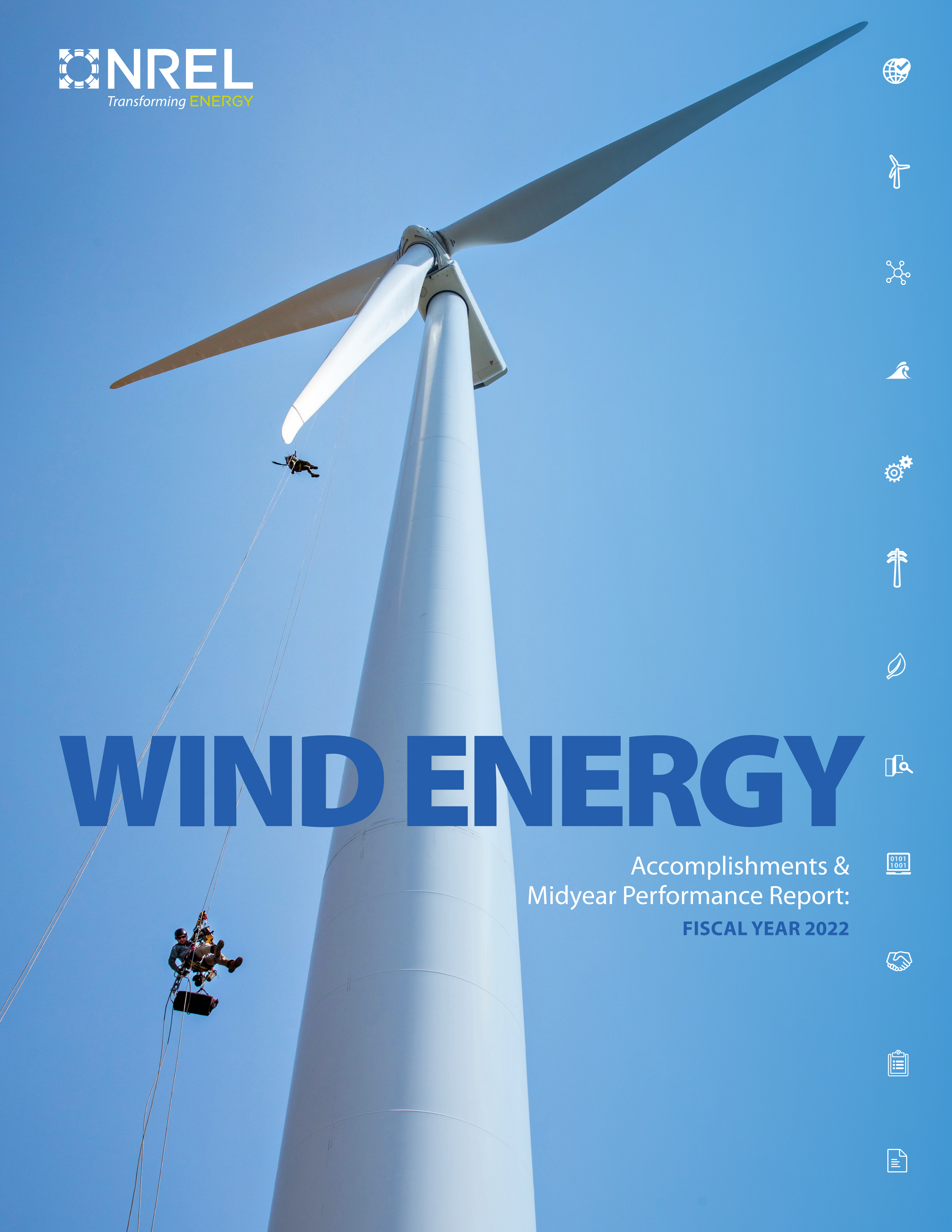
NREL
Transforming ENERGY



# WIND ENERGY

## Accomplishments & Midyear Performance Report:

**FISCAL YEAR 2022**

# Notice

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government. This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications. U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

# Foreword

2022 marks 43 years of innovation through the National Wind Technology Center at the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) Flatirons Campus. Scientists, engineers, analysts, and researchers continue to build on NREL's legacy of innovation at this world-class hub for wind energy technology research and development.

