC)
8:00 Welcome and Goals – Sue Ellen Haupt – Project PI, NCAR

8:10 Introduction to DOE Wind Energy Technologies Office – Bob Marlay, WETO Director

8:20 DOE Panel

- Vision for DOE's Wind Program - Mike Derby, DOE WETO
- Vision for Atmospheric Science Research - Shannon Davis, DOE WETO
- Current Atmospheric Science Research - Sue Ellen Haupt, NCAR
- Discussion

Moderator: Mike Robinson, DOE/NREL

9:20 Industry Panel – visioning talks

- Mark Ahlstrom, NextEra
- Philippe Beaucage, UL / AWS Truepower
- Greg Oxley, Siemens-Gamesa
- Pieter Gebraad, Siemens-Gamesa

Moderator: Caroline Draxl, NREL

10:30 Directions for Break outs

10:40 Break-out groups – Goal is to solicit input on the vision of the group members for the future of atmospheric modeling for the wind industry. This can span methods, technologies, uses, etc. Participants will be assigned a "room" to mix the interests and backgrounds.

11:30 Full group – reports outs (5 min each) and full group discussion

Noon Adjourn for the day

Figure 3. Workshop agenda.

Figure 3. Workshop agenda (continued).

Tuesday, Oct. 20 - Technical Research Conversations
Join Zoom Meeting

8:00 Welcome back and summary of day 1 – Larry Berg, PNNL

8:10 Panel 1 – Offshore Wind Modeling opportunities and challenges

- **Keynote:** Where Are We and Where Do We Need To Go on Data? – Charlotte Bay Hasager & Xiaoli Guo Larsén,, DTU
- Data & Mesoscale modeling – Branko Kosovic, NCAR
- Industry perspective – Andreas Knauer, Equinor
- Microscale Modeling – Matt Churchfield, NREL
- Wind/wave coupling - Peter Sullivan, NCAR
- Discussion

Moderator: Will Shaw, PNNL

9:30 Short break

9:40 Panel 2 – Modeling Challenges for Wind Energy

- Dynamic nature of the atmosphere as captured by MMC – Jeff Mirocha, LLNL
- Industry use of high fidelity modelling - Mark Zagar, Vestas
- Evaluating Model Errors – Colleen Kaul, PNNL
- Using SCADA to infer Information - Vijayant Kumar, Sentient Science
- Discussion

Moderator: Sue Ellen Haupt, NCAR

10:30 Parallel Sessions for More Detailed Technical Conversation – Attendees are invited to choose one of the following break-out sessions – see zoom links for each

Parallel Session 1: Details of Downscaling
Opening Presentations:

- Turbulence Generation – Domingo Munoz-Esparza, NCAR
- Terra Incognita Research – Raj Rai, PNNL
- The Gap Between Modelers and End-Users - Pep Moreno, Vortex

Discussion Topic: What have we learned and where is more research needed?
Moderator/Discussion Leader: Jeff Mirocha, LLNL
Rapporteur: Colleen Kaul, PNNL
Join Zoom Meeting

Parallel Session 2: Modeling for Turbines
Opening Presentations:

- Use for Loads – Eliot Quon, NREL
- Modeling for Controls - Paul Fleming, NREL
- Modeling Challenges - Jennifer Newman, REsurety, Inc.
- Modeling for Plant Design - Shreyas Ananthan, NREL

Discussion Topic: What additional Research is needed for turbine control?
Moderator/Discussion Leader: Matt Churchfield, NREL
Rapporteur: Amy DeCastro, NCAR
Join Zoom Meeting

Parallel Session 3: Using AI in Atmospheric Modeling
Opening Presentations:

- Better ML models of the Surface Layer - David John Gagne, NCAR
- Downscaling with Deep Learning - Ryan King, NREL
- Improving Forecasts with ML –Daniel Kirk-Davidoff, UL/AWS Truepower

Discussion Topic: How else can ML best be used?
Moderator/Discussion Leader: Tim Juliano, NCAR
Rapporteur: Pat Hawbecker, NCAR

11:30 Short report outs + large group discussion
Return to Main Room at: Join Zoom Meeting

Noon Adjourn Workshop

1.4 Report Contents and Organization

The remainder of the report will proceed along the agenda of the workshop itself, reporting on the content and outcomes of the presentations and conversations during the two-day virtual meeting. Section 2 reports on Day 1 and Section 3 on Day 2. A summary and synthesis are provided in Section 4.

2.0 Big Picture Vision for Atmospheric Science Research

Day 1 of the workshop emphasized the big picture vision for wind energy research, taking stock of what research we have accomplished and what is needed to further enable wind energy deployment. Descriptions of the outcomes of the panels and breakout sessions are detailed in the following sections.

2.1 DOE's Vision and Current Efforts

Dr. Robert Marlay opened the workshop with an introduction to WETO. WETO focus areas include offshore, land-based, and distributed wind; systems integration, including the grid; and data, modeling, and analysis. Current priorities include aggressive cost reduction, scaling and light-weighting, addressing environmental and siting challenges, providing grid services, cybersecurity, and hybrid systems.

This led to a panel addressing Research Challenges & Investments in Atmospheric Sciences. Dr. Mike Derby (WETO) highlighted the grand challenges in the science of wind energy, which includes accurate prediction of hub-height aerodynamics and requires resolution of physical phenomena across disparate spatial and temporal scales. Wind plants are designed with limited attention to physics, and MMC is particularly needed to understand wind-wave interactions and to characterize the marine atmospheric boundary layer, air-sea processes, and complex terrain flows. To elaborate, Dr. Shannon Davis (WETO) put forth three challenges: first, to better characterize the local atmosphere, with new observations leading to better representations in model physics; second, to enhance our ability to observe and simulate flows; and third, to understand the up- and downstream relationships among the wind plants, the wind resource, and the environment during long (e.g., decadal) timescales.

The final panel speaker was Dr. Sue Ellen Haupt, who summarized current atmospheric science research by the DOE MMC team. MMC is needed to capture the forcing and transfer of energy across scales for realistic turbulence-resolving simulations driven by real data. Expected outcomes include more accurate resource assessment, as well as improved wind plant design, layout, and control. Current research highlights include the characterization of the *terra incognita*, defined by the height of the boundary layer; the representation of complex surface layers using a three-dimensional planetary boundary layer scheme; and the development of an improved surface layer parameterization using machine learning (ML).

The questions during this session related to research areas. The first was about the inputs for the ML surface layer scheme. Inputs to ML for the surface layer include surface (skin) temperature, soil temperature and moisture (if available), two levels of wind speed and temperature (potential temperature) above the surface, and at least one level of specific moisture content above the surface. For training, fluxes of momentum, sensible heat, and moisture are required at one level above the surface. For the best performance, long (preferably multiyear), quality-controlled records are needed.

2.2 Industry Vision

Following the DOE panel, the workshop continued with a suite of industry presentations describing the challenges and opportunities involving MMC from the perspective of industry leaders.

The first presentation was given by Mark Ahlstrom from the perspective of NextEra, the largest wind and solar energy company in the world. The future for renewable energy deployment is very bright; however, there is some speculation that solar deployment and integration with emerging storage technologies could outpace wind development during the next decade or so, before wind comes back into the portfolio at a higher level, provided that the cost of wind energy (including financing) continues to fall.

The aspirational goal that some industry leaders use as a planning target is an 80 percent renewable electricity grid sometime in the 2030s. This constitutes a huge challenge, requiring a four- to five-times increase per year. It is, however, seen as possible, with continuing rapid maturation of technologies. The role of political support is important to meet these ambitious goals; however, transmission infrastructure is critical, as well. Discussions of infrastructure improvements as components of future economic stimulus provide confidence in an improved transmission landscape to handle increased renewable production during the near-term time horizon.

A vision for hybrid renewable energy plants—consisting of wind and solar production combined with storage—was also articulated. The effectiveness of such a framework would depend on robust integration of analytical data from the grid, allowing the plant to integrate production, storage, and grid services in a manner that maximizes both grid services and profitability. Such a plant would appear to function as a dispatchable, conventional power source from the perspective of the grid, and perhaps even offer extended capabilities—including ancillary services in some conditions—with nearly instantaneous start-up and relaxed requirements for minimum run time, ramp-down, and other operational constraints.

