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Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Wind Systems Integration Workshop

Wind Energy Technologies Office Wind

Workshop Summary Report

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Preparation and Authorship

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Cover image: Photo artwork of sunset view of electrical power towers overlaid with wind turbines (photos by Warren Gretz / NREL; photo illustration by Raymond David / NREL).

Acronyms

AC	alternating current
ARIES	Advanced Research on Integrated Energy Systems
CAISO	California Independent System Operator
DC	direct current
DER	distributed energy resource
DOE	U.S. Department of Energy
FERC	Federal Energy Regulatory Commission
HVDC	high-voltage DC
IEEE	Institute of Electrical and Electronics Engineers
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
PV	photovoltaics
U.S.	United States
WETO	Wind Energy Technologies Office

Executive Summary

The U.S. Department of Energy's Wind Energy Technologies Office (WETO) Wind Systems Integration Workshop had several objectives. These included facilitating an exchange of information, soliciting feedback to inform WETO's near- to mid-term research priorities, and working to accelerate near-term rapid deployment and integration of wind technologies at both the transmission and distribution levels

Through increased awareness and understanding of existing and planned stakeholder efforts and needs, WETO can prioritize research areas that will support and not duplicate stakeholder efforts to do the following:

- Incorporate energy equity principles and the Justice40 Initiative into wind integration research.
- Enhance and deliver grid services to increase value streams and improve system reliability.
- Improve system modeling and decision-support tools to inform integration processes.
- Advance power electronics to lower cost, increase reliability, and improve grid operations.
- Address the emerging physical grid infrastructure challenges related to the integration of higher contributions of weather-based energy resources.
- Improve coordination of the transmission system with increasingly active distribution networks.

Workshop participants identified the following key research challenges and opportunities:

Grid services, power electronics, and decision-support tools are important overlapping research opportunities. Power electronics and associated controls enable provision of grid services from wind. For modeling and decision-support tools to be useful for control design, performance analysis, planning, and system operations, they need to represent power electronics and grid services.

New transmission and coordinated grid planning can facilitate increased wind integration. Increased transmission is one important enabler for integrating large amounts of wind energy. Coordinating transmission planning more broadly and including distribution networks and distributed energy resources could also be a significant enabler.

Energy equity principles can be incorporated into wind integration research. Some energy equity research opportunities include understanding the equitable allocation of wind integration costs and benefits with respect to energy burden and accounting for wind system social values (e.g., emissions reduction, job creation, wealth creation, and energy cost reduction) in wind energy valuation and modeling.

Grid services needs are evolving. As inverter-based resources displace synchronous machines, some grid services will remain the same, some will increase or decrease in magnitude, and some new services will be introduced. Power electronics are key to enabling provision of grid services through wind. Scenario modeling can help understand future needs and requirements.

Enhanced decision-support tools are needed. Key research priorities are the standardization of models, libraries, and analyses; development of models that account for physics, fast dynamics, and all control loops; and the improvement of decision-support tools for operators and planners.

Power electronics are needed to support power delivery and performance and cost reduction. Power electronics are needed for all types and scales of wind generation (i.e., land-based, offshore, and distributed). Design can be enhanced to improve performance and reduce cost.

Opportunities exist for better coordination between transmission and distribution systems. Opportunities include developing integrated modeling capabilities and planning tools, balancing transmission and distribution capacity expansion, and enabling increased visibility into distributed energy resources for transmission operators.

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1 Introduction

The Energy Act of 2020 authorizes the U.S. Department of Energy's (DOE's) Wind Energy Technologies Office (WETO) to conduct research that integrates wind energy technologies with "the electric grid, including transmission, distribution, microgrids, and distributed energy systems; and other energy technologies, including other generation sources; demand response technologies; and energy storage technologies" (Sec. 3003.b.2.B.v). In addition, WETO's research will play a role in DOE's efforts in achieving the Biden administration's objectives of tackling the climate crisis at home and abroad, transforming the electric grid to be more resilient and able to support increased amounts of clean energy technologies, and implementing the Justice40 Initiative.

To inform this research, the Wind Systems Integration Workshop convened over 120 participants and guest speakers from the organizations listed in Table 1 over three 3-hour workshop sessions. National laboratory and DOE guest speakers included Alejandro Moreno (DOE), Bob Marlay (WETO), Maggie Yancey (WETO), Bethel Tarekegne (Pacific Northwest National Laboratory [PNNL]), Henry Huang (PNNL), Jason Fuller (PNNL), and Dave Corbus (National Renewable Energy Laboratory [NREL]). Industry guest speakers included Charlie Smith (Energy Systems Integration Group), Ryan Quint (North American Electric Reliability Corporation [NERC]), Julia Matevosyan (Electric Reliability Council of Texas), and Debrup Das (Hitachi ABB).

Guest speakers provided thought leadership and context on the workshop topics to seed discussions. Workshop participants were asked for feedback based on their own expertise and experience. The findings presented in this report do not represent consensus findings on the part of participants but rather recurring themes from the individual feedback provided during the workshop, as summarized by the authors.

This report summarizes the proceedings; key themes; and research, development, and deployment acceleration challenges and opportunities identified by workshop participants. Appendix A provides the workshop agenda.

Table 1. Workshop Participant Organizations

Participant Type	Participants
U.S. Government	Department of Agriculture, Rural Utilities Service Department of Defense Naval Facilities Engineering & Expeditionary Warfare Center Department of Energy Wind Energy Technologies Office Department of Energy Solar Energy Technologies Office Department of Energy Office of Electricity Department of Energy Advanced Manufacturing Office Department of the Interior Bureau of Ocean Energy Management
DOE National Laboratories	Brookhaven National Laboratory Idaho National Laboratory Lawrence Berkeley National Laboratory National Renewable Energy Laboratory Oak Ridge National Laboratory Pacific Northwest National Laboratory Sandia National Laboratories
Institutions and Associations	Electric Power Research Institute Energy Systems Integration Group Institute of Electrical and Electronics Engineers (IEEE) North American Electric Reliability Corporation National Rural Electric Cooperative Association
Independent System Operators	California Independent System Operator (CAISO) Electric Reliability Council of Texas Independent System Operator New England Midcontinent Independent System Operator New York Independent System Operator PJM Southwest Power Pool
Consultants	Alison Silverstein Consultants Centrica Business Solutions EnerNex
Universities	Clemson University Illinois Institute of Technology University of Illinois at Chicago University of Southern Florida University of Texas at Austin University of Washington Virginia Polytechnic Institute and State University
Utilities/Electric Cooperatives/Power Providers	Bonneville Power Administration East Kentucky Power Cooperative Iowa Lakes Electric Cooperative Mountrail Williams Cooperative National Grid New York Power Authority Nodak Electric Cooperative, Inc. San Isabel Electric Association Umatilla Electric Cooperative
Original Equipment Manufacturers	Bergey WindPower Co. General Electric Hitachi ABB Intergrid Prysmian Syndem LLC Vestas Windurance
Wind Owners and Operators	Foundation Windpower Invenergy Juhl Energy

2 Key Workshop Findings

The intent of the workshop was to identify research challenges and opportunities associated with increased and rapid deployment of wind technologies and their integration into the bulk transmission and distribution systems. However, workshop participants recognized the need for a holistic, technology-neutral research approach, as the grid of the future will have increased amounts of inverter-based resources, not just wind.

