Accomplishments and Year-End Performance

REPORT

WIND ENERGY PROGRAM: FISCAL YEAR 2021

Foreword

The National Wind Technology Center (NWTC), located at the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) Flatirons Campus, has been a driving force in advancing wind energy technology research worldwide since its designation as a DOE national research center in 1992. Enabled by the Flatirons Campus's world-class facilities, scientists, engineers, analysts, and researchers are pushing the frontiers of science to pursue wind energy innovation.

In Fiscal Year (FY) 2021, NREL continued to provide the technical expertise, research capabilities, and industry understanding to support DOE's ambitious climate action and research goals by advancing technology, addressing market and deployment barriers, and driving down costs with more efficient, reliable, and predictable wind energy systems.

One of several highlights, NREL received an R&D 100 Special Recognition Award for its Thermoplastic Resin System for Wind Turbine Blades. This breakthrough in the wind turbine manufacturing process will enable the production of recyclable blades that are stronger, longer, and less expensive, while increasing energy capture, decreasing energy and transportation costs, and increasing blade reliability.

In a year when the entire U.S. economy struggled to address workforce gaps, an NREL study compared wind industry needs, training programs, and hiring practices with perspectives from students and recent college graduates. Researchers hope that, by pinpointing areas of disconnect, the expectations of employers who have difficulty filling entry-level jobs can better align with the preparation of the potential applicants who find it hard to break into the field.

The lab also made numerous new data and modeling resources available in FY 2021. Recent NREL releases include a modeling tool for predicting the power performance and structural loads of wind turbines within a wind farm (FAST.Farm), a computational framework for modeling golden eagle behavior near wind farms, and 20 years of offshore wind data. Updates were also made to the widely used Wind Plant Integrated Systems Design and Engineering Model (WISDEM®), which couples engineering and cost models to examine system-level trade-offs.

Now, bolstered by a renewed national commitment to tackle climate change and revitalize the U.S. economy through increased investment in clean energy—particularly in offshore wind energy—NREL stands poised to lead the way to a sustainable future that powers the United States with significant levels of reliable, low-cost, accessible wind energy.

This report provides an overview of the achievements NREL made on behalf of DOE's Wind Energy Technologies Office (WETO) and other partners during FY 2021 (between Oct. 1, 2020, and Sept. 30, 2021).

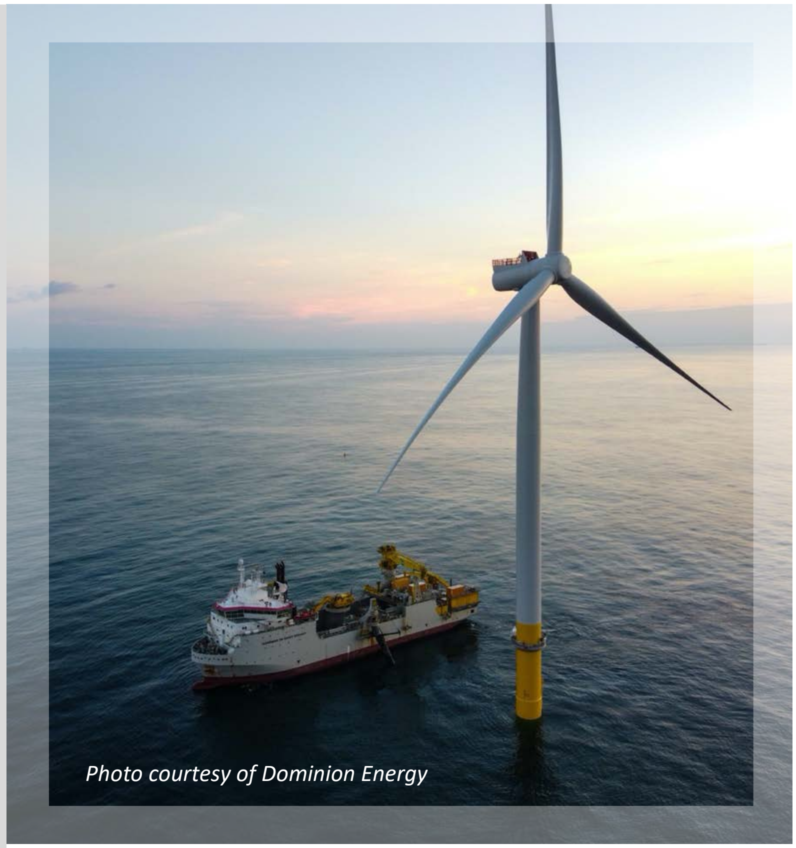

Photo courtesy of Dominion Energy

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Partnerships

ATLANTIS Projects Help Ensure Floating Offshore Wind Energy Technology Innovation

Point of Contact: Amy Robertson, Amy.Robertson@nrel.gov

NREL researchers continue working on revolutionary floating offshore wind energy projects funded under three DOE Advanced Research Projects Agency-Energy awards within the Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control (ATLANTIS) program. The 2-year research projects will help ensure that innovative floating offshore wind energy technologies will continue to develop and expand U.S. offshore wind energy capacity by:

- Creating an open-source software toolset called Wind Energy with Integrated Servo-control, which will enable floating offshore wind energy system engineers to design radically new systems at greatly reduced costs. NREL is partnering with the University of Illinois Urbana-Champaign on this project.

- Developing the Floating Offshore-wind and Controls Advanced Laboratory, the first public floating offshore wind turbine scale-model data set to include advanced wind turbine and hull controls, as well as hull flexibility. NREL is partnering with the University of Maine and DNV GL on this project.

- Lowering floating offshore wind costs by simplifying the construction and maintenance logistics for deep-water wind systems. The project, dubbed Ultraflexible Smart FLoating Offshore Wind Turbine (USFLOWT), leverages NREL's innovative SpiderFLOAT technology, which features a spider-like substructure. Both the SpiderFLOAT substructure and the larger USFLOWT system use innovative designs and materials best suited for the requirements of each component to make offshore wind energy systems more cost competitive. USFLOWT involves a partnership among NREL, the Colorado School of Mines, the University of Colorado Boulder, the University of Virginia, the University of Illinois Urbana-Champaign, and the American Bureau of Shipping.

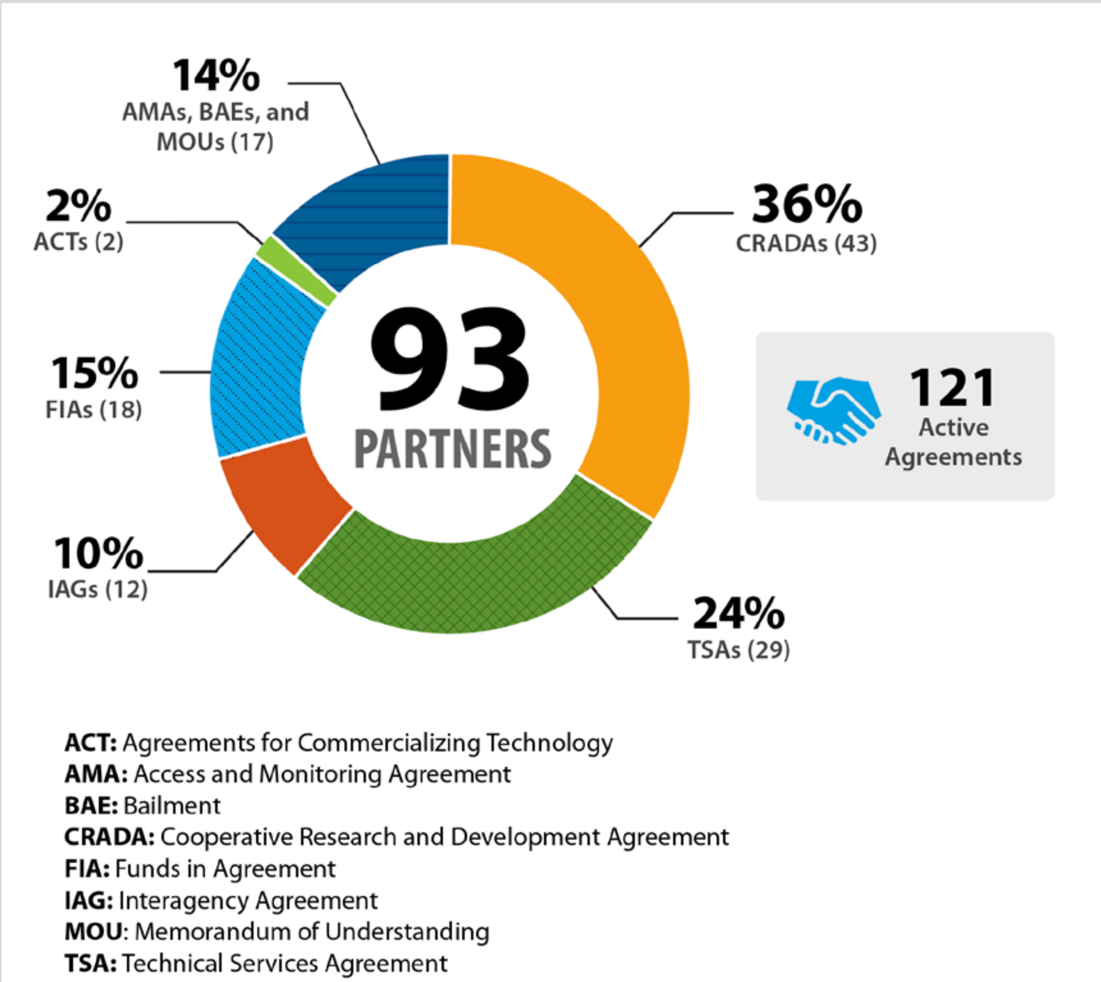
Funding provided by DOE's ARPA-E ATLANTIS program is enabling NREL to develop new and potentially disruptive innovations for floating offshore wind energy technologies. *Photo by Senu Sirnivas, NREL*

NREL Partners Help Accelerate Wind Energy

In FY 2021, NREL and the NWTC worked with 93 partners through 121 active agreements designed to advance wind energy science and lower the cost of wind-generated electricity.

NREL offers partners across the wind energy industry access to world-class wind research capabilities and technical expertise. By partnering with NREL, companies can answer specific design challenges, share costs to develop state-of-the-art wind energy technology, and document their wind turbine components' performance for certification.

By developing new, innovative ways to build partnerships, NREL works side by side with the wind energy industry to make wind a cost-effective electricity source for the world.



With 93 partners, NREL's wind energy program participated in 121 various kinds of active agreements. *Graphic by NREL*

Flatirons Campus Research Facilities

NREL's Microgrid Powers Campus Through Outage

Points of Contact: Przemyslaw Koralewicz, Przemyslaw.Koralewicz@nrel.gov, and Robb Wallen, Robb.Wallen@nrel.gov

After an outage cut power to NREL's entire Flatirons Campus, the lab's Advanced Research on Integrated Energy Systems (ARIES) research platform repowered the entire campus for a continuous 24 hours. Acting like a microgrid, ARIES kept the campus running with 100% renewable wind and solar energy. This inadvertent trial run provided the opportunity to demonstrate how future renewable microgrids could restore power during utility-scale outages and enhance the resilience and flexibility across power systems, large and small.

The microgrid at NREL's Flatirons Campus validated a core principle of NREL's Advanced Research on Integrated Energy Systems (ARIES): renewables can enhance resilience and flexibility across power systems, large and small. The ARIES platform achieved 24 hours of continuous run time on 100% renewable sources after the utility-scale power outage—a critical demonstration of the platform's proof of concept. *Photo by Dennis Schroeder, NREL 62222*

Annual Instrument Check Keeps Field Research Moving

Point of Contact: Dave Simms, David.Simms@nrel.gov

To perform real-world research on how atmospheric conditions affect wind turbines, the Flatirons Campus relies on two meteorological towers: an 80-meter (m) weather monitoring tower and a 135-m atmospheric research tower. Recently, NREL's Research Operations team completed its annual instrument inspection to ensure these towers collect accurate data and operate safely and reliably. This annual inspection enables NREL, DOE, and industry partners to conduct valuable and dependable field research with the DOE 1.5-megawatt (MW) research wind turbine, ultimately helping to make the wind energy industry smarter, more efficient, and cost-effective.

Annual change-outs to meteorological tower instruments ensure these assets can reliably facilitate DOE and industry-partner field research activities. *Photo by Jerry Hur, NREL 36267*

Flatirons Campus Earns Letter of Accreditation

Point of Contact: John Morris, John.Morris@nrel.gov

The Flatirons Campus received a letter of reaffirmation from the American Association of Laboratory Accreditation, signifying successful renewal of all Flatirons-based accredited research measurement processes. All Flatirons Campus research activities conducted in accordance with International Electrotechnical Commission (IEC) standards are accredited by the American Association of Laboratory Accreditation, which is an independent organization that audits and monitors labs to ensure quality-control procedures and processes are followed to produce internationally recognizable, reliable test results.

NREL's Flatirons Campus, shown here, earned renewed accreditation from the American Association of Laboratory Accreditation. *Photo by Joshua Bauer, NREL 61830*

Building a Second Controllable Grid Interface To Study How Renewables Connect With the Grid

Point of Contact: Jeroen van Dam, Jeroen.van.Dam@nrel.gov

The Flatirons Campus is procuring a second controllable grid interface, which can quickly and cost-effectively verify how wind turbines, solar cells, and energy storage systems interact with the grid. With controllable grid interfaces, researchers can create a customized, fully controllable research grid that is isolated from the utility grid. This research helps the electrical grid evolve to include more variable power generators like wind and solar, increase energy storage levels, and design "smarter" or more autonomous grids that can, for example, charge electric cars during off-peak hours. NREL's new controllable grid interface can help reduce costs and certification time while providing a better understanding of how renewable energy power plants react to grid disturbances.

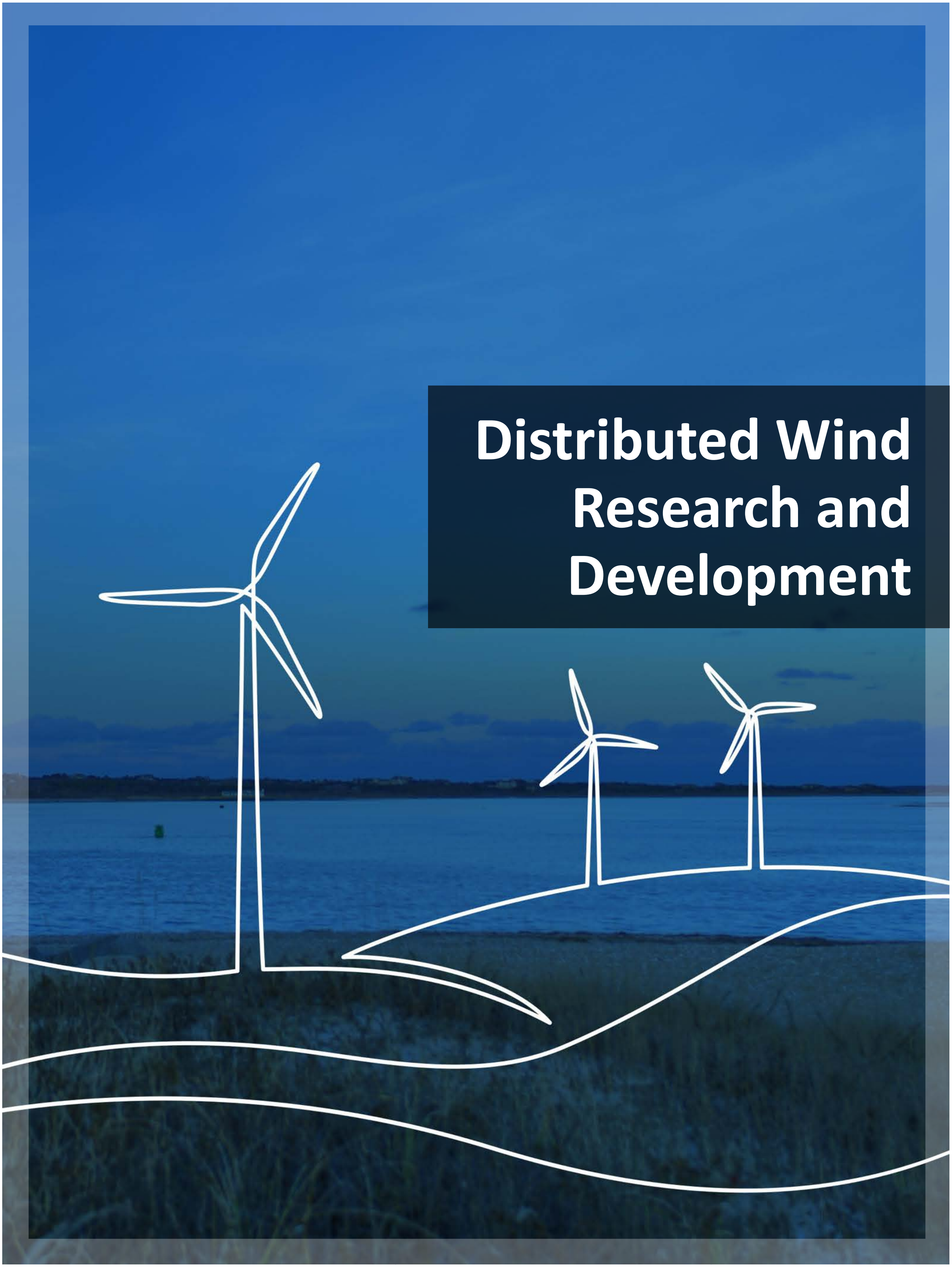
This converter assembly is a central component of the second controllable grid interface at the Flatirons Campus. When complete, it will help the U.S. electrical grid evolve by allowing a greater contribution from variable power generators, increased levels of energy storage, and smarter grid devices. *Photo from ABB Group*

Eagle Supercomputer Helps Wind Energy Research Soar

Point of Contact: Brian Smith, Brian.Smith@nrel.gov

With the Eagle supercomputer, NREL researchers can explore how complex wind dynamics affect the energy output, reliability, and cost of wind energy systems. Thanks to the Office of Energy Efficiency and Renewable Energy investing in and allocating space for Eagle, WETO research can pursue critical projects using high-performance computing, such as: (1) identify U.S. sites where significant wind resources correlate with high demand for electricity, (2) create high-resolution simulations to study long-term wind resource quality and site conditions for distributed wind energy, and (3) perform the first high-fidelity simulations of a megawatt-scale wind turbine in turbulent flow, enabling new wind turbine designs that increase overall energy production while decreasing overall cost.

NREL researchers used the Eagle supercomputer to visualize flow fields for the International Energy Agency Wind Task 29 validation campaign, which will enable new designs to help reduce levelized cost of wind energy. *Photo by Dennis Schroeder, NREL 53840*



Distributed Wind Research and Development

Technical Support Provided to Awardees Results in Industry-Scale Impact

Point of Contact: Ian Baring-Gould, Ian.Baring-Gould@nrel.gov

In addition to financial support, the Competitiveness Improvement Project (CIP) provides technical support that enables small U.S. wind manufacturers to develop innovative distributed wind energy technology. In FY 2021, NREL helped to:

- Validate the blade of Bergey Windpower's 15-kilowatt (kW) wind turbine
- Analyze and address an overheating issue with Primus Wind Power's 160-watt Air Breeze wind turbine
- Tackle cybersecurity and certification for Intergrid's inverter
- Modify existing aerodynamic models for use in Xflow Energy's vertical-axis wind turbine design.

NREL technical support enabled Bergey Windpower to validate the blade of its 15-kW wind turbine, shown here. *Photo from Bergey Windpower*

By providing laboratory equipment and expertise that CIP awardees are unable to receive privately, NREL enables awardees to develop tools that, over time, will help advance the entire distributed wind energy industry.

Workshop Helps Small Wind Manufacturers Generate Successful Proposals

Point of Contact: Ian Baring-Gould, Ian.Baring-Gould@nrel.gov

For wind energy technology manufacturers interested in applying to DOE's CIP solicitations, NREL hosted an all-day virtual workshop in December 2020. Speakers provided an overview of the CIP process, evaluation criteria, certification requirements, and NREL's technical support opportunities. To further support manufacturers interested in applying for CIP awards, NREL also posted the workshop presentations and the workshop recording on its public-facing website. This workshop, which is held every year prior to issuance of CIP's request for proposals, led to a successful response to the solicitation. In late 2021, eight small businesses were selected to receive $2.2 million in DOE funding and $1.3 million in industry cost share.

Distributed Wind Turbines Expand ARIES Research Platform Investments at Flatirons Campus

Point of Contact: Ian Baring-Gould, Ian.Baring-Gould@nrel.gov

Following a notice of intent issued in fall 2020, NREL selected three manufacturers of small- and medium-sized wind turbines to install their wind research turbines on the NREL Flatirons Campus, expanding capabilities under the ARIES research platform. Bergey Windpower's 15-kW wind turbine, QED Wind Power's 20-kW turbine, and Eocycle America's 90-kW turbine will be used to conduct research focused on integrating wind energy in distributed applications. These applications include hybrid systems, (isolated and grid-connected) microgrids, and (in-front-of and behind-the-meter) distribution feeders, partially in support of the Microgrids, Infrastructure Resilience, and Advanced Controls (MIRACL) research project.

The QED PHX20, a three-bladed, 20-kW upwind turbine, is one of three modern wind turbines selected for installation at NREL's Flatirons Campus. The turbines will be used to conduct research focused on integrating wind energy in distributed applications. *Photo from QED Wind Power*

Tools Assessing Performance WETO.1.2.2.401

Mesoscale Modeling to Enable 20-Year Time Series Data for Alaska

Point of Contact: Heidi Tinnesand, Heidi.Tinnesand@nrel.gov

To develop time series wind resource data for Alaska, the NREL Tools Assessing Performance team ran multiple simulations for the state. The team simulated wind resources with different parameterizations for the land surface model and the planetary-boundary-layer scheme—the most important physics influencing wind simulations. These simulations resulted in a statistical variation of the possible spread of wind resource estimates. This process allowed the team to characterize uncertainty within the models and select a set of physics parameterizations that produces the lowest possible model error. One of these configurations, which shows the best overall performance for Alaska, will be used to create a new 20-year time series data set of wind resources for the state.

Mesoscale Modeling Allows Wind Resource Uncertainty Quantification

Point of Contact: Heidi Tinnesand, Heidi.Tinnesand@nrel.gov

The NREL Tools Assessing Performance team created multiple wind resource time series data sets across the country's 48 continental states to characterize model uncertainty. These data sets were then compared to wind resource measurements at different heights across the country, considering wind speed in different ranges to understand the model performance with lower wind speed, higher wind speed, and extremely high wind speed. In addition, the project team conducted simulations for winter and summer months and multiple simulations with slightly different initial conditions to determine the internal variability spread of wind resources. Determining variability of wind resources using multiple simulations is important because if one simulation starts at one date and another simulation starts on a different date, the solution can be different. Running multiple simulation times enables wind energy producers to quantify that uncertainty.

Automatic Obstacle Identification Method Could Increase Distributed Wind Deployment

Point of Contact: Heidi Tinnesand, Heidi.Tinnesand@nrel.gov

The NREL Tools Assessing Performance team developed an automatic obstacle identification method for rural and industrial areas that could benefit from distributed wind energy but feature obstacles that might impede power generation. The method uses a data-driven approach to understand the practical impacts of performance estimation, mesoscale models, and downscaling using automatic obstacle detection. In addition, an obstacle-description file format and revised application programming interface accommodate obstacle definitions. The team also continues to evaluate the performance of mesoscale models, obstacle models, and practical limitations for applying these models to real-world siting.

Automatic obstacle detection methods could help increase distributed wind energy deployment by automating an error-prone, manual obstacle assessment process and quantifying existing large-scale opportunities. *Photo from Nergica and International Energy Agency Wind Task 41*

Simplified Obstacle Models Evaluate Distributed Wind Energy Wake Deficits

Point of Contact: Heidi Tinnesand, Heidi.Tinnesand@nrel.gov

The NREL Tools Assessing Performance team leveraged several hundred high-fidelity simulations of air flow past idealized buildings (of various shapes and orientations) to create simplified (low-order) models. These reduced-order obstacle models can easily be used by members of the wind energy industry to evaluate wind speed deficit in the wakes behind buildings. The team combined simulated and observed data with machine-learning approaches and used analytical models of the flow equations to develop models that are significantly faster than high-fidelity simulations and with reasonable accuracy for the intended application. These new obstacle models leverage the automatic obstacle detection capability, along with the most accurate methods for spatial and vertical interpolation, to calculate accurate, site-specific wind resource estimates for distributed wind energy projects with minimized computational cost compared to high-fidelity simulations.

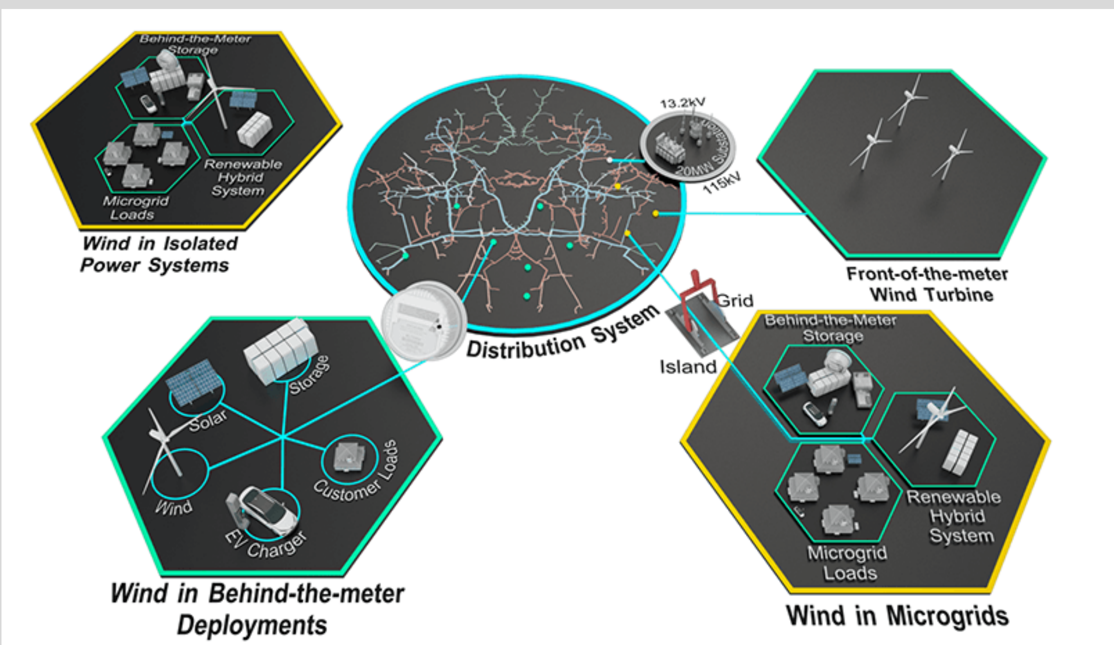
MIRACL Publications Expand Information About Wind as a Distributed Energy Resource

Point of Contact: Jim Reilly, James.Reilly@nrel.gov

NREL's work leading the MIRACL project resulted in several NREL publications that provide key information to wind turbine manufacturers, inverter manufacturers, distributed energy resource implementors and technology developers, storage manufacturers, electric utilities, and others. These publications reflect ongoing research and analyses in validating wind energy technology to support the stability of future high contributions of wind energy in distributed grids, isolated grids, and microgrids and include the following:

- Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) Fact Sheet
- Distributed Wind Controls: A Research Roadmap for Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL)
- Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL): Use Cases and Definitions
- Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) Research: Controls
- Integration of Storage in the DC Link of a Full Converter-Based Distributed Wind Turbine: Preprint
- Distributed Wind Considerations From the IEEE 1547-2018 Revision.