Improved resource forecasting is crucial to the effective operation of such a hybrid plant, providing information for when to charge and discharge batteries, how to manage the risk of delivering promised power, and being able to balance voltage and current fluctuations over timescales of minutes due to meteorological variability. Probabilistic meteorological information becomes increasingly valuable in this context, as the confidence becomes equally important to the actual number.

The second presentation, by Philippe Beaucage of UL/AWS Truepower, focused on challenges of wind power production, noting that wind flow modeling (either at the P50 or P95 levels) remains the largest source of uncertainty (~4 percent) among the various factors influencing wind plant profitability. Some practitioners believe that one pathway to significantly reducing this uncertainty would be an ability to conduct simulations at high spatial resolution (~50 meters [m]) over domains of 25 kilometers (km) or greater, as required to capture the impacts of turbulence, terrain, and other environmental variability. All the relevant flow regimes impacting a region must be represented, which is a challenge due to the expense of incorporating all the important atmospheric physics.

An additional challenge beyond the expense of the simulations is the amount of training and sophistication to set up, run, and interpret such high-fidelity simulations. A typical client expects to spend about $5,000 for a resource assessment to be completed within two to three weeks. There might be room to charge more or draw out the time horizon, but the value of that extra time and expense must be clear to the client.

Mesoscale simulation models coupled with simple wind plant domain models (mass consistent approaches) have been shown to provide superior results relative to linearized or Reynolds-averaged Navier-Stokes (RANS) models, with up to 50 percent improvement over complex terrain. Large-eddy simulation (LES) approaches might be better still; however, better understanding of how to interpret LES errors and how to set up and run these more complicated codes is needed. This is also true for planetary boundary-layer (PBL) parameterizations in weather models, where regime-switching schemes can perform better than more robust schemes when used appropriately. For example, nonlocal schemes perform better in convective regimes, but local schemes perform better in stable regimes.

ML methods are also being pursued to better connect inputs to outputs of relevance; however, this is another area where expertise is required to set up and interpret the approaches. There is a steep learning curve.

Currently, there is only one International Electrotechnical Commission standard for resource assessment. In addition, there is no standard for turbine-induced wake modeling, with most practitioners using relatively simple approaches. With larger wake losses anticipated offshore, as well as increased wake variability, perhaps more sophisticated wake models will become more widely used.

In addition to the complications of using higher fidelity codes, they are also just too slow. Improved clock rates for codes should be a high priority. The possibility of developing a graphics processing unit (GPU) version of the Weather Research and Forecasting (WRF) model was raised as a point of interest.

In the future, industry would like to be able to track wind plant losses by category (e.g., wakes, resource errors, forecasts, etc.). Also, resource assessment will eventually need to incorporate climate change impacts, as well.

The third presentation, by Greg Oxley of Siemens Gamesa Renewable Energy, focused on the integration of domain knowledge with modern data science and engineering methods to accelerate innovation, with a view toward holistic design, operation, and integration. Many companies are attempting to increase the fidelity of their simulation pipeline, relying heavily on mesoscale, computational fluid dynamics (CFD), and ML approaches. There is a strong desire to accelerate bringing the mesoscale down to the microscale as quickly as possible. At the same time, budgets for high-performance computing (HPC) resources are being driven down. Even deploying CFD-RANS approaches is becoming difficult. When looking at ~2,000 sites per year, even using simpler forms of higher fidelity modeling becomes very difficult. Moreover, how useful is a 36-sector RANS exercise if the flow over complex terrain is not handled well? For these reasons, there is a push toward high-fidelity model surrogates and other ML approaches.

It was also expressed that there is wide interest in pursuing offshore challenges; however, there remain significant challenges on land that requires continued investment in simulation approaches.

Siemens Gamesa is moving toward an open innovation framework to address challenges by using DVLpy, a Python-based set of codes managed through a GitHub environment, to facilitate the future of multilevel optimization. This is viewed as the antithesis of vertical hierarchy: submit a problem and allow the organization to solve it horizontally—i.e., find a way to do more with less. Currently, DVLpy is looking for more partners, especially U.S. partners, because the community is presently dominated by Europeans.

These three presentations were followed by a discussion in which one topic was the relative importance of more model development efforts versus more observations. While observations can be used to inform ML-based tools, an issue is the tremendous amount of training data required for the construction of robust ML methods. High-fidelity models, properly validated, can provide data for use in developing ML-based approaches.

This led to a question of how much faster high-fidelity simulations would need to be to be useful in design and layout applications. Would a 10-times speedup be sufficient? The consensus is that would get us part of the way there. The likely application of high-fidelity modeling in the future is in providing a basis for surrogate modeling and other ML-based approaches and possibly some forensics. High-fidelity models are simply too complicated and expensive to be used "in the loop."

A related comment from the chat was that even if high-fidelity models were made perfectly accurate and 1,000 times faster, the lack of detailed information to specify input, boundary conditions, and interpret output still creates bottlenecks and difficulties. One answer for a path forward is to correlate the analytical information upstream to the wind plant owners in a way that they can directly ascertain the value. This could be more effective than working with the independent system operator.

A final discussion centered on how many LESs would be needed to train a surrogate model and what would be considered acceptable errors between the surrogate model and the LES model? The answer to the first part of this is probably hundreds to thousands, over multiple wind directions and stability classes, per site.

2.3 How Participants See Progress and the Future

The remainder of the first day of the workshop broke the attendees into virtual discussion rooms according to their interests. Each discussion was guided by an MMC team member with a series of rotated questions so that each question was covered by at least two groups. In each room, a rapporteur was also assigned to capture the conversation.

2.3.1 Room 1 Report

In Breakout Room 1, the discussion focused on four questions. The first was, "**For offshore deployment, how do you gauge the importance of coupling to ocean and wave models?**" The group agreed that this coupling would be very important for floating turbines, because the motion of the tower would be induced by both wind and waves. Further, it was discussed that wave-driven winds have already been shown to impact the wind field, which makes this coupling important; however, one of the main points of the conversation revolved around the difficulties of gathering data for verification and validation over the open ocean. Because of this, it is difficult to determine the true importance of wind-wave interactions on the wind field. It was proposed that turbine supervisory control and data acquisition (SCADA) system data might be our best source, even with the issues involved with these data sets (wake effects, for example). Another aspect of importance was discussed to be timescale dependent: short-term impacts might be less important in many aspects, whereas the long-term bulk effects might become very important. This research area is relatively new, with many open questions; however, it might also be possible to borrow from other applications (e.g., sailing) to expedite progress in this area.

The second question was, **"How is ML seen to impact industry modeling tools?"** Several applications of ML are currently in use, including for bias correction in forecasting, power forecasting, and building surrogate models. Future applications in resource assessment could also be very fruitful. That said, a word of caution was issued that we cannot simply rely on a “black box” approach with ML models. First-principle models and physics need to be considered first and foremost, with ML techniques used to assist and improve these models. If used properly, these techniques can prove very useful and help model development with the inclusion of large amounts of observations. These observations were the focus of the final thoughts in the conversation. More data are needed for training. Future field campaigns should have ML techniques in mind when deciding which variables to collect and at what rate. If there is more interest in ML techniques, there will be more interest in building large data sets for training ML models, creating a positive feedback loop.

The group next focused on the third question, **“What are the likely HPC platforms for the future (owned versus cloud)? Are you considering next-generation accelerators (like GPUs)?”** Most of the discussion revolved around GPU uses and the difficulties associated with porting code that was not originally written with the GPU architecture in mind. For example, porting WRF to be GPU-compatible is not planned and would not likely end up with much of a performance boost because of large input/output between the central processing unit and GPU. Further, all parameterizations within models such as WRF would need to be converted, making for a very time-intensive activity. New GPU-based codes—both mesoscale (Energy Resource and Forecasting) and microscale (FastEddy®)—are currently being written. These new codes allow for extreme improvements in both simulation speed and energy requirements. GPUs themselves are also being developed for these types of applications, as opposed to the common, media-based GPUs that have been around for decades. In terms of companies considering purchasing their own HPC systems, much of the discussion focused on how the cost/benefit of owning HPC systems might not lead many companies to purchase them. There are high costs associated with the critical machinery, maintenance, and support. Cloud storage does not seem to be a good fit for much of model output data that was discussed due to the massive size of some of these data sets (hundreds of gigabytes to several terabytes). The conclusion was that a hybrid approach will persist for some time. Some users will invest in HPC due to the amount of data that needs to be handled and the cost of data egress on cloud services; however, the cloud provides flexibility and can be used when data egress is not an issue.