In addition, workshop participants recognized the tension between addressing the challenges of today while preparing for the future. The U.S. power system was designed around the use of synchronous machines that provide fault current for system protection and other grid services to balance load and maintain reliability. There are research challenges and opportunities both to support the transition for the long term and to deal with the current system in the short term.

Key research challenges and opportunities identified during the workshop are summarized below.

Overarching Themes

Significant amounts of wind and solar energy are being adding to grid systems, and deployment is expected to continue and accelerate. Increased transmission development is one important option as a means to integrate renewable energy. Coordinated and proactive planning for transmission has the potential to expedite the transmission build out needed for large-scale renewable integration at a lower cost than siloed and reactive planning. Expanded use of distributed energy resources (DERs) may also be an important means of meeting clean energy goals and increasing resilience.

Load- and generation-forecasting improvements will support wind deployment and the ability of wind to provide grid services. Market designs, price signals, and other compensation strategies are needed for high renewable energy grid scenarios. The availability and stability of tax credits and loan programs also strongly affect wind deployment; this is particularly true for distributed wind for which benefits such as capacity and resilience contributions have not been fully monetized.

Throughout the workshop, participants noted the overlapping research needs associated with grid services, power electronics, and decision-support tools. Power electronics and associated controls enable provision of grid services from wind. Decision-support and modeling tools need to accurately represent grid services required by, and achieved through, power electronics for control design, performance analysis, planning, and system operations.

Energy Equity

The following key areas of interest were identified with respect to incorporating energy equity principles into wind integration research:

- Understanding the costs and savings (or benefits) of wind integration in light of energy burden.
- Accounting for wind system social values (e.g., emissions reduction, job creation, wealth creation, and energy cost reduction) in wind energy valuation and modeling.

In addition, workshop participants recognized opportunities to address workforce diversity, equity, and inclusion in the wind energy industry through hiring and educational processes. Suggestions included hiring in low-income areas and offering educational and research partnerships with minority-serving institutions.

Grid Services

System operators participating in the workshop indicated that they are still working to understand the types of grid services needed with increasing amounts of inverter-based resources and which grid services original equipment manufacturers could focus on providing. Modeling and large-scale demonstrations are needed to understand controls for entire wind plants, across regions, and for hybrid systems. This will allow wind plant operators and system operators to evaluate the grid services they could provide along with risks and uncertainties. Additional topics of interest included the following:

- Understanding the role power electronics play in providing or supporting grid services.
- Understanding how grid services will affect the dynamic response and characteristics of power converters and control loop requirements.
- Forecasting at different timescales to understand the need for operating reserves.
- Understanding how active distribution networks can be optimized to support transmission operations.

Workshop participants recognized that, while the performance requirements associated with grid services need to be standardized, performance-based, technology-neutral, and compensated, the types of grid services needed and the value of services may change over time, especially as wind contributions to grid systems increase.

Modeling and Decision-Support Tools

Modeling and decision-support tools research opportunities have overlap with the other topics, particularly grid services (i.e., modeling and simulations are needed to demonstrate the value of grid services). One key theme that gained traction with participants was the idea of not adding unnecessary complexity to modeling and decision-support tools. Instead, stakeholders can focus on creating simpler, more elegant solutions that are easier to explain and that improve our understanding of when to use existing tools, so that new tools are only created when appropriate. Workshop participants also identified the following key research priorities:

- Improving access to datasets.
- Standardizing models, libraries, and analyses.
- Developing models that account for physics, fast dynamics, phasor domain, and all control loops (not just static behavior).
- Developing models for wind hybrid systems.
- Incorporating risk and uncertainty within models.

Other recognized priorities include improving decision-support tools for operators and planners, particularly for the distribution level. Tool improvements are needed to capture resilience benefits to incorporate in long-term planning and to conduct high-fidelity, high-speed simulations of transient behavior.

Power Electronics

Workshop participants identified the need for power electronics that can support power delivery for all types and scales of wind generation (i.e., land-based, offshore, and distributed) as a primary research gap. Workshop participants also noted that the design of power electronics can be enhanced to improve performance and reduce cost of wind and other inverter-based resources. The opportunities and challenges of standardization, certification, and cybersecurity of power electronics were key issues discussed. Another research area identified was the need to take a holistic approach and consider the cumulative implications of electronically coupled loads and different types of inverter-coupled supply and, starting with fundamental grid dynamics, develop a control architecture to accommodate diverse power electronics.

Transmission and Distribution Coordination

In discussing how transmission and distribution systems could be better coordinated, workshop participants explored the question of whether or not transmission and distribution systems were working together to support each other or unknowingly working against each other by incentivizing different aspects. Historically, the distribution system has had a more passive role in the overall operation of the bulk transmission system, but increasing amounts of controllable and flexible DERs could enable a more active and bidirectional relationship between transmission and distribution systems. Workshop participants discussed both the benefits and challenges of high contributions of DERs and the potential benefits of co-located, distributed wind, solar, and storage assets for resilience at the community level. Finally, participants noted the need to better integrate transmission and distribution modeling capabilities, in particular expansion planning models.

3 Overarching Research Challenges and Opportunities

A context-setting presentation about the grid of the future and how to achieve higher amounts of renewable integration included the ideas that significantly more wind and solar are needed to meet clean energy targets, and increased amounts of transmission capacity is an important option to consider for achieving increased renewable integration. In order to meet the Biden administration's 100% clean energy goals, some estimate that the United States may need 1 TW or more of new wind and solar capacity, which is about five times the current wind and solar capacity. Decarbonizing the entire U.S. economy (including transportation and electrification of industrial loads) may require twice that.