Also published under the MIRACL project were two major publications by Idaho National Laboratory and Pacific Northwest National Laboratory.

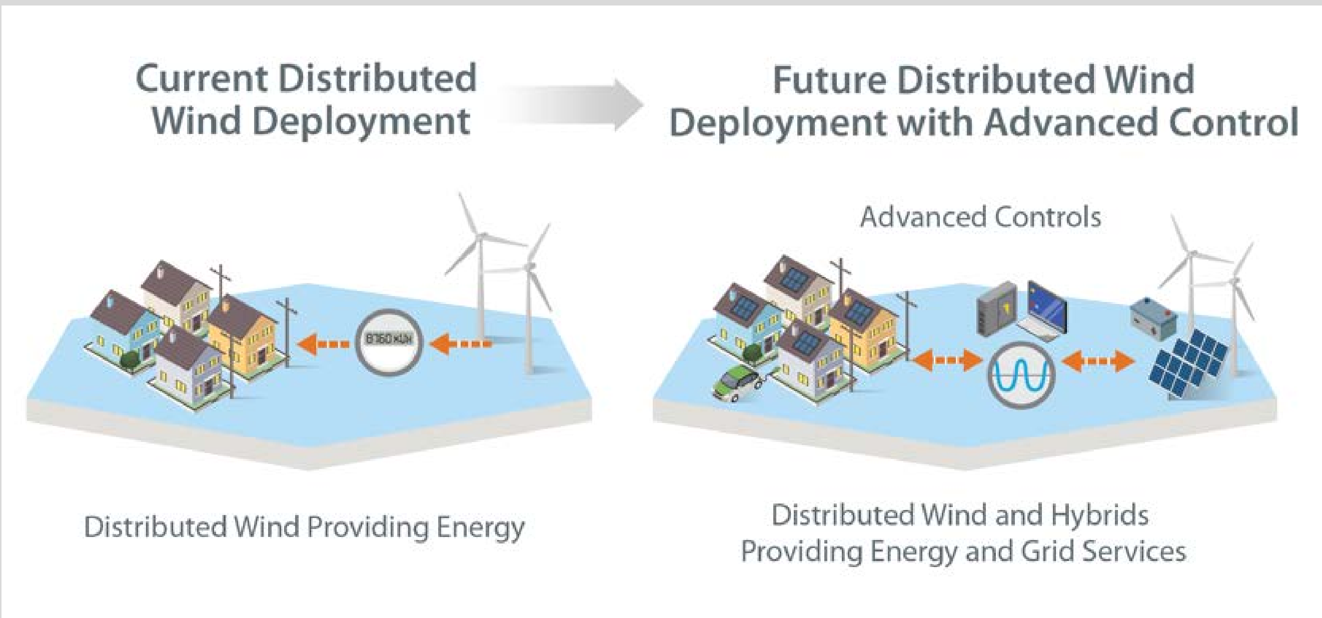


The Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad project is designed to advance wind-hybrid distributed energy systems to provide flexibility, security, and resilience to distribution systems and microgrids. This graphic shows how integrating wind energy with diverse technologies creates a larger system that provides a range of benefits, including improved resiliency and flexibility. *Image by Josh Bauer, NREL*

Research Demonstrates Advanced Controls for Distributed Energy Systems Can Support Isolated Grids

Point of Contact: Jim Reilly, James.Reilly@nrel.gov

Under the MIRACL project, NREL researchers demonstrated how high contributions of wind energy in isolated grids can be supported by advanced controls (such as inverters and human-machine interfaces) on distributed wind turbines. Models of the NREL Flatirons Campus and Sandia National Laboratories' (Sandia's) Scaled Wind Farm Technology facility, which featured distributed wind turbines, battery storage, solar photovoltaics, a diesel generator, and dynamic loads, illustrated how advanced controls can support grid frequency for distribution systems. In other research, desktop simulations using the Flatirons Campus MATLAB Simulink model configured as an isolated grid enabled researchers to evaluate how the controls currently perform, how they may be used in the future, and what the technical benefits of these advanced controls are for a wind turbine in an isolated grid. These simulations resulted in a forthcoming technical report.

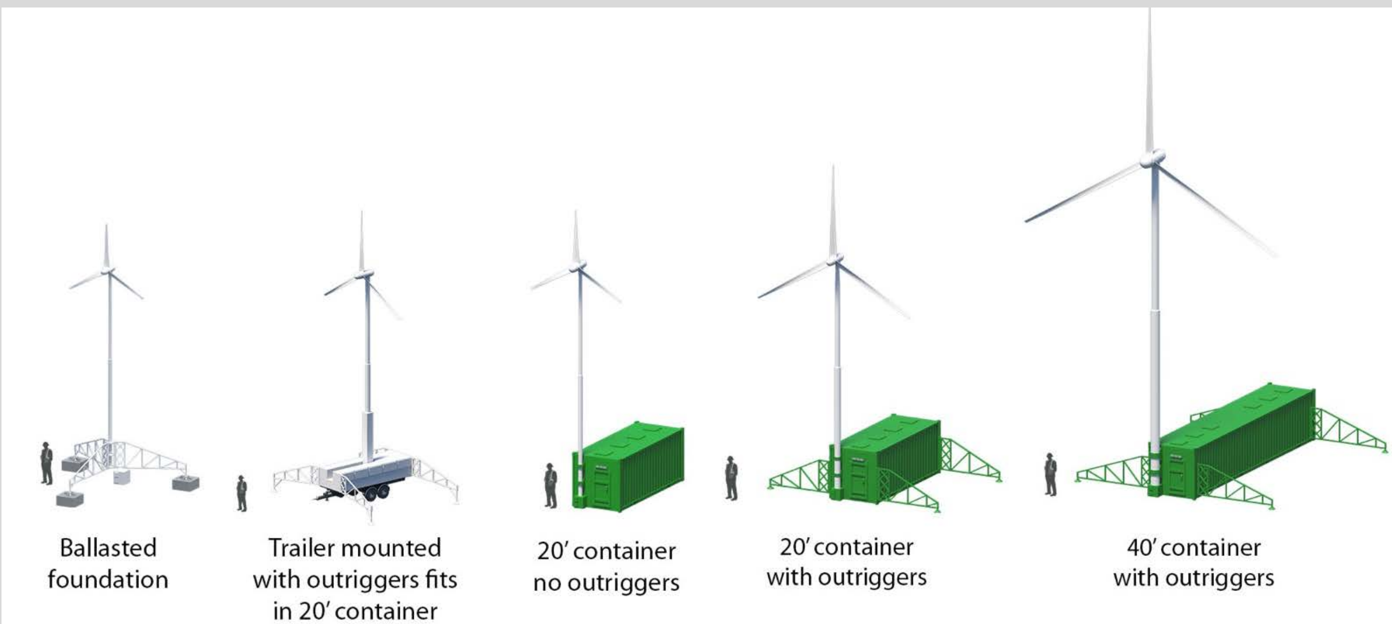


Traditional distributed wind energy deployments, shown on the left, supply power in kilowatt-hours (kWh) to distribution systems such as homes and businesses. The graphic on the right illustrates how MIRACL research will demonstrate advanced wind turbine controls that benefit distribution grids of the future. The sine wave in the center represents how wind, using advanced controls (such as inverters and human-machine interfaces), can support grid frequency for distribution systems. *Illustration by Fred Zietz, NREL*

Design Guidelines Established for Deployable Defense and Disaster Turbines

Point of Contact: Brent Summerville, brent.summerville@nrel.gov

As part of DOE's Defense and Disaster Deployable Turbine (D3T) project, NREL researchers conducted a desktop analysis to examine how container size and nonpermanent foundation requirements constrain the maximum deployable wind turbine size. The analysis indicates that a 20-foot (ft) shipping container can accommodate a wind turbine with a rated capacity of up to roughly 20 kW and a 40-ft shipping container can accommodate a turbine with a rated capacity of up to roughly 90 kW. This information will help inform the D3T design guidelines and procurement specification and is general enough to support multiple potential technology providers. This information will also be included in a pending report, *Design Guidelines for Deployable Wind Turbines for Defense and Disaster Response Applications*, which is scheduled to be released by Sandia before the end of 2021. The overall D3T effort (a partnership of Sandia, NREL, Idaho National Laboratory, and the University of Dayton Research Institute), will help assess the extent to which a viable market for deployable wind turbines in defense and disaster scenarios may exist and, if a potential market exists, how to best meet the needs of that market.



This figure shows various potential deployable wind turbine foundation options. *Image by Besiki Kazaishvili, NREL*

Microgrid Technical Requirements Released for Public Consideration

Point of Contact: Ian Baring-Gould, Ian.Baring-Gould@nrel.gov

NREL researchers participated in an international standards committee that released a draft of the Microgrids Technical Requirements Part 3-3: Self-regulation of dispatchable loads (IEC WD-1.1 62898-3-3). This guidance focuses on addressing load behavior that can support grid stabilization in response to frequency and voltage excursions. It could ultimately be used to improve the requirements for loads in general, because the same issues will develop on main grids as they become dominated by inverter-based power generation and motor and resistor loads are replaced with power-electronic-connected loads.

Simplified Method Proposed for Modeling Small Wind Turbine Blade Fatigue Spectra

Point of Contact: Scott Dana, Scott.Dana@nrel.gov

Minimizing material use and manufacturing cost while increasing annual energy production is important for the continued adoption of small wind turbines. High unit costs can be attributed to design conservatism when calculating fatigue loads of key structural components, such as blades. To address this challenge, NREL collaborated with international university researchers on a study published in *Wind Energy* that presents a modified method for calculating the fatigue spectra of small wind turbine blades. Intended for implementation early in the blade design stage, the method does not require complex aeroelastic simulations or field measurements and allows for rapid comparison of multiple rotor configurations.

Minimizing material use and manufacturing cost while increasing annual energy production is important for the continued adoption of small wind turbines like the Southwest WincsdPower Skystream turbines shown here on NREL's Flatirons Campus. *Photo by Dennis Schroeder, NREL 36248*

Research Leads to Improvements in Aeroelastic Modeling for Distributed Wind Turbine Archetypes

Point of Contact: Ian Baring-Gould, Ian.Baring-Gould@nrel.gov

NREL, in partnership with RRD Engineering and Windward Engineering, is working to improve the aeroelastic modeling tools for distributed wind turbines. These simulation tools enable designers to understand how their wind turbines will behave in the field, manage parameters that have the highest impact on the design, optimize the configuration, provide a basis for design certification, and simplify conformity assessment efforts following a change in the turbine design. The team has collected available models for key wind turbine archetypes and has identified gaps and research needs required to improve current modeling tools, such as OpenFAST, to better serve the distributed wind energy industry. Project deliverables identify a strategy to quantitatively redefine international standard requirements, enabling an informed upcoming revision of the IEC 61400-2 standard for distributed wind turbines.

U.S. National Small Wind Turbine Standard Receives Important Updates

Point of Contact: Ian Baring-Gould, Ian.Baring-Gould@nrel.gov

Following a decade of testing, design, and certification to the U.S. national standard for small wind turbines, a new revision to the ANSI/ACP-101-1 standard has been developed based on lessons learned. The revision focuses on streamlining requirements and minimizing compliance cost and time while maintaining the quality of certified wind turbines in the U.S. market, ensuring that the distributed wind energy industry can rapidly bring innovation to market, and driving down the cost of energy. This effort was led by NREL experts in collaboration with the Distributed Wind Energy Association and managed by the American Clean Power Association (ACP), an American National Standards Institute (ANSI) accredited standards development organization. A 2021 report provides the technical background of the revisions. The ANSI/ACP-101-1 standard is moving through the final stages of approval and is expected to be published in 2021.

NREL led a collaboration that revised the U.S. national standard for small wind turbines, like the one shown here. *Photo from Ray Byrne, International Energy Agency Wind Task 41*

IEA Wind Task 41 Launches International Distributed Wind Research Collaboration

Point of Contact: Ian Baring-Gould, Ian.Baring-Gould@nrel.gov

Under NREL leadership, the International Energy Agency Wind Technology Collaboration Programme (IEA Wind) Task 41 – Enabling Wind to Contribute to a Distributed Energy Future launched the Distributed Wind University Research Collaboration to facilitate global distributed wind research. IEA Wind Task 41 researchers conducted a series of virtual workshops at the end of November 2020, resulting in three university teams joining the collaboration: Murdoch University (Australia), RMIT University (Australia), and University of Massachusetts (United States). With a goal of matching the pace of cost reductions seen in other renewable energy technologies, specific research efforts include determining opportunities to scale down large wind turbine designs and upscale small wind turbine designs for use as distributed wind turbines.

NREL Partners with DTU To Change Worldwide Distributed Wind Energy Technology Standards

Point of Contact: Ian Baring-Gould, Ian.Baring-Gould@nrel.gov

Through IEA Wind Task 41, NREL is partnering with the Technical University of Denmark to build international support for a revision of the IEC 61400-2 standard and develop domestic and international standards for small and midsized wind turbines. The team is summarizing the shortcomings of the current standards, developing a research plan to update domestic and international standards, and working with partner organizations to change the standards.

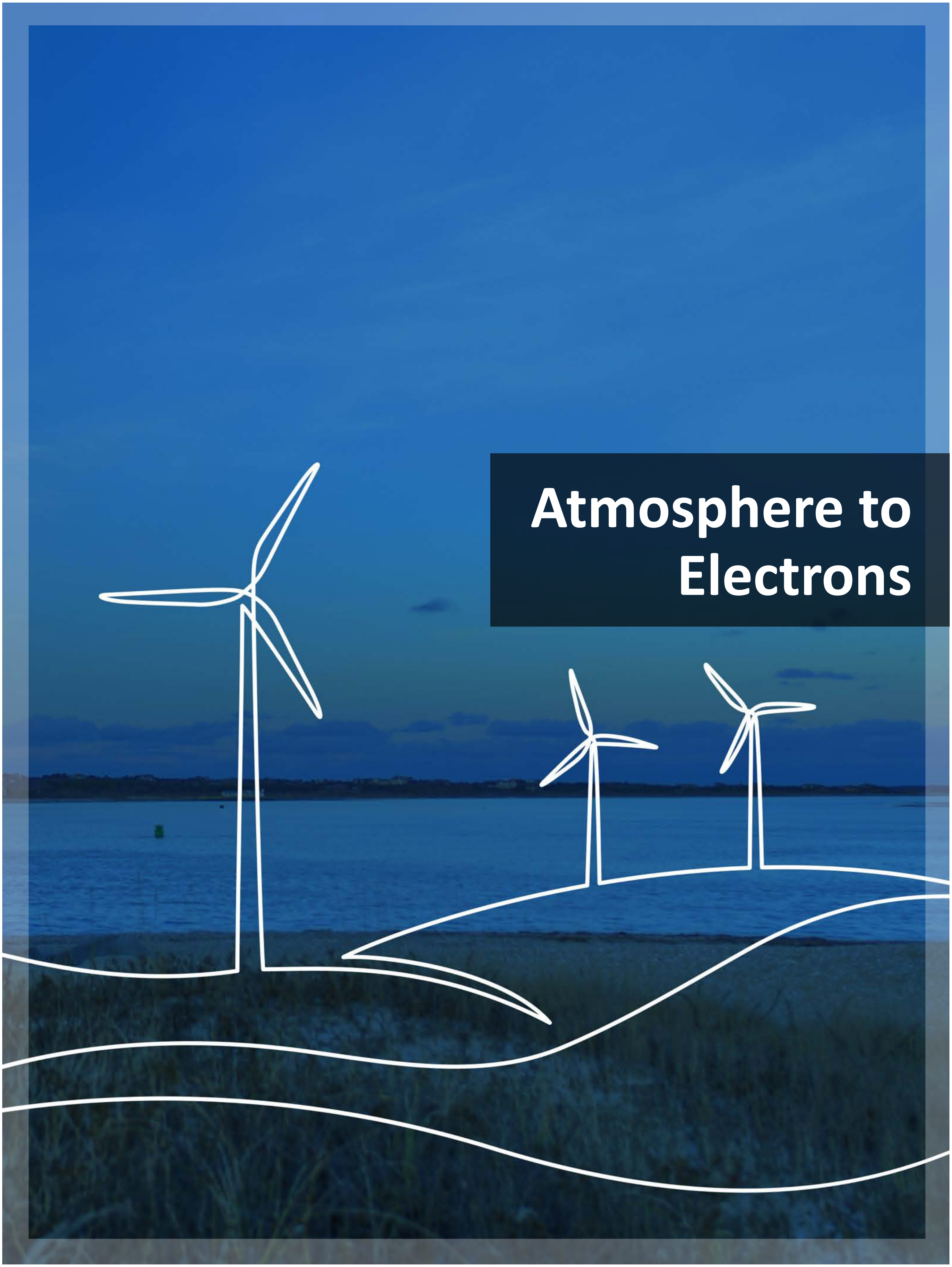
New Modeling Capabilities Reveal Distributed Wind Energy Balance-of-System Cost Drivers

Point of Contact: Parangat Bhaskar, Parangat.Bhaskar@nrel.gov

NREL researchers developed a new extension to the Land-Based Balance-of-System Systems Engineering model to estimate and analyze the balance-of-system capital costs for distributed wind systems installed in the United States. *Technology Innovation Pathways for Distributed Wind Balance-of-System Cost Reduction* features analysis results of these cost-reduction opportunities. NREL researchers also open-sourced the Windfarm Operations and Maintenance cost-Benefit Analysis Tool, which estimates operation and maintenance costs for distributed wind and utility-scale wind projects. In addition, NREL researchers developed a new model to generate power curves for stall-regulated machines and updated the current and future representative project cost and performance characteristics (including power curves) for distributed wind energy for residential, commercial, midsize, and large turbines.

An extension to NREL's Land-based Balance-of-System Systems Engineering model can estimate and analyze the balance-of-system capital costs for distributed wind energy systems installed in the United States. *Photo from Eocycle Technologies, Inc.*

Atmosphere to Electrons



Forecasters Get Wind of Mountain Impacts on Wind Power Performance

Point of Contact: Caroline Draxl, Caroline.Draxl@nrel.gov

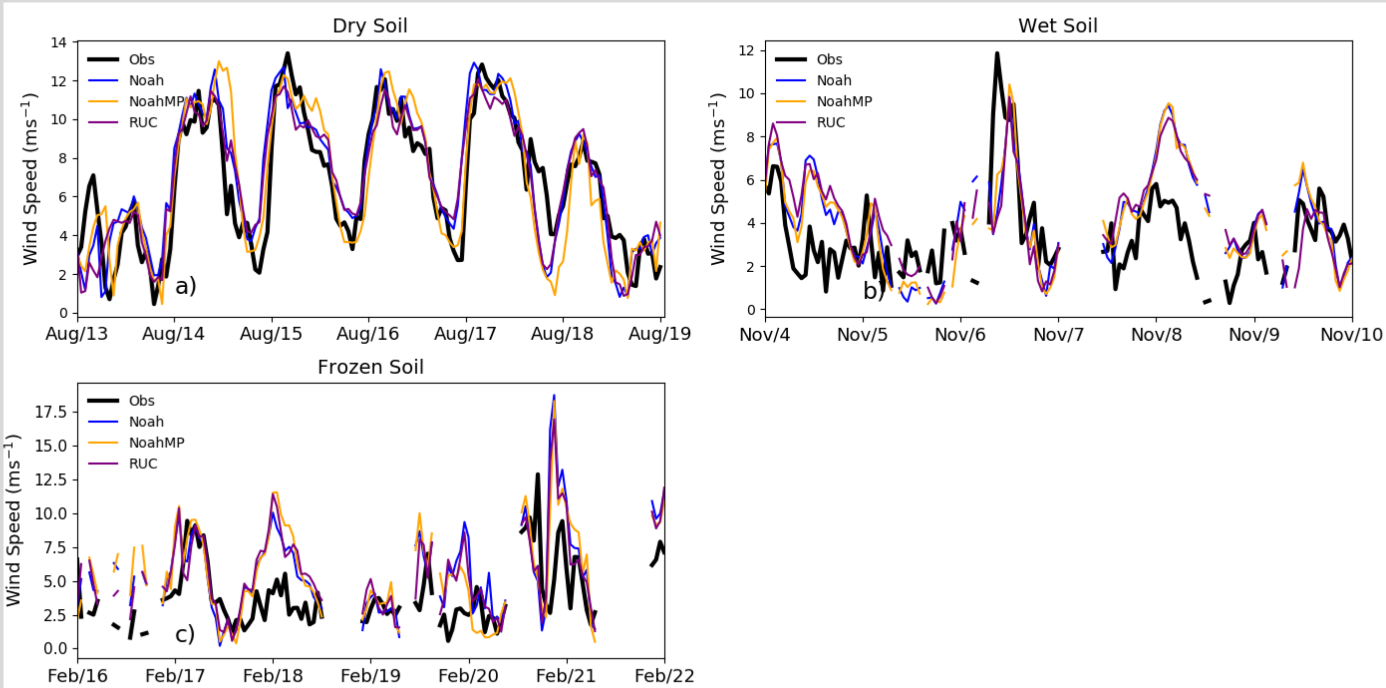
As part of the Second Wind Forecast Improvement Project (WFIP2), NREL researchers investigated the ability of the Weather Research and Forecasting Model to simulate mountain wave events and their impact on hub-height wind speed. The ascent of air over a mountain barrier can generate mountain waves that can impact annual energy production at wind power facilities. In this first of two similar studies, researchers found that the model can simulate and consistently predict the impacts of mountain wave events on hub-height wind speeds. In the second study, researchers discovered that the speed of wave propagation, magnitudes of wind speeds, and their wavelengths are important parameters for forecasters to recognize the risk for mountain waves and associated large drops or surges in power. For the wind power plant analyzed in this study, mountain-wave-induced fluctuations translate to approximately 11% of the total wind farm output being influenced by mountain waves. Predicting details of these events is valuable to wind energy stakeholders when designing, building, and forecasting at wind plants.

The ascent of stably stratified air over a mountain barrier can trigger the generation of mountain waves that can impact annual energy production at wind facilities. *Photo from Iberdrola Renewables, NREL 16105*

Soil Properties Impact Land Surface Modeling of Hub-Height Wind Speed

Point of Contact: Caroline Draxl, Caroline.Draxl@nrel.gov

To improve understanding of the physics of wind energy forecasts using the Weather Research and Forecasting Model, NREL researchers investigated the impact of three land surface models on simulating wind-turbine-hub-height wind speed under dry, wet, and frozen soil conditions. They compared the simulated wind speed, surface energy budget, and soil properties with the observations collected from WFIP2. Research results suggest that soil states affect land surface models on hub-height wind speed more than the type of land surface model. Over dry soil, there is a strong physical connection between the land surface and hub-height wind speed through near-surface turbulent mixing. Over wet soil, the simulated hub-height wind speed is less impacted, and over frozen soil, the land surface model seems to have limited impact on hub-height wind speed. These results provide useful potential guidance for future land surface model development.



Time series of observed and simulated wind-turbine-hub-height wind speeds over different soil conditions. *Figure from Monthly Weather Review*

Mesoscale-Microscale Coupling – Model Development and Validation WETO.1.3.2.401

Benchmark Cases Capture Features Necessary To Create High-Fidelity Flow Simulations

Point of Contact: Matt Churchfield, Matt.Churchfield@nrel.gov

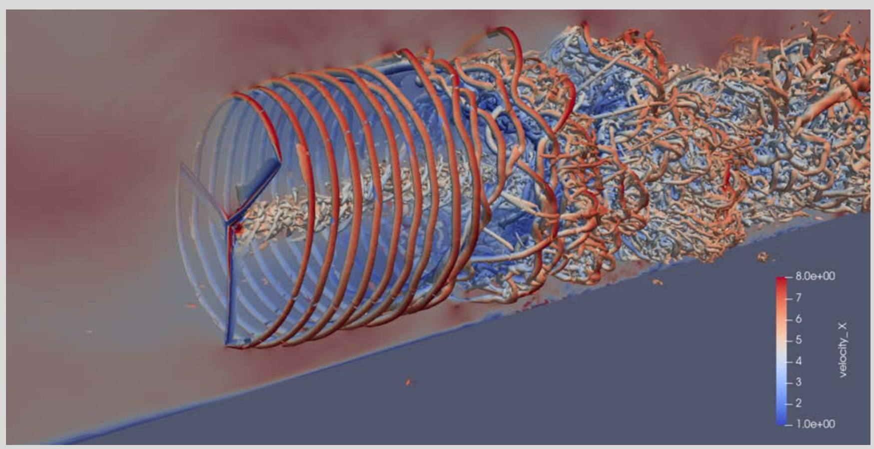
The complex terrain of the WFIP2 experiment region along the Columbia River in northeastern Oregon features hundreds of wind turbines and rugged terrain that can trigger atmospheric gravity waves—waves that move through a stable layer of the atmosphere. This region is also highly influenced by the regional-scale weather and the upstream Cascade Mountains. These conditions provide NREL researchers the features they need to create high-fidelity, ultrarealistic atmospheric flow simulations as part of the mesoscale-microscale coupling (MMC) project. The MMC project also developed offshore-wind-specific benchmark cases and applied MMC techniques to offshore conditions to better understand offshore-specific MMC research.

High-Fidelity Modeling WETO.1.3.3.401

Heavy Turbulence Ahead! Predicting Wind Power Plant Flow Dynamics

Point of Contact: Mike Sprague, Michael.A.Sprague@nrel.gov

A new hybrid computational fluid dynamics solver for blade-resolved wind turbine simulations was demonstrated by NREL researchers and collaborators. In this approach, the near-blade flow is solved by the unstructured grid code Nalu-Wind, which is embedded into—and two-way coupled with—the structured grid code AMR-Wind using overset meshes. A loosely coupled approach to solving the global linear systems is described in an article the team published in the *Journal of Computational Physics*. With this hybrid approach, Nalu-Wind can capture the thin boundary layers around wind turbine blades while the highly efficient data structures and algorithms of AMR-Wind can be leveraged for the far-field flow.