Last, the group discussed, **“What are the challenges of wind plant interactions?”** It was very clear that tools are needed to model wind farm communications and interactions. Aside from modeling, there exist many legal challenges of building wind farms upstream of existing wind farms. The models and tools that are developed need to be able to convince developers that these interactions are significant and must be considered in site assessments and allocations. For example, one group member brought up a study (no author or title information was given) in which wake recovery over the ocean in stable conditions was shown to be greater than 150 km. In the offshore leased areas for wind energy off the East Coast of the United States, observations have recorded high occurrences of stable conditions, making this type of understanding critical in future developmental procedures. Onshore, general rules of thumb have been produced for such procedures. It can be expected that wind plant wakes will be more pronounced offshore. The same must be done for offshore; models could play a critical role in determining what these are.

2.3.2 Room 2 Report

The first question discussed by Breakout Group 2 was, **“To what extent might MMC methods be applied to enable greater confidence in promoting innovative design and deployments?”** The first major point brought up by one of the participants was whether we will need more or less observational data in the future as modeling improves. By and large, the group agreed that we likely will need more data, and the need to collect data will not go away any time soon. Data are especially important as ML applications continue to increase. Moreover, we learn what measurements we need to add or improve based on our higher fidelity models (e.g., LES), which inform our lower fidelity models and, furthermore, as the accuracy of high-fidelity modeling improves, it can help us gather better data (e.g., through instrument siting). In this context, MMC methods are on the end of high-fidelity modeling, so they will play an important role in the wind energy community moving forward. Another participant wondered whether there is an opportunity for the MMC group to use resources to better understand interactions among components in, for example, a hybrid (wind + solar + storage) plant. Currently, there is not a great way to model the complicated level of interactions among the different components; ML methods are often used, but they tend to oversimplify the situation, and there is not great coupling with the physics. Also, the design and layout of the plant is constantly changing, so we must better understand how this will affect the performance. This conversation sparked the question of how industry can avoid having the same experience with ML as they have had with RANS models (i.e., RANS has often been misused and, therefore, is not well trusted). One group member thought that controlling expectations is important, and ultimately conveying and convincing financial decision-makers about the cost-benefit analysis and uncertainty is key moving forward. We must also understand how much better the new ML-driven models will perform in the context of individual projects versus the overall big picture. Another subtopic discussed was framing the concept of validation to be useful for industry (e.g., modeling pre- and post-turbine installation to elucidate the impact of turbines and emphasizing model-data interactions to validate models when uncertainty exists in the initial and boundary conditions). The last discussion point within this first question was whether time-accurate models (LES) can be useful outside of ensemble averages, given the challenges involved in validating LES models (for example, how to get appropriate estimates of turbulent kinetic energy and comparing with lidar [volume] data). One participant put it bluntly: “You have to know what you don’t know!”

The next question posed to the group was, **“What are the unique challenges for offshore deployment and operation?”** The consensus was that better understanding of blockage and wake effects is the top challenge, because these factors can have a bottom-line impact of approximately several percentage points (site-specific) on the wind forecast. One participant suggested that there is a lot of confusion about the combined effect of blockage and waking, but in reality, these phenomena are not decoupled from—but rather part of—the same wind farm-atmosphere interaction system. Nonetheless, someone else remarked that engineers like to have these phenomena exposed explicitly in their tools (e.g., to be able to vary percentage of blockage effect directly). Additionally, one regime where the wake effect is especially pronounced is in the stably stratified, offshore environment with low surface roughness where wakes can be more persistent than over land. In general, numerical models (e.g., LES) tend to perform not as well in these stable conditions due to the relatively shallow PBL depth. In turn, modeling the shallow PBL environment leads to challenges, such as not resolving the turbulence cascade well enough unless very high spatial resolution is used, issues related to the inversion/entrainment processes, and the requirement of longer/more expensive model spin-up time. A second theme under this question was the relatively scarce wind observations that are available at offshore sites, which significantly influences the applicability of ML methods. As a community, we must identify exactly which types of information are needed (e.g., simultaneous wind and wave data to better understand their relationship). While they are very useful, offshore meteorological masts, lidars, and buoys can be expensive, and we need to consider the uncertainty associated with remote sensing platforms.

The third and final question that the group discussed was, **"What atmospheric processes are most important yet challenging to model?"** As mentioned in the discussion for the prior question, the combined effect of blockage and wake is at the top of the list. One participant suggested that, in regions of complex terrain, improving the modeling of the inverse energy cascade—which is not currently handled well—needs two-way coupling methods. Moreover, top-down effects should be explored in more detail, because parameterizations (such as those widely used within WRF) do not accurately model shallow PBLs, especially those over terrain and within the upper-level rotor region. The participant suggested that we can think of this topic as being important for combined wind and solar forecasting. Along this topic, another group member stated that entrainment processes are crucial for wind forecasting: the microscale models are not capturing features that could extend higher in the atmosphere, and we need to think of better ways to model these processes, aside from using standard boundary condition methods. The breakout group also discussed the importance of differences between extreme events offshore versus onshore, because the United States is unique in terms of the variety of atmospheric phenomena it experiences—for example, hurricanes in the Gulf of Mexico and along the East Coast, derecho events that begin on land but can propagate offshore; and ramp/extreme turbulence events that can have different characteristics depending on the geographic region. Finally, the participants all agreed that low-level jets and sea breeze processes are important yet challenging to model for near-shore locations and that we should strive to better understand surface exchanges, including irrigation and soil effects.

2.3.3 Room 3 Report

In Breakout Room 3, the first question discussed was, **"What atmospheric processes are most important yet challenging to model?"** An initial point mentioned was that even after constructing and using a model, it is challenging and important to know how much confidence one has in the results obtained. This tied back to the discussion earlier about the relative values of the characterization of a model's behavior and biases (confidence in the model) versus its accuracy in representing some key physics more completely, as well as the possibility of failing to set up a more accurate model properly due to more detailed information needed to run a higher order model. All models can be "abused" when run outside of limits. It is crucially important that new codes contain assessment of their characteristics and accuracy in relevant applications, as well as documentation of best practices for reliable use.

Among the atmospheric processes discussed were events related to ramp-ups and ramp-downs at different timescales (e.g., minutes, days, even longer). How to manage instability in power grids dependent upon these processes and the consequent effects that happen within the boundary layer (transitions, low-level jets, internal boundary layers) in the range of a few hours can be relevant.

Regarding offshore-specific challenges, there was much discussion about the modeling of land-sea interactions, including diurnal land-sea circulations, effects of coastal terrain, and changes in surface roughness and thermal forcing as flow moves on- or offshore. Events such as low-level jets can be very important, especially as the turbines become larger, and low-level jets can persist for longer durations than on land due to the reduced impact of diurnal forcing relative to advection. A related issue discussed is that we do not have many observations offshore, so we rely on models and buoys, which are not very useful for profiling the vertical structure of the wind. It was mentioned that having better observation data sets can be helpful.

Although not considered a "process," there was again some discussion about integrating uncertainty into model applications. Uncertainty quantification is seen as highly useful, and it was mentioned that an important issue is the need to understand the limitations for ensemble forecasting and probabilistic forecasting and to be able to predict their related uncertainties, as well.

Another challenge that was discussed is the incorporation of local effects within the wind plant—for example, whether models can properly capture wake interaction processes. What is the best way to go about incorporating small-scale wind plant processes? Are ML-based methods superior or simpler to implement than full-physics methods? Moreover, can we go straight from mesoscale to the wind plant through ML and entirely skip the expensive and difficult-to-execute downscaling efforts with good ML-based approaches? This is an application of ML that many industry partners are moving toward. In this application, again the high-fidelity codes would be useful—not so much in any specific individual simulation but as a basis for developing surrogates or other ML-based relationships between atmospheric inputs and turbine and power plant performance outcomes.