However, currently the United States does not have the transmission required to connect significant amounts of new renewable resources to load. Research suggests that national transmission expansion is a cost-effective enabler of electricity system decarbonization, although it has construction, cost allocation, and permitting challenges (Brown and Botterud 2020). To address those issues, a proactive, rather than reactive, national transmission planning process has the potential to expedite the transmission build out needed for large-scale renewable integration. Rather than building one-off transmission segments to interconnect individual projects, proactive, interregional transmission projects could connect large quantities of renewable energy, including offshore wind. Transmission would not just deliver resources to load, it could also provide resource adequacy (i.e., can reduce necessary planning reserve margins and associated costs), system balancing, and dynamic stability. DERs may also be an important part of the solution. A clearer understanding is needed of the balance between transmission and distribution capacity expansion.

After the presentation, workshop participants brainstormed overarching and crosscutting challenges and opportunities to increase and accelerate wind deployment. Key points from this discussion are summarized below:

Develop grid-forming inverter technologies. Grid-forming inverter technologies are needed to provide reference frequency, system strength, and control capability. This point is addressed further in the power electronics section of the report.

Make forecasting improvements. Widely available load- and generation-forecasting improvements, enabled by data access and transparency, will support accelerated wind deployment and the ability of wind to provide grid services.

Address workforce needs. A new, diverse generation of professionals with the skills needed to operate and plan the grids of the future with high contributions of renewable energy is needed. These skills include training and certifying workers to perform high-voltage, 'up-tower' maintenance on existing wind turbines. Another specific need is for workers who can develop and operate transient models and understand and model advanced power electronics.

Develop new, or improve, modeling and assessment tools. Develop integrated transmission and distribution planning tools and models. Strengthen and develop resource adequacy tools and methods that can characterize the capacity contribution of wind. Develop and improve real-time stability assessment tools. Address the challenges of modeling controls with proprietary vendor models. Use machine learning and digital twins to support operations and planning. These issues are addressed further in the modeling tools section of this report.

Improve understanding of wind grid services. Wind is no longer just an energy product. Industry needs to understand the changing requirements for grid services with increased amounts of variable generation, how to access all capabilities of wind to provide needed grid services, and how to value those grid services. This is addressed further in the grid services section of this report.

Improve understanding of protection services. A review and modification of existing short-circuit programs and legacy protection for transmission and distribution systems with high contributions from inverter-based resources would be beneficial. This is addressed further in the modeling section of this report.

Address markets, price signals. and economics. Market designs, price signals, and other compensation strategies that are based on the value provided are needed for high renewable energy grid scenarios. The availability and stability of tax credits and loan programs also strongly affect wind deployment; this is particularly true for distributed wind.

Address manufacturing issues. Address manufacturing limitations and bottlenecks. Address issues of standardization versus innovation and at what level it is appropriate for each to occur. Support availability and access to off-the-shelf inverters, converters, and power electronics.

Develop standards. Develop interconnection standards with specific performance requirements and standardized analyses and techniques to evaluate the impact of inverter-based resources on grid operations and stability.

Advance wind hybrid and paired systems. Enable and advance wind hybrids at all scales, including wind plus storage deployments and wind plus flexible demand. Enable dispatchable and flexible wind-generating plants. Address how wind and other DERs work together, including controls and protection.

4 Energy Equity Challenges and Opportunities

Workshop participants discussed energy equity and Justice40 (see the Energy Equity Definitions[1] text box) during designated sessions and throughout the workshop. There's a strong interest in considering equity in wind energy integration practices, but more work is needed to enhance the understanding of energy equity in the wind energy research and practitioner community and the role

[1] Definitions are taken from the Initiative for Energy Justice: https://iejusa.org/section-1-defining-energy-justice/#section1_1.

of wind energy in advancing equity. Participants brainstormed ideas to advance energy equity through the approaches of program and service delivery, decision-making, and organizational practices. The organizational practices method was the easiest concept for attendees to understand, as this includes workforce development, hiring practices, and incorporating diversity, equity, and inclusion practices into a business.

The following are specific energy equity research challenges and opportunities identified during the workshop.

Pursue workforce development initiatives. Opportunities exist to address workforce diversity, equity, and inclusion at the institutional or process level by building resources and creating a path for equitable access for all to participate in the wind energy industry. There was a specific example raised about the need for a new generation of engineers and skilled workers that are trained to operate the 100% clean energy grid, especially a workforce for high- and medium-voltage direct current (DC) systems and ensuring targeted inclusion of those historically underrepresented in the talent pipeline. The wind industry can examine hiring and educational processes to ensure wind energy follows equitable practices through hiring in low-income areas, procuring from minority-owned businesses, and offering educational partnerships with minority-serving institutions.

Understand costs and savings in light of energy burden. Energy burden is a key metric of energy equity. As wind energy potentially enhances delivery of grid services and increases value streams, the underlying cost effects of these services need to be equitably allocated to manage tradeoffs between services provided and energy burden on customers. Capturing the distributed cost effects across different segments of society allows for better planning on how to distribute wind integration benefits and burdens more equitably. A similar discussion point raised was on power electronics and equity in billing structures, mainly in relation to harmonization between smart meters and grid systems to allow utilities to lower costs to ratepayers and plan for targeted equity measures.

Account for wind system social values (e.g., emissions reduction, job creation, wealth creation, and energy cost reduction) in wind energy valuation exercises. This research area would entail examining the potential conflicts or tradeoffs in emerging grid and community values. This research area would also include developing modeling and simulation capabilities to better understand the societal

Energy Equity Definitions

Energy Equity (also referred to as Energy Justice): The goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those historically harmed by the energy system ("frontline communities").

Energy Burden: The percentage of gross household income spent on energy cost. Six percent is considered a high burden and 10% a severe energy burden.

Just Transition: A transition away from the fossil-fuel economy to a new economy that provides dignified, productive, and ecologically sustainable livelihoods; democratic governance; and ecological resilience.

Justice40 Initiative: Biden administration’s Executive Order 14008 established the Justice40 Initiative with the goal that 40% of the overall benefits of certain federal investments—including investments in clean energy and energy efficiency, clean transit, affordable and sustainable housing, training and workforce development, the remediation and reduction of legacy pollution, and the development of clean water infrastructure—must flow to disadvantaged communities.

impacts of wind energy in respect to cultural, human health and well-being, and local economic and fiscal impacts.