Visualization of the flow field around the 2-MW NM80 wind turbine under turbulent inflow. The isosurfaces highlight vortical structures, and the colors indicate velocity magnitude. The simulation was performed to validate the code against the DanAero experiment as part of IEA Wind Task 29 using NREL's Eagle supercomputer, producing 120 million grid points. *Image courtesy of Ganesh Vijayakumar, Shreyas Ananthan, and Michael Brazell, NREL*

Overset Meshes for Incompressible-Flow Simulations Help Predict Wind Plant Aerodynamics

Point of Contact: Ashesh Sharma, Ashesh.Sharma@nrel.gov

Motivated by the development of next-generation simulation capabilities to improve our understanding of the acoustically incompressible flow physics governing whole wind power plant performance, NREL researchers and industry partner Parallel Geometric Algorithms LLC explored the use of overset meshes as a means to greatly accelerate simulations and facilitate mesh generation. In this approach, meshes for individual wind power plant components (e.g., blades, tower, terrain) can be created independently then coupled through their overlapping domains. Findings indicate good accuracy is achieved for engineering quantities of interest and show great promise for faster simulations. Most importantly, this research demonstrates how different computational fluid dynamics codes can be rigorously coupled so that optimal solvers can be chosen for their respective domains.

Energy Research and Forecast Modeling	WETO.1.3.3.402

Forecasting Model Plants Seeds for Understanding Energy Available for Harvest

Point of Contact: Eliot Quon, Eliot.Quon@nrel.gov

Built on the AMReX software framework, researchers from NREL, Lawrence Livermore, Argonne, and Pacific Northwest national laboratories finalized the requirements and design and began developing the new Energy Research and Forecasting model. This model will address a gap in next-generation computing capabilities by improving our ability to simulate a wide range of physical phenomena in environmental flow fields at a dramatically reduced computational cost. When coupled to a computational fluid dynamics solver, such as AMR-Wind, these flow fields provide essential information about the real wind power plant environment and improve understanding of the energy available to harvest.

High Fidelity Modeling Toolkit	WETO.1.3.3.403

Advanced Siting Capabilities Result in Optimal Layouts of Wind Power Plants

Point of Contact: Shashank Yellapantula, Shashank.Yellapantula@nrel.gov

An NREL team is developing a design tool that will enable advanced siting capabilities for optimal layouts of wind power plants. With an increased demand for wind power generation, it is critical to improve the ability to design efficient wind turbines and site-specific wind plant layouts for maximum power capture. Current wind industry practices do not accurately account for blockage, site-specific variations, complex terrain, and mesoscale influences. Relying on the ExaWind tool suite, the team is operationalizing state-of-the-art models with multiple fidelity levels to address gaps through predictive, high-fidelity simulations on high-performance computing resources in engineering models currently used in the wind industry.

Researchers Partner With GE Renewable Energy To Investigate Physics of Large, Land-Based Wind Turbine Rotors

Point of Contact: Paula Doubrawa, Paula.Doubrawa@nrel.gov

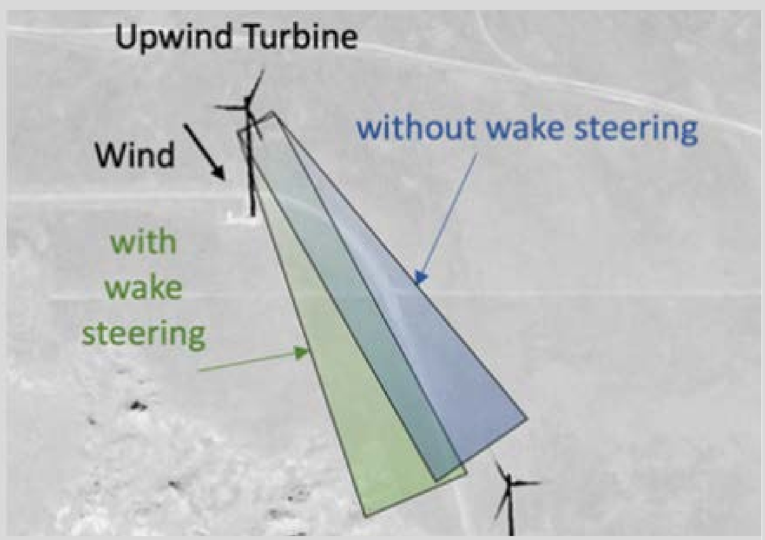
NREL and Sandia are partnering with GE Renewable Energy to collect detailed field measurements of a large, land-based wind turbine operating in Texas. The wind around the rotor will be measured with 18 different sensors. The bending motions of the 200-ft-long blades will be captured with a camera system, which will take high-resolution photos of the entire turbine. The data collected will allow researchers to evaluate and improve upon the quality of computer simulations that are used for wind turbine research, design, and control. Improved simulations will enable a more efficient capture of wind resources, contributing to the country's renewable generation goals.

This 2.8-MW General Electric wind turbine, located in the Texas wind belt, will be the focus of a 2022 field experiment undertaken by NREL, Sandia, and GE Renewable Energy. *Photo by Chris Kelley, Sandia*

Researchers Assess the Structural Load Impacts of Wake Steering

Point of Contact: Paula Doubrawa, Paula.Doubrawa@nrel.gov

NREL engineers determined that wake steering is a viable control approach for wind turbines that does not push the load envelope beyond normal operational values. The aerodynamic footprint on a downwind turbine will change based on how much of the upstream wake it experiences. Researchers steered an upwind turbine into and out of the wind in intervals with a yaw mechanism. By analyzing the loads on the blades, tower, and turbine shaft of a downstream turbine, the researchers found minimal differences in loading when the upstream rotor is aligned versus misaligned with respect to the wind.



A schematic demonstrating wake steering shows how an upwind wind turbine can be controlled to steer its wake out of the way of downwind turbines. *Image by Katherine Fleming and Eric Simley, NREL*

Aeroacoustic Assessment of Wind Plant Control WETO.1.3.4.403

New Data Sound Good for Wind Energy

Point of Contact: Nicholas Hamilton, Nicholas.Hamilton@nrel.gov

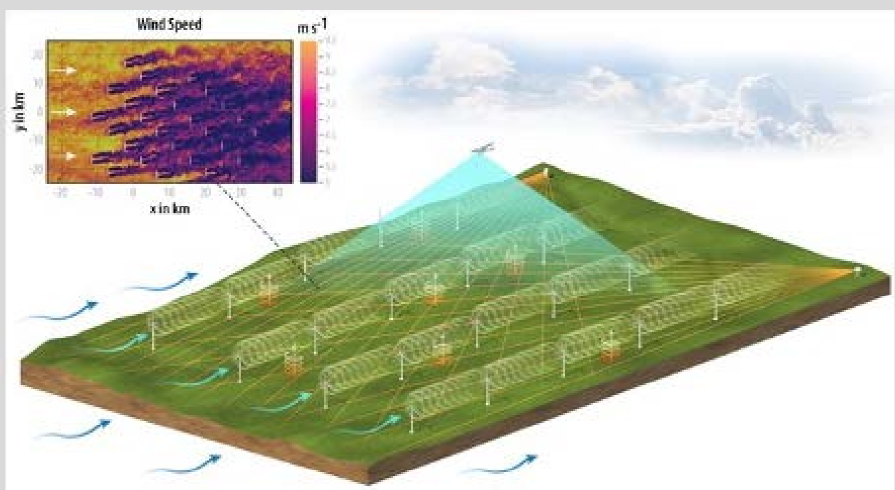
Researchers developed new aeroacoustic measurement capabilities to make full-field noise observations. They collected two types of sounds beneath a DOE 1.5-MW wind turbine: audible range and infrasound, too low for human ears to perceive. They also captured full-field data and created a map of variations in sound levels near the wind turbine. Results show that operating at 25 degrees of yaw reduces wind turbine noise up to 6 decibels in certain areas around the wind turbine, almost halving the total sound pressure level in those areas. Data collected were validated against aeroacoustic models in OpenFAST, which will later be made publicly available through the Atmosphere to Electrons Data Archive and Portal. According to this research, modern wind plants could be quieter than expected, and that sounds good!

American WAKE experimeNt (AWAKEN) WETO.1.3.4.404

Field Campaign Set To Create World's Highest-Resolution Map of Wind Plant Atmospheric Effects

Point of Contact: Patrick Moriarty, Patrick.Moriarty@nrel.gov

NREL researchers laid the groundwork to launch the American WAKE experimeNt (AWAKEN), an international, multi-institutional wind energy field campaign funded by WETO. From January 2022 through October 2023, NREL researchers used sensors, drones, and manned aircraft to study how winds move through Oklahoma wind power plants. With that data, the team will create the highest-resolution map of atmospheric effects in and around wind plants. By detailing how wind turbine wakes affect turbines downstream, AWAKEN could help wind plants recover some of the 10% (or more) of potential energy and revenues lost by wakes.



The AWAKEN team will deploy advanced instrumentation and partner with wind power plant owners, wind turbine manufacturers, and remote-sensing technology companies to create the highest-resolution map of atmospheric effects in and around wind plants. *Illustration by Besiki Kazaishvili, NREL*

Study Finds Increased Model Accuracy When Accounting for Flow Conditions Near Wind Turbine Wakes

Point of Contact: Paul Fleming, Paul.Fleming@nrel.gov

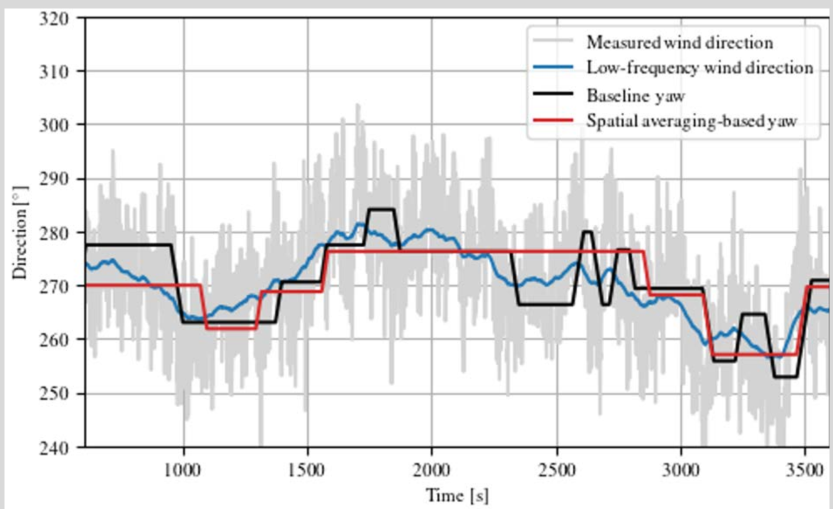
Models that consider air flow conditions near wind turbine wakes more closely match observed power production data from the first four rows of offshore wind turbines at the Lillgrund Wind Plant in Sweden, according to an NREL study. Results indicate that deep-array, wake-superposition schemes have the greatest influence on decreasing model error. Incorporating wake-loss-reduction strategies into simulations that model airflow around wind turbines could help users raise the annual energy production at wind power facilities.

Enabling Autonomous Wind Plants Through Consensus Control WETO.1.3.5.402

Consensus Control Demonstration Shows Promise for Improved Power Output

Point of Contact: Jennifer King, Jennifer.King@nrel.gov

Researchers demonstrated the effectiveness of Collective Consensus Controller for Performance Optimization technology—a cooperative wind farm controller that incorporates information from local sensors in real time to better align wind turbines to the prevailing wind direction—in new analysis using wind farm data. The study, conducted in partnership with Renewable Energy Systems, showed that yaw activity of turbines can be significantly reduced while potentially boosting power production. This work advances research that treats the entire wind farm as a control system with individual turbines in the network acting as separate agents. Findings may boost wind farm production by improving communication between wind turbines in a network.

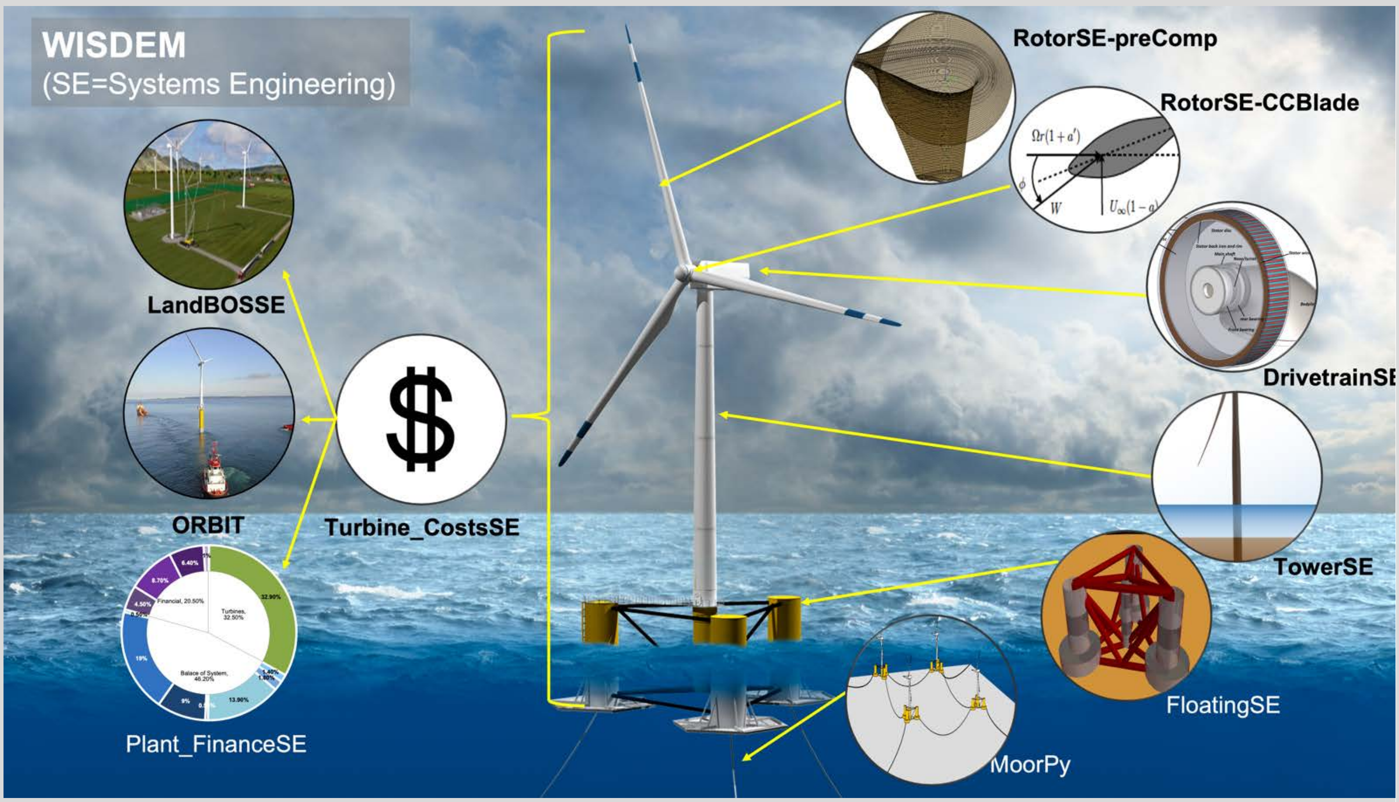


A simulation showing the reduction in yaw activity when using wind direction measurements aggregated across wind turbines (red) versus using only turbine information (black). *Image courtesy of Michael Sinner, NREL*

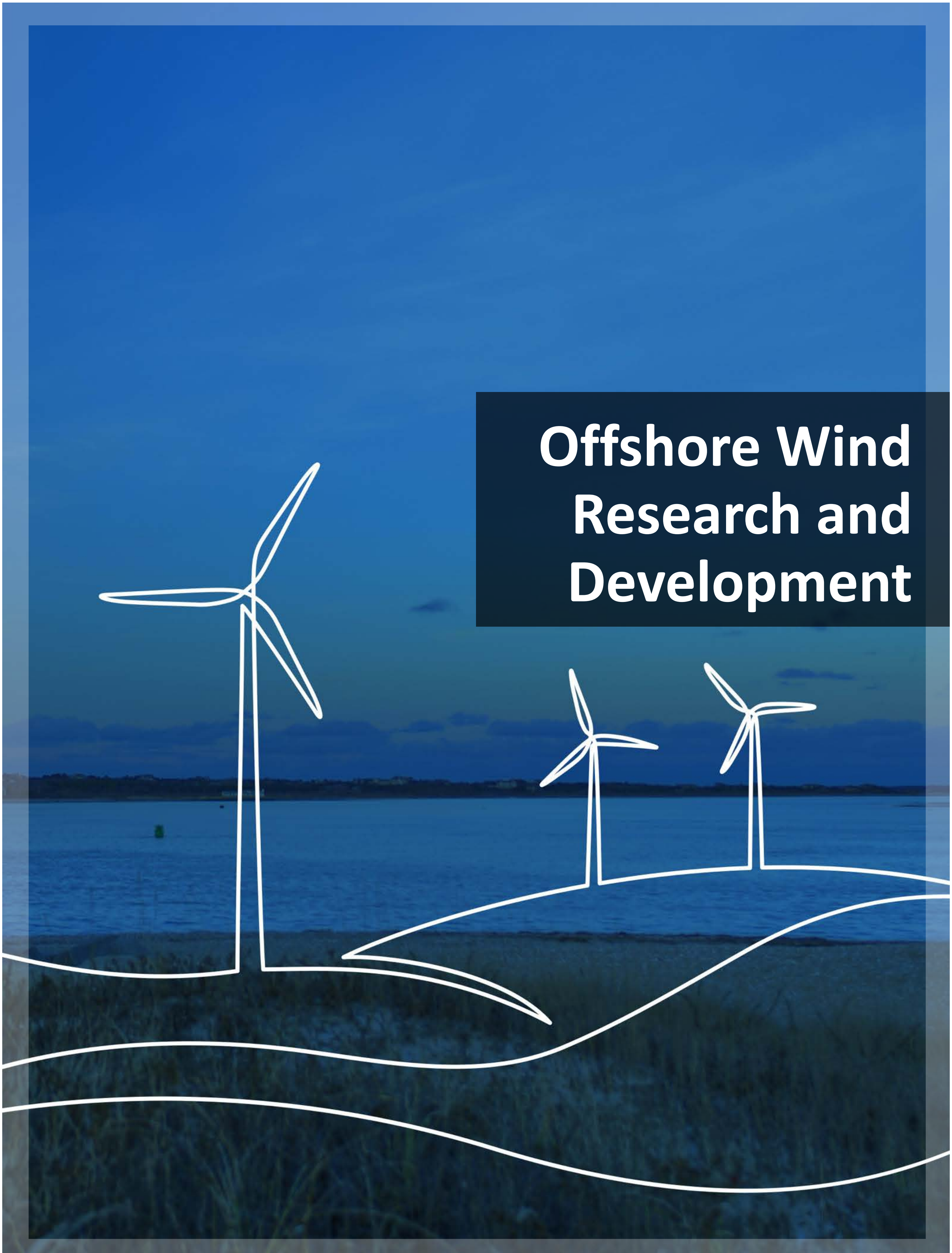
Words of WISDEM—Software Upgrade Improves User Experience

Point of Contact: Garrett Barter, Garrett.Barter@nrel.gov

Recently upgraded to enhance usability, the Wind Plant Integrated Systems Design and Engineering Model® (WISDEM®) creates a virtual, vertically integrated wind power plant that uses modules that cover the full turbine engineering and cost-of-energy balance sheet to capture system-level, cost-benefit trade-offs, from components to operation. WISDEM can help engineers improve system-level performance and reduce costs. The new release represents a complete overhaul of how the user interacts with WISDEM and how the modules couple with each other. Notable enhancements include documentation, example problems, new input files, new models, and expanded testing.



WISDEM modules cover the full turbine engineering and cost-of-energy balance sheet to capture system-level cost-benefit trade-offs.
Illustration by NREL



Offshore Wind Research and Development

Demonstration of NREL Modeling Capability to Design the Next Generation of Floating Offshore Wind Turbines (TCF) WETO.1.4.0.400

New Public Capability for Designing Floating Substructures of Offshore Wind Turbines Released

Point of Contact: Jason Jonkman, Jason.Jonkman@nrel.gov

A collaborative project with industry partners Stiesdal Offshore Technology and Magellan Wind resulted in an upgraded version of OpenFAST, which has been released to the public wind energy community to enable next-generation floating wind turbine designs. The new capability to compute floating substructure flexibility and member-level loads was verified through model-to-model comparisons using data from the full-scale TetraSpar Demonstrator, provided by Stiesdal. The new capability in the upgraded release of OpenFAST is critical for enabling the design of floating offshore wind turbine substructures, especially newer designs that are streamlined, flexible, and cost-effective.

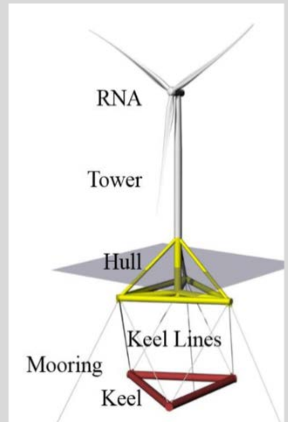


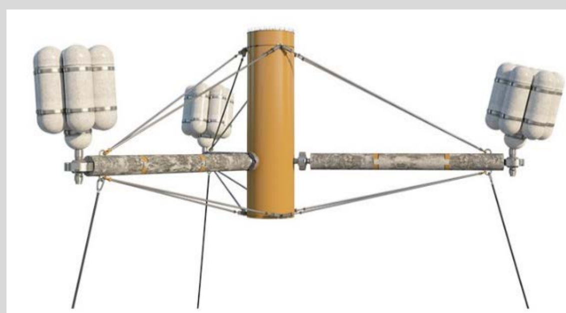
Illustration of the full-scale TetraSpar Demonstrator. *Image from Stiesdal Offshore Technologies*

Model Test of an Innovative Offshore Floating Wind System (TCF) WETO.1.4.0.401

Innovative Offshore Floating Wind Platform Moves Closer to Commercialization

Point of Contact: Senu Sirnivas, Senu.Sirnivas@nrel.gov

SpiderFLOAT, NREL's patent-pending floating offshore wind system, moved closer to commercialization after plans to conduct subscale model evaluations of the technology were finalized with the University of Iowa wave basin facility. Results of the wave-tank research will inform design modifications that computer simulations alone cannot achieve. Featuring modular components that resemble spider legs, SpiderFLOAT began as an NREL Laboratory Directed Research and Development project and was then selected to participate in the DOE Energy I-Corps and Technology Commercialization Fund (TCF) programs. Equinor, owner of the world's first floating offshore wind farm off Scotland, provided funding through the TCF that will enable this upcoming scale-model research. SpiderFLOAT has the potential to make floating systems cost competitive with land-based and offshore fixed-bottom systems, thereby unlocking the U.S. market in deep-water areas.

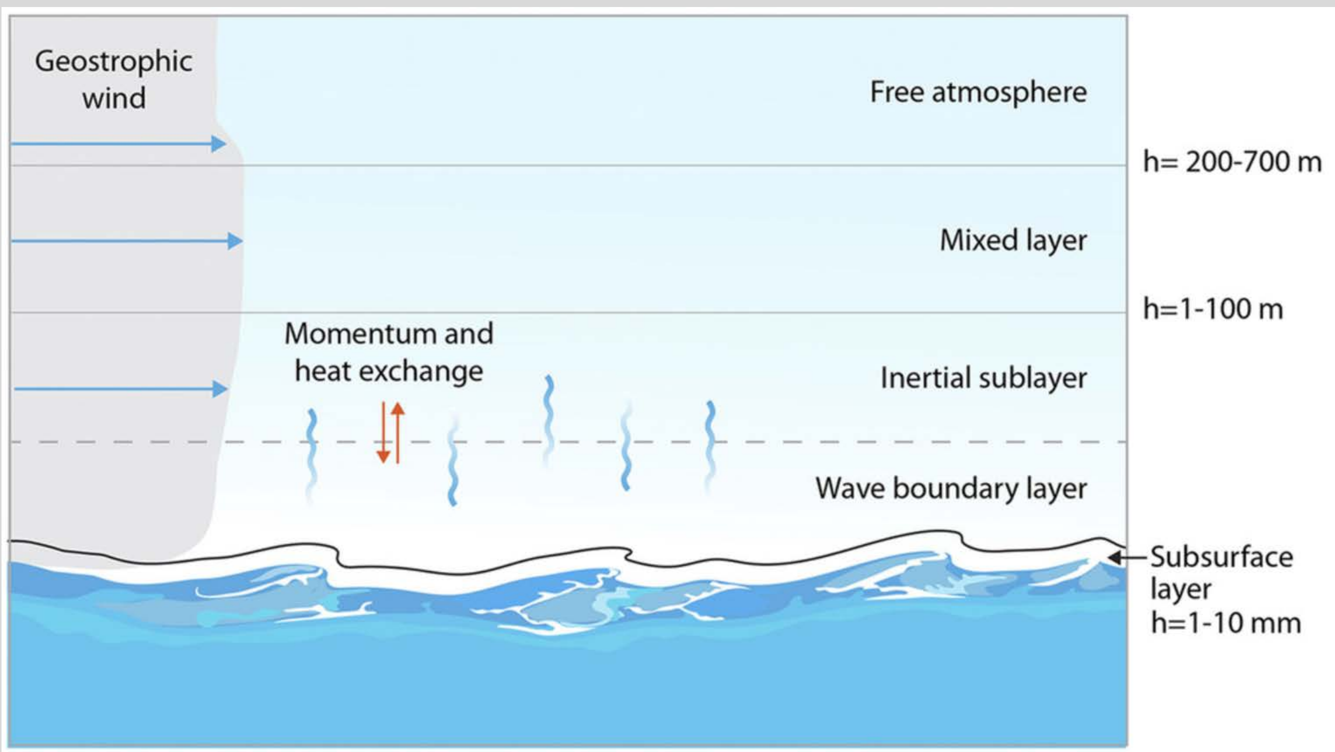


SpiderFLOAT has the potential to substantially reduce costs by simplifying construction and maintenance logistics for deep-water wind systems in challenging offshore marine environments. *Image by Josh Bauer, NREL*

Simulations Show Waves Play Important Role in Wind-Water Interaction Dynamics

Point of Contact: Caroline Draxl, Caroline.Draxl@nrel.gov

Accurately depicting the interactions between winds and ocean waves in numerical models is critical to offshore wind energy development. A team of NREL researchers reviewed existing wind-wave parameterizations and coupling models that have advanced the understanding of marine meteorology. The team conducted simulations that show that interactions have confirmed a hypothesis that ocean waves can impact wind at the ocean-atmosphere boundary layer. Nalu-Wind, a verified, open-source, high-fidelity computational fluid dynamics model, was used to obtain direct numerical simulations of turbulent air flow above waves and large-eddy simulations of an atmospheric boundary layer over swells. The data can be used to develop lower-fidelity engineering tools, highlight the state of the art in modeling air-sea interactions, and shed light on future model development. The results, which suggest that wind speed and its fluctuations are affected by ocean wave age and steepness, can improve assessment of offshore wind power plant design, production, mechanical loads, and optimization.