This topic concluded with mention of whether—in the context of hybrid plants that can absorb some fluctuations in the forecasts—industry will move away from trying to decrease real-time meteorological forecasting errors and associated issues and instead focus more on capturing the effect of processes that more directly influence power prediction.

The second question discussed was, **"What are the likely HPC platforms for the future (owned versus cloud), and are you considering next-generation accelerators (such as GPUs)?"** This discussion was relatively short, and it revolved around two main issues. The first point discussed is that the flexibility in resources that cloud-computing provides is key. It depends on the application, but some industry members are actively exploring cloud-based solutions.

Another major topic of discussion involved the challenges of data management. Frequently, high-fidelity simulations generate so much data that its storage and post-processing create additional, significant challenges. It was mentioned that sometimes post-processing is more challenging than actually running the simulations to generate the data. Sharing databases across the community (e.g., high-fidelity solutions that could be used to build surrogates or ML-based approaches) was a topic discussed that could potentially alleviate some of the issues.

Last, some comments were shared about combining stochastic with high-fidelity solutions as an alternative to the extreme data management issues related to high-fidelity model data sets. One example was the relative ease of running many smaller simulations versus fewer very large ones and that, in turn, combining these smaller simulations can provide additional benefits in the estimation of design parameters.

Next, the question discussed was, **"To what extent does industry require high-fidelity solutions rather than lower order approaches?"** The general consensus is that the industry does require high-fidelity simulations—both for specific applications as well as to form a basis for surrogate or other ML-based approaches—but, in general, cannot afford it for routine workflows.

Another topic of discussion was how to feed the physics captured from high-fidelity models into the lower fidelity or reduced-order models that industry actually runs in their everyday workflows. The discussion followed with how teamwork is needed between the high-fidelity modelers and the reduced-order modelers and how expertise across the spectrum of fidelity is needed; it is important to have people that know both ends of the fidelity spectrum in making the connections between the approaches.

Further discussion was dedicated to the need for high fidelity for turbine impacts, such as loads or other damage modes, which are impacts that are relatively certain yet for which lower fidelity codes are often used. This was contrasted with the routine use of high-fidelity codes for weather prediction, for which the subject of study is not nearly as predictable, even with those higher fidelity codes. It was mentioned again, for emphasis, that for real-time operations, high fidelity is not feasible in the short-term. The idea of a shared database was revisited again, emphasizing that it can facilitate downscaling studies and be more readily available and useful.

The last question discussed by the group was, **"For offshore deployment, how do you gauge the importance of coupling to ocean and wave models?"** A point made was that industry does require fully coupled simulation capabilities but will not be able to pay for those with shrinking funds allocated to research and development. A key to motivating management to increase investment in such developments is to demonstrate in a quantifiable manner that wind-wave coupled effects are important to the governing economics. The example given was blockage effects: an experiment was made, data collected, and its effects quantified. After that, once it was demonstrated that blockage effects can account for 1 to 2 percent of losses, then they became relevant. The same needs to be done with wind-wave coupled effects.

The experimental data required to validate any such codes are critical. One quantity mentioned that can be helpful to model validation is the rate of mechanical energy transfer that occurs within the surface layer. The acceptance from the industry must start from the experimental campaign, then proceed to model development and validation.

2.3.4 Room 4 Report

The first question in Breakout Room 4 was, **"To what extent does industry require high-fidelity solutions rather than lower order approaches?"** The general feedback was that both low- and high-fidelity solutions are needed by industry, but the expense and complexity of high-fidelity solutions is justified only if the improvement in accuracy and return on investment is demonstrated. One industry representative defined "low-fidelity" as anything that can be run on a desktop, whereas "high-fidelity" requires HPC or contracting to an outside organization. Low-fidelity solutions are useful early in the contracting process for a new wind farm to get a rough estimate of feasibility. High-fidelity solutions are most helpful later in the development process when it comes time to invest in buying land and building towers. High-fidelity solutions, such as multiyear WRF runs, can be useful in areas with no or limited observations. One challenge with high-fidelity solutions is the volume of data output from the simulations. If customers are provided too much information, then they will not be able to use it effectively. For offshore wind, a key benefit of a high-fidelity system is coupling wind and wave modeling together. Currently, wind and wave modeling output come from separate companies, and the resulting analyses of winds and waves do not match up with each other. Coupled wind-wave data provide much more accurate estimates of the expected stress on an offshore wind tower.

The discussion then turned to, **"What are the challenges of wind plant interactions?"** One challenge is merging wakes from different scales (single-turbine versus farm). Modeling full wind farm wakes and single-turbine wakes is still really tricky. Each source of observational data provides only a partial picture of the wakes. Satellite data provide infrequent snapshots of a given area, flight data are only available for select cases, and mast data require careful processing, akin to putting puzzle pieces together. Field campaigns are being organized to address the observational data issues. There is also a concern about end users not understanding the limitations of the available instrumentation. Lidar is very attractive, because people think it can do everything; however, lidar can provide only a macroscopic picture of the wake, and it cannot capture the full extent of the turbulence. The lack of observations also limits our ability to measure losses from wakes and from the blockage imposed by the wind farm itself. Customers might have an overly optimistic estimate of wind energy generation based on preconstruction data.

Next, the room covered, **“To what extent might MMC methods be applied to enable greater confidence in promoting innovative design and deployments?**” A key benefit from MMC is bringing larger scale atmospheric forcing into the LES beyond what is normally prescribed. One example is open cells from the passage of cold fronts. In these instances, coherent structures appear in the turbulence field spatially. Larger scale atmospheric forcing is also very relevant with tropical cyclones. A goal for MMC should be to show that value can be added in a relatively short time frame, such as less than a year. More accurate modeling from MMC could reduce the risk in building at some sites—in particular, by reducing the levelized cost of energy (LCOE). MMC can also bias correct errors from mesoscale wind field data. The last part of the discussion led into the scope and ambitiousness of MMC modeling exercises. One participant argued that we do not necessarily need a high-resolution wind field over the entire domain, only in select areas. They advocate scaling the LES domain from a few points to only the area that is needed to reduce computational costs. This approach is justified based on the history of success in wind farm planning with limited observations and low-fidelity models. There are groups that have methods for calculating statistics in an area and using it to force small LES runs.

The discussion ended on, **“What are the unique challenges for offshore deployment and operation?**” There was very little time for this discussion, but the importance of wind and wave coupling was reiterated here.

3.0 Technical Research Details

During the second day, the workshop focused on some of the technical details of the research that has been accomplished and fostered conversations on what is needed from the atmospheric science research community to continue to support wind energy deployment. Here, we describe those details as gleaned from the two panels and three parallel breakout sessions.

3.1 Offshore Wind Modeling Opportunities and Challenges

Day 2 of the workshop began with a panel focused on offshore wind opportunities and challenges. The opening keynote, “Where Are We and Where Do We Need to Go?” was presented jointly by Dr. Charlotte Bay Hasager and Dr. Xiaoli Guo Larsén of DTU, and it focused on modeling and data.

In Europe, the goal is to install 14 gigawatts per year for the next 30 years (Wind Europe 2019), which will require planning activities. At DTU, researchers use synthetic aperture radar (SAR) satellite maps for analyses (Envisat, Sentinel-1) to look at mean wind conditions, coastal wind speed gradients, wind farm wake effects, and model validation. DTU maintains a satellite archive (https://satwinds.windenergy.dtu.dk) which can be accessed via web portal. A comparison of SAR and WRF model output data has been performed for the U.S. East Coast (Ahsbahs et al. 2020). With regard to model validation, offshore winds have been mapped with SAR and model simulations around Iceland (Hasager et al. 2015). SAR data have also been used for Europe’s offshore wind resource assessment in the New European Wind Atlas (Hasager et al. 2020). Satellites observe wind at 10 m, so methods have been developed that include stability corrections to extrapolate the wind speeds to hub heights. Dr. Bay Hasager recommends using satellite SAR data for spatial details in the flow and lidar data (including floating lidar systems) to measure the wind speed at various heights. The uncertainty of SAR winds can be estimated based on the model functions used, and it amounts to 1 m s^{-1}. A correlation between SAR winds and sea surface temperature (SST) was found.