Address equity in access to technology. Electrification, smart buildings, and increasing DERs introduce many new participants with smaller resources or devices. Right now, it is cost-prohibitive to put meters on small devices. If the right hardware and incentives were available to participate in programs, it could provide benefits to the grid and help alleviate supply and demand issues. Power electronics may be able to help address current limitations and allow more people to participate in programs, either generation or demand response.

Address equity in resource siting. Another key point raised was the issue of siting, which is critical for pursuing a just energy transition. Energy communities that have historically hosted fossil fuel power plants need post-decommissioning replacement options that can compensate for the economic and cultural losses, mainly through revenue generation, local economic stimulation, and job creation. The locational value of wind energy needs to balance resource and cost-efficiency with community-centered equitable outcomes. At the same time, as new transmission systems and corridors are considered to enable higher levels of onshore and offshore renewable energy, care must be taken to ensure that traditionally disadvantaged communities do not disproportionately bear the burden of new transmission siting. Opportunities in rural windy areas for distributed wind and distributed wind hybrids may help lessen the need for new transmission siting.

Other research suggestions include addressing the following questions:

- What are the long-term economic impacts of wind energy to rural communities?
- While still considering parcel sizes and types that are appropriate for distributed wind development, can distributed wind be deployed on smaller pieces of land?
- What business models allow for lower cost of distributed wind energy for easy and affordable access to community renewable projects?
- What hybrid technology configuration and locations yield the greatest long-term emissions benefit reduction?
- How can decision-makers navigate economic and human health tradeoffs?
- What is the life-cycle value of wind energy compared to fossil fuel plants?

5 Grid Services Challenges and Opportunities

Grid operators manage reliability and electricity supply and demand on the electric system by providing a range of grid services (see Grid Services text box). Workshop participants acknowledged that the grid services available today have been defined and designed for a grid based on synchronous machines. However, the characteristics of the grid, and thus the associated grid services needed, are changing. Some, but not all, necessary services are currently included as market products. Inverter-based resources can provide grid services, but their characteristics are fundamentally different from synchronous machines. As inverter-based resources displace synchronous machines, some grid services will remain the same, some services will increase or decrease in magnitude, and some new services will be introduced. Future grid services will be more distributed, more complex, and provided by different technologies, raising interoperability concerns. The ability of inverter-based resources to provide grid services differs between solar, wind, and energy storage. For example, solar photovoltaics (PV) and battery energy storage cannot provide inertia, but due to the rotating mass of wind turbines, with appropriate controls, wind can provide a limited amount of system inertia. All types of inverter-based resources can provide synthetic inertia through grid-forming technologies.

Areas with very high levels of inverter-based resources are now pushing the envelope even further. Now, services that were inherently provided by synchronous machines, such as system strength, inertia, and synchronizing torque, must be unbundled into smaller components, so they can be delivered separately through modification of inverter-based resource controls or through other technologies, such as synchronous condensers.

In areas with very high levels of inverter-based resources, various types of fast frequency response are being introduced as new market products that support grid operation at low inertial levels. Voltage support capabilities of inverter-based resources have been enhanced to support stable operations in weak grids by providing droop control and fast fault current injection. However, there are physical limitations (i.e., current limits, synchronization mechanisms, availability to buffer on the DC side of the inverter) as to what inverter-based resources can provide. Consequently, further development is needed for inverter-based resources to provide the services required at very high deployment levels of inverter-based resources.

Grid Services

Grid services allow grid operators to manage reliability and electricity supply and demand on the electric system. Variable generation sources, such as wind, can provide certain grid services, in addition to energy. Some grid services are offered as products by independent system operators while others are simply grid or resource characteristics necessary for reliable operation. Grid services, and how they are defined, can vary by region, market, and type of electric system (i.e., distribution or bulk). Key types of grid services in addition to energy and capacity include, but are not limited to, the following:

- Frequency response, including inertial, primary frequency response, and fast frequency response
- Regulating reserves
- Contingency reserves include spinning reserves, non-spinning reserves, and replacement reserves
- Ramping reserves
- Voltage support, including providing and absorbing reactive power
- Restoration support, such as black-start capability
- Short circuit contribution

The workshop participants identified the following research challenges and opportunities for grid services:

Examine, identify, and define new grid services needed for grids with high amounts of inverter-based resources. Conduct research to examine, identify, and define the new grid services that are needed in grids with large amounts of inverter-based resources. From these, develop high-level technical performance requirements for inverter-based resources that are technology-neutral, standardized, performance-based, and not overly prescriptive. A priority can be to develop a common methodology for measuring different types of services. Equipment manufacturers have expressed a willingness to upgrade equipment to provide services. It is important to determine which services are needed and have value, so that equipment manufacturers can focus on what the industry needs. Continue development of standards (e.g., IEEE P2800) and include a broad stakeholder group for information dissemination and advancing best practices.

Model the grid services that inverter-based resources can contribute. The examination and definition of new grid services needed in grids with large amounts of inverter-based resources needs to be done hand-in-hand with developing capabilities to model inverter-based resources. Modeling and demonstrations are needed to understand controls for entire wind plants and across regions and for hybrid systems, so wind plant operators, as well as system operators, can evaluate grid services. Advanced controls must be implemented to enable wind systems to provide frequency support, but may not be necessary on all wind plants. Modeling is needed to understand the extent of what services are necessary and what technologies can provide the services. Modeling could also support better understanding of the coordination of inverter-based resources with reactive power/var devices, such as synchronous condensers. Of note, Texas has installed synchronous condensers to enhance grid strength, so more wind can be integrated, but synchronous condensers can introduce new stability issues. Therefore, modeling also needs to capture the dynamics of converters.

Demonstrate ability of wind to provide grid services. A concerted effort is needed to evaluate how ancillary services and essential reliability grid services can be demonstrated for wind turbines and plants with and without energy storage. Larger demonstrations are needed to understand controls and distribution level demonstrations are needed to address distribution level grid services such as voltage control. The research needs to address the capabilities for both type 3 and 4 wind generators[2] and include the response over different timescales and for future market conditions, as shown in Figure 1. Demonstrations that address interoperability would also be valuable.