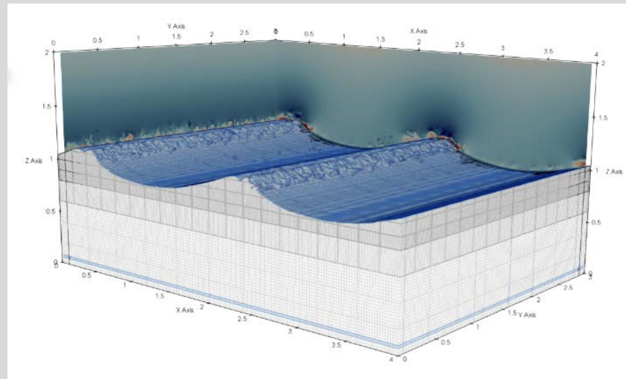


This schematic shows the vertical structure of the atmosphere above ocean waves. NREL researchers recently conducted a review of models that couple wind and wave dynamics. *Source: Deskos, G.; Lee, J.; Draxl, C.; and M. Sprague. (2021).* Journal of the Atmospheric Sciences. *78(10):3025–3045.* [10.1175/JAS-D-21-0003.1](https://doi.org/10.1175/JAS-D-21-0003.1)

Multiphase Flow Capabilities Added to High-Fidelity Offshore Wind Simulations

Point of Contact: Mike Sprague, Michael.A.Sprague@nrel.gov

In collaboration with Sandia, NREL researchers implemented and validated a proof-of-concept, volume-of-fluid method using AMR-Wind. This is the first step toward simulating multiphase flows present at floating and fixed-bottom offshore wind power platforms and air-sea interfaces. The team also coupled AMR-Wind with OpenFAST, one of the three open-source codes in NREL's Floating Turbine High-Fidelity Modeling and Simulation project's ExaWind software stack, introducing actuator-line, whole-turbine modeling capabilities for midfidelity offshore wind simulations. These efforts will improve understanding of aerodynamics and hydrodynamics at floating and fixed-bottom offshore wind power plants, helping further technology development that can decrease cost and increase energy capture potential.



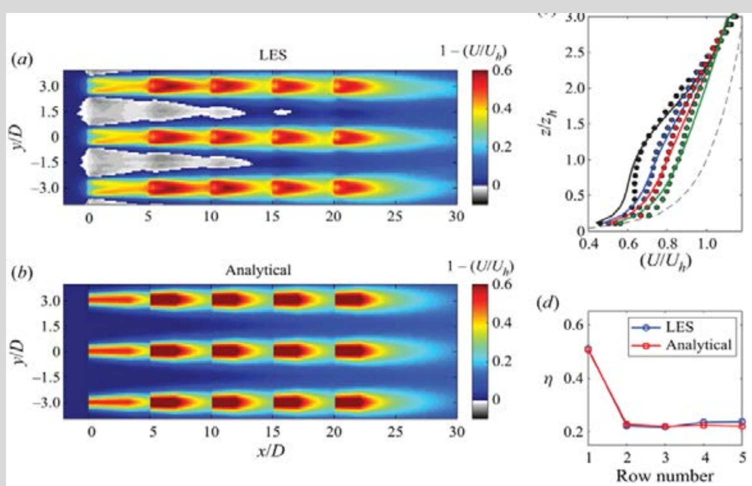
This figure shows the flow structure around an NREL 5-MW wind turbine rotor generated by the ExaWind Nalu-Wind high-performance computational code. *Graphic by Shreyas Ananthan, NREL*

Offshore Wind Plant Controls WETO.1.4.2.402

NREL Improves Offshore and Hybrid Wind Power Plant Array Model

Point of Contact: Paul Fleming, Paul.Fleming@nrel.gov

NREL researchers completed a major update to the FLOw Redirection and Induction in Steady State (FLORIS) framework, adding new and improved models of wakes, wake velocity, and wind farm blockage. These models can be used to better coordinate and optimize large, multiturbine offshore wind power plant arrays. The team also incorporated electrical and non-wind-generation models and dispatch strategies into FLORIS. These new features can help optimize the design and dispatch of hybrid wind-solar energy and wind energy storage systems, which could enable renewable energy use in a wider range of situations and potentially lower costs of renewable power generation. Finally, in collaboration with Durham University, the research team developed a new cumulative model that requires no ad hoc superposition to evaluate turbine wakes in offshore wind farms. The team also compared this new analytical model with large-eddy simulations.

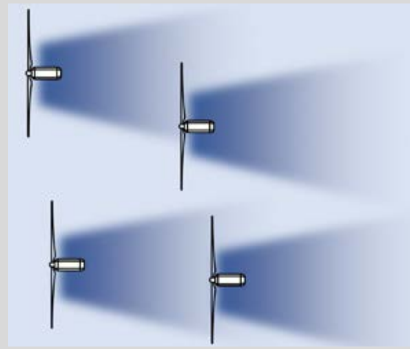


This image shows good agreement when comparing between the new, analytical, cumulative wake model and large-eddy simulations (LES). *Source: Bastankhah, M.; Welch, B.; Martínez-Tossas, L.; King, J.; and Fleming, P. (2021).* Journal of Fluid Mechanics*. 911(A53). doi:10.1017/jfm.2020.1037*

Researchers Estimate Cumulative Wake Effects of Wind Turbines in Wind Power Plants

Point of Contact: Paul Fleming, Paul.Fleming@nrel.gov

Working together with partners at Durham University, NREL researchers determined how to estimate cumulative wake effects in wind power plants based on engineering wake models, solving an approximate form of conservation of mass and momentum for a wind turbine in an array. Researchers directly solved flow-governing equations for a turbine that experiences upwind turbine wakes; therefore, the developed model can predict the flow distribution in a wind power plant without the need for any ad hoc superposition method. Results show that there are important non-negligible terms other than the momentum deficit and thrust force in the mass and momentum equations.

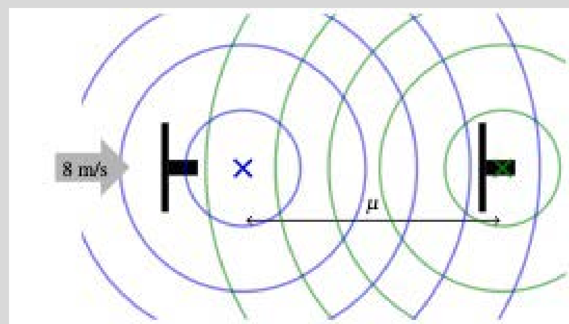


NREL researchers determined a simple way to predict the cumulative wake deficit within a wind farm with an arbitrary layout, like the one shown here. *Graphic by NREL*

Wind Direction Spatial Filtering Increases Energy Production

Point of Contact: Paul Fleming, Paul.Fleming@nrel.gov

NREL researchers set out to determine whether using spatial averaging between wind turbines to generate wind direction estimates could improve the energy production of a wind power plant. Using a weighted average approach, the team found that estimates employing spatial filtering were able to provide a small increase in wind energy production in a simulated six-turbine wind power plant. When wake steering was implemented together with spatial averaging, the energy production was increased by around 0.7% compared to using wake steering alone in the wind conditions studied. They also found that the use of averaging resulted in considerably lower overall turbine yaw activity.

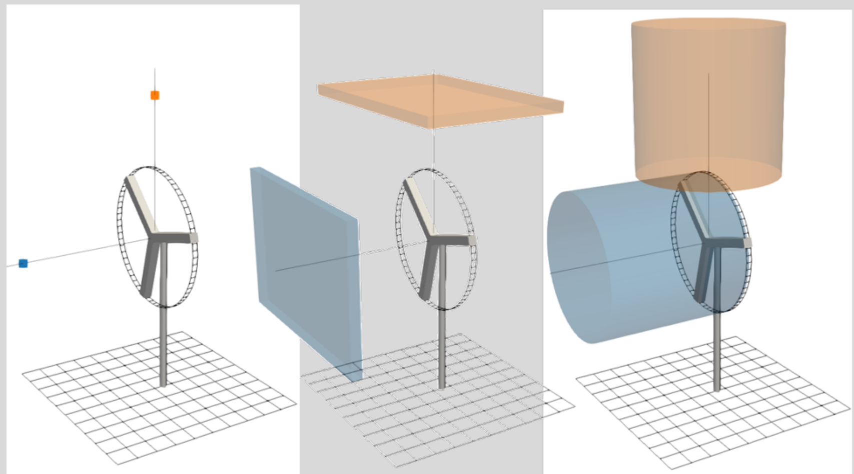


Wind turbines share measurements to improve wind direction estimates; weighting functions determine the contributions from each turbine. *Image by Michael Sinner, NREL*

Study Identifies Contributors to Wind Farm Blockage

Point of Contact: Garrett Barter, Garrett.Barter@nrel.gov

To the wind, an entire farm is one large obstacle. "Blockage" at a wind farm refers to the slowdown of air even before it encounters wind turbines. Some of the media have considered this the culprit behind disappointing power production in some offshore wind energy projects. Recent NREL work has sought to better quantify and measure blockage as a performance metric and understand its sensitivities, such as how blockage changes with turbine spacing and alignment. With these metrics defined, NREL's research also shows how blockage can be minimized when designing wind turbine layouts for new offshore wind energy projects.



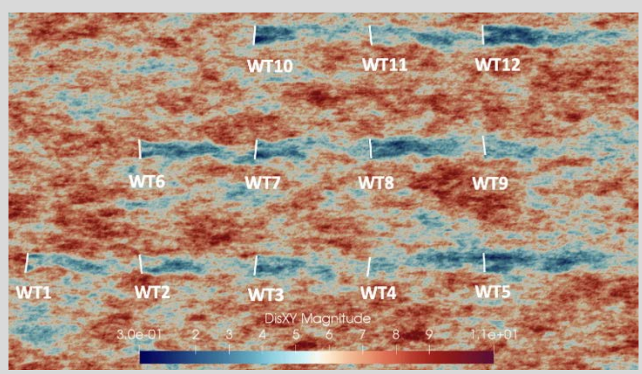
A schematic shows the quantitative measures or metrics of wind farm blockages. *Image by Ethan Young, NREL*

Floating Turbine Design and Validation Tools WETO.1.4.2.405

Multiturbine Engineering Simulation Now Available to the Public

Point of Contact: Jason Jonkman, Jason.Jonkman@nrel.gov

FAST.Farm, a new NREL engineering software, is now publicly available to help users improve wind plant-level design, inform the impact of plant control on turbine loading, and innovate the design of wind turbines in a plant environment. Working as an expansion on OpenFAST, the physics-based FAST.Farm engineering platform can simulate each wind turbine within a multiturbine land-based, fixed-bottom offshore, or floating offshore wind power plant. To better predict overall wind power plant performance and structural reliability, such as ultimate and fatigue loads of each individual turbine, FAST.Farm allows users to isolate physical aspects of a wind plant. This includes ambient winds, super controllers, wind turbine response, and wake effects. FAST.Farm is computationally efficient enough to be used for integrated loads analysis in a design context—a capability that can help improve wind plant performance and reliability.

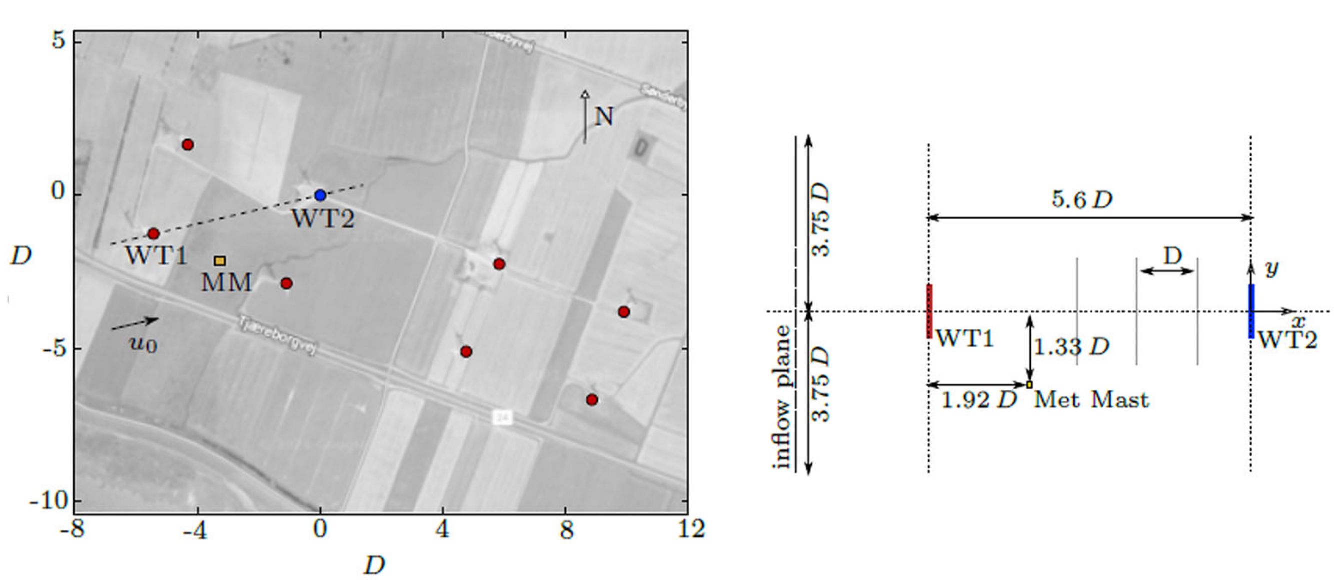


This snapshot of a FAST.Farm simulation of a wind plant with 12 fixed-bottom offshore wind turbines and random yaw misalignments highlights how the wakes of upwind turbines impact the response of downwind turbines. *Image by Kelsey Shaler, NREL*

Aeroelastic Wind Turbine Models Validated With Field Experimental Data

Point of Contact: Jason Jonkman, Jason.Jonkman@nrel.gov

NREL researchers and other members of IEA Wind Task 29 used field data and high-fidelity models to validate and improve wind turbine aeroelastic models. The team used data from a heavily instrumented NM80 2-MW wind turbine at Tjaereborg, Denmark, along with NREL's OpenFAST and FAST.Farm models. One upstream wind turbine imposed a wake on the heavily instrumented turbine that was used to model cases with turbulent wind inflow and wake influence. The validation work of IEA Wind Task 29, which recently concluded, will continue under the new IEA Wind Task 47, which will focus on new aeroelastic experiments and improvement of aeroelastic models for large 15-MW rotors.

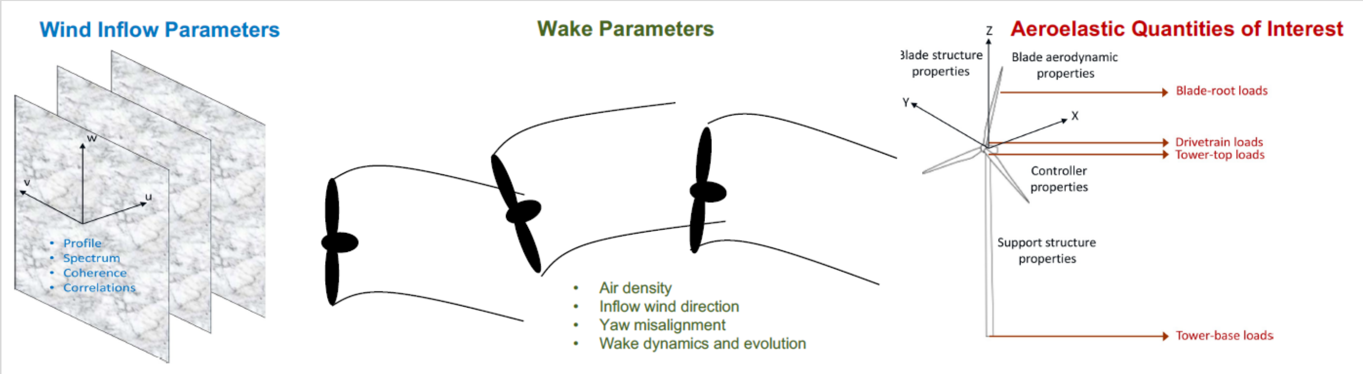


Experimental (left) and numerical (right) setup for the wake study within IEA Wind Task 29. Airflow passes through the upstream wind turbine (WT1) and the meteorological mast (MM) on its way to the downstream wind turbine (WT2). *Image by Jason Jonkman, NREL*

Sensitivity Assessment Identifies Most Influential Parameters on Wind Turbine Loading

Point of Contact: Jason Jonkman, Jason.Jonkman@nrel.gov

NREL researchers assessed the sensitivity of engineering model predictions of structural loading for turbines in a small wind power plant to identify the most influential parameters. This assessment involved running 126,000 simulations using FAST.Farm across a broad range of inflow and wake parameter variations. The team calculated how ultimate and fatigue loads for various wind turbine quantities of interest might change with inflow and wake parameters. The results of this work could not only better inform the wind turbine design process and site-suitability analyses but also help identify important measurement quantities when planning wind power plant measurement campaigns.

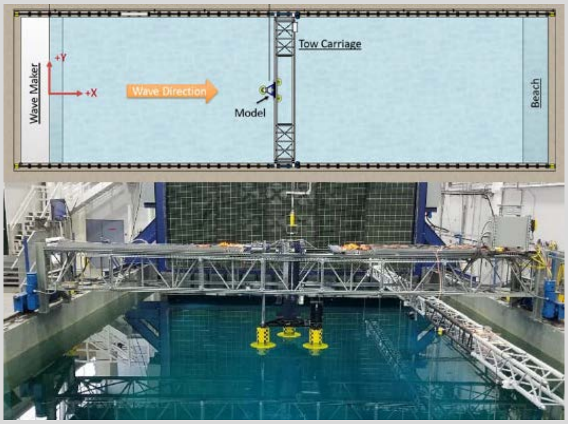


Various inflow and wake parameters were assessed to identify which most influence wind turbine ultimate and fatigue loads. *Image by Jason Jonkman, NREL*

Wave Tank Validation to Inform Floating Offshore Wind Energy Industry

Point of Contact: Amy Robertson, Amy.Robertson@nrel.gov

Using a wave tank at the University of Maine, a team of international researchers gathered data regarding the physics of floating wind power plants to better determine how water interacts with floating platform components. These data have been used to validate high-fidelity models and inform the improvement of lower-fidelity models. These more accurate modeling capabilities can be used to drive design innovation for the U.S. offshore wind energy industry. The information is publicly available on [DOE's Data Archive and Portal]() and incorporated into the NREL-led Offshore Code Comparison Collaboration, Continued, with Correlation and unCertainty (OC6) project under the IEA Wind Technology Collaboration Programme.

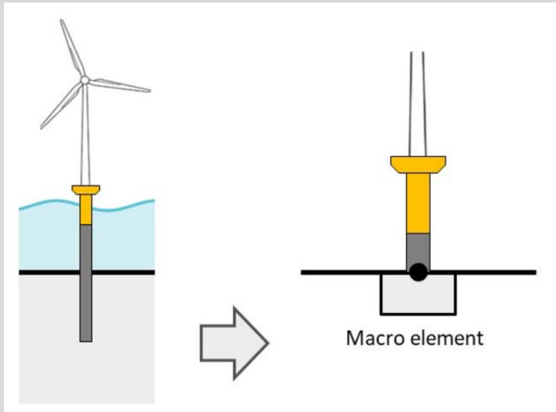


This photo shows the setup of the model floating wind component experiment in the W2 wave basin at the University of Maine. *Photo from the University of Maine*

Project Verifies Model Prediction of Loads With Soil-Structure Interaction

Point of Contact: Amy Robertson, Amy.Robertson@nrel.gov

In Phase II of the NREL-led OC6 project, researchers advanced capabilities for modeling interaction between piles in offshore wind jackets and monopiles and the soil around them. OC6 researchers coupled the REDucing cost of offshore WINd by integrated structural and geotechnical design approach (developed by the Norwegian Geotechnical Institute) with traditional offshore wind modeling tools to increase the accuracy of modeled soil-structure interactions. This capability will decrease the uncertainty in the offshore wind turbine design process, enabling the optimization of more cost-effective designs.



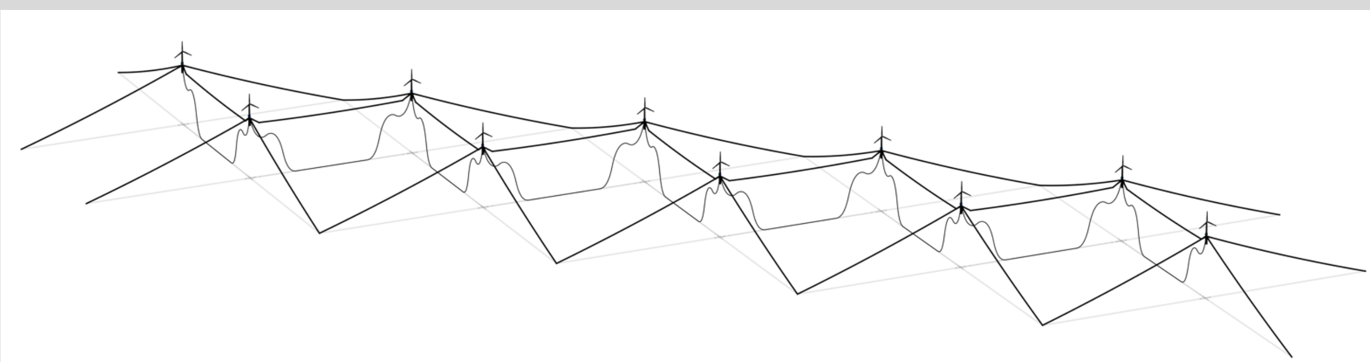
This illustration shows an offshore wind turbine (left) and macroelement modeling approach for soil-structure interaction (right). *Image by Amy Robertson, NREL*

Shared Mooring Systems for Deep-Water Floating Wind Farms (NYSERDA)	WETO.1.4.91.401

Shared Mooring Systems Advance Floating Wind Plant Design

Point of Contact: Matthew Hall, Matthew.Hall@nrel.gov

NREL researchers are designing floating wind power plants that use networks of interconnected mooring lines to improve structural efficiency in deep waters. The team developed a first-of-its-kind optimization framework for designing shared mooring systems and an enhanced NREL FAST.Farm simulation tool to analyze these interconnected floating wind turbine arrays. After analyzing more than 40 design concepts, the team developed and optimized a novel 10-turbine, shared-mooring array that demonstrates reduced mooring system costs, greater reliability, and a smaller environmental footprint.



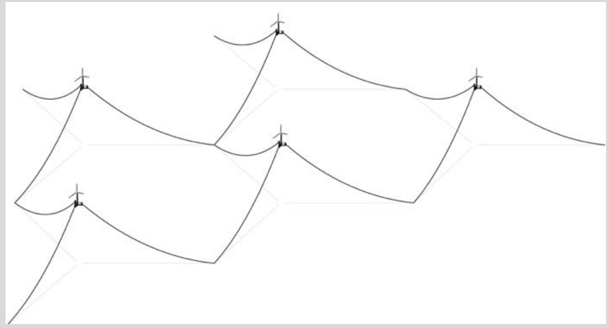
This illustration shows a 10-turbine, shared-mooring array concept developed and optimized by NREL researchers after they analyzed more than 40 design concepts. *Image by Matthew Hall, NREL*

Innovative Deepwater Mooring Systems for Floating Wind Farms (DeepFarm) (NYSERDA—Principle Power) WETO.1.4.91.402

Shared, Multiline Anchor Solutions Could Benefit Floating Wind Plants

Point of Contact: Matthew Hall, Matthew.Hall@nrel.gov

NREL researchers are working with Principle Power to explore the potential of floating wind power plants that use fewer anchors by sharing them between wind turbines. To properly evaluate these new designs, NREL is enhancing its FAST.Farm and MoorDyn modeling tools to accurately represent the effects of waves, currents, and seabed variations across all parts of a floating wind farm, including the mooring lines and power cables. These improvements will enable accurate estimation of the loads on multiline anchors, helping ensure their reliability.



This illustration shows five floating wind turbines moored to shared, multiline anchors. *Image by Matthew Hall, NREL*

A Validated National Offshore Wind Resource Data Set with Uncertainty Quantification (NYSERDA) WETO.1.4.91.404

Offshore Wind Resource Data Release Propels Wind Prospecting

Point of Contact: Nicola Bodini, Nicola.Bodini@nrel.gov

NREL has released several new offshore wind data sets that more accurately represent the U.S. offshore wind resource on a geospatial basis. Developed using a 20-year ensemble approach of state-of-the-art weather modeling tools and sophisticated resource assessment technologies, these updated data sets provide wind energy developers, consultants, and researchers with high-quality U.S. wind resource data that can inform offshore wind energy siting decisions and research. Additional data collected by DOE's wind resource characterization buoy, managed by the Pacific Northwest National Laboratory, help validate DOE's new offshore wind data set, available to the public on Wind Prospector, NREL's map visualization tool.

This map shows the 20-year average wind speed (in meters per second [m s^{-1}]) at 100 meters for the U.S. Mid-Atlantic region. *Map courtesy of Nicola Bodini, NREL*

Materials, Manufacturing, and Design Innovation

Additive Manufacturing in Wind Turbine Components and Tooling WETO.1.5.0.401

The Value of Advanced Manufacturing for Wind Energy

Point of Contact: William Scott Carron, William.Carron@nrel.gov

Advanced manufacturing—including three-dimensional (3D) printing and automation—can significantly advance wind energy technology research. But first, researchers and industry leaders need a better understanding of how 3D printing can improve wind turbine designs and manufacturing methods and, in so doing, increase wind turbine efficiency, supply chain resiliency, and domestic production. To accomplish this goal, NREL used data from Oak Ridge National Laboratory and Vestas to analyze the economic performance of three methods to manufacture a component of a wind turbine's nacelle (the casing that holds its generator). This work helps determine which manufacturing methods are most cost effective and efficient.