Today, the nation's goals to tackle climate change and revitalize the U.S. economy through increased investment in clean energy—particularly in land-based, offshore, and distributed wind energy—are more ambitious than ever. From advancing wind energy science, technologies, and materials to demonstrating thought leadership on a worldwide scale, NREL's Wind Energy Program played a powerful role in maximizing the impact of wind energy in the first half of Fiscal Year 2022. NREL's technical expertise, research capabilities, and industry understanding continued to support DOE's efforts to champion clean energy, addressing market and deployment barriers and driving down costs with more efficient, reliable, and predictable wind energy systems.

This report provides an overview of the achievements NREL made on behalf of DOE's Wind Energy Technologies Office and other partners between October 1, 2021, and March 31, 2022. A few of these many accomplishments are highlighted here:

- NREL published *The Demand for a Domestic Offshore Wind Supply Chain* coauthored by members of the Business Network for Offshore Wind and DNV. The study examines the components, ports, vessels, and workforce required to achieve the nation's goal of reaching 30 gigawatts of offshore wind energy by 2030.

- In a milestone for renewable energy integration, NREL partnered with General Electric to demonstrate how the company's popular type-3 wind turbine can help stabilize the bulk power grid, significantly reducing the need for conventional sources of grid stability, such as coal- or natural-gas-fired generators.

- Researchers at NREL's Composites Manufacturing Education and Technology Facility explored a revolutionary combination of thermoplastics and three-dimensional printing that can be used to produce easier-to-recycle wind turbine blades that require fewer heavy and expensive adhesives.

- An analysis-based study showed that uniting the eastern and western U.S. electric grids could significantly strengthen the power system's ability to share generation resources and flexibility across regions, as well as deliver up to $2.50 in benefits for every $1 in related costs.

- The laboratory released Version 3.0 of FLOw Redirection and Induction in Steady State, an optimization tool designed to increase wind energy facilities' productivity.

- Researchers are preparing to launch the WETO-funded American WAKE experimeNt wind energy field campaign, which will amass the world's most comprehensive set of high-resolution data on wind energy atmospheric phenomenon to help wind power plants produce more energy and become more competitive in the marketplace.

The following provides a roundup of NREL's National Wind Technology Center accomplishments. They set the stage for wind energy research and development efforts for the next 30 years of the National Wind Technology Center's history.