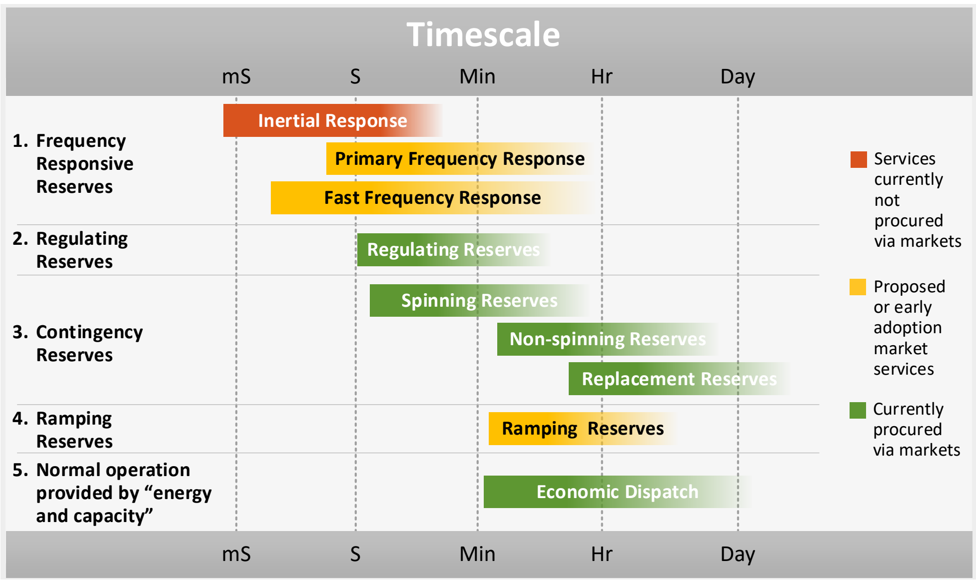

Figure 1. Timescales and Status of Markets for Different Grid Services (Denholm et al. 2019)

Implement broad collaboration. Research would benefit from broad collaboration with transmission and distribution system operators; plant owners, operators, and developers; original equipment manufacturers; researchers; software developers; consultants; and agencies and organizations such as the Federal Energy Regulatory Commission (FERC) and NERC. Dissemination of information on existing capabilities and examples of wind supplying grid services to key stakeholders is needed. New collaborative research activities could also benefit from coordination with existing work efforts like the Global Power System Transformation Consortium.[3]

Implement advanced forecasting. Integrating advanced forecasting with wind plants providing grid services is a need. Better wind forecasting can reduce system operating reserves. Tools are needed to quantify risk and uncertainty and dynamically quantify system reserve requirements.

[2] Type 3 turbines have a doubly-fed induction generator interface where power electronics couple the turbine rotational frequency with the grid frequency. This is also referred to as a partial power electronics interface. Type 4 turbines have a full power electronics interface.
[3] For more information on Global Power System Transformation Consortium: https://globalpst.org/.

Understand grid services impacts to dynamic response of power converters. There's a need to evaluate how different grid services will affect the dynamic response and characteristics of power converters (down to the synchronization, current, voltage, and power loops) and the requirements of different control loops (e.g., constant reactive power, Q-V droop, and P-f droop).

Assess wind's role in contingency events and providing black-start capability. Analysis is needed on wind's contribution during different contingency events (with and without storage) over various geographic areas and how wind and wind coupled with energy storage can be used for black-start grid restoration.

Understand grid-forming functionality. Research is needed to understand the capabilities of grid-forming functional inverters and power flow control for microgrid interconnectivity. Some workshop participants suggested that grid-forming controls can be more difficult to implement in wind applications because of the mechanical components of wind turbines and the associated stress. Demonstration and proof of concepts of grid-forming controls for wind systems would help improve understanding of limitations and implications.

Develop market rules and mechanisms. There's a need to evaluate different market rules for compensation of grid services and to develop the tools to understand the value of different wind services. Market and policy standards are needed to understand and value curtailment to provide all types of active power controls. Curtailment can allow for achieving more grid services, such as frequency response; however, curtailment reduces the amount of clean energy delivered. Compensation schemes, informed by models and tools, need to be developed that realistically account for potential beneficial curtailments.

Understand distribution-scale voltage support, ramping, and peak contributions of wind. Distribution utilities currently focus on the capacity, peak shaving, and energy value of wind. Understanding distributed wind's contribution to voltage support on distribution networks and ramping would provide additional benefit to distribution utilities and cooperatives. On the distributed wind scale, better data are needed, by location, on the potential for wind production to help address peak load. Improved models and tools are needed to represent the distribution impacts of wind and other distributed resources. Improved analysis is needed to understand how increasing deployment can shift the system peak and the subsequent rate design implications from wholesale providers down to distribution utilities.

Address challenges and opportunities specific to offshore wind. These include the following:

- Enable the coupling of onshore transmissions systems with offshore transmission systems for the provision of grid services
- Address black-start capability for meshed offshore grids and multiterminal high-voltage DC (HVDC)
- Identify best practices for operating DC ties for offshore wind
- Understand reliability and characterize system disturbances
- Evaluate HVDC contribution to grid services with an understanding of contingencies and the need for offshore transmission studies and analysis
- Understand harmonics and harmonic controls from wind plants, both onshore and offshore, and lessons from Europe
- Implement protection and the provision of fault current for offshore HVDC wind systems.

Use Advanced Research on Integrated Energy Systems (ARIES) research platform for demonstration projects. ARIES is a research platform at NREL that can support validation and demonstration of wind-providing grid services and related research at the distribution and transmission levels. ARIES represents a substantial scale-up in experimentation capability from existing research platforms, including but not limited to multi-MW systems integration at scale to support validation of modeling and simulation, hardware-in-the-loop, controls integration, hybrid systems development, and controls and protection. ARIES can be used to demonstrate grid services needs and provision over larger geographic scales, such as among different balancing areas as part of a multi-entity research and demonstration project.

6 Modeling and Decision-Support Tools Challenges and Opportunities

While informed decisions require studies, and studies need models, workshop participants discussed that researchers, system operators, and other stakeholders need to be confident that the studies and models represent reality. In addition, models and simulations need to be validated in noninvasive ways. Some relevant studies include long-term planning assessments, interconnection studies, detailed electromagnetic transient simulations, power flow simulations, dynamic simulations, and short-circuit studies. All these studies are required before resources are interconnected. As the number of inverter-based resources and hybrid power plants are increasing, models and simulation tools need to be able to handle the associated capabilities and complexities and still be tractable, accurate, and validated. At the same time, workshop participants discussed not adding unnecessary complexity to modeling and decision-support tools but focusing on simple and explainable solutions and creating new tools only when appropriate.