Dr. Xiaoli Guo Larsén pointed out that challenges in modeling and wind resource assessment include modeling the impact of wind farms on downstream flow (in particular, their presence is neglected) or limited accuracy in modeling physical processes across scales (e.g., coastal flows, wind farm wakes, and turbine wakes). Larsén et al. (2019a) calculated wakes from offshore wind farm clusters and investigated their introduction to the Danish power integration system. They used wind-wave-wake coupled modeling (Larsén et al. 2019b). WRF and the Simulating Waves Nearshore (SWAN) model were coupled, and inside SWAN they implemented the Wave Boundary Layer Model, which considers shallow water effects and wave breaking. Momentum transfer to the atmosphere is modeled through fluxes. Results show that extremes are not well captured: the mesoscale variability is missing; the interaction of wind, waves, and ocean during extremes is poorly modeled; and measurements are missing to understand physical processes during storms. Combining physical and statistical approaches (such as ML and spectral correction methods) seem to yield the best results.

Dr. Branko Kosović of the National Center for Atmospheric Research (NCAR) talked about offshore mesoscale modeling challenges and observations. For offshore wind energy applications, the atmospheric boundary layer cannot be isolated from the larger scale flows. The offshore environment presents new challenges to mesoscale modeling, the parameterization of physical processes, and the modeling of wind (e.g., land and sea breezes, low-level jets, tropical cyclones, wind-wave coupling, ocean circulations, SST variability, upwelling off

California, Gulf Stream current, significant temperature gradients, wave effects on hub-height winds). The ocean surface can be considered flat for mesoscale modeling, nor can it be considered horizontally homogeneous due to the proximity of land or variations in the ocean surface state. Dr. Kosović pointed out that, in the summer, a shallow stable marine boundary layer can persist for days over the shelf current off the U.S. East Coast. When winds blow from the northwest, a low-level jet is created. In the winter, cold air outbreaks result in convective conditions offshore, which are difficult to model for one-dimensional PBL schemes. The areas where this occurs coincide with planned offshore wind deployment. Three-dimensional PBL schemes should be employed when grid cell resolutions are finer than 2 km. To improve the PBL and surface layer parameterizations, we need collocated atmosphere, wave, and ocean state observations. The team has used FINO1 observations for model validation. In the United States, the National Oceanic and Atmospheric Administration's buoy network provides information about wind speed and direction, significant wave height, wave direction, and wave period. Observations are available from the Air Sea Interaction Tower and Cape Wind tower, which are adjacent to the U.S. offshore wind lease areas. Preliminary results of applying ML to improve surface layer parameterizations are encouraging. NCAR developed ML models (random forest and artificial neural networks) using wind, wave, and flux measurements from FINO1. Dr. Kosović concluded that in the United States, we need to learn from offshore environments where wind turbines have already been deployed (e.g., Europe), recognize special characteristics and related physical processes in different offshore environments, recognize that the offshore environment is not necessarily homogeneous, explore ML to improve parameterizations where theoretical assumptions are not satisfied and data are not available, and that we need more observations for model development and validation.

Dr. Andreas Knauer from Equinor provided an industry perspective on wind modeling for offshore wind energy. He pointed to the great potential of floating wind farms and predicted significant growth of floating wind from 2030 to reach ~15 to 20 percent of total offshore wind by 2050. The key growth markets in the United States are predicted to be in California, Oregon, Maine, and the Gulf of Mexico. Equinor's wind modeling focuses on the impact on power and loads. For the optimization of structural components, the spectral content of the load is extremely important. More detailed load descriptions allow LCOE reductions. Their Hywind Scotland wind farm is heavily instrumented, with nacelle-mounted lidars and a scanning lidar installed on a nacelle. Challenges for offshore wind farms include internal wakes, external wakes, park-park interactions, far-wake developments, and wake blockage effects, including gravity waves—all of which should be simulated. As offshore wind farms increase in size and density, the interaction between wind farms and the PBL becomes increasingly important. For future wind farms, LCOE reductions are mandatory. Andreas recommended that models need to be applied to actual park design challenges, and flow control aspects should be addressed.

Dr. Matt Churchfield, from the National Renewable Energy Laboratory (NREL), provided an overview of microscale offshore wind modeling opportunities and challenges. Those are used for very localized wind resource assessments, to study wake physics to inform engineering models, for advanced control/operational systems virtual labs, and to understand mechanical loads. Offshore, one must consider coupling with waves, because waves modify the flow in the turbine layer and wind modifies the waves; atmospheric phenomena over the ocean, such as coastal low-level jets, land-sea breezes, and hurricanes; and moisture and its effect on heat transfer. At NREL, microscale modeling involves applying actuator disk and line models (Figure 4), blade-resolved simulations, and flat surface with proper stress to two-phase models.

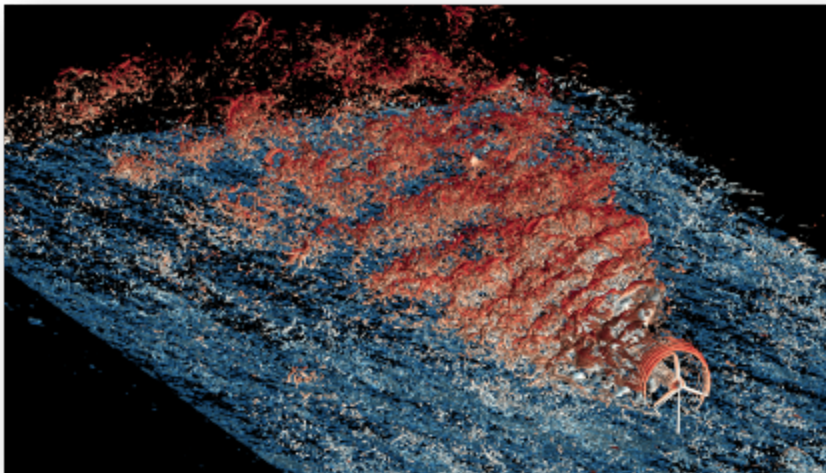

Figure 4. Actuator line wind turbine in nocturnal, stable boundary layer. Isosurfaces of vorticity magnitude are colored by velocity.

Dr. Churchfield recommends using high-fidelity modeling as a discovery tool to improve lightweight tools. He also emphasizes the importance of understanding the adequacy of design-standard turbulence models and improving them, understanding wind farm blockage, improving surface stress/flux modeling for waves, and planning field campaigns. He suggests that next-generation wake models involve more physics but be fast enough to utilize for controls, and that they should be able to compute both the individual turbine wakes and farm wakes.

Peter Sullivan of NCAR talked about coupling the marine atmospheric boundary layer winds to the ocean surface. Many scales are involved in the physical processes that occur at the interface of ocean and atmosphere (millimeter: sea spray, hundreds of meters: swell, and tens of km: surface heterogeneity).

The atmosphere drives the ocean on the big scales, but air-sea interaction is scale dependent, and when one looks at the smaller scales, the water drives the atmosphere. At the submesoscale, instabilities, fronts, vortices, and SST anomalies occur in the upper ocean. The question is: What is the impact of the submesoscale features on the atmosphere?

Problems of LES with one-way coupling with an ocean surface include surface waves and heterogeneous SST. Computational challenges for simulating turbulent winds with LES include:

- Understanding the surface drag: What scales support the wind stress as wind speed varies? Where does the drag come from? What part of the wave spectrum carries the drag? How important are small waves?
- Should we use statistical, measured, or phase-resolved waves?
- How should one couple waves and the atmosphere (nonlinear wave models)?

A very important problem is nonequilibrium: waves propagate from far away, so they are not in equilibrium with local conditions; we might find misaligned winds and waves, and unstable to stable stratification. For coupling, we need to consider heterogeneous SST and currents, finite water depth, the ocean boundary layer, and submesoscale turbulence. To make the problem simpler, we can consider using a flat surface with measured drag.

3.2 Modeling Challenges for Wind Energy

The second session of the morning was devoted to examining broad challenges for the wind energy industry. In this session, Jeffrey Mirocha of Lawrence Livermore National Laboratory presented on the dynamic nature of the atmosphere as captured by MMC, Mark Zagar of Vestas shared a perspective on industry use of high-fidelity modeling, Colleen Kaul of Pacific Northwest National Laboratory (PNNL) reported on model error evaluation, and Vijayant Kumar of Sentient Science discussed using system-level representation to reduce prediction uncertainty.