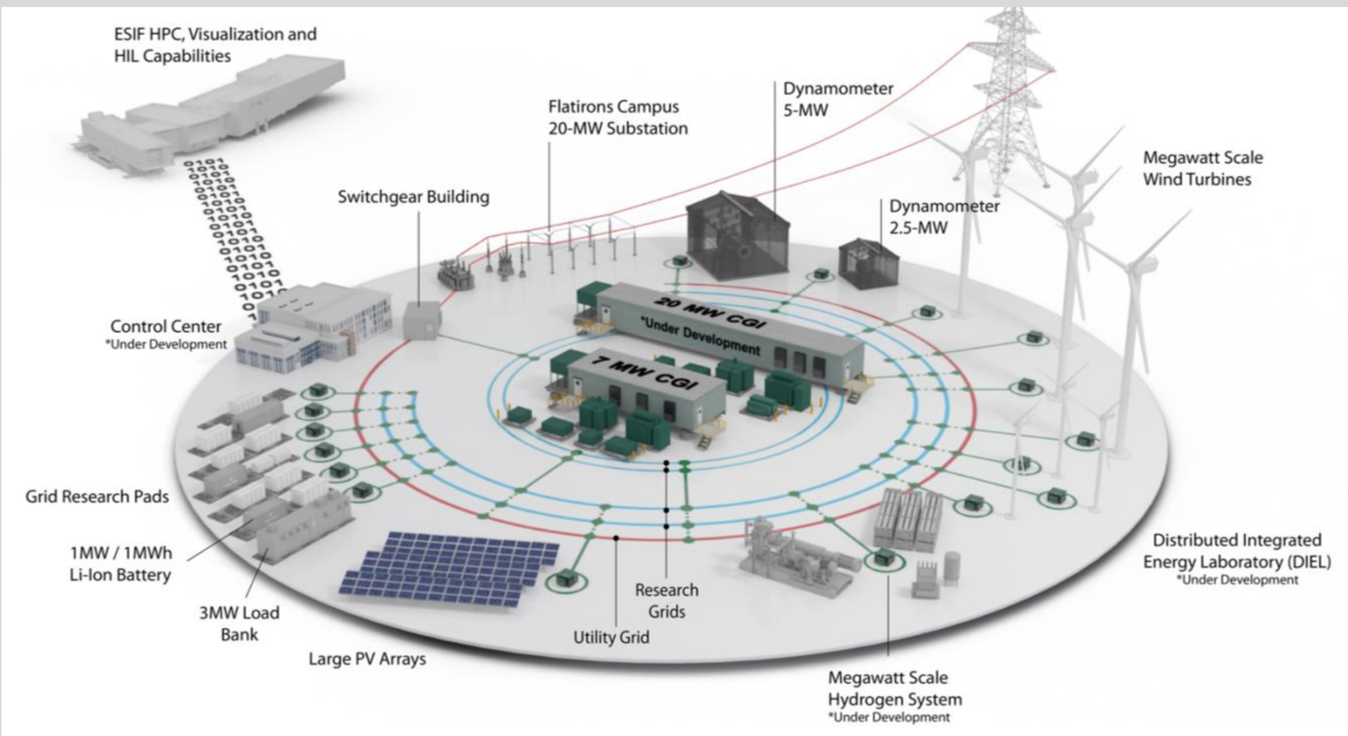
# Table of Contents

# Testing Infrastructure, Standards Development, and International Engagement

**Point of Contact:** Jeroen van Dam, [Jeroen.van.Dam@nrel.gov](mailto:Jeroen.van.Dam@nrel.gov)

# Construction Begins on Second Controllable Grid Interface

The construction phase of the 20-megawatt (MW) Controllable Grid Interface (CGI-2) at the Flatirons Campus has started. This is the final phase of the CGI-2 project, with construction scheduled to be substantially complete by the end of 2022. Once complete, CGI-2 will allow for experiments at higher power levels (up to 20 MW) and different voltages. By increasing capacity for research and development on the National Renewable Energy Laboratory's (NREL's) Flatirons Campus, CGI-2 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.




The 20-MW CGI-2 will operate alongside the existing 7-MW CGI and will also be able to connect to different integrated energy systems at scale—such as wind turbines, photovoltaic arrays, and battery storage—at the Flatirons Campus in support of NREL's Advanced Research on Integrated Energy Systems (ARIES) research platform. *Graphic by Josh Bauer, NREL*

OSW Testing Facilities and Capabilities at NWTC—HPC WETO.1.1.0.404

**Point of Contact:** Kristen Munch, Kristen.Munch@nrel.gov

## WETO Projects Soar With NREL's Eagle

NREL's high-performance computing data center, housing Eagle, an 8-petaflop supercomputer. *Photo by Dennis Schroeder*

NREL's high-performance computing (HPC) system, Eagle, is the world's largest supercomputer dedicated to energy efficiency and renewable energy. Supercomputers, or HPCs, have the capability to simulate complicated scenarios prior to investing in wind energy infrastructure. Demand for HPC computing using Eagle has consistently increased in recent years among the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) program offices. In Fiscal Year (FY) 2020, to ensure program success and continuity of research, DOE's Wind Energy Technologies Office (WETO) entered a lease-to-own procurement and installation agreement for additional Eagle HPC hardware and services. This agreement gave WETO projects the largest priority access to the HPC within the EERE portfolio (with 288 computing nodes). In FY 2022, NREL has managed lease payments and periodic maintenance for WETO on Eagle and ensured that WETO-funded priority research projects use allocated time with Eagle efficiently. The WETO hardware has ensured that nearly 50% of the year-to-date WETO workload has run at the highest priority.