Workshop participants discussed the following research and development challenges and opportunities for modeling and decision-support tools:

Develop interconnection and performance standards and analysis techniques. Analyses, assumptions, and tools are different across regions. For example, General Electric is being asked by different authorities to evaluate weak grids and short-circuit contributions of inverter-based resources differently in different parts of the country. Standardized interconnection and performance standards and analysis techniques across regions in the United States, to the extent reasonable, would help speed and smooth the integration of inverter-based resources.

Develop standardized models and libraries to meaningfully model operations with proprietary controls. Generic generator and grid models are not always representative of reality, and renewable energy system models are not as well understood as synchronous machine models. Standard model libraries for wind turbine converters are needed because original equipment manufacturer versions are proprietary. Consequently, generic control models are used instead, but generic control models are limited and are often misapplied.

Develop models that account for fast dynamics. Researchers need models that account for physics, fast dynamics, and all control loops, including dynamics, harmonics, and protection. System operators need decision-support tools and stability analysis tools that can account for fast dynamics, controls, and power electronics. Advancements in modeling and tools would enable fast simulations that could help determine reliability issues. Incorporating artificial intelligence and machine learning techniques may improve accuracy. Wind hybrid simulation tools are needed to simulate fast dynamics of an increasing number of inverter-based resources. Open-source simulation models are needed that represent the dynamic behavior of wind turbines of different sizes and at different grid voltage interconnection levels. Risk and uncertainty need to be better incorporated into these models using probabilistic methods.

Develop decision-support tools for wind systems operators, grid operators, and grid planners. Tools and intelligence are needed for wind system operators, so they understand when to participate in the markets, like when to curtail for spinning reserves. Control room operators need tools to manage and control inverter-based resources, and they need to know what resource options are available and the opportunity costs for operating one resource instead of another. In areas with very high inverter-based resources, such as CAISO, operators need decision-support tools that help with ramps and decision-making in the N-0, or no contingency scenario. For example, CAISO, under normal operating conditions, is seeing 1,000–2,000 MW of changes in solar PV generation in 10 minutes. CAISO has no visibility into customer systems and has difficulty predicting timing and quantity of exports to the grid, particularly when electric vehicle charging and battery charging are also happening. Grid operators need support to know when to make decisions to dispatch other generators on the system, in the face of uncertainty stemming from an increasing number of inverter-based resources and electrification.

Give more focus to modeling practices. Researchers and utility planners need a better understanding of when to use what model for what problem and when to transition from one model to another. They need to know when to use different types of simulations and when and how to model faster dynamics, when needed. They also need to know the changing data requirements for the models to accurately capture necessary information for decision-making.

Perform more holistic wind integration studies. Holistic interconnection studies are needed, so that wind is not considered in isolation, and so that valid assumptions about other resource types and loads are included. Assumptions about demand response, other types of distributed generation, energy storage, and electrification of buildings and transportation affect the analysis of wind integration. A holistic approach would also address various planning processes, from generation expansion all the way to stability.

Improve model validation techniques. Researchers need better ways to validate models in noninvasive ways. System operators need to be confident that models represent reality. They need to be clear on model validity for dynamic and steady-state power flow base cases, so that they can have confidence in scenario analysis and more detailed studies, including electromagnetic transient type studies. If issues are discovered with existing models, they need to know when and how to make necessary changes and when to go into more detailed time-intensive studies. There is also a need to generate and share grid (or microgrid) data for validation.

Pursue advanced electromagnetic transient modeling. Researchers, utility planners, system operators, and other stakeholders need improved electromagnetic transient modeling tools to integrate wind into grids with low strength and resolve stability, protection, and power quality issues. For example, Australia has very high deployment of inverter-based resources and has identified system-strength-related issues as key barriers. Improving electromechanical transient simulations and simulating high-speed power electronics at scale were identified as research gaps.

Improve tool capabilities for technological advancements. Advancements in information and grid technologies are happening quickly, and high technology readiness level research is needed to bring commercial innovation to a practical level that industry participants can use. The industry may not need more tools but rather better tools. Tools need to be able to make use of cloud computing to incorporate increasing amounts of data.

Improve the representation of distributed wind in tools. Better mapping and modeling of the ability of distributed wind and distributed wind hybrids to contribute energy and capacity at daily and seasonal peaks are needed. Distributed wind's representation in tools and models could be improved by adding siting capabilities and methods for understanding value and how value may change over time. Additional improvements could be the development of screening tools for siting, characterizing how wind varies with time and corresponds to customer load, and addressing planning, permitting, integration, and construction in a collaboration platform.

Create integrated transmission and distribution models. Bridging transmission and distribution models is necessary to understand the interactions between resource types and impacts to the grid. Researchers and transmission and distribution planners need ways to realistically and meaningfully consider both transmission and distribution systems together. Holistic modeling can help determine how DERs could add value as bulk grid resources, how systems parameters such as voltage and flow are affected at both the transmission and distribution level, and how distribution resources impact transmission protection schemes.

7 Power Electronics Challenges and Opportunities

Power electronic research is important to reduce cost, improve efficiency and reliability, and enhance capabilities of power electronics devices that are critical to rapid wind deployment at scale. Those devices include wind converters of all sizes, HVDC converters, multiterminal converters, and other grid-tied solid-state equipment. For example, as wind turbines and wind farms are getting bigger, technological limits are being reached at the component, subsystem, and system levels, including the converters, collector system, and delivery system. Many power electronics research opportunities are about addressing situations when power and voltage technological limits are exceeded and how they can be redesigned with innovative topologies and the latest semiconductor components. Power electronics research opportunities also exist around how power electronics can support the energy, capacity, and ancillary service needs of the grid with increasing amounts of inverter-based resources. Particularly in offshore wind systems, there are needs to have fewer components and compact power converters that will meet the unique requirement for offshore wind and mitigate installation and maintenance challenges. International examples of multiterminal DC systems, DC breakers, and HVDC gas-insulated switchgear were pointed to as important examples that can be learned from and built upon. Finally, there is a need for increased understanding of how power electronic devices interact with each other and the grid system and how those can be incorporated into grid planning. There are important interoperability issues that need to be addressed before devices and converters from multiple vendors can work together.