Dr. Jeffrey Mirocha highlighted several challenges that the MMC project is tackling associated with the project's move to the offshore environment and integration with artificial intelligence (AI). Although the project's WRF setup and downscaling techniques allow simulations to capture mesoscale frontal passages, the *terra incognita* presents challenges for flow entering the computational domain. The project has developed turbulence generation methods for nested domains that address this challenge. The project continues to make progress on improvements to surface layer models, specifically by replacing Monin-Obukhov with explicit canopy methods. Integration of physics-based modeling with AI approaches will improve lower fidelity design codes that are useful to industry. Dr. Mirocha also highlighted an evolution of the program's research direction to new focus areas, including complex terrain and the offshore environment.

Dr. Mark Zagar offered an industry perspective on the use of high-fidelity models with the goal of reducing uncertainty, as well as relating it to the risk of investment. Ideally, the industry would like to predict the energy output of wind plants over timescales of 20 years and be able to predict the size of storage requirements and what hybrid mix would best provide customers the greatest return on investment. Significant uncertainty persists in turbine interactions with the climate system, which presents potential for real microscale modeling to understand these interactions. Zagar explained the importance of uncertainty reduction from the industry perspective: certainty in return on investment leads to lower cost of financing and implicitly lower energy costs. A higher perceived risk for wind compared to solar energy drives up the cost of investment for wind—even though, in principle, solar power is more expensive. Dr. Zagar suggested that the technology needed to achieve reduction of risk includes advances in estimating climate trends (what will wind conditions look like in 20 years?) and data assimilation in the wind farm.

Dr. Colleen Kaul highlighted PNNL work on parameter sensitivities for WRF mesoscale and microscale simulations. This work addresses the question of how uncertainty arises from physical assumptions in the models and how observations can be used to constrain those models, with the goal of making recommendations for field campaign measurements. Dr. Kaul presented results of perturbed parameter ensembles for mesoscale and LES implementations of WRF. The study focused on the Columbia River Basin, which is an important region for wind energy. The main takeaway from Dr. Kaul's presentation was that sensitivity is dominated by a few parameters, which can be related to known flow physics.

Dr. Vijayant Kumar talked about how system-level representations can be used to reduce prediction uncertainty when data are unavailable. Sentient Science is asked to predict the susceptibility of specific components of specific turbines to damage. The company's customers are large wind farm operators who need to be able to trust Sentient's product when they make decisions about whether to send technicians out to find damage. Few data sources needed to provide this information to wind farm operators are actually available. In the absence of data, the company focuses on high-fidelity modeling systems (which are often not validated for real-world conditions), takes all available data, and uses it to deploy simpler, low-fidelity models that are diverse (risk-aware decision-makers use them to check if something is going wrong). Missing data (e.g., no meteorological towers) can also be substituted with other knowledge (e.g., how does the complexity of terrain relate to the risk of loading?). Dr. Kumar stressed that validation is key to making a difference to a real-world wind farm operator and that much work remains to be done to validate both reduced-order models and high-fidelity tools.

3.3 Details of Downscaling

This parallel session featured presentations by Dr. Domingo Muñoz-Esparza from NCAR, Dr. Raj Rai from PNNL, and Dr. Pep Moreno from Vortex FDR. The first two presentations focused on specific technical aspects of downscaling from mesoscale to LES models, whereas the third presentation offered a counterpoint by contrasting the outlooks of modelers and wind resource data end users.

Dr. Domingo Muñoz-Esparza reviewed work on "Turbulence Generation in Coupled Meso-to-Micro Simulations," specifically highlighting results from several of his publications (Muñoz-Esparza et al. 2014, 2015, 2018) on the development and utilization of the cell perturbation method to more rapidly produce realistic turbulence in LES that receive inflow data from coarser resolution models (i.e., mesoscale models) that do not resolve boundary layer turbulence. In broad overview, the cell perturbation method consists of applying stochastic potential temperature perturbations near the inflow region of an LES computational domain and was described as offering advantages over alternative methods in terms of computational performance and generality of application. While many of the results shown in the presentation used WRF coupled to WRF-LES, Dr. Muñoz-Esparza also shared recent results using cell perturbation methods with NCAR's Research Applications Laboratory's GPU LES model, known as FastEddy.

Dr. Raj Rai provided an overview of work (Rai et al. 2019) directed toward bridging the *terra incognita*, a term for the range of horizontal grid resolutions over which both mesoscale and LES modeling assumptions break down. Dr. Rai presented results of downscaling within WRF using various combinations of grid refinement ratios between nested domains, analyzing the simulations in terms of coherent flow structures and turbulence spectra. A key conclusion of the presentation was that the boundary layer depth sets a minimum horizontal grid spacing for mesoscale simulations.

Dr. Pep Moreno offered his perspective on "The Gap between Modelers and End-Users" from his experience as CEO of Vortex, a company that offers modeled wind resource data for industry use. He posited that although modelers are excited by the "how" of advanced simulation techniques and modeling frameworks (citing the example of the Model for Prediction Across Scales), end users of modeled data are concerned only with "what" information is contained within the model's output, with high priority on extensive model validation. Dr. Moreno highlighted Vortex's achievements in providing WRF-LES on a commercial basis and also pointed out that it is essential for end users to have appropriate tools to manipulate and use simulation data for modeling to achieve its full value.

Limited time was available at the end of the session for discussion; however, the meeting chat was used to communicate among panelists and attendees. The chief point of interest was the availability of the cell perturbation method in public releases of WRF. There is not currently such a release, but one might become available in the future. An unofficial release under the MMC project's GitHub fork of WRF is planned. Additionally, the FastEddy code with its version of the cell perturbation method might be made available upon request.

3.4 Modeling for Turbines

The focus of this parallel session was on how the design of turbines and wind farms is impacted by atmospheric flow modeling and how that will evolve as wind turbines and farms evolve in the future. The presenters were Eliot Quon, a research engineer at NREL; Jennifer Newman, vice president of research at REsurety, Inc.; Paul Fleming, senior engineer at the NREL; and Shreyas Ananthan, senior scientist at NREL.

Eliot Quon's presentation, "Mesoscale-to-Microscale Coupling for Loads Analysis," poses the central question: As high-fidelity, turbulence-resolving, microscale simulation with more sophistication toward coupling with the mesoscale weather, along with access to HPC, becomes more readily available, can we improve upon the design-standard turbulence models used for turbine loads analysis? In his presentation, he showed an LES-based MMC method in which he was able to well replicate a day of turbulence-resolving atmospheric flow at the Peetz Table wind farm in northeastern Colorado. The day includes interesting mesoscale-driven events and shear-driven turbulent bursts that the LES well captures. He then takes sampled flow data and uses it as input to aeroelastic simulations. Dr. Quon plans to compare the aeroelastic response using this LES-generated inflow with design-standard turbulence model input to quantify the differences. If there are significant differences, this opens a research area in how to use computationally expensive, sophisticated, site-specific inflow generation tools to either generate libraries of data or to enhance the computationally light inflow generation tools that industry can easily use in a more site-specific way.

Jennifer Newman's presentation, "Industry Needs for Wind Flow and Wake Modeling," covered flow modeling needs mainly directed at wind resource assessment, forecasting, and annual energy production estimation. She emphasized that there is a need for P50 energy yield estimation that also considers diurnal and seasonal variability, which highlights the need for improved site-specific flow modeling that accounts for thermal stratification. Key wind flow and wake modeling challenges she highlighted are: 1) the fact that under certain conditions, simple linear flow models still outperform high-fidelity CFD; 2) wind plant blockage is difficult to both model and quantify; and 3) incorporating thermal stratification effects into wind flow and wake models is difficult without using a time-series approach. Dr. Newman elaborated on the "time-series" versus "matrix" approaches. The matrix approach bins performance by wind speed and direction, and then it convolves that information with the wind speed/direction probability distribution to estimate annual energy production. The time-series approach is more expensive and relies on mesoscale weather model data extracted over a long time period, such as a year, to estimate annual energy production. She poses the question: Is there some method that lies between the matrix and time-series approaches? Dr. Newman ended her talk with the following questions for consideration: 1) Are there specific regions/types of terrain where numerical weather prediction (NWP)/CFD approaches struggle? 2) Is there a way to accurately estimate blockage effects without taking a full CFD approach? And 3) Is a full time-series approach necessary for accurately modeling diurnal variation in plant production? This talk provided a great industry perspective toward flow modeling and presented the questions industry sees as important to answer in the near future.