Wind Standards Development WETO.1.6.1.401

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

## NREL Experts Are a Driving Force Behind Standards Development

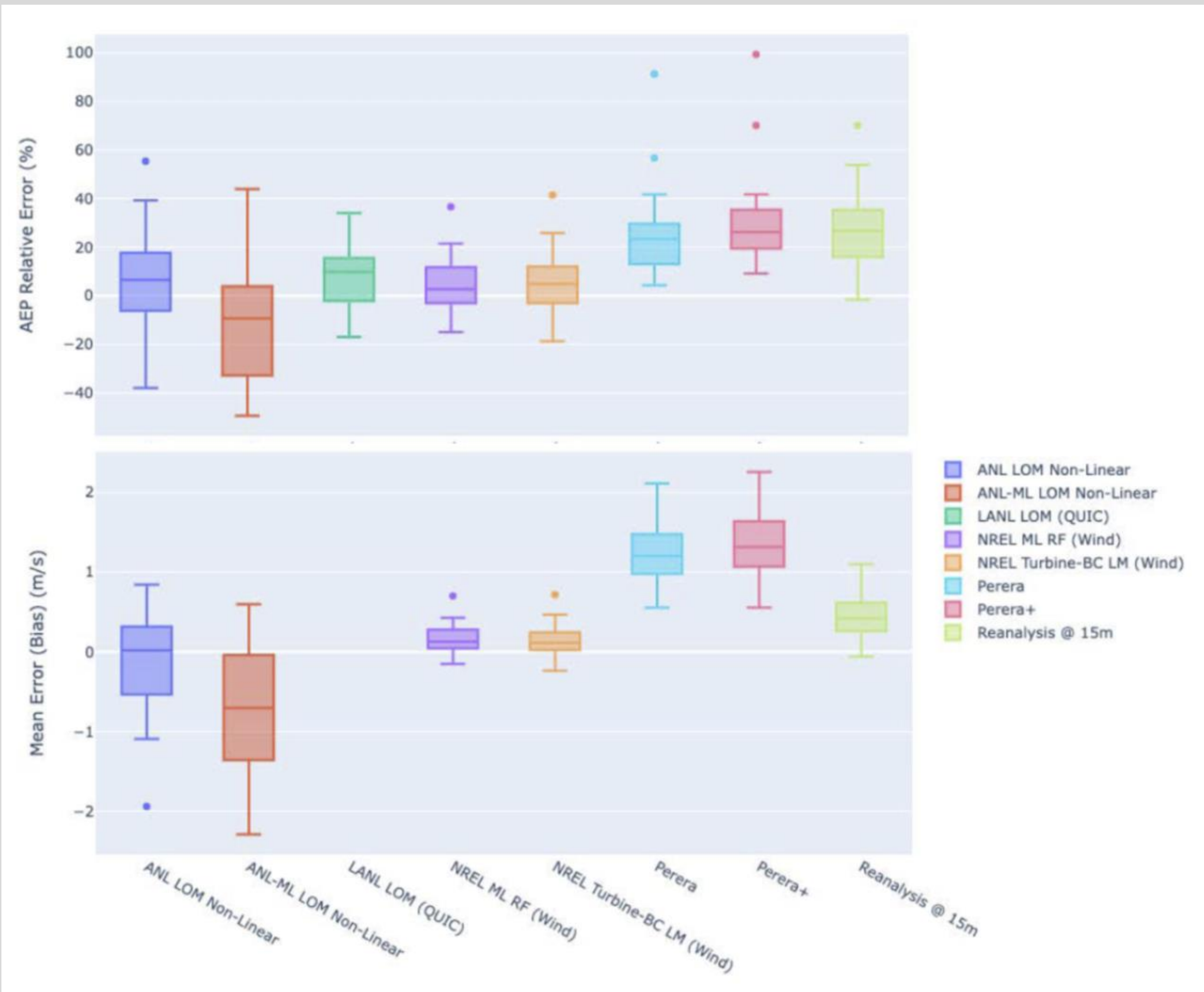
On March 29 and 30, 2022, NREL, in collaboration with the American Renewable Energy Standards and Certification Association, organized the 2022 U.S. Wind Energy Standards Summit. The objective of the summit was to educate industry stakeholders on ongoing standards developments efforts and solicit their participation and input. 130 people registered, and 91 people attended some part of the meeting (of which many were first-time attendees). Next year's summit is intended to be both in person and virtual to maximize potential audience participation

# Distributed Wind Research and Development

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

# Evaluation of Obstacle Modeling Approaches for Resource Assessment

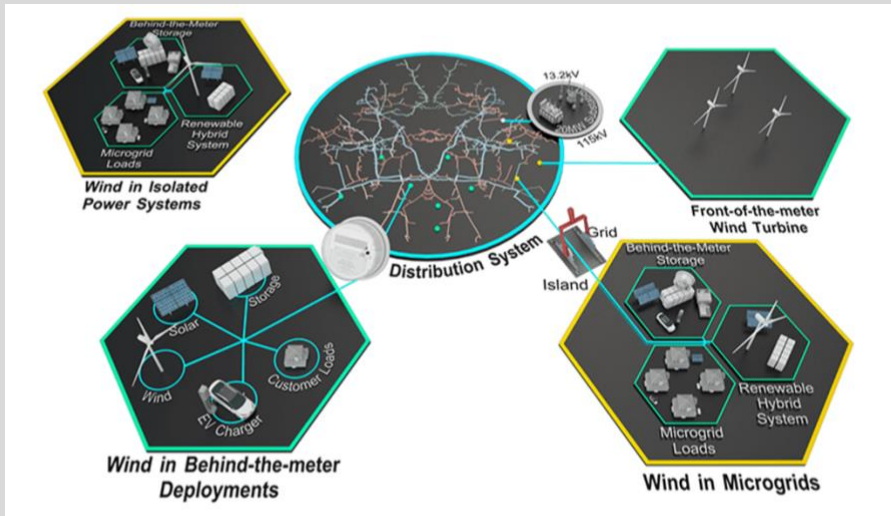
NREL researchers evaluated wind resource assessment and obstacle models against performance data from approximately 300 wind turbines deployed in the Netherlands. This study evaluated classical and commonly used methods along with new state-of-the-art lower-order models derived from computational fluid dynamics simulations and machine-learning approaches. The team found that data-driven (e.g., machine-learning and statistical-modeling) methods are most effective at predicting wind turbine production at real sites with an average error in annual energy production of 2.5%. When sufficient data may not be available to support these data-driven approaches, models derived from high-fidelity simulations show promise and reliably outperform classical methods. Results were recently published in *Wind Energy Science*.