Workshop participants discussed the following research and development challenges and opportunities for power electronics:

Develop power electronics that can provide power delivery of all wind generation. Power electronics are needed that can support power delivery for all wind generation at multiple scales, from microgrids to macrogrids, and from distributed wind to offshore wind. Aspects that need to be addressed include meshed multiterminal DC networks, HVDC breakers, low-frequency alternating current (AC); hybrid AC/DC systems, grid-optimized power converters, and reconducting from AC to DC. Different technologies are required for different applications. For example, offshore wind has unique requirements for lightweight compact converters. Floating offshore wind may require multiterminal HVDC if a shared DC network is proven cost effective. Land-based and distributed wind have more standard interconnection requirements. In addition, a shared converter for a wind hybrid system could further improve the controllability of wind and reduce the system cost. It was suggested that integrated, DC-based hybrid systems might be needed at all voltage levels, from distributed wind to offshore. Modular designs of these systems would have the benefit of allowing multiple vendor participation.

Create standardization and certification of power electronics for all stages of the grid. Standardization and certification offer both opportunities and challenges. Standardization efforts can be additions to the IEEE 1547 and IEEE P2800 standards or new standard development, as well as alternatives to standards like guideline documents issued by NERC or through industry consensus. The power electronics industry is moving fast, and standards development often falls behind, which makes alternative approaches necessary and valuable for many power electronics applications.

Standardization may provide the opportunity to lower power electronics costs. A fleet of multivendor standardized power electronics could provide scaled reliability improvements quicker than one original equipment manufacturer could alone.

Use a holistic approach. Controllable loads are changing the way that customers can interact with the system. Inverter-based resources are changing the characteristics of generation production. Both are changing in the way they interact and respond with each other and the grid. There is concern about the unknowns of adding even more power electronics, as it may create an even more complex and hard-to-predict set of system operations. Rather than focusing too narrowly on how one electronic device should perform, the research needs to look at the implications of all these devices holistically, including the cybersecurity implications.

Design control architecture to accommodate diverse power electronics. For a future grid with a majority of power-electronics-based equipment and controls, more research is needed to redefine the grid control starting from first principles and derive necessary specifications for power electronics equipment connected to the grid. With high levels of inverter-based resources, there will be a fundamental change in dynamics, stability, control, and protection. More research is needed on the impact of coordinated power-electronics-based controls on grid stability. Research into hierarchical coordinated control and defining different control layers is needed.

Address challenge of HVDC breakers for wind. DC circuit breakers are not currently a mature or affordable technology, and advancements are needed for both medium-voltage DC and HVDC systems. Additional pilots and demonstrations on DC breakers and multiterminal HVDC would be beneficial.

Develop affordable and efficient power electronics for grid services. Technologies of interest include flexible AC transmission systems, grid-forming inverters, multiterminal inverters, and wide-bandgap-based power electronics. Grid-forming inverters are of increasing importance. More research is needed to design the unique controls and to understand the needs and impacts of grid-forming wind for system reliability and resilience. Research on incentives for power-electronics-based grid services is also necessary to support policy and market design that would facilitate and accelerate the deployment and use of such grid services.

Implement passive systems that can backstop power electronics. Many of the advanced functions of power electronic devices rely on robust communications. It is suggested to design power electronics with built-in ‘passive systems’ (or droop-like behaviors) that could operate using local measurements to keep systems running in stressed conditions.

Design protection schemes for power-electronics-heavy power systems. More work is needed on understanding and designing protection schemes for power-electronics-heavy power systems. Systems with high levels of inverter-based resources are having problems with legacy protection devices; adaptive digital protection schemes are a potential solution. One area of research is how inverter-based resources could incorporate protection functions, such as fault and low-voltage ride through, within themselves. There are also opportunities to collaborate across technologies (i.e., solar, battery energy storage systems, and power supplies) with respect to reliability and how to protect power electronics from grid voltage surges and cosmic rays.

Model and simulate power electronics and power systems at scale. Research and development on device and control modeling, model validation, and calibration; electromagnetic transients modeling; and co-simulation are needed for studying large-scale power electronics deployment and assessing the performance of the resulting power system.

Improve power electronics supply chain, manufacturing, and maintenance. A U.S. power electronics supply chain is needed, along with ways to lower cost and scale up manufacturing. Shipping costs and availability of parts are nontrivial issues. For example, one specific concern, at present, is the low availability of silicon carbide. With respect to manufacturing, there is uncertainty around cybersecurity requirements. There is also the need for quality control and quality assurance programs to increase reliability. New tools and procedures are needed to anticipate equipment failure or to enable preventive maintenance before failure.

Increase power electronics technology demonstration and transfer. It can be difficult for start-ups to perform necessary reliability tests, making it difficult to transfer technology. The use of testing sites, such as the Testing Expertise and Access for Marine Energy Research, PNNL's Electricity Infrastructure Operations Center and Grid Storage Launchpad, and NREL's ARIES, can enable technology transfer. There are also many testing and demonstration facilities at power electronics vendors and power companies to be leveraged.

8 Transmission and Distribution Coordination Challenges and Opportunities

Historically, the flow of power has been unidirectional, from the transmission system to the distribution system, but increasing amounts of controllable and flexible DERs could enable a more active and bidirectional relationship between transmission and distribution systems. Workshop participants brainstormed what role distribution systems and DERs could play in increasing and accelerating wind integration and discussed the following research and development challenges and opportunities for transmission and distribution coordination:

Follow the "do no harm" principle. System operators do not want DERs to harm system stability and reliability. Improved forecasting for distributed wind and increased visibility into DERs, in general, would help system operators maintain stability and reliability. Beyond visibility, operators having some level of control of DERs would be preferred, yet transmission system operators have different objectives than distribution system operators. One opportunity is the new distributed system operator business model being considered in New York, California, and Texas because transmission system operators cannot model or account for every individual DER.

Develop tools for distribution system planners. There are questions about which tools distribution planners need in order to plan for the right sizing of distribution equipment as DERs are added. Distributed wind can reduce the need for generation capacity and may reduce the need for distribution capacity; however, planners may not have the tools or practices they need to recognize that.

Facilitate coordination in modeling and operations. There are always more opportunities for increased coordination between operators of distribution systems and transmission systems. Connection points between transmission and distribution systems need to be examined to mitigate potential bottlenecks that prevent DERs from providing benefit to the transmission system. With respect to modeling, DERs need to be included in system modeling, including controllable loads.