Paul Fleming's presentation, "Modeling for Controls," addressed the wind turbine/wind plant controls community's needs for atmospheric flow modeling. A key point that he made is that wind turbine wake models used for controls are now becoming sophisticated enough that we can no longer give simply the hub-height wind speed and some measure of turbulence. Instead, quantities such as shear and veer are now necessary, because they have important implications for wake evolution and how wind plant control systems must respond. Dr. Fleming also stressed the point that controls-oriented wake models must be computationally fast, especially if used within an actual control system; therefore, one must choose to include only the atmospheric physics that has the greatest impact on wind plant flows. He also pointed out that capturing flow spatial heterogeneity and temporal dynamics is now recognized as very important to wind plant controls. Until now, the controls community has been applying more idealized homogeneous flow conditions (e.g., through canonical atmospheric LES) to simulate new controls ideas, but there is growing need to understand how such control systems behave in more realistic conditions as industry adopts these advanced controls ideas and is actually marketing them as new products. Further, real-world validation data from wind farms, which is becoming more readily available and can be used to predict wind plant control behavior, is filled with spatial heterogeneity and temporal dynamics.

Last, Shreyas Ananthan presented on the "Need for Accurate Inflow Characterization in Aerodynamic Design of Wind Turbines," the central theme of which was that modern wind turbine blades operate in a flow environment with large portions of the blade undergoing major unsteady aerodynamic effects. This is highly influenced by the turbulence within the atmosphere, and that turbulence could be very site-, time-, and season-specific. Industry still relies on 1980s blade aerodynamics models even though today's blades are very different than they were four decades ago. The inputs for turbulence have not changed, but there are likely better ways to input turbulence quantities. High-fidelity blade-resolving CFD can naturally capture blade unsteady aerodynamics effects, but such techniques are very expensive and can rarely be justified for design purposes. He advocates for the use of ML-based models for blade unsteady aerodynamics effects, and he shows that such methods hold great promise. He also advocates for providing an ensemble of different atmospheric inputs to account for inflow uncertainty and then basing designs on the range of outcomes rather than basing designs on one single atmospheric condition. That ensemble of atmospheric inputs could be site-specific and rely on flow modeling techniques pursued by the MMC team.

3.5 Using AI in Atmospheric Modeling

The third parallel session dealt with ML/AI technical details. Three presentations were given in which ML techniques were applied in different stages of the atmospheric modeling process. The first presentation was titled "Better ML Models of the Surface Layer," given by David John Gagne from NCAR. This presentation focused on work to devise a new surface layer scheme through ML to potentially replace the prominent Monin-Obukhov similarity theory (MOST), which was semiempirically derived. The new surface layer parameterization was built using long time series of surface observations and flux data. Inputs into the ML model do not include any MOST inputs in an attempt to develop a solution that is entirely independent of MOST. This new surface layer scheme was incorporated into the WRF model with some success; however, issues with nonphysical fluctuations and interactions between the surface layer, land surface model, and planetary boundary layer parameterizations still need to be addressed. Through this research, it is clear that investment in ML training and software infrastructure for tighter integration of ML into modeling systems across scales is paramount.

The second presentation, “Downscaling with Deep Learning,” was given by Ryan King from NREL. This work uses generative adversarial network models and super resolution to enhance the spatial and/or temporal resolution of climate (coarse) model output to mesoscale (fine) output. This technique has vast applications from numerical coupling across scales to inflow generation for wake or wind turbine modeling. Further, the developed architectures are not scale-specific (i.e., they can be applied anywhere across the spectrum). The training data, on the other hand, are scale-specific; thus, new training data will be needed for applications at different scales. This approach displays the potential for physics-informed learning techniques that explicitly or implicitly inject known physical relationships (e.g., partial differential equations, conservation laws, symmetries) into the training process or model architecture, which can effectively speed up the training process and/or improve the quality of outputs. Additionally, adversarial training techniques, such as those used in this research, appear to be an effective way to train ML models for wind energy applications. For more information on the work of Ryan King and his colleagues, the reader is referred to Stengel et al., 2020.

The final presentation, “Improving Forecasts with ML,” was given by Daniel Kirk-Davidoff from UL/AWS Truepower. In this work, ML techniques are used to improve probabilistic forecasting, especially within the tails of the probability distribution. Through this research, ML has been shown to allow for significant improvements in post-processing NWP model output for renewable energy and load forecasting; however, large amounts of training data from these models is critical and not always available. Thus, the need for long temporal coverage of model data for training should weigh on forecasting centers when they consider how much time to invest in generating reforecasts when the model systems are updated. Significant changes in the NWP models (especially changes in grid structure and specified variable outputs) mean that training the ML post-processing must start over to generate forecasts using NWP plus post-processing. This underscores the importance of forecasting centers producing ample amounts of reforecast data (two years or more is ideal) and making it available as soon as the new models come online.

The discussion that followed the presentations focused on the question, “How else can ML best be used?” It was mentioned that several groups are already working on ML applications for data assimilation and post-processing but might still be in the early stages. The development of surrogate models from high-fidelity models through ML techniques could be promising for use in low-fidelity models. To do this, the typical outputs of high-fidelity models would need to cater to the demands of ML techniques. The need for quality training data was highlighted several times for all applications and was a recurring theme in any discussion about ML in atmospheric modeling.

From here, the discussion shifted toward how industry and academic trust in ML techniques can be increased. It was noted that while ML/AI techniques are on the cutting edge, clients still need to be convinced that the results will be cost beneficial. Up front, the use of these techniques could be positive; however, there is still a lack of general knowledge about the differences between methods because this is so new. When showing the benefits of ML, it is often difficult to define the exact improvements due to the case-dependent nature of some applications. For example, in some instances, ML can improve on generating the correct statistics of a time series (i.e., mean, variance) but not show improvement on generating the exact time series. To answer the question of “Which is more important: the statistics or the time-series?” is on a case-to-case basis. Additionally, it is difficult to define how “similar” is “similar enough.” If techniques do not significantly reduce the error, it is difficult to build this trust at this time. Knowledge transfer and the definition of an understandable metric will be important in increasing industry and academic trust in ML techniques and applications.

4.0 Summary and Synthesis

As described, the presentations and conversations at the industry workshop were robust and productive. The combination of prepared talks, panel discussions, guided breakout discussions, and topical presentations and discussions in breakout rooms provided insight into both the state of the science of atmospheric research for the wind industry and into what is needed by industry to advance further.

4.1 What We Heard as Needed for Industry

One way that the workshop solicited feedback from the community was through guided discussion around several preplanned topics. The specific questions and some bulleted responses are summarized here based on the discussions documented in more detail in Section 2.3.

1. To what extent does industry require high-fidelity solutions rather than lower order approaches?
   - High fidelity is needed for loads and damage models.
   - High fidelity is not feasible for short-term applications due to computational cost and time to solution.
   - High fidelity is needed to feed into low-order models and ML applications.
   - Data volume from high-fidelity models is excessive, and managing that data is challenging—both for the provider and for the end user.
   - Summary: Both high fidelity and low order are useful for specific needs.
2. What are the likely HPC platforms for the future (owned versus cloud)? Are you considering next-generation accelerators (such as GPUs)?
   - GPUs improve both simulation speed and energy requirements.
   - Codes need to be GPU-compatible, and not all current codes are (e.g., WRF).
   - The high cost of HPC is prohibitive for industry.
   - Cloud resources are not always a good fit due to the need for large storage—data egress is expensive on cloud services.
   - But cloud resources do provide flexibility, and some users are migrating in that direction.
   - There is a possibility to combine high-fidelity solutions with stochastic and ML approaches.
3. What atmospheric processes are most important yet challenging to model?
   - A variety of processes were mentioned, and there was discussion in the breakouts, including:
     - The combined effect of wakes and wind farm blockage.
     - The difficulty posed by complex terrain, and the reverse cascade from microscale to mesoscale might be important but is seldom modeled.
     - Shallow boundary layers during stable conditions, which make an impact on the wind turbine rotor layer.