Mean error of seven wind turbine performance modeling approaches alongside the raw reanalysis results for 300 distributed wind turbines in relatively consistent terrain, showing relatively large variations in model outputs, with some quite close to actual performance. *Graphic by NREL*

| Microgrids, Infrastructure Resilience and Advance Controls Launchpad (MIRACL) | WETO.1.2.3.401 |
|---|---|
| **Point of Contact:** Aaron Barker, Aaron.Barker@nrel.gov | |

# Flatirons Campus Power Grid Simulations Will Drive U.S. Distributed Wind Energy Capabilities



A graphical representation of MIRACL's four distributed wind energy use cases. *Graphic by Josh Bauer, NREL*

NREL's Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) team, in collaboration with the Pacific Northwest National Laboratory (PNNL), the Idaho National Laboratory, and Sandia National Laboratories, implemented new power grid simulation models for the Flatirons Campus that provide insight into how power systems behave when they are connected to the grid and "islanded," or operating without connection to the grid. This work represents a key first step in developing control approaches, valuation, and eventually hardware-in-the-loop validation of these approaches using the Advanced Research on Integrated Energy Systems (ARIES) research platform at the Flatirons Campus. The implementation of these models places ARIES at the forefront of microgrid modeling capabilities and will help to drive the development of new and innovative distributed wind energy capabilities in the United States.

| Distributed Wind Research, Development, and Testing | WETO.1.2.1.401 |
|---|---|
| **Point of Contact:** Brent Summerville, Brent.Summerville@nrel.gov | |

# NREL Holds Competitiveness Improvement Project Workshop for Industry

NREL hosted a 4-day virtual workshop for wind energy manufacturers interested in applying to Competitiveness Improvement Project (CIP) solicitations. Speakers provided an overview of the CIP process, evaluation criteria, certification requirements, and NREL's technical support opportunities. As a result of industry feedback provided during the workshop, a new topic area focused on wind turbine commercialization and market development was initiated within the 2022 CIP solicitation. This new topic continues to demonstrate how CIP helps distributed wind energy companies develop low-cost, certified technology to meet the growing need of distributed renewable energy.

Distributed Wind Research, Development, and Testing WETO.1.2.5.401

**Point of Contact:** Brent Summerville, Brent.Summerville@nrel.gov

## NREL Hosts Workshop To Advance Aeroelastic Modeling of Distributed Wind Energy Technology

NREL, in partnership with RRD Engineering and Windward Engineering, led a virtual workshop on distributed wind aeroelastic modeling. With stakeholder participation, the workshop identified gaps and needs in aeroelastic modeling of distributed wind energy technology and detailed actions to advance this critical design tool. More than 45 industry participants, representing the global distributed wind energy industry, provided real-time feedback via an online survey tool.