Enable wind as a DER to provide more than energy. Distributed wind needs to be able to provide reliability services, such as voltage support, ride through, and grid-forming functionality, rather than just energy. Standards have been developed that address reliability services, but some of the standards, such as IEEE 1547, already need to be enhanced to include things like grid-forming capabilities. There are also certification burdens association with meeting standards.

Consider the role of dynamic demand. Dispatchable supply is currently being used to manage variable supply, but there is a longer-term vision in which distributed demand could be used to help address variable supply issues. This will require the development of certain customer-side technologies to be able to use the distribution system in that way.

Consider beneficial curtailment as a market strategy. Wind curtailment could be a market-based activity that could help operators move away from significant investments needed to respond to worst-case grid conditions. Wind curtailment could be a better and lower-cost market activity that would benefit distribution and transmission, but reasonable compensation strategies are needed.

Address the costs of metering requirements and DER integration. Revenue grade meters are needed for distribution system aggregators and operators to use DERs as system assets. However, the cost of metering is still a burden for small DERs. And currently, in most cases, the cost of distribution system upgrades is paid by the DER provider who pushes the system over the capacity threshold. Other options are needed that proactively consider DER-enabling investments and socialize costs, so DER owners are treated equitably and DERs can continue to be built out.

Develop demonstration capabilities. Pilots and demonstrations at different scales can be used to demonstrate how distributed wind can interact with the grid and to test out different solutions. Pilot projects lower the barriers to entry and allow people to learn from the experience of others and adopt things that are most effective for their particular system.

Overcome institutional challenges. Real life friction exists in how to get services from the distribution side. There are institutional layers between FERC, states, utilities, independent system operators, and regional transmission organizations that might prevent distribution systems from providing valuable services in the near term. Some traditional utility preferences for utility-owned and -controlled poles and wires investments might be hard to overcome. The challenge exists of how to enable customers to adopt new, smart, controllable distribution technologies that allow them to “do no harm” to the system without having to wait for utility business model and incentives issues to be solved.

9 Conclusion

Workshop participants acknowledged that broad continued collaboration is needed from transmission and distribution system operators; plant owners, operators, and developers; original equipment manufacturers; researchers; software developers; consultants; and agencies such as FERC and NERC. In addition, opportunities exist for U.S. stakeholders to learn from relevant international experience. WETO is well positioned to continue advancing wind integration through its research and development activities informed by this workshop and by its ability to continue to convene domestic and international stakeholders.

With respect to specific technical topics, workshop participants emphasized a range of needs. These include the need for new transmission, interconnection, and performance standards along with consistent and standardized grid impact analysis methods. Workshop participants expressed interest in an enhanced understanding of grid services needs and provision in grids with large amounts of inverter-based resources and improved modeling tools that consider controls, power electronics, and grid services. Power electronics that can support power delivery for all scales of wind generation was also identified as a key opportunity to facilitate increased wind deployment.

In addition, more work is needed to enhance the understanding and advancement of energy equity in the wind energy research and practitioner community. However, current opportunities exist to advance equity in organizational practices, such as workforce development, hiring practices, and procurements.

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Appendix A - Workshop Agenda

U.S. Department of Energy's Wind Energy Technologies Office Wind Systems Integration Workshop

Virtual: June 22, 23, and 30, 2021

Tuesday, June 22, 2021, Eastern Time	
11:00–11:15 a.m.	**Welcome** • Workshop objectives, expectations, and format and Zoom basics • Introductions **Opening Remarks** Alejandro Moreno | Deputy Assistant Secretary for Renewable Power, U.S. Department of Energy (DOE)
11:15–11:30 a.m.	**WETO Introduction** Robert Marlay | Director, DOE Wind Energy Technologies Office (WETO)
11:30–11:40 a.m.	**Icebreaker**
11:40 a.m.–12:15 p.m.	**Brainstorming Activity** What are the biggest needs to accelerate high wind contributions and near-term rapid deployment? *Facilitator:* Juliet Homer, Pacific Northwest National Laboratory (PNNL)
12:15–12:45 p.m.	**Grid Visionary Speaker** Charlie Smith | Executive Director, Energy Systems Integration Group
12:45–12:55 p.m.	**Break**
12:55–1:25 p.m.	**Justice40 Initiative & Energy Equity** *Session Leads:* Bethel Tarekegne | PNNL, Maggie Yancey | DOE WETO
1:25–2:00 p.m.	**Introduction to Day 2 Technical Sessions** • Modeling and Decision Support Tools: Ryan Quint | Senior Manager, BPS Security and Grid Transformation at North American Electric Reliability Corporation • Grid Services: Julia Matevosyan | Lead Planning Engineer at Electric Reliability Council of Texas • Power Electronics: Debrup Das | Head of Research, North America at Hitachi ABB
2:00 p.m.	**Day 1 Closeout and Adjourn**

Wednesday, June 23, 2021, Eastern Time	
12:30–12:50 p.m.	Welcome Session & Check-In
12:50–1:35 p.m.	Technical Topic #1: Enhance and Deliver Grid Services to Increase Value Streams *Session Lead:* Dave Corbus | National Renewable Energy Laboratory
1:35–2:20 p.m.	Technical Topic #2: Improve System Modeling and Decision Support Tools to Inform Integration Processes *Session Lead:* Jason Fuller | PNNL
2:20–2:35 p.m.	Break
2:35–3:20 p.m.	Technical Topic #3: Advance Power Electronics to Lower Cost, Increase Reliability, and Improve Grid Operations *Session Lead:* Henry Huang | PNNL
3:20–3:30 p.m.	Day 2 Closeout and Adjourn

Wednesday, June 30, 2021, Eastern Time	
12:30–12:40 p.m.	Welcome Session & Check-In
12:40-12:50 p.m.	DOE WETO Research – Context Setting Patrick Gilman | Analysis and Modeling & Distributed Wind Program Manager, DOE WETO Jian Fu | Systems Integration Program Manager, DOE WETO
12:50–2:10 p.m.	Summary and Research Prioritization • Energy Justice • Grid Services • Modeling and Support Tools
2:10–2:25 p.m.	Break
2:25–2:50 p.m.	Summary and Research Prioritization, continued • Power Electronics
2:50–3:20 p.m.	Digging Deeper The role of distributed energy resources and distribution systems in accelerating wind integration. *Facilitator:* Juliet Homer, Pacific Northwest National Laboratory (PNNL)
3:20–3:30 p.m.	Day 3 and Workshop Closeout

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