3D Printed Core Structures for Wind Turbines WETO.1.5.0.404

Building Next-Generation Blade Core Structures Through 3D Printing

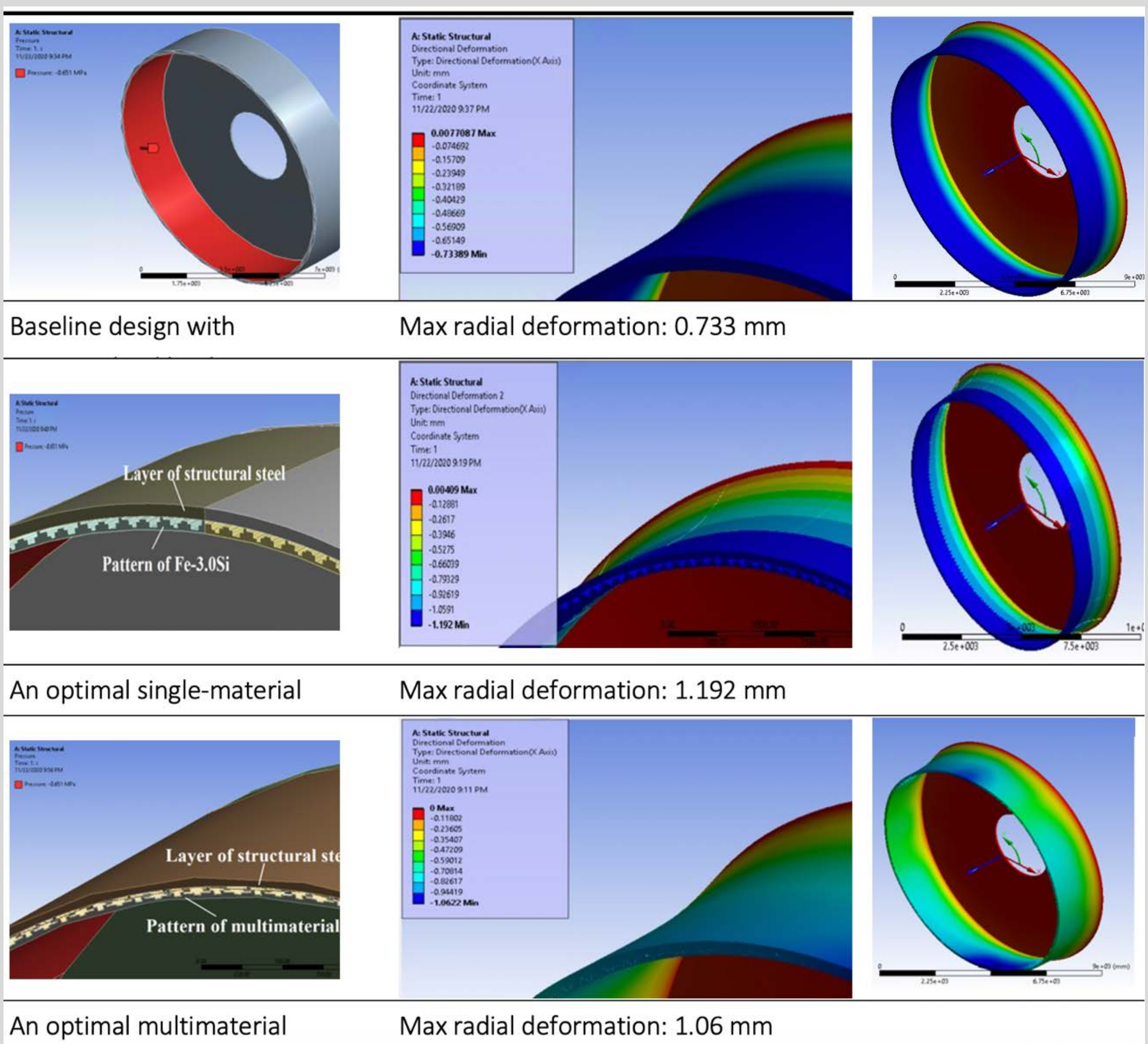
Point of Contact: William Scott Carron, William.Carron@nrel.gov

Wind turbine blades depend on sandwich composite technology (materials layered together, like a sandwich) to meet rigorous strength, stiffness, and buckling requirements. To achieve these standards and reduce costs, blade manufacturers rely on balsa and foam cores as layers in the blade sandwich. Through the 3D Printed Core Structures for Wind Turbines project, researchers at NREL are investigating how advanced manufacturing technologies, such as 3D printing, coupled with advanced structural optimization tools can improve current core solutions. For example, the team is exploring incorporating domestically sourced balsa to reduce dependency on foreign-sourced materials and minimize blade mass (other materials can absorb resin and become heavier). The research has the potential to not only improve the structural efficiencies of wind turbine blades but lay the foundation for new blade designs that can only be achieved through advanced manufacturing technologies.

Machine Learning and 3D Printing Trim Fat From Tomorrow's Generators

Point of Contact: Latha Sethuraman, Latha.Sethuraman@nrel.gov

Additively designed, 3D-printed, hard and soft magnets can help realize lighter wind turbine generators. They also enable optimized use of rare-earth elements in regions where they are most needed. Existing approaches to finding optimal magnet topologies can be time-consuming and result in wasting critical materials. Now, NREL researchers have used their novel software, called Manufacturing and Additive Design of Electric Machines enabled by 3-Dimensional printing – advanced machine learning (MADE3D-AML) to explore a more optimal magnet distribution for a 15-MW wind turbine generator. The MADE3D-AML approach took far less computational time, improved accuracy of performance predictions, and further reduced costs up to 9% by helping identify a wider choice of lightweight designs with 3D-printable novel compositions for magnets.



NREL's team is leading the charge on the design and manufacture of cost-effective, fully additively manufactured, direct-drive electric generators. *Image courtesy of Latha Sethuraman, NREL*

Drivetrain Reliability Collaborative Seeks Gearbox Failure Causes, Solutions

Point of Contact: Jonathan Keller, Jonathan.Keller@nrel.gov

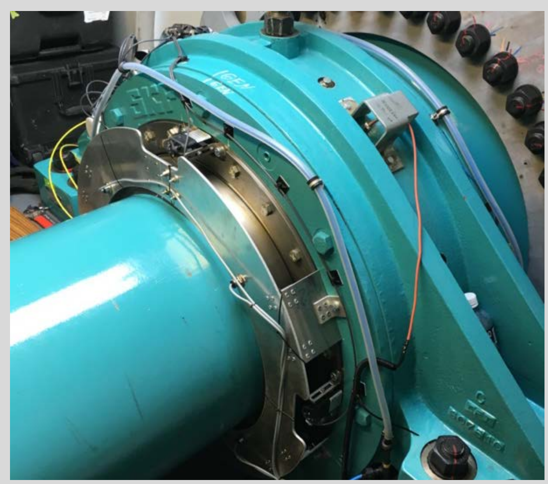
NREL and Argonne National Laboratory researchers teamed up with industry partners, such as SKF, Winergy, General Electric, and Afton Chemical, to address the most common cause of wind turbine gearbox failure: axial or white-etching cracks in the rolling-element bearings inside a gearbox. Their work was designed to understand the causes of axial cracking, create a design life equation that accounts for it, and develop and validate solutions to reduce this and other causes of gearbox failure. NREL researchers outfitted a 1.5-MW wind turbine at NREL's Flatirons Campus with tailored instrumentation to gather experimental data at scale. Their findings confirmed that bearing slip occurs under heavy loads during wind turbine operations and is caused by factors that include bearing design, load, speed, lubrication, and temperature. Using these data, NREL developed a roller sliding model that is scalable to different wind turbine and gearbox platforms and a probability of failure model that fills a gap in the wind energy industry to evaluate component reliability. A second damage metric was also developed with the Technical University of Denmark.

Grease is often used as a lubricant for rolling bearings to alleviate friction and wear. Over time, main bearing failures can still occur, which can increase maintenance costs and decrease wind power plant productivity. *Photo from Mark Dunn, SKF*

Wind Turbine Bearings Fail More Than Expected—Does It Matter?

Point of Contact: Jonathan Keller, Jonathan.Keller@nrel.gov

Wear-related failures of spherical roller bearings in three-point-mount wind turbines have been higher than expected and can contribute to increased operation and maintenance costs. In a 3-year collaborative project with bearing supplier SKF, an NREL team confirmed that axial motion of the main bearing caused by gusts, turbulence, and similar motions would not disrupt the proper lubrication of the bearing. Now, the team plans to further examine bearing loads and lubrication characteristics to understand what factors may result in premature wear. This work will ultimately help reduce wind power plant operation and maintenance costs and increase wind plant productivity.

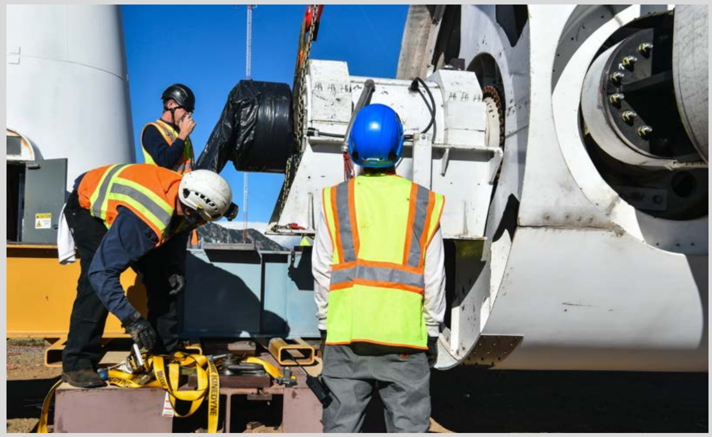


NREL researchers used this gearbox instrumentation and hardware to demonstrate how the axial motion of the main bearing can affect the life span of wind turbine bearings. *Photo by Jerry Hur, NREL*

From Diagnostics to Prognostics: New Tool Assesses Turbine Bearing Reliability

Point of Contact: Shawn Sheng, Shawn.Sheng@nrel.gov

NREL's new modeling software can help predict the reliability of individual components within an entire wind power plant. With this tool, operators and designers can now more effectively assess and proactively address potential bearing failure risks. A partnership with wind power plant optimization specialist WindESCo makes it possible to evaluate and accelerate commercialization of the NREL tools based on data and experience from real-world wind power plant operations. Eventually, the software will help designers and operators monitor various types and sizes of wind plants, encouraging growth in the industry, reducing risk, and stimulating investment.



New tools from NREL are making it possible to predict individual component reliability for entire wind power plants. *Photo by Dennis Schroeder, NREL 49410*

Advanced Drivetrain Lubricants (TCF) WETO.1.5.2.403

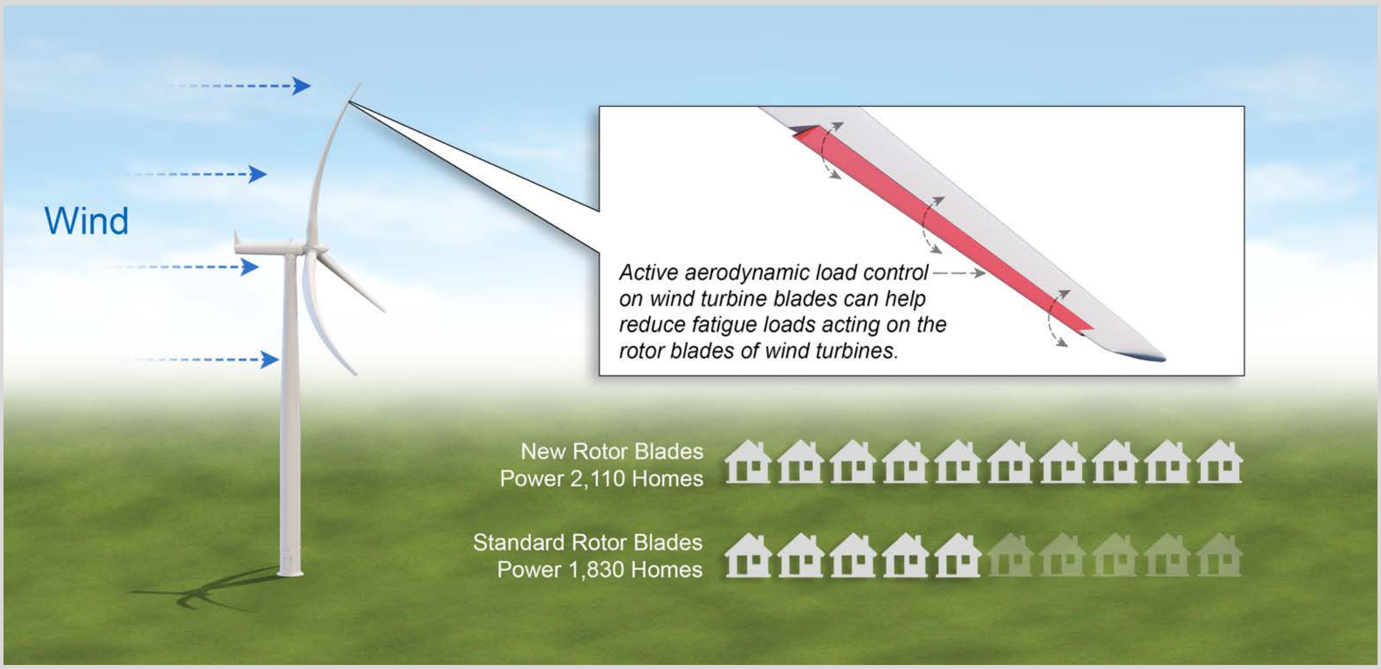
Novel Lubricant Could Prolong Life Span of Wind Turbine Drivetrains

Point of Contact: Jonathan Keller, Jonathan.Keller@nrel.gov

Wind power plant operation and maintenance costs are higher than anticipated. Life-limiting failures that drive up those costs can happen in wind turbine drivetrains when current materials and lubricants fail to prevent bearings and gears from rubbing against other materials. As a result, NREL researchers are gearing up to assist Argonne National Laboratory in commercializing a nanoparticle-based lubricant for use in greases for wind turbine drivetrain components. The goal of this project is to optimize this novel lubricant, validate its performance in field trials, and eventually commercialize it as a more reliable lubricant option.

Flexing the Limits of Land-Based Rotor Growth

Point of Contact: Nick Johnson, Nick.Johnson@nrel.govLarger rotors can increase a wind turbine's average capacity factor by 10% or more. Under the Big Adaptive Rotor project, NREL researchers are providing crucial insights about flexible blades (required for larger rotors) and novel rotor designs to help make larger land-based rotors a reality. In 2021, the multilab team published two articles on novel big, adaptive rotor designs (publicly available on GitHub), which shows that it is feasible to transport wind turbine blades of up to 100 meters on railroads by bending them during transportation. The team currently has two more publications in review; one discusses the benefits and challenges of increasing the size of wind turbine blades, and the other summarizes work completed. Next, the team will work on validating their numerical models and demonstrate the most promising technologies in collaboration with the Rotor Aerodynamics, Aeroelastics and Wake team.



Bigger can be better. NREL's Big Adaptive Rotor team is working to supersize land-based wind turbines—and their capacity. *Graphic by Besiki Kazaishvili, NREL*

Standards Support and International Engagement

Record-Breaking Attendance Demonstrates Industry Interest in Standards Development

Point of Contact: Jeroen Van Dam, Jeroen.van.Dam@nrel.gov

NREL organized the U.S. Wind Energy Standards Summit, which attracted more than 90 participants and focused on developing U.S. and international wind energy standards. *Photo from Artist DOCK90, Principle Power*

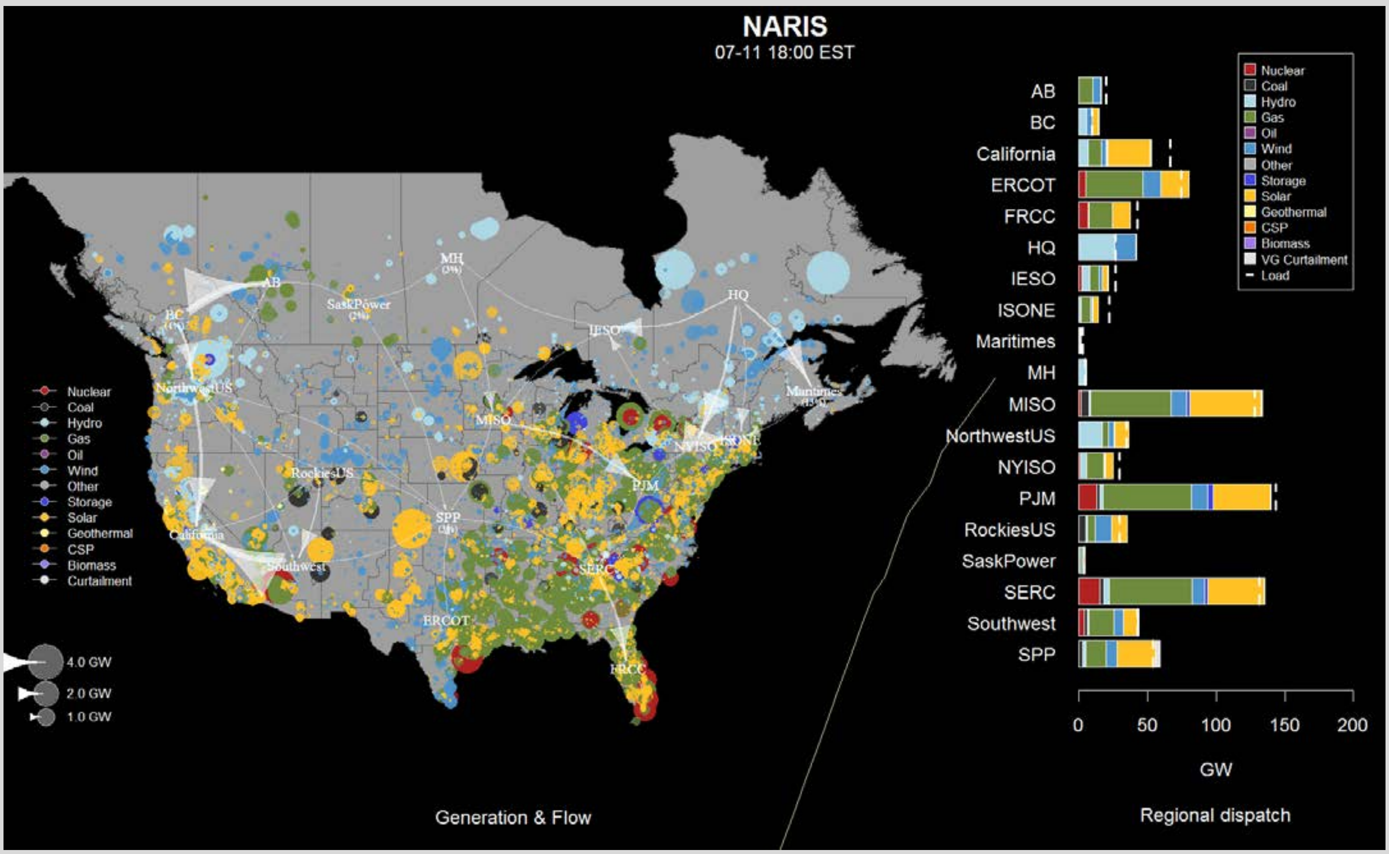
A record number of wind industry participants attended the sixth annual U.S. Wind Energy Standards Summit, which NREL organized with support from the American Renewable Energy Standards and Certification Association. The summit featured 16 virtual presentations designed to explain, describe, discuss, and encourage participation in the development of U.S. and international wind energy standards and the evolving IEC certification process. The format of two 3-hour sessions allowed broad participation through the different U.S. time zones and attracted 90 participants representing original equipment manufacturers, government agencies, consultancies, universities, certification bodies, developers, and owner/operators—3 times more than previous, in-person attendance levels.

Grid Integration

Project Sets Forth Vision for Interconnected Grid Across North America

Point of Contact: Greg Brinkman, Greg.Brinkman@nrel.gov

The North American Renewable Integration Study (NARIS) is the first detailed power system integration study for the entire North American continent. NREL's NARIS team completed its analysis of possible scenarios for modernizing the Canadian, Mexican, and U.S. power grid through efficient transmission, generation, and demand planning. Five years of research, featured in *The North American Renewable Integration Study (NARIS): A U.S. Perspective*, reveals how an integrated grid can enable cross-continent reliability, economic efficiency, and high renewable resource contributions. Researchers produced a new model to demonstrate the efficacy and reliability of adding renewable energy—especially wind and solar—to the power grid. This project lays the groundwork for power systems planners and operators, government agencies, and regulators to formulate a strategy for cross-border and interregional energy integration. By early September 2021, the report had been downloaded 3,854 times since its publication 3 months earlier.



The multiyear North American Renewable Integration Study (NARIS) found that multiple combinations of electricity generation (including wind power), transmission, and demand can result in 80% carbon emission reduction by 2050. This data visualization shows projected regional generation, flow, and dispatch on January 12, 2050, under a low-cost, variable-generation scenario. *Image courtesy of NREL*

FLORIS Improves Forecasting With More Rapid and Robust Estimates

Point of Contact: David Corbus, David.Corbus@nrel.gov

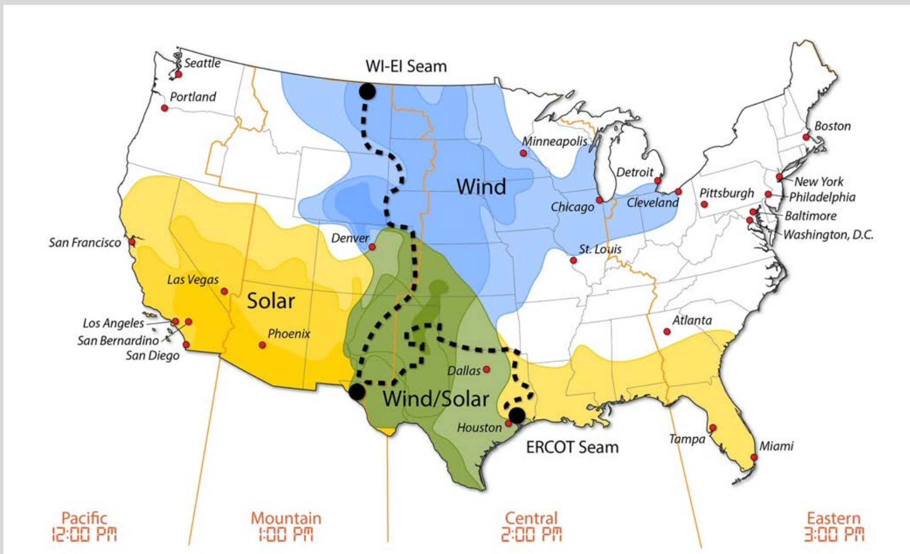
NREL updated its Atmosphere to Electrons to Grid wind power plant controller to provide more accurate estimates of short-term (e.g., 10-minute) wind plant power curves and day-ahead forecasts. The rapid method for robust power predictions integrates NREL's FLORIS model with a data-driven Gaussian process using learned long short-term memory connections. FLORIS handles unseen conditions, and the Gaussian method can learn model and data mismatches. Updated online a few times each day, its run time amounts to only tens of minutes. Ongoing upgrades and developments will enhance forecasting and inform future improvements.

Continental-Scale Planning Tools WETO.3.1.0.418

Enhanced Tools Examine Trade-Offs Between Energy Resources in Capacity Planning

Point of Contact: Greg Brinkman, Greg.Brinkman@nrel.gov

Enhanced methods and data parameters for transmission congestion modeling allow grid operators to analyze trade-offs between energy resources, improving grid dispatchability and resiliency. To better assess the value impacts of long-distance wind energy transmission, NREL researchers improved the Regional Energy Deployment System based on Interconnections Seams Study findings. Greater understanding of energy choke points will lead to more accurate assessments of wind energy's potential contributions to the continental-scale U.S. power grid's reliability and resilience. These upgraded capacity planning tool and grid operations model components can increase confidence that the grid can operate stably with high penetrations of renewable energy.



Uniting the major regions of the U.S. power system, represented here conceptually, could enhance the ability to harness abundant renewable resources and balance loads across the country. *Illustration by Billy Roberts, NREL*

Leadership Propels Development of International Inverter Interconnection and Interoperability Standard

Point of Contact: Andy Hoke, Andy.Hoke@nrel.gov

Modern wind and solar power plants all interface with the electric grid through inverters. This makes establishing a new standard for interconnection and interoperability of inverter-based resources that interconnect with associated transmission electric power systems a high priority for both WETO and the U.S. Department of Energy Solar Energy Technologies Office. NREL is working closely with the wind industry and Institute of Electrical and Electronics Engineers (IEEE) to formulate this standard, which will impact how all wind plant systems are designed. Input to IEEE 2800 helped inform the creation of a standard verification framework compatible across a wide range of power plants.

Advanced Modeling, Dynamic Stability Analysis, and Mitigation of Control Interactions in Wind Power Plants	WETO.3.1.0.420

Scanning Tool Helps Stabilize Wind Power's Impact on the Grid

Point of Contact: Shahil Shah, Shahil.Shah@nrel.gov

NREL developed a first-of-its-kind, Python-based impedance scan tool for power systems computer-aided design models that characterizes the response of power electronics devices (e.g., wind turbines, wind power plants, static synchronous compensators, and high-voltage direct current converters) at different frequencies to understand their impact on grid stability at various time scales. Vendors protect their intellectual property with black-box power electronics device models. As a result, NREL's impedance scan tool leverages high-fidelity power electronics black-box models to characterize a device's dynamic behavior and evaluate its impact on grid stability, particularly during periods of high wind generation. The NREL tool was featured in an IEEE Electrification Magazine article.

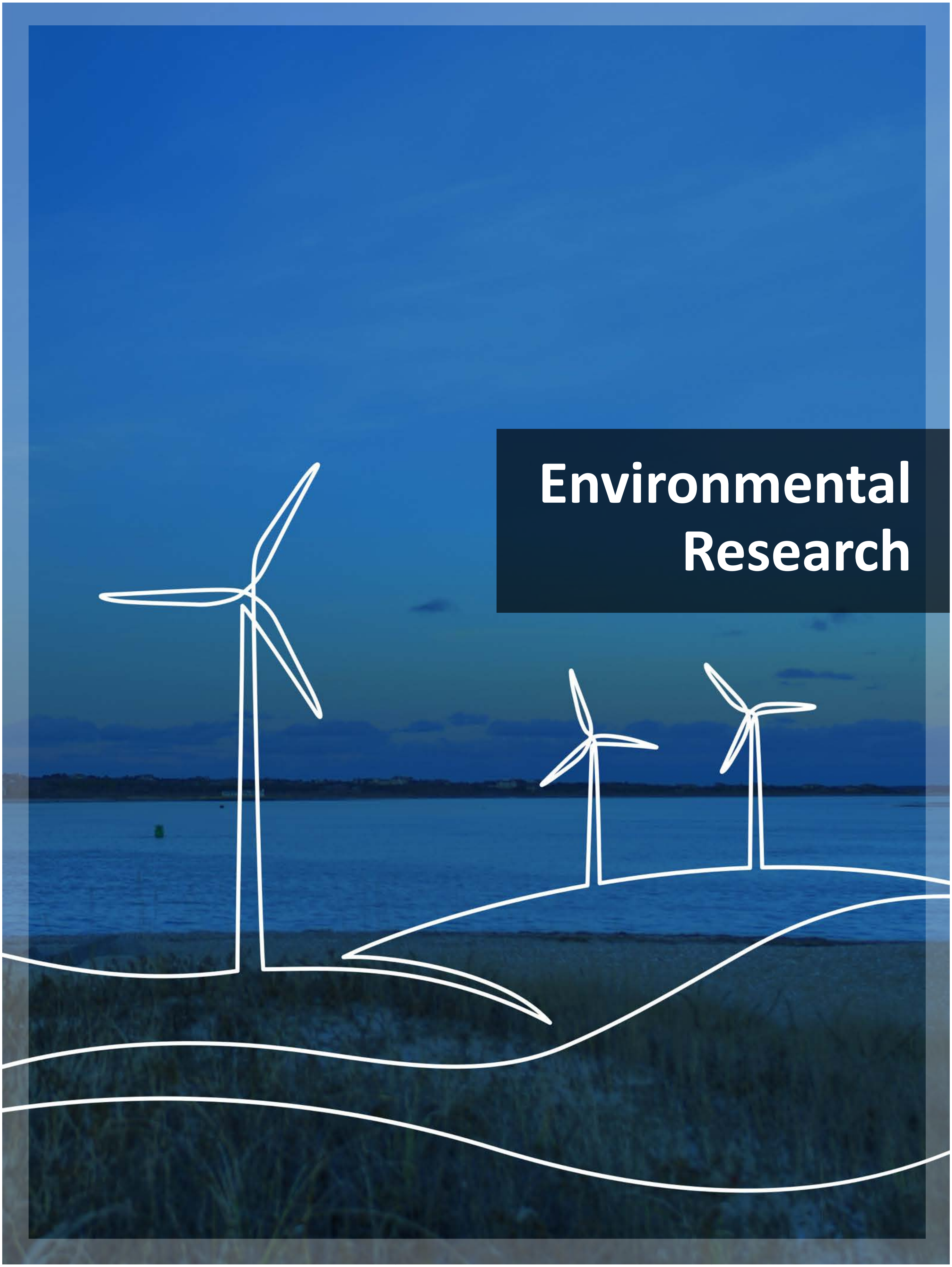
Wind Power as a Virtual Synchronous Generator (WindVSG)	WETO.3.1.0.421

Successful Grid-Forming Demonstration Opens Market Opportunities

Point of Contact: Vahan Gevorgian, Vahan.Gevorgian@nrel.gov

Researchers from NREL and General Electric demonstrated the world's first Type 3 utility-scale wind turbine generator operating in grid-forming mode (or when the generator can set grid voltage and frequency, and if necessary, operate without power from the electric grid). Type 3 wind turbines typically need to connect to an electrified grid to operate. This demonstration of their ability to operate independently from the grid—and recover from total or partial shutdown—creates new market opportunities for this type of wind turbine.