    - Extreme events both onshore and offshore. The United States displays more of such events (e.g., tropical cyclones, derechos) than some other places in the world.
    - Low-level jets and sea breeze processes and their diurnal variations.
    - Entrainment processes, which require models reaching higher into the atmosphere than typically used for microscale modeling.
    - Modeling ramp-ups and ramp-downs accurately is important for grid integration.
    - Modeling for hybrid plants that include a combination of wind, solar, and storage.
  - Industry is interested in power production rather than the raw information on meteorological phenomena and conditions.
  - More offshore observations, including vertical profile information, is needed to improve and validate the models.
  - Downscaling with ML might be promising.
  - Quantifying the uncertainty is highly useful and helps to understand the limitations of probabilistic prediction.

4. What are the unique challenges for offshore deployment and operation?
   - Understanding wake effects and wind farm blockage is critical. Although these are based on the same atmosphere-farm interaction process, they are seldom modeled holistically.
   - The shallow (stable) boundary layer is a critical operating environment, but it not yet modeled well.
   - There are insufficient offshore wind observations for both improving and validating models, as well as for training ML models.
   - Wind-wave coupling is important but not fully understood.
5. To what extent might MMC methods be applied to enable greater confidence in promoting innovative design and deployments?
   - MMC can provide the impact of a large scale on a smaller scale.
   - Industry understands usefulness in terms of value added, such as reducing the LCOE.
   - To be useful for industry, they must have confidence that it is well validated and that uncertainty in initial and boundary conditions is quantified.
   - One might not need the high resolution over the entire domain but rather use for targeted areas to reduce computational cost.
   - Could MMC be used more for planning and integrating hybrid wind, solar, storage plants?
6. What are the challenges of wind plant interactions?
   - Current tools to model interactions are not yet adequate.
   - Wakes from the differing scales (turbines versus farms) merge and should be modeled together.
   - Interactions between farms could be particularly important during stable conditions, which are prevalent off the northeast coast of the United States but can be important for very long distances.

- Observational data are important but limited, and users do not understand the limitations of the instrumentation.
- There could be legal challenges to building farms upstream of existing farms.
- Developers will consider the interactions when the tools are improved and the linkage to financing becomes clear.

7. How do you see ML impacting your industry's modeling tools?
   - Machine learning is necessary for bias correction in power forecasting and in building surrogate models.
   - There is a requirement for a large amount of observations to build the models. This should be considered when planning field campaigns to define the variables needed and their rate of measurement.
   - ML must be more than a black box but rather combine first-principle models and physics and use ML to assist. Interpretable methods could take this in the right direction.
8. For offshore deployment, how do you gauge the importance of coupling to ocean and wave models?
   - It is clear that waves and ocean circulations influence the wind field beyond hub height. This should be reflected in models.
   - It requires full coupling, but it might be too expensive to use in practice. Industry is interested in the governing economics. Is it possible to quantify the value of the impact?
   - Data are needed to validate the codes. It is hard to gather such data. Industry will accept experimental data, but that could then influence model development and validations.
   - This will become increasingly important for floating turbines.

Additional points were made during panel discussions and in the parallel breakouts on the second day. Some of these points include the following:

- Industry notes that their decisions are based on financial constraints. Some important considerations when showing the value of improved modeling are related to LCOE, return on investment, and annual energy production.
- Industry is anxious to obtain validated codes that are documented and ready to use. One example is the stochastic cell perturbation implementation in WRF.
- Lack of data implies uncertainty. One example is in predicting component damage due to atmospheric conditions. Code improvements to minimize and quantify that uncertainty would be helpful.
- Real data from within wind farms would be helpful to advance understanding of physical processes and producing more accurate models.
- Probabilistic forecasts of power out are needed for grid integration. This would also be useful for hybrid wind, solar, and storage plants.
- For wind farm control, models need to capture the spatial heterogeneity and temporal dynamics to provide more realistic conditions. This requires MMC.

- For wind plant design, it would be helpful to have an ensemble of potential atmospheric inputs for estimating flow uncertainty and to feed each ensemble member into a design code to estimate a range of outcomes. This could be site-specific.
- Industry also requires information on expected impact of a changing climate on the wind resource and its geographic and temporal variability.

4.2 Archival of Talks

The PDFs from the talks from this workshop are archived online at https://ral.ucar.edu/events/2020/atmospheric-challenges-for-the-wind-energy-industry-workshop. In addition, some of the presentations were recorded and are also available at the same website.

4.3 Implications for Future Research

The results of this workshop are being discussed within the MMC team and WETO management. This report will be archived as a formal report so that it can be referred to when planning future research initiatives and directions. The MMC team will actively seek to use the recommendations from this report to influence the team’s research. We look forward to continuing to engage with the community and to maintaining a long-standing dialog.

5.0 References

Ahsbahs, T., G. Maclaurin, C. Draxl, C. R. Jackson, F. Monaldo, M. and Badger, 2020: US East Coast Synthetic Aperture Radar Wind Atlas for Offshore Wind Energy, *Wind Energy Science*, **5,** 1191–1210, doi:10.5194/wes-5-1191-2020.

Hasager, C. B., M. Badger, N. Nawri, B. R. Furevik, G. N. Petersen, H. Björnsson, and N.-E. Clausen, 2015: Mapping Offshore Winds Around Iceland Using Satellite Synthetic Aperture Radar and Mesoscale Model Simulations. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, doi: 10.1109/JSTARS.2015.2443981.

Hasager et al. 2020: Europe's Offshore Wind Resource Assessed with Synthetic Aperture Radar, ASCAT and WRF, *Wind Energy Science*, **5**, 375–390, doi: 10.5194/wes-5-375-2020.

Larsén, X. G., P. Volker, M. Imberger, J. Fischereit, E. Langor, A. Hahmann, T. Ahsbahs, M. Duin, S. Ott, P. Sørensen, M. Koivisto, P. Maule, S. Hawkins, A. Kishore, and J. Du, 2019: Calculation of Wakes from Offshore Wind Farm Cluster and the Introduction to the Danish Power Integration System. *WindEurope Offshore 2019*, Copenhagen.

Larsén, X., Du, J., Bolanos, R., Badger, M., Kelly, M., and Larsen, S., 2019b: Estimation of Offshore Extreme Wind from Wind-Wave Coupled Modeling, *Wind Energy*, **22**, 1043-1057, doi: 10.1002/we.2339.

Muñoz-Esparza, D., B. Kosović, J. Mirocha, and J. van Beeck, 2014: Bridging the Transition from Mesoscale to Microscale Turbulence in Numerical Weather Prediction Models. *Boundary-Layer Meteorology* 153, 409–440, doi: 10.1007/s10546-014-9956-9.

Muñoz-Esparza, D., B. Kosović, J. van Beeck, and J. Mirocha, 2015: A Stochastic Perturbation Method to Generate Inflow Turbulence in Large Eddy Simulation Models: Application to Neutrally Stratified Atmospheric Boundary Layers. *Physics of Fluids* **27**, 035102, doi: 10.1063/1.4913572.

Muñoz-Esparza, D., and B. Kosović, 2018: Generation of Inflow Turbulence in Large-Eddy Simulations of Nonneutral Atmospheric Boundary Layers with the Cell Perturbation Method. *Monthly Weather Review*, **146**, 1889–1909, doi: 10.1175/MWR-D-18-0077.1.

Rai, R. K., L. K. Berg, B. Kosović, S. E. Haupt, J. D. Mirocha, B. L. Ennis, and C. Draxl, 2019: Evaluation of the Impact of Horizontal Grid Spacing in Terra Incognita on Coupled Mesoscale–Microscale Simulations Using the WRF Framework. *Monthly Weather Review,* **147**, 1007–1027, doi: 10.1175/MWR-D-18-0282.1.

Stengel, K., A. Glaws, D. Hettinger, and R. N. King, 2020: Adversarial super-resolution of climatological wind and solar data. *Proceedings of the National Academy of Sciences,* **117**(29), 16805-16815, doi: 10.1073/pnas.1918964117.

Wind Europe, 2019: https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Our-Energy-Our-Future.pdf.

Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354
1-888-375-PNNL (7665)

www.pnnl.gov