Windward Engineering performs model validation at their test site in Spanish Fork, Utah. Workshop participants identified the lack of guidance for code verification and model validation as a weakness in distributed wind energy aeroelastic modeling. *Photo by Brent Summerville, NREL*

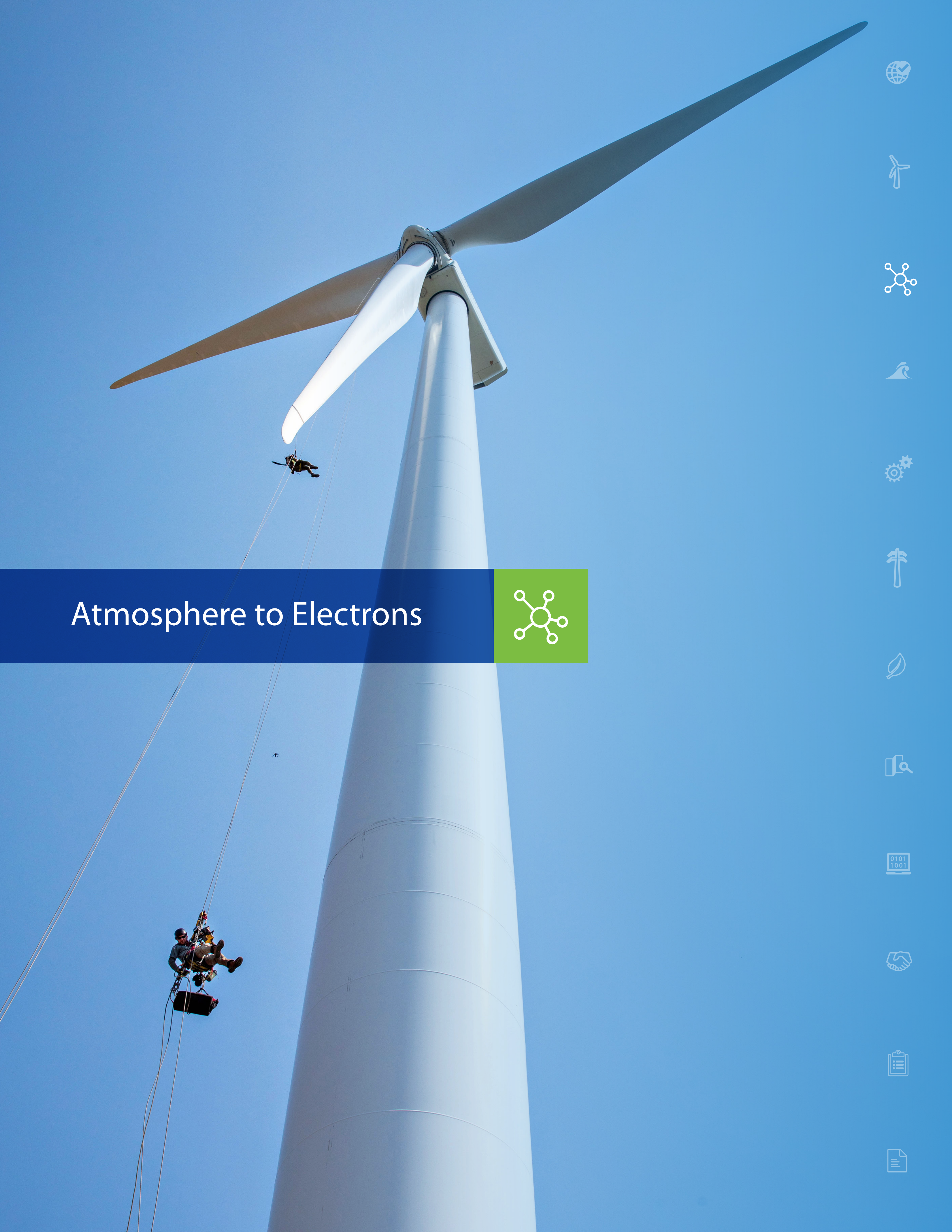
Distributed Wind Strategic and Technical Engagement WETO.1.2.5.401

**Point of Contact:** Brent Summerville, Brent.Summerville@nrel.gov

## NREL Provides Overview of New ACP 101-1 Standard, Collects Stakeholder Input on How To Implement

At the 2021 CIP informational workshop, NREL provided an overview of the new Small Wind Turbine Standard from the American National Standards Institute (ANSI) and American Clean Power (ACP), ANSI/ACP 101-1-2021, including changes from the previous edition. ACP 101-1 includes optimized technical requirements and an increased scope of application, enabling a more cost-effective route to distributed wind turbine certification. Further stakeholder engagement was facilitated in a meeting following the Distributed Wind Energy Association's conference in March 2022. Participants provided input via real-time polling questions focused on what is needed to support successful implementation of the standard.

Star Wind Turbines in East Dorset, Vermont, is in the process of testing and certifying their six-bladed Star72 turbine (like this one on a monopole tower at the RenewTest facility in Pampa, Texas) to the new Amercian Clean Power 101-1 standard. *Photo from David Carr, RenewTest*