Environmental Research



NREL and Partners Join Forces To Help Wind Energy Projects and Wildlife Coexist

Point of Contact: Cris Hein, Cris.Hein@nrel.gov

NREL and Defenders of Wildlife launched *Wildlife and Wind Energy: Considerations for Monitoring and Managing Impacts*, a nine-part webinar series to help familiarize stakeholders with the nuances of land-based wind energy development in the context of species conservation. Held from September through December 2020, the webinar series helped attendees understand a variety of topics ranging from species-specific discussions and methodologies for reducing impacts on wildlife to regulatory and financing perspectives on effective mitigation strategies for species protection.

The Wildlife and Wind Energy: Considerations for Monitoring and Managing Impacts webinar series, hosted by NREL and project partners, focused on land-based wind energy development in the context of protecting vulnerable species like this silver-haired bat. *Photo by Cris Hein, NREL*

NREL Issues Research Goals for Studying Bat Behavior at Wind Turbines

Point of Contact: Cris Hein, Cris.Hein@nrel.gov

NREL, on behalf of the Bats and Wind Energy Cooperative, developed a set of goals to direct research on priority issues. These goals include: (1) advancing technology, methodology, and analysis tools for research; (2) characterizing bat behavior near wind turbines; (3) characterizing collision events; and (4) evaluating the effectiveness of strategies to reduce mortality. These goals will help ensure that the Bats and Wind Energy Cooperative—an alliance of government, industry, academic, and nongovernmental wildlife experts—can effectively develop and disseminate solutions to mitigating the dangers that wind energy facilities pose to bats.

NREL Request for Proposals to Support Coexistence of Bats and Wind Energy

Point of Contact: Cris Hein, Cris.Hein@nrel.gov

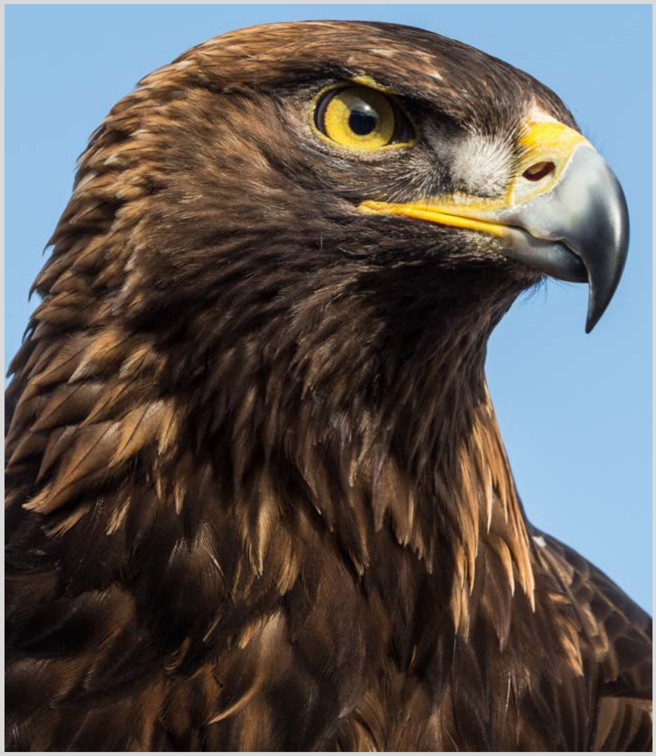
Clean energy is vital to our planet's health—and so are bats. To help wind energy projects coexist with bats, NREL announced a request for proposals for studying bat interactions with wind turbines and improving deterrent technology. After the request closes on January 14, 2022, NREL expects to award up to four winners \$450,000 to \$700,000 each under this competitive solicitation. This funding will help minimize the impact of wind energy technologies on bats.

NREL requested proposals for projects that work to better understand how bats, like this red bat, interact with wind turbines and power plants and to improve deterrents. The funding, which will be awarded to up to four projects, will help minimize the impact of this growing source of clean, renewable energy on these flying critters. *Photo by Cris Hein, NREL*

New Modeling Tool May Help Reduce Golden Eagle Interactions With Wind Turbines

Point Of Contact: Eliot Quon, Eliot.Quon@nrel.gov

NREL scientists and fellow researchers at the U.S. Geological Survey, Western EcoSystems Technology Inc., and Conservation Science Global Inc. are developing a computational framework for modeling golden eagle behavior near wind power plants. The team has focused their atmospheric modeling on a specified region in the United States and has begun validating the framework's behavioral component using flight data from global-positioning-system-tagged eagles. The team will use updated modeling to pair atmospheric data with behavioral data on golden eagles and create a tool to help guide wind power plant siting decisions and curtailment strategies informed by real-time eagle flight path prediction.



NREL requested proposals for projects that work to better understand how bats, like this red bat, interact with wind turbines and power plants and to improve deterrents. The funding, which will be awarded to up to four projects, will help minimize the impact of this growing source of clean, renewable energy on these flying critters. *Photo by Cris Hein, NREL*

Wind Operational Issue Mitigation (WOIM)	WETO.3.3.0.407

Workshop Explores Solutions for Reducing Bat Interactions With Wind Turbines

Point of Contact: Cris Hein, Cris.Hein@nrel.gov

NREL published the findings of the "State of the Science and Technology for Minimizing Impacts to Bats from Wind Energy" workshop in a technical report. These findings characterize the status of current technologies, identify emerging technologies, and discuss the research and development opportunities to implement effective strategies for minimizing bat interaction with wind turbines. In addition, the workshop focused on the biological, economic, and regulatory aspects associated with validating and integrating deterrents or smart curtailment systems at wind energy facilities.

Study Identifies Methods for Understanding Wind Energy Development's Impact on Bat Populations

Point of Contact: Cris Hein, Cris.Hein@nrel.gov

NREL released a technical report highlighting research methods to assess the population status and trends of bats that are vulnerable to wind energy development. The report showed that systematic acoustic surveys and genomic data collected over time can assess whether bat populations are stable, increasing, or decreasing. This information will help wind energy project developers determine whether wind turbines pose a population-level risk to bats and, if so, what level of minimization is necessary to ensure viable populations persist.

Assessing the population status of species, like this hoary bat, will help wind project developers determine whether wind turbines pose a population-level risk to an area's bats and, if so, how to ensure bat populations stay viable. *Photo by Cris Hein, NREL*

Analysis Determines Wind Turbines Unlikely to Cause Barotrauma in Bats

Point of Contact: Michael Lawson, Michael.Lawson@nrel.gov

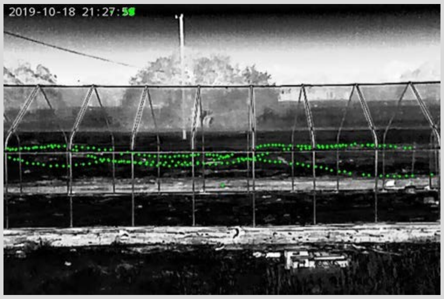
NREL researchers published an article in PloS One examining the potential for air pressure variations caused by rotating wind turbine blades to harm bats. Combining analyses of bat physiology and simulations of the aerodynamics of operating wind turbines, the article concluded that barotrauma is unlikely to be responsible for most turbine-related bat fatalities. This research is critical for developing strategies to reduce impacts to bats at wind energy facilities.

Ultrasonic Acoustic Deterrent (NREL) WETO.3.3.0.408

Thermal Imaging Illuminates Effectiveness of Ultrasonic Acoustic Deterrents

Point of Contact: Cris Hein, Cris.Hein@nrel.gov

Ultrasonic acoustic deterrents may represent a beneficial, flexible bat impact reduction strategy. NREL researchers investigated the effectiveness of a deterrent technology developed by NRG Systems by using thermal imaging to track the movements of various species of bats in response to different ultrasonic signals in an open-air flight cage. The team then presented these findings at the 13th North American Coordinating Collaborative Wind Wildlife Research Meeting. Preliminary results for red bats suggest that deterrents can be used to influence flight and echolocation behaviors and may encourage wind farm operators to incorporate those deterrents into wind energy projects, minimizing bat-turbine interactions. This work was completed under DOE Funding Opportunity Announcement 1924 – Evaluating Advanced Deterrent Stimuli for Increasing Species-Specific Effectiveness of an Advanced Ultrasonic Acoustic Deterrent.



NREL researchers investigated the effectiveness of an ultrasonic acoustic deterrent by using thermal imaging to track the movements (shown here as dotted lines) of different species of bats in response to different ultrasonic signals in an open-air flight cage. *Image from Brittany Stamp, Texas State University*

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Working Together to Resolve Environmental Effects of Wind Energy (WREN) WETO.3.3.0.403

Short Science Summaries Deliver Up-to-Date Data on Vulnerable Species

Point of Contact: Cris Hein, Cris.Hein@nrel.gov

Working Together to Resolve Environmental Effects of Wind Energy Short Science Summaries provide concise, up-to-date information on species that may be impacted by land-based and offshore wind energy development. These summaries also offer risk monitoring and management strategies and identify research priorities for impacted species. In 2021, the project, IEA Wind Task 34, produced three additional summary documents for soaring raptors, European grouse species, and white storks. The information in these summaries can help communities and developers make environmentally responsible decisions about siting and operating wind energy projects.

The IEA Wind Task 34, Working Together to Resolve Environmental Effects of Wind Energy, Short Science Summaries can help communities and developers make environmentally responsible decisions about wind energy development. *Photo by Dennis Schroeder, NREL* 35730

Stakeholder Engagement

Video Tutorial Helps Users Understand Wind Resource Maps

Point of Contact: Chloe Constant, Chloe.Constant@nrel.gov

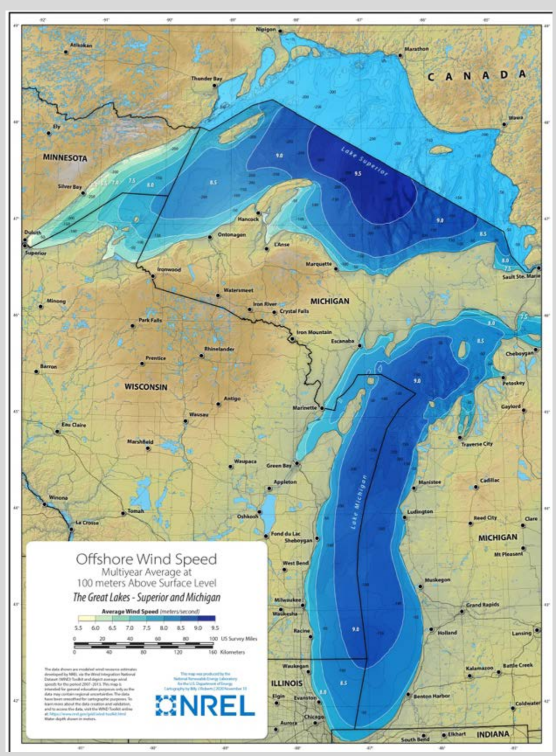
NREL developed a new video tutorial on DOE's WINDExchange wind resource maps. WINDExchange continues to publish 100-m wind resource maps to provide users with snapshots of wind energy potential at 100 m above the surface based on validated data specific to different regions in the United States. The tutorial explains how to read the new maps, where to access them, and the differences between land-based and offshore wind resource maps, facilitating better understanding of an area's comprehensive wind resource potential.

NREL developed a new video tutorial explaining how to read, access, and understand DOE's WINDExchange wind resource maps. *Video still courtesy of NREL*

WINDExchange Maps Illustrate U.S. Wind Resources

Point of Contact: Ruth Baranowski, Ruth.Baranowski@nrel.gov

NREL produced and published 100-m wind resource maps for several regions in the United States, including the Great Lakes region and the West Coast. NREL also produced land-based maps for Michigan, Indiana, Ohio, Illinois, Wisconsin, and Minnesota, and the Southeastern region of the United States. The team is currently working on 100-m maps for the Gulf Coast. These open-source maps provide wind developers and community leaders with a tool to help assess and characterize a region's available wind resources, which will support the development, siting, and operation of wind energy projects throughout the United States.



NREL leads several efforts to accurately define, measure, and forecast the nation's land-based and offshore wind resources and distribute those findings to the community through the help of WETO funding. These maps help wind project developers and community leaders assess and characterize a region's available wind resources, which will support the development, siting, and operation of wind projects around the United States. *Map by Billy Roberts, NREL*

WINDExchange Presents an Overview of Offshore Wind Fixed-Bottom Technology

Point of Contact: Elizabeth Gill, Elizabeth.Gill@nrel.gov

Offshore wind energy can create good-paying jobs and contribute to a clean, secure, national energy mix. A foundational, technical offshore wind webinar produced by NREL provided an overview of this exciting and rapidly growing segment of renewable energy. In this webinar, offshore wind energy researcher Walt Musial discussed fixed-bottom offshore wind technology, including offshore wind basics, fixed-bottom foundation types, and construction considerations. This webinar aimed to improve understanding of offshore wind technology, which will help increase its deployment.

Offshore wind holds great promise as a source of clean, domestic, renewable energy that can meet the needs of communities along the nation's coastlines. NREL produced a foundational technical offshore wind webinar to provide an overview of this rapidly growing segment of renewable energy. *Photo by Dennis Schroeder, NREL 40389*

New Resources Help Communities Realize the Benefits of Wind Energy

Points of Contact: Corrie Christol, Corrie.Christol@nrel.gov, Jeremy Stefek, Jeremy.Stefek@nrel.gov

Wind energy projects offer a wide range of benefits to nearby communities, but planning such projects can be complex. To help local decision makers evaluate whether a wind energy project is right for their community, NREL developed two new resources: the "Land-Based Wind Energy Siting: A Foundational and Technical Resource" report and online Land-Based Wind Energy Economic Development Guide. These comprehensive, easy-to-read resources provide useful information about the siting considerations and economic opportunities associated with a potential wind energy project.

Two new WINDExchange resources developed by NREL help communities understand how wind energy projects can create jobs, increase tax revenues, provide landowner income, and generate clean, homegrown energy. *Photo by Dennis Schroeder, NREL 57714*

Workforce Development

Collegiate Wind Competition Organizers Help Build the Future Wind Energy Workforce

Point of Contact: Elise DeGeorge, Elise.DeGeorge@nrel.gov

NREL staff, who organize the DOE Collegiate Wind Competition, facilitated the virtual 2021 event, culminating in the Pennsylvania State University claiming first place overall. Johns Hopkins University won second place, and California Polytechnic State University won third. The CWC aims to prepare students from multiple disciplines to enter the wind energy workforce by providing real-world technology experience. This year's contest met that goal with 173 students from a range of disciplines, including engineering, economics, and architecture. The unique challenges of the 2021 competition gave students the opportunity to plan ahead, practice active risk management, and adapt quickly—essential skills for the wind and renewable energy industries. In addition, NREL organizers selected 11 teams and five learn-along teams to participate in the 2022 competition.

The organizers of the CWC integrated the theme of adaptability into the 2021 challenge, which called on teams to research, design, and build a model wind turbine for deployment in highly uncertain times with a large degree of unknown risks and delays. *Photo by Werner Slocum, NREL*

Wind Workforce Webinar Series Illuminates Path to a Career in Wind Energy

Point of Contact: Corrie Christol, Corrie.Christol@nrel.gov

NREL hosted a three-part Wind Workforce Webinar Series in observance of American Wind Week. Held in partnership with ACP, the webinar covered wind workforce challenges, highlighted programs—like KidWind and the CWC—that are helping develop the future wind workforce, and identified opportunities for industry members and others to engage in these ongoing efforts. Through this webinar series, NREL brought together members of the wind energy industry, educators, and technical experts to support a robust wind energy workforce of tomorrow.

The Wind Webinar Series featured examples of wind workforce development programs, such as the KidWind Challenge, which introduces kids and teens to the excitement of wind energy at an early age by giving them the opportunity to build and test their own model wind turbines. *Photo by Werner Slocum, NREL*

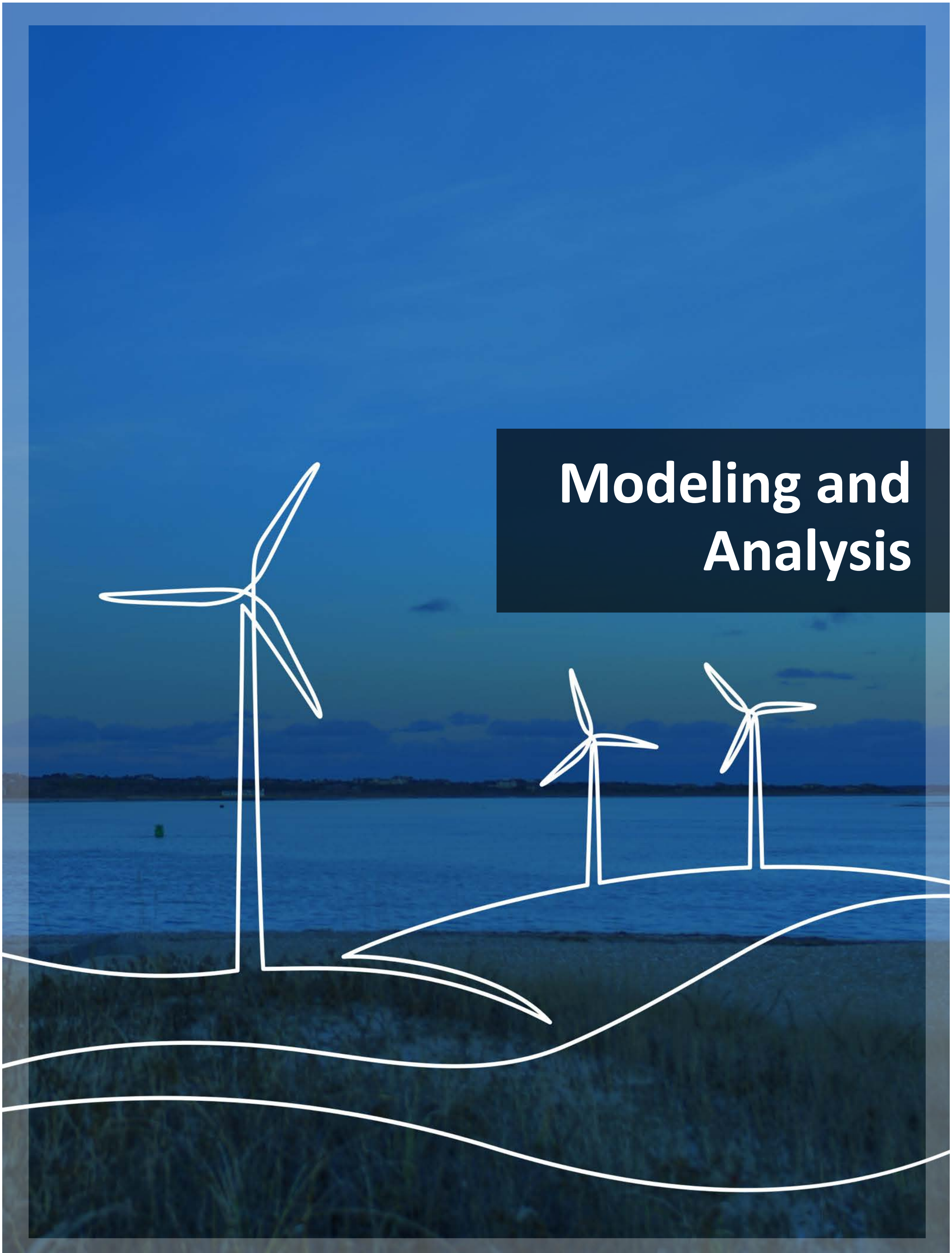
Research Helps Bridge the Wind Energy Workforce Gap

Point of Contact: Jeremy Stefek, Jeremy.Stefek@nrel.gov

Wind energy industry employment grew more than 50% between 2015 and 2019, according to the *U.S. Energy Employment Report*. However, 68% of wind energy employers reported difficulty filling entry-level jobs while 83% of entry-level wind energy applicants reported difficulty finding positions in the industry. NREL conducted a survey to address this wind energy workforce gap, finding that the difficulty in filling entry-level positions stems from applicants lacking in training, education, or experience and a shortage of applicants. These findings illuminate ways to better connect students, recent graduates, education institutions, and industry together to develop a highly qualified workforce that can meet the growing demands of the wind energy industry. To support this research, NREL developed an offshore-specific wind energy workforce network and hosted an offshore wind workforce summit with the Business Network for Offshore Wind during the 2021 International Partnering Forum Conference.

NREL's wind energy workforce research seeks to meet growing wind energy industry demands by improving connectivity between employers and qualified candidates and filling the wind energy workforce gap. Programs, such as CWC (shown in this photo from the 2019 competition) offer competitors the opportunity to engage with members of the industry, helping prepare them for wind energy careers. *Photo by Werner Slocum, NREL*

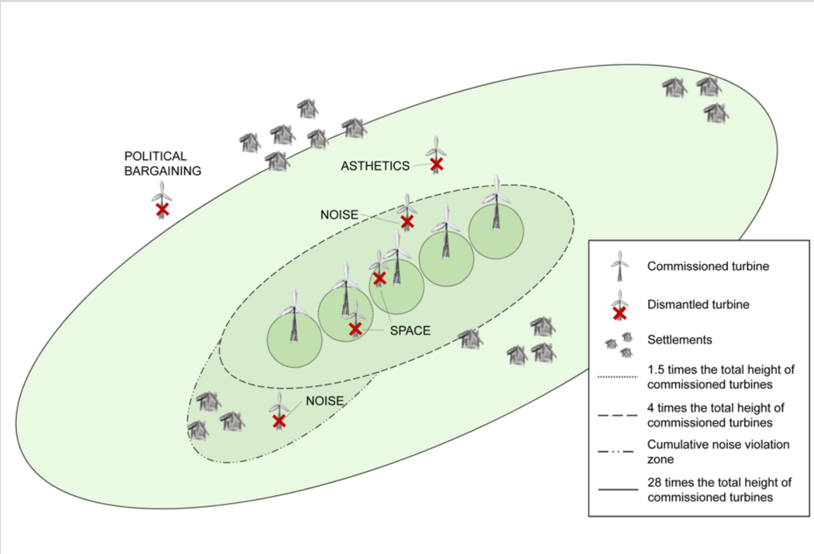
Modeling and Analysis



Repowering Crucial To Unlocking Wind Energy's Full Potential

Point of Contact: Eric Lantz, Eric.Lantz@nrel.gov

A Nature Energy article explores the decisions behind land-based wind energy repowering—the combined activity of dismantling or refurbishing existing wind turbines and commissioning new ones. Through an analysis of repowering efforts in Denmark, members of the Cost of Wind Energy IEA Wind Task 26, which is led by NREL, found that the physical space needed for a new wind turbine was the primary motivation for repowering. Other reasons included lowering noise emissions, aesthetics, and political considerations. As a negotiated process between host communities and wind energy developers, repowering will play a crucial role in unlocking the full potential of wind energy as part of the world's transition to renewable energy.

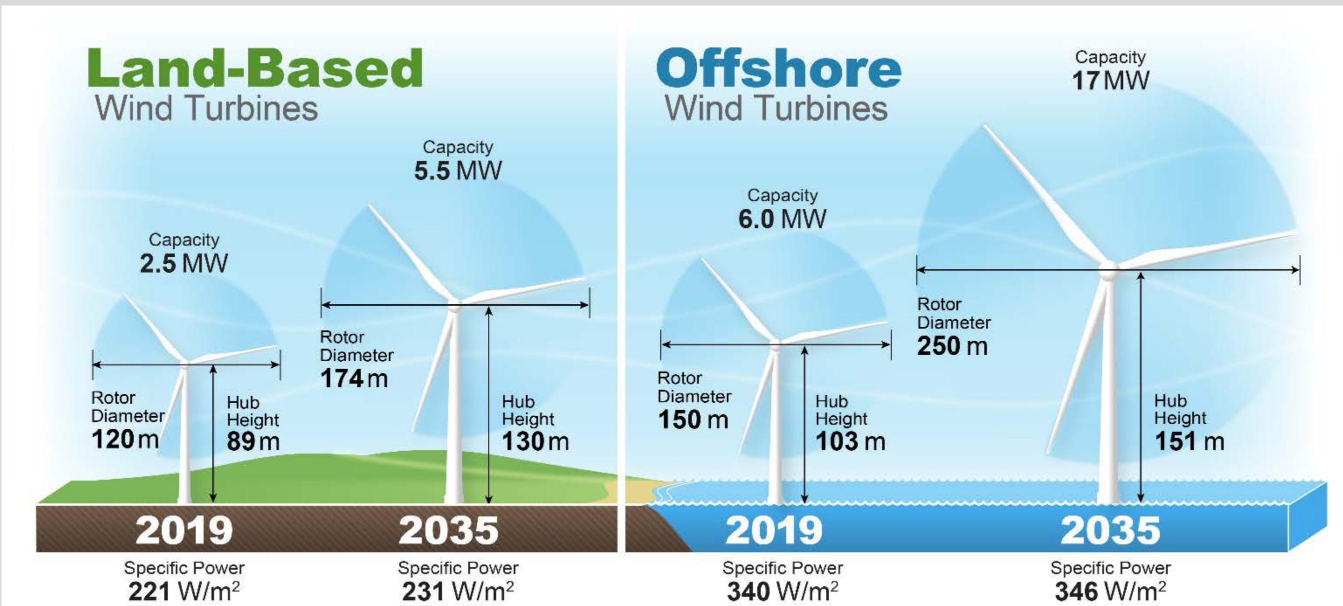


This fictional Danish repowering wind energy project demonstrates common reasons for wind energy repowering decisions, including zones of construction for new wind turbine projects based on their size relative to the existing commissioned turbine (600 kW in this case). *Image from L. Kitzing and M. K. Jensen, Technical University of Denmark*

Experts Predict Wind Cost Declines of 37%–49% by 2050

Point of Contact: Eric Lantz, Eric.Lantz@nrel.gov

Bigger and more efficient wind turbines, lower capital and operating costs, and other advancements will drive wind energy cost reductions of 17%–35% by 2035 and 37%–49% by 2050. These findings are described in a *Nature Energy* journal article authored by researchers at Lawrence Berkeley National Laboratory and featuring significant contributions from researchers and officials within NREL, DOE, the University of Massachusetts, and other IEA Wind Task 26 partner organizations. A survey of 140 of the world's foremost wind power experts, which leveraged the professional networks of IEA Wind Task 26 participants, informed the work. This study provides the energy sector with current wind energy cost forecasts.



Anticipated growth in land-based and offshore wind turbine size, based on responses to a global expert survey. Wind turbine size represents a significant driver in lowering the cost of wind energy. *Graphic by John Frenzl, NREL*

Utility-Scale Wind Energy Costs Continue to Fall

Point of Contact: Tyler Stehly, Tyler.Stehly@nrel.gov

NREL released the ninth annual cost of wind energy review, which details the continued downward trend of utility-scale wind energy costs—56% for land-based wind and 68% for fixed-bottom offshore wind since 2010. This is the first time the report has included costs for residential- and commercial-scale distributed wind energy systems. The research estimates the levelized cost of energy (LCOE) for residential distributed wind energy at $159 per megawatt-hour and $104 per megawatt-hour for commercial distributed wind energy. The data provide insight into current component-level costs as well as a basis for understanding variability in the wind LCOE across the country.

NREL Research Identifies Methods for Achieving a Circular Economy for Wind Energy

Point of Contact: Aubryn Cooperman, Aubryn.Cooperman@nrel.gov

Research into end-of-life issues involving wind turbine blades is outlined in an NREL journal article, "Wind Turbine Blade Material in the United States: Quantities, Costs, and End-of-Life Options." Achieving a circular economy for wind turbine components includes reusing and recycling towers, generators, and foundations. Large wind turbine blades made from sturdy composite materials can be difficult to recycle, however. This research points to several process alternatives for recovering material and energy from wind turbine blades. NREL scientists and engineers are already working on thermoplastic resin systems, as well as reversible and bio-based thermoset resins, which could allow a blade to be melted down and its component parts recycled.

Many wind turbines installed decades ago are reaching the end of their lifetimes, which has prompted NREL researchers to investigate what can be done with old turbine parts. *Photo by Dennis Schroeder, NREL*

Further Wind Power Cost Reductions Expected on the Horizon

Point of Contact: Eric Lantz, Eric.Lantz@nrel.gov

The cost of wind energy has decreased by more than 80% since the 1980s and by 30% or more in the last 5 years. NREL analysts expect further cost reductions to continue for both land-based and offshore wind energy, driven by improvements in technology, manufacturing, and operations. The journal article "Wind Power Costs Driven by Innovation and Experience With Further Reductions on the Horizon" explores forecast methods, expectations, and factors that may influence the cost of wind energy in the future. IEA Wind Task 26, which is led by NREL, conducted this research.

Wind Analysis for Priority Needs	WETO.4.1.0.402

Wind Analyses Underpin DOE Response to Congressional Requests

Point of Contact: Eric Lantz, Eric.Lantz@nrel.gov

Since the beginning of FY 2021, the priority analysis task has handled several significant and important projects in support of WETO priorities. This work included responding to two congressional requests for specialty analyses, which comprised of characterizing the potential for airborne wind energy to contribute to future U.S. electricity needs, resulting in two publications: "Proceedings of the 2021 Airborne Wind Energy Workshop" and "Airborne Wind Energy" and contributing to a congressional report outlining strategies to accelerate U.S. offshore wind energy deployment.

Wind Energy Development Has Positive, Long-Term Community Effects

Point of Contact: Jeremy Stefek, Jeremy.Stefek@nrel.gov

NREL released a report detailing the positive long-term economic impact wind power plant operation and maintenance workers bring to their communities from spending at local businesses to the role that these companies and workers play in quality of life within the community. The report estimates that 8,204 operation- and-maintenance-specific workers—who have the potential to live in or near communities where wind power plants are built and contribute economic value that extends well beyond the date a wind plant goes live—were employed to support 94,971 MW of operational wind capacity as of 2019.

Almost 99% of wind turbines in the United States exist in rural areas—like the ones shown here near Dumas, Texas—making research on workforce impacts in these communities a critical area of study. *Photo by Werner Slocum, NREL*

Energy Sector Modeling and Impacts Analysis	WETO.4.1.0.405

Open-Source Tools Analyze Resource Adequacy of Bulk Power Systems

Point of Contact: Jennie Jorgenson, Jennie.Jorgenson@nrel.gov

NREL's Probabilistic Resource Adequacy Suite provides an open-source, research-oriented collection of tools for analyzing the ability of bulk power systems to meet demand for electricity, known as resource adequacy. This software package simulates power system operations under a range of operating conditions to study the risk of failing to meet demand—resulting from a lack of electricity supply or deliverability—and identify the time periods and regions in which that risk occurs. An NREL technical report documents the Probabilistic Resource Adequacy Suite model. Related publications include a *Wind Energy* article that evaluates the degree to which wind energy can contribute to meeting resource adequacy requirements (also known as capacity credit) in the western United States and an NREL case study comparing capacity credit calculations in Texas.

Wind Siting Interactions With U.S. Power System Evolution Prove Complex

Point of Contact: Trieu Mai, Trieu.Mai@nrel.gov

A study published in *Energy* reveals that despite vast U.S. land-based wind resource potential, siting restrictions can have a measurable impact on future wind energy development. NREL analysts used resource potential estimates and siting constraints from a companion analysis as inputs to NREL's publicly available Regional Energy Deployment System capacity expansion model. Studying the impacts of different degrees of siting constraints, ranging from open (least restrictive) to limited access (most restrictive), the researchers modeled 24 scenarios of how the U.S. electricity system might evolve from now until 2050. The results? Siting can lead to substantial differences in emissions and the cost to decarbonize the grid. This work was featured in *The Wall Street Journal* and *Inside Climate News*.

Siting can lead to substantial differences in emissions and the cost to decarbonize the grid—and can also interact with future transmission expansion and plant design in complex ways. *Photo from iStock*

Analysts Make the Case for Quantifying Wind's Value Using Economic Profitability Metrics

Point of Contact: Trieu Mai, Trieu.Mai@nrel.gov

The most commonly used metric for electric sector technology competitiveness is LCOE. And yet, while LCOE may capture the direct costs of a technology, it does not accurately reflect its full economic value. In *The Electricity Journal*, NREL analysts assess how to compare wind and other electric system technologies through a "benefit-cost" framework rather than LCOE or integration cost-based measures. Researchers determine that replacing established metrics with economic profitability metrics—including a new profitability-based adjustment to LCOE—keeps comparisons on an equivalent monetary basis and therefore represents a more robust method for evaluating technology competitiveness. This work was featured in an NREL technical report, "Competitiveness Metrics for Electricity System Technologies," and a second article in *The Electricity Journal* that offers a framework to break down the economic value of wind and other grid technologies.

Video Proposes Ways to Protect the Future Energy Grid

Point of Contact: Paul Denholm, Paul.Denholm@nrel.gov

NREL has learned a lot about how to integrate large amounts of wind energy and solar power onto the grid. But one outstanding challenge is making sure the grid is protected if there's a fault, such as a short circuit. An educational video explains how fault protection can be maintained with higher levels of inverter-based resources—such as wind turbines, photovoltaics, and battery storage—in the future grid. The video is designed to help nontechnical audiences understand this complex power systems engineering concept and identify the technical solutions that are available and under investigation to enable power systems transformations.

New Data Standard Establishes Universal Language for Digital Resource Assessments

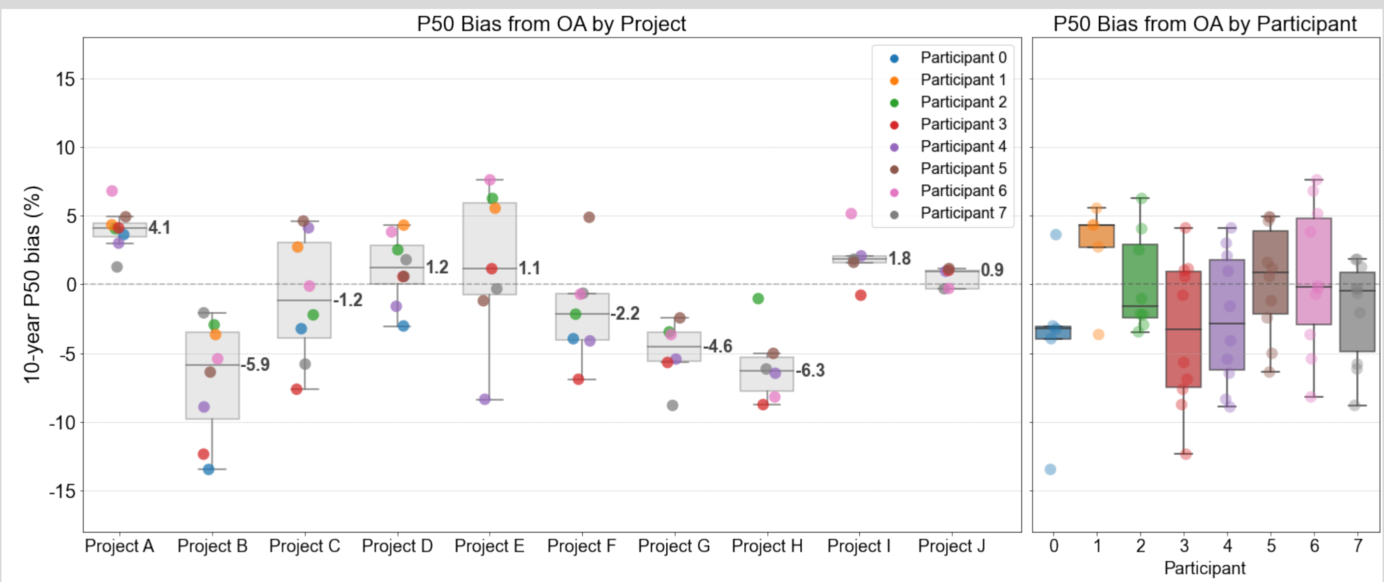
Point of Contact: M. Jason Fields, Michael.Fields@nrel.gov

IEA Wind Task 43, which is led by NREL, officially launched the new digital wind resource assessment data standard. Intended as universal building blocks for wind energy resource assessment applications, this repository and its associated tools are designed to make the process more efficient, accurate, and scalable. By establishing a universal way to describe the data and metadata in the wind resource assessment process, the standard will transform how data are structured and transferred throughout the wind resource assessment process.

Benchmark Report Provides Near-Term Pathway to Improving Wind Plant Financial Performance

Point of Contact: M. Jason Fields, Michael.Fields@nrel.gov

NREL completed the Wind Plant Performance Prediction Benchmark Phase I initiative, resulting in publication of a technical report. Results of the study, which was designed to improve the accuracy and confidence of preconstruction energy yield assessments, indicate broad disagreement in the quantification of wind resource levels, losses, and uncertainties—as well as wind-turbine-level production. Considering the increasing market pressures for low-cost, high-performing assets, this research establishes a way to improve the financial performance of wind power plants and reduce the cost of energy for wind.



Distribution of energy yield assessment prediction biases grouped by the 10 wind plant projects and 8 participating consultants for the Wind Plant Performance Prediction Benchmark Phase 1 initiative. Overall, energy yield is underpredicted by 1.2%, but large variability exists between individual projects and participants. *Graphic courtesy of Eric Simley, NREL*

Research Highlights Opportunities to Reduce Wind Energy Prediction Uncertainty

Point of Contact: M. Jason Fields, Michael.Fields@nrel.gov

The accuracy and precision of preconstruction energy estimates can dictate the profitability of a wind project. In a recent journal article, NREL analysts identify a long-term trend of reduction in the overprediction bias, summarize recent advancements of the wind resource assessment process that justify the bias reduction, and examine estimated and observed loss and uncertainty values from the IEC 61400-15 wind resource assessment standard. Research findings reveal opportunities for the industry to reduce prediction uncertainty and prevent energy losses caused by wake effect and environmental events.

Journal Raises Worldwide Awareness of OpenOA Software

Point of Contact: M. Jason Fields, Michael.Fields@nrel.gov

NREL's Open Operational Assessment (OpenOA) software, an analysis toolkit for wind power plant operational data, was accepted into the *Journal of Open Source Software*. Publishing in this journal raises awareness of the software among academic and professional research communities worldwide and makes OpenOA research easier to find, cite, link, assess, and reuse. In addition to implementing rigorous backend modifications to make the OpenOA software conform to the journal's standards, the OpenOA team created a Zenodo entry that can be continuously updated with new versions of the software.

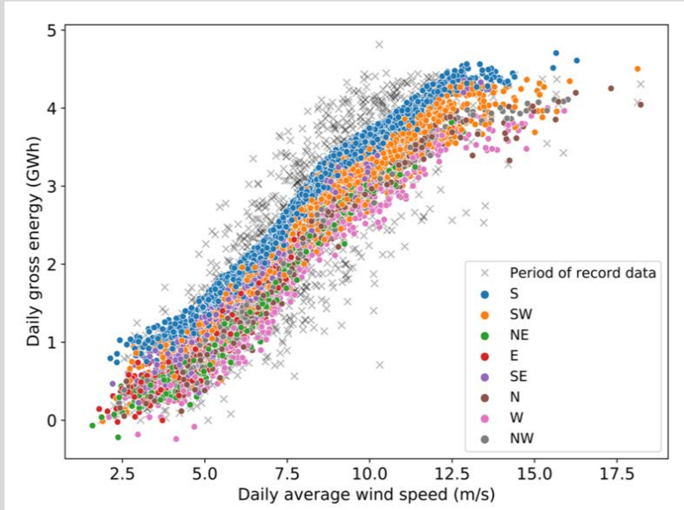
Annual Energy Production Uncertainty Calculations: More Than the Sum of the Squares

Point of Contact: Nicola Bodini, Nicola.Bodini@nrel.gov

Accounting for uncertainty when calculating annual energy production (AEP) helps quantify risk and determine financing terms. A popular industry practice is to assume that different uncertainty components within an AEP calculation are uncorrelated and can therefore be combined as the sum of their squares. In this *Wind Energy Science* journal article, NREL researchers assess the validity of this assumption for operational-based uncertainty. By performing operational AEP estimates for more than 470 U.S. wind power plants, researchers found that correlations between the identified uncertainty components should be considered to assess the total AEP uncertainty more accurately.

The Next Generation for Wind Plant Power Curves

Point of Contact: Nicola Bodini, Nicola.Bodini@nrel.gov



This wind plant power curve uses the augmented approach proposed in this research and shows how the use of more complex relationships between multiple atmospheric variables (wind speed in meters per second [m/s]) and wind plant energy production (gross energy in gigawatt-hours [GWh]) can model wake effects, which are shown by the different colors in the plots based on the wind direction sector. *Graphic courtesy of Nicola Bodini, NREL*

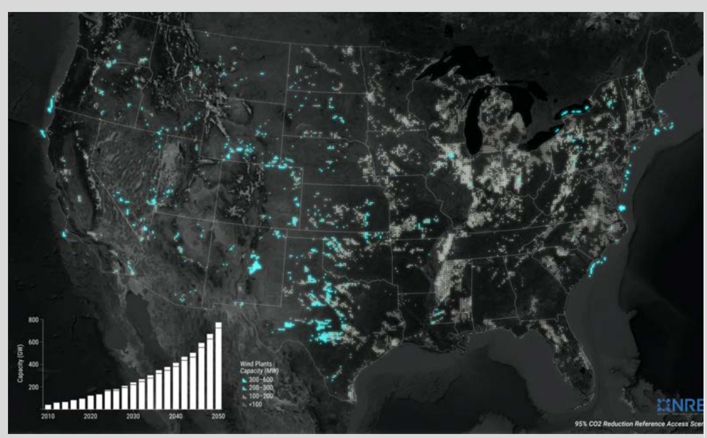
Many operational analyses of wind power plants require a statistical relationship, which can be called the wind plant power curve, to be developed between wind plant energy production and atmospheric variables. Currently, a simple, linear relationship between monthly wind speed and energy production is the industry standard for this type of application. In a *Wind Energy* journal article, NREL researchers leveraged NREL's OpenOA software to evaluate the benefits of augmenting this conventional approach by testing alternative models using machine learning. Research results show up to an 80% reduction in long-term energy production uncertainty, which can translate to important savings for wind energy stakeholders.

Spatial Analysis for Wind Technology Development	WETO.4.1.0.407

Siting Considerations Can Impact Wind Energy's Technical Potential

Point of Contact: Anthony Lopez, Anthony.Lopez@nrel.gov

NREL analysis published in *Energy* demonstrates how different siting considerations and carbon-dioxide reduction strategies can influence wind power plant sizes, how many wind facilities are built in the United States, and how quickly we move toward decarbonization. To examine U.S. land-based wind resource potential, analysts used NREL's Renewable Energy Potential Model to simulate siting constraints, regulations, landscape, and infrastructure, revealing that wind has a technical potential of 7,800 gigawatts in the continental United States. Under a more restrictive siting regime, this potential could decline to 2,280 gigawatts. This work was featured in *The Wall Street Journal* and *Inside Climate News*. Members of the public can download the resulting supply chain curves.

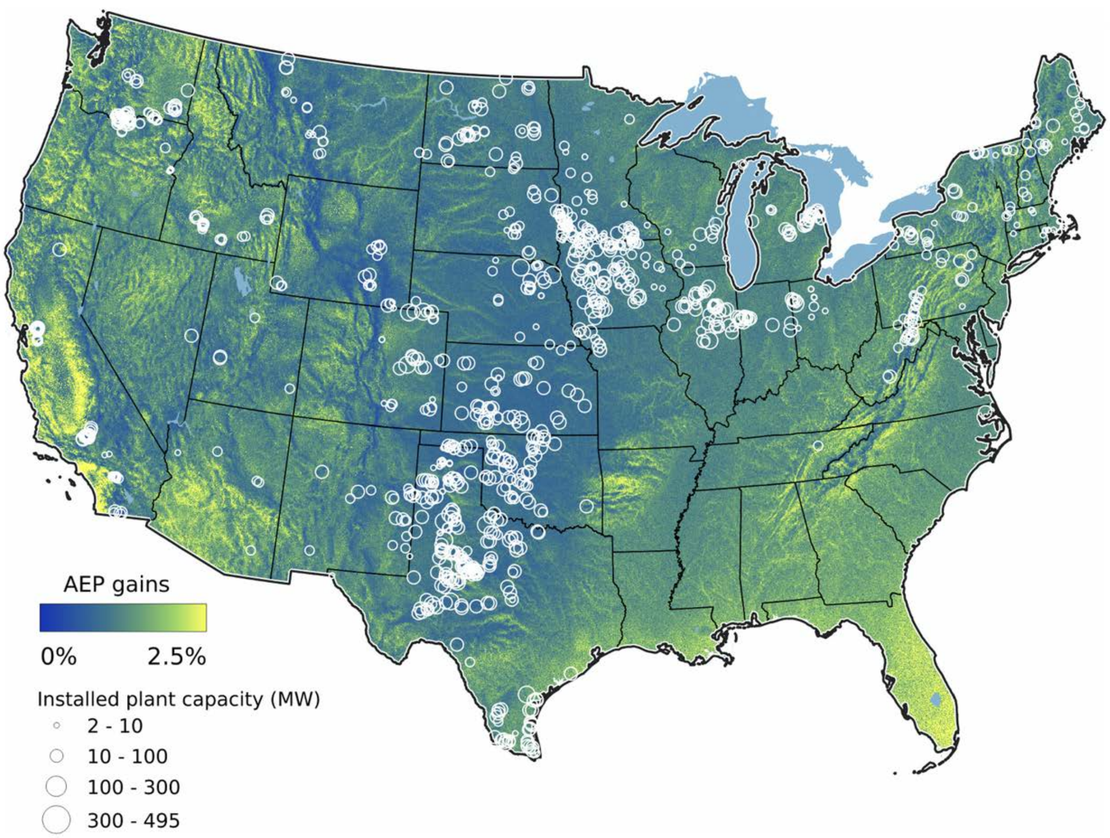


NREL analysis demonstrates how different siting considerations and carbon-dioxide reduction strategies can impact wind power plant sizes and the expansion of wind plant capacity across the United States. Those siting decisions impact how many wind facilities are built in the United States and how quickly we move toward decarbonization. *Image courtesy of Billy Roberts, NREL*

Surrogate Models Reveal New Opportunities for Wind Power

Point of Contact: Anthony Lopez, Anthony.Lopez@nrel.gov

Scalable surrogate models developed by NREL researchers provide unprecedented geographic insight into new wind power opportunities. For instance, regions previously considered unsuitable for wind energy deployment because of moderate wind resources can be enhanced by wake-steering strategies, resulting in boosts to annual energy production. Trained on millions of simulations produced by FLORIS, the surrogate models can accurately predict annual energy production for arbitrary plant layouts in any location. Sensitivity analyses suggest that wake steering could help overcome land constraints and inflexible layout options, potentially identifying new deployment opportunities. The models can be scaled rapidly across large geographic regions, improving techno-economic analysis capabilities and exploration of future technology advancements. This work was published in *Wind Energy*.



In contrast to current patterns of wind energy deployment, annual energy production gains from wake-steering strategies are most pronounced in regions of the country that have historically not experienced significant wind energy development. For instance, regions with higher AEP gains tend to have less installed wind plant capacity. *Graphic courtesy of Dylan Harrison-Atlas, NREL*

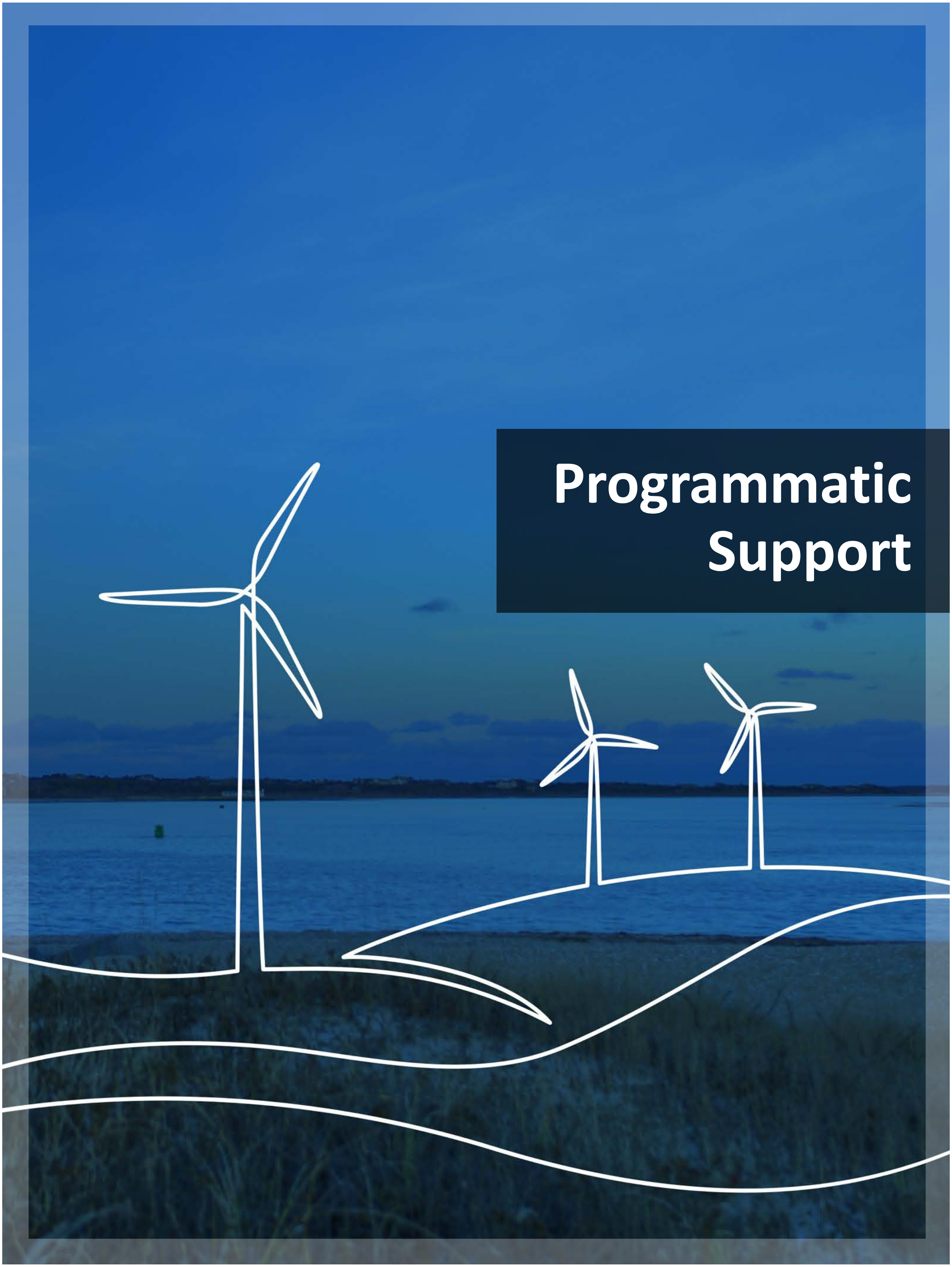
2020 U.S. Offshore Wind Project Pipeline Grows 24% Over 2019

Point of Contact: Matt Shields, Matt.Shields@nrel.gov

The "Offshore Wind Market Report: 2021 Edition," written by NREL researchers, reports that the pipeline for U.S. offshore wind energy projects grew to 35,324 MW—a 24% increase over the previous year. Covering the status of more than 200 globally operating offshore wind energy projects through Dec. 31, 2020, the report also provides a deeper assessment of domestic offshore wind energy developments and events through May 31, 2021. Complementing reports for land-based and distributed wind energy, the offshore wind market report is intended to inform policymakers, researchers, and analysts about current wind energy technology and market trends, delivering the most up-to-date discussion about this evolving industry.

Driven by falling offshore wind energy prices, federal action, and state-level commitments, the U.S. offshore wind energy pipeline grew 24% over 2019, with 35,324 MW now in various stages of development. *Image courtesy of NREL*

Programmatic Support



Leadership Series Advances Wind Energy Science Conversation

Point of Contact: Alex Lemke, Alexsandra.Lemke@nrel.gov

The ongoing Wind Energy Science Leadership Series highlights NREL wind energy research through presentations and discussions designed to advance participant understanding of the challenges facing wind energy and pathways for ensuring wind's place as one of the future's most prevalent energy sources. During the year, speakers covered seven critical topics, including the increasing size of land-based wind turbine rotors, floating offshore wind systems off the coasts of the United States, and hybrid energy systems with wind at their core. To date, the series has been viewed more than 37,000 times on YouTube.

Participants in the March webinar, "Hybrid Energy Systems of the Future," discussed the design and control of the wind energy systems of the future. *Screenshot courtesy of NREL*

NREL Leads Global Wind Efforts

Point of Contact: Brian Smith, Brian.Smith@nrel.gov

In partnership with DOE, NREL experts led or co-led 12 international, collaborative IEA Wind research tasks, including three new tasks—enabling wind turbine blade recycling, integrated design of floating wind arrays, and hybrid power plants. NREL Wind Energy Laboratory Program Manager Brian Smith served as vice chair and U.S. alternate member of the IEA Wind Executive Committee, and NREL communications staff wrote the U.S. chapter of the 2020 IEA Wind annual report. By participating in 21 of the 24 IEA Wind research tasks, NREL strengthened the nation's presence and influence among member countries, the European Commission, the Chinese Wind Energy Association, and WindEurope.

This graphic details NREL's 2021 participation in IEA Wind tasks. *Graphic by John Frenzl, NREL*

Wind Research Impact Cultivated Through Sound Programmatic Support

Point of Contact: Brian Smith, Brian.Smith@nrel.gov

The NREL Wind Energy Program actively manages one of the largest wind-energy-dedicated research, development, demonstration, and deployment portfolios in the world with 79 projects funded by WETO. These efforts have resulted in:

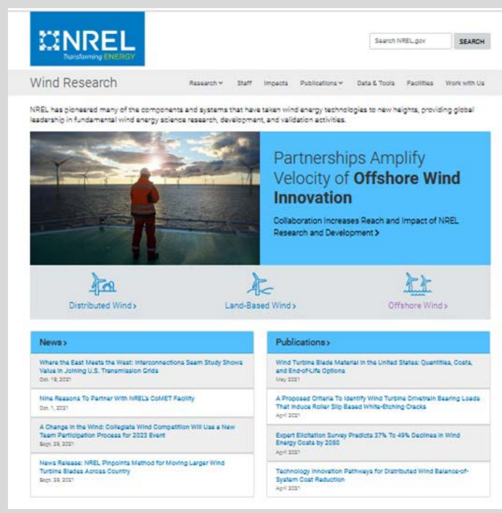
- An increase in the impact of WETO's mission by leading research, innovation, and strategic collaborations to deliver advanced science and technology solutions
- Stewardship, management, and safe operation of world-class wind energy research facilities at NREL's Flatirons Campus and within the ARIES research platform
- Technology-to-market initiatives that explore transformative energy technologies and create pathways for commercial development
- Partnerships between WETO's multidisciplinary experts and industry, academia, and governmental institutions, including GE Renewable Energy, Technical University of Denmark, New York State Energy Research and Development Authority, U.S. Bureau of Ocean Energy Management, Institute for Advanced Composites Manufacturing Innovation, Equinor Energy, and Siemens Gamesa Renewable Energy.

Communications Support	WETO 5.1.0.402

Strategic Communications Amplify WETO's Mission

Point of Contact: Amy Howerton, Amy.Howerton@nrel.gov

The NREL communications team created videos, graphic designs, newsletters, web content, press releases, and social media posts to share information on the laboratory's wind energy research findings, accomplishments, and capabilities. In particular, NREL communications staff developed 167 social media posts for DOE and the Office of Energy Efficiency and Renewable Energy, which garnered 303,961 impressions and 4,767 engagements; published on NREL.gov 38 original online news items, feature stories, and news releases about wind energy research and development; and managed multiple websites, including 245 CWC and 821 WETO web pages on Energy.gov. These communications products helped inform, raise awareness, garner support, and trigger action among technical peers, industry organizations, government agencies, potential partners, the media, and the public about both NREL's and DOE's efforts to lead the nation in accelerating the deployment of wind energy technologies.



NREL FY 2021 communications activity included enhancements to the laboratory's Wind Research website and a series of features on NREL partnerships with industry, academia, government, academia, and other entities to advance wind research and development. *Screenshot courtesy of NREL*

NREL Advisors Help Define, Shape, and Support Research Portfolio Implementation

Points of Contact: Alexsandra Lemke, Alexsandra.Lemke@nrel.gov, Mike Robinson, Mike.Robinson@nrel.gov, and Rich Tusing, Richard.Tusing@nrel.gov

NREL's Alexsandra Lemke, Mike Robinson, and Rich Tusing provided strategic support and guidance to WETO through management and operations detail assignments designed to define, develop, shape, and support the implementation of WETO's research and development portfolio. Serving in various leadership roles, these advisors contributed to high-quality deliverables, such as the Multi-Year-Program Plan, provided timely and effective management of analytical and technical support activities, contributed to two congressional reports, and exhibited strong leadership in targeted areas (early-stage research and development, high-performance computing, technical and economic analysis, technology to market, external affairs, and communications) with high market impact.

OpenOA Version 2 Shaped by Energy I-Corps Beginnings

Point of Contact: M. Jason Fields, Michael.Fields@nrel.gov

A year since OpenOA's first launch and guided by user feedback through Energy I-Corps, NREL released OpenOA Version 2, which helps wind power plant operators identify and analyze the factors that drive wind plant performance. The opportunity to collaborate with eight major wind power plant owners and 10 third-party consultants through Energy I-Corps helped shape the new release of the OpenOA software framework, as the OpenOA team conducted wind plant performance modeling to identify an industry gap—the lack of existing standards for conducting detailed operational assessments—which OpenOA helps fill.

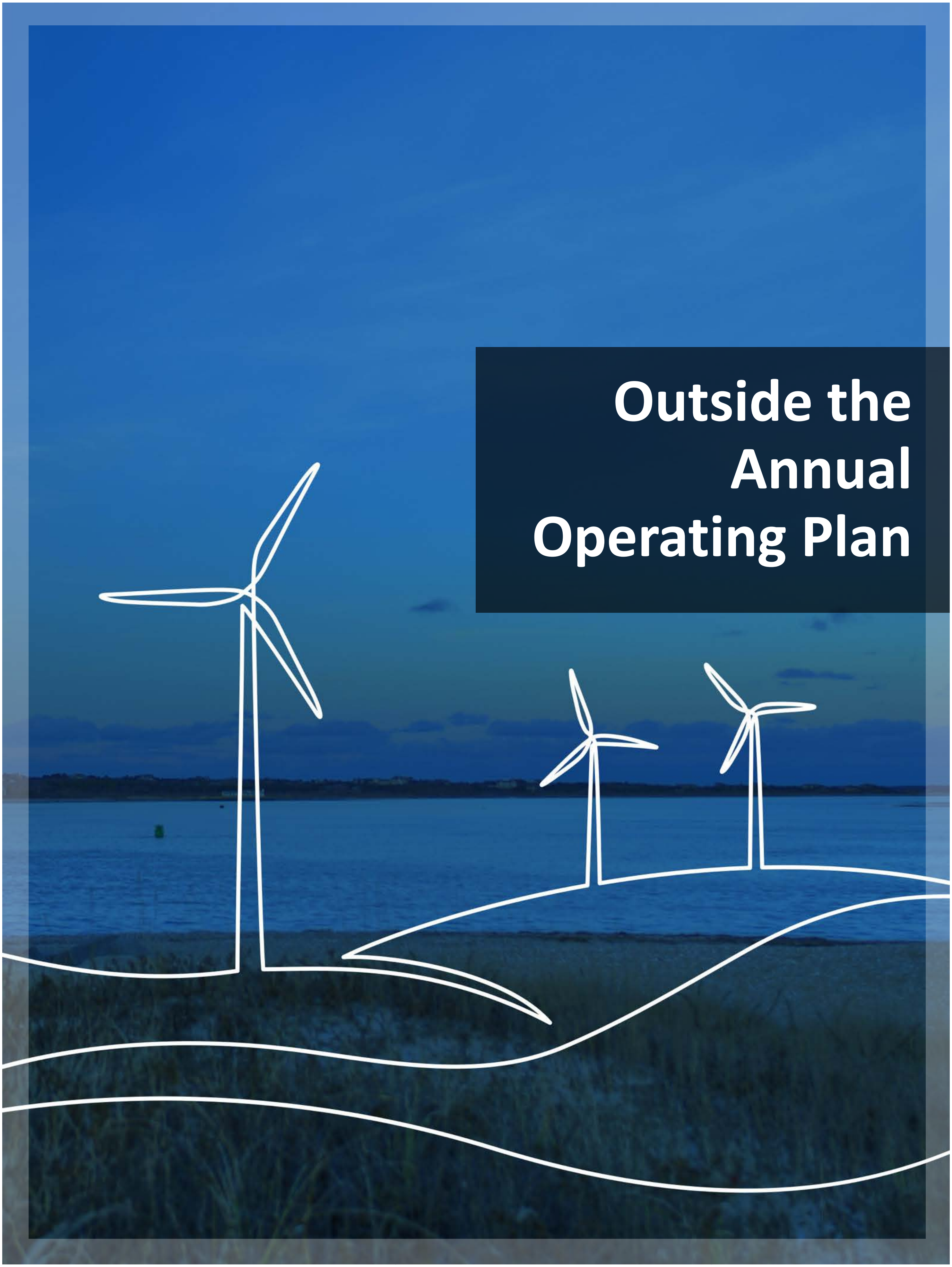
NREL recently released an update to the open-source modeling and analysis tool OpenOA with features designed to help wind plant operators identify and analyze the different factors that drive wind plant performance. *Design by Jennifer Breen-Martinez, NREL*

Software Could Expedite U.S. Hybrid Renewable Energy Industry Development

Point of Contact: Aaron Barker, Aaron.Barker@nrel.gov

By engaging with the energy industry through the Energy I-Corps program, the Hybrid Optimization and Performance Platform (HOPP) software team tailored the software's development to provide the greatest benefit to users. The tool enables detailed analysis and optimization of hybrid power plants down to the component level and can assess and optimize projects containing combinations of wind energy (land-based and offshore), solar power, energy storage, geothermal, and hydropower. This software could expedite the development of the U.S. hybrid renewable energy industry by answering the crucial question: When and where do hybrid plants make sense (from a market and resource perspective), and how can we design them optimally?

Outside the Annual Operating Plan



Grid-Scale Hybrid Power Plant Will Accelerate Transition to Renewable Energy-Powered Electric Grid

Point of Contact: Vahan Gevorgian, [Vahan.Gevorgian@nrel.gov]

NREL researchers are developing FlexPower—a variable, hybrid-generation power plant enhanced with energy storage—which will be stationed at NREL's Flatirons Campus. A priority project for the ARIES platform, FlexPower will help accelerate the adoption of utility-scale variable wind and photovoltaic resources by demonstrating how hybrid power plants can smooth the transition to an electric grid primarily powered by renewable energy. Funded by the DOE Grid Modernization Laboratory Consortium, the FlexPower project is a collaboration among NREL, Idaho National Laboratory, and Sandia.

The FlexPower project will help accelerate the adoption of utility-scale variable wind and photovoltaic resources by demonstrating how hybrid power plants can provide essential reliability and resiliency services to the grid. *Photo by Dennis Schroeder, NREL 20691*

Study Finds Offshore Wind Energy Costs in California Could Decrease by 44%

Point of Contact: Philipp Beiter, Philipp.Beiter@nrel.gov

The deep waters along the California coast are well suited for floating offshore wind energy technology currently in a precommercial phase. An NREL study funded by the Bureau of Ocean Energy Management provides site-specific cost and performance data for floating offshore wind energy to inform California's long-term energy planning. The analysis focuses on five geographically dispersed study areas that represent regions where offshore wind energy has development potential. Key results from the study include a 44% average decrease in estimated LCOE between 2019 and 2032, reaching levels of \$53–\$64 per megawatt-hour.

Wind Turbine Rotor Rotation and Inflow Conditions Can Influence Wake Behavior

Point of Contact: Julie Lundquist, Julie.Lundquist@nrel.gov

A new study investigates the relationship between wind turbine rotor rotation and wind inflow profiles and the resulting impacts on wind turbine wakes. Veering profiles, or increases of wind direction with height, are common in nighttime conditions in the Northern Hemisphere. Using large-eddy simulations, the research team evaluated combinations of rotor rotation and inflow wind conditions and found that, in veering conditions, the direction of rotor rotation can change the behavior of the wake, impacting power output at a wind energy facility.

NREL's Autonomous Energy Grids Research Leads to 85% Drop in Resident Utility Bills

Point of Contact: Jennifer King, Jennifer.King@nrel.gov

A housing complex in Basalt, Colorado, is interconnected through a microgrid that allows 27 households to seamlessly share electricity, providing residents with utility bills that are estimated to be 85% lower than typical electrical bills in the state. NREL partnered with the local electrical utility Holy Cross Energy to implement the autonomous energy grid (a grid capable of self-organization and control that can respond to energy demands in near-real time), and additional autonomous energy grid applications could feature wind energy. An autonomous-energy-grid-enabled future means that control techniques, like the ones deployed at Basalt Vista, will autonomously manage large wind power plants using consensus control.

The Basalt Vista housing project, a collaboration between NREL and Holy Cross Energy, demonstrates the real-life applications of NREL's autonomous energy grid research. *Photo by Josh Bauer, NREL*

Research Puts Forth Best Practices for Validating U.S. Offshore Wind Resource Models

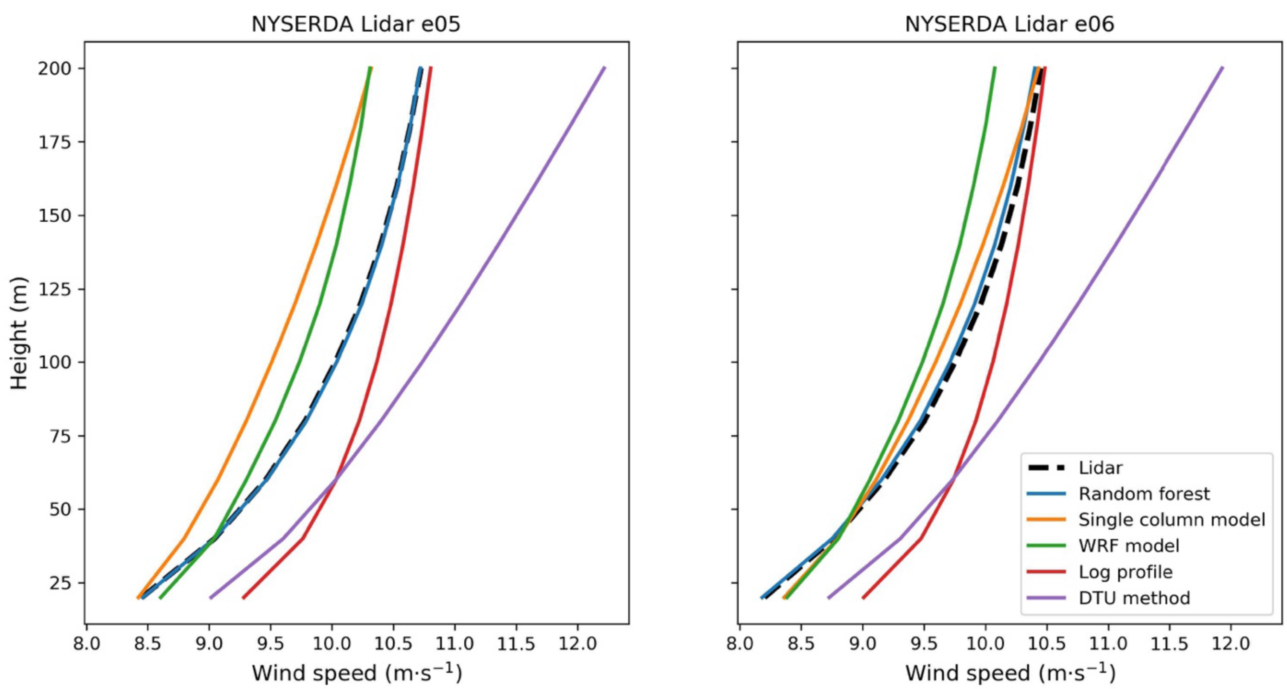
Point of Contact: Nicola Bodini, nicola.bodini@nrel.gov

NREL researchers provided a comprehensive set of best practices for working with both modeled and measured U.S. offshore wind resource datasets in a new technical report for the Bureau of Ocean Energy Management. Offering nine recommendations, researchers determined the most reliable data sources and methods for validating modeled wind resource estimates, as well as methods for vertically extrapolating near-surface wind speed measurements, to heights that span the rotor-swept area of modern offshore wind turbines. Among other findings, researchers found that a machine-learning approach was able to extrapolate near-surface winds to hub height at much greater accuracy than conventional methods. These best practices can help inform improved offshore wind resource characterization efforts, thereby aiding future offshore wind energy deployment efforts.

NREL Identifies Model to Extrapolate Winds at Turbine Height from Near-Surface Data

Point of Contact: Nicola Bodini, nicola.bodini@nrel.gov

With most of the offshore wind speed observations coming from near-surface measurements, an NREL research team evaluated three novel modeling techniques that can be used to extrapolate offshore wind speeds at wind turbine rotor-swept heights from observed, near-surface data. A model that incorporated machine learning outperformed the others across a broad range of offshore conditions, which suggests it can provide the most accurate information about the wind speeds they can expect offshore wind turbines to encounter.



The picture shows the mean observed (left) and modeled (right) wind profiles at two offshore locations on the U.S. mid-Atlantic Coast. The proposed machine-learning model has the best agreement with the black dotted line, which shows the observed profile. *Figure courtesy of Nicola Bodini, NREL*

National Offshore Wind R&D Consortium Funding Advances NREL Research

Point of Contact: Rebecca Green, Rebecca.Green@nrel.gov

Funding through the National Offshore Wind R&D Consortium is enabling NREL researchers to contribute to state-of-the-art technology and supply chain advances for offshore fixed-bottom and floating wind energy systems. To date, approximately $6.3 million in funding is advancing NREL's research with strategic partners in multiple areas, including:

- Development of advanced methods for evaluating grid stability impacts by HVAC and HVDC interconnected offshore wind power plants
- A supply chain roadmap for offshore wind development in the United States
- Shared mooring and anchoring systems for deep-water floating wind power plants
- Wind plant control and layout optimization for U.S. offshore wind power plants
- Validated national offshore wind resource datasets.

This research will help accelerate national targets for offshore wind energy generation.

Technology and supply chain advances for offshore fixed-bottom and floating wind systems will help accelerate national targets for offshore wind energy generation. *Photo from Lyfted Media for Dominion Energy*

Partnerships Boost Wind Blade Recycling Technology and Automated Wind Blade Finishing

Point of Contact: Derek Berry, Derek.Berry@nrel.gov

NREL signed two partnership agreements with the state of Colorado's Office of Economic Development and International Trade, representing more than $800,000 of funding to the laboratory. The first agreement provides funds to develop economically viable wind turbine blade recycling methods at NREL, furthering the goal of developing the Composites Manufacturing Education and Technology Facility into a premier center for composite wind blade recycling research. The second completes the procurement of an automated wind blade finishing system at NREL and develops the application of this technology to full-scale composite wind blade structures.

NREL signed two partnership agreements that will advance wind turbine blade recycling and automated wind blade finishing technology. *Photo by Samantha Rooney, NREL*

Research Strengthens Reliability as Wind Power Shifts into High Gear

Point of Contact: Shawn Sheng, Shawn.Sheng@nrel.gov

New tools from NREL make it possible to predict individual component reliability for the entire wind power plant, reduce operation and maintenance costs through early design decisions, and take maintenance measures to extend gearbox life spans. Keeping gearboxes in operating condition is essential to efficient and cost-effective wind power plant operation, as gearboxes account for as much as 11% of overall wind turbine costs. Gearboxes convert low-speed blade rotations to the high speeds required by most generators for electricity generation.

Keeping wind turbine gearboxes in operating condition is essential to efficient and cost-effective wind power plant operation. New tools from NREL are making that possible. *Photo by Brad King, RENEW Energy Maintenance*

Lightning No Match for Wind Turbine Blade Protection System

Point of Contact: Robynne Murray, Robynne.Murray@nrel.gov

NREL scientists created a wind turbine "lightning shield" that can prevent damage or failure in blades manufactured with a novel process. The lightning protection system diverts about 80% of a lightning strike's current away from metal heating elements in wind turbine blades, which are made from a new type of more easily recyclable material—thermoplastic resin composites—and manufactured with a new, patent-pending thermal welding process. The research overcomes a critical barrier in the commercial development of the process. The research team's next step is to structurally validate thermally welded blade bond lines and blade tip segments. The lightning shield was developed in partnership with General Electric and LM Wind Power and with funding from DOE's Technology Commercialization Fund (TCF).

NREL researchers designed a way to protect thermally welded wind turbine blades from failure caused by lightning strikes. The research makes commercialization of this technology more likely. *Photo by NREL*

NRELians Recognized for Excellence by Energy Systems Integration Group

Points of Contact: Robert Thresher, Robert.Thresher@nrel.gov, Bethany Frew, Bethany.Frew@nrel.gov, and Shawn Sheng, Shawn.Sheng@nrel.gov

Three NREL researchers—Bob Thresher, Bethany Frew, and Shawn Sheng—received 2021 Excellence Awards from the Energy Systems Integration Group, a nonprofit educational organization dedicated to critical analysis of wind energy for utility applications. Sheng received an excellence award for expanding the characterization and understanding of phenomena in wind turbine component operations and technical issues. Frew received an excellence award for contributions to market design for a renewable energy future. Emeritus researcher Thresher received a lifetime achievement award for his contributions to advancing wind energy technology internationally through his work at NREL.

The Energy Systems Integration Group awards recognize energy professionals for their contributions to the planning and operation of energy systems across multiple pathways and geographical scales in ways that are reliable, economic, and sustainable. *Photo by Dennis Schroeder, NREL*

Van Dam Receives Thomas A. Edison Achievement Award

Point of Contact: Jeroen Van Dam, Jeroen.van.Dam@nrel.gov

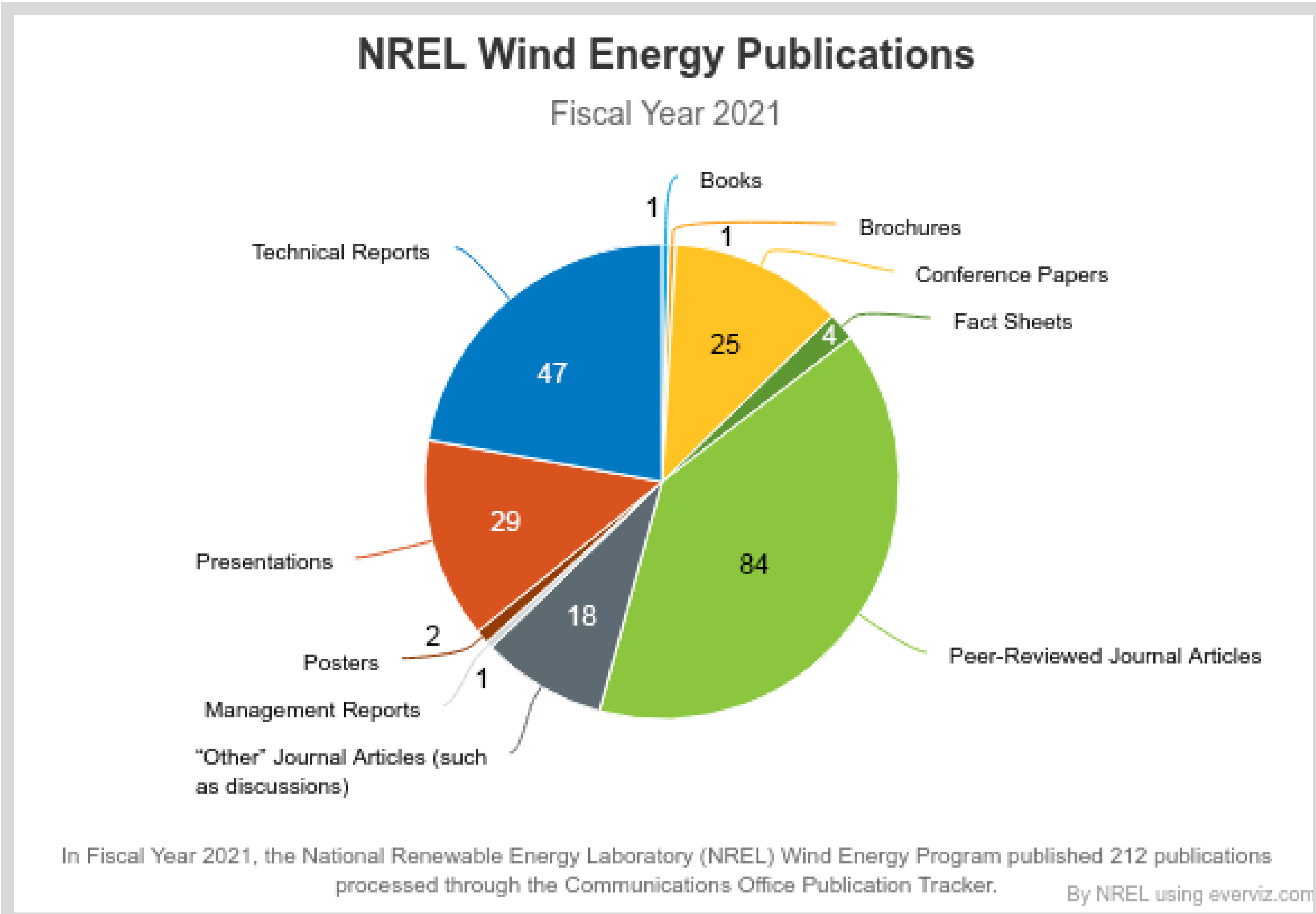
NREL researcher Jeroen Van Dam received the IEC Thomas A. Edison Award for his exceptional achievements as chair of IEC TC 88. TC 88 is an IEC technical committee designed to develop standardization in the field of wind energy generation systems, including wind turbines, land-based and offshore wind power plants, and interaction with the electrical system(s) to which energy is supplied. A record 100 people attended the virtual plenary TC 88 meeting in 2021, which can be compared with 40–50 people at past meetings.

NREL researcher Jeroen Van Dam (left) received the IEC Thomas A. Edison Award for leading an international committee designed to develop standardization in the field of wind energy generation. *Image by NREL 56127*

Publications

Publications produced by NREL Wind Energy Program staff provide information about the many areas of wind energy research conducted at the lab.

In FY 2021, NREL researchers published their latest scientific findings and breakthroughs in 212 technical reports, peer-reviewed journal articles, conference papers, fact sheets, and other materials.



These publications provide reliable, unbiased information that researchers from academia, other national laboratories, government agencies, and private industry organizations can use to advance wind energy science.

Notable Publications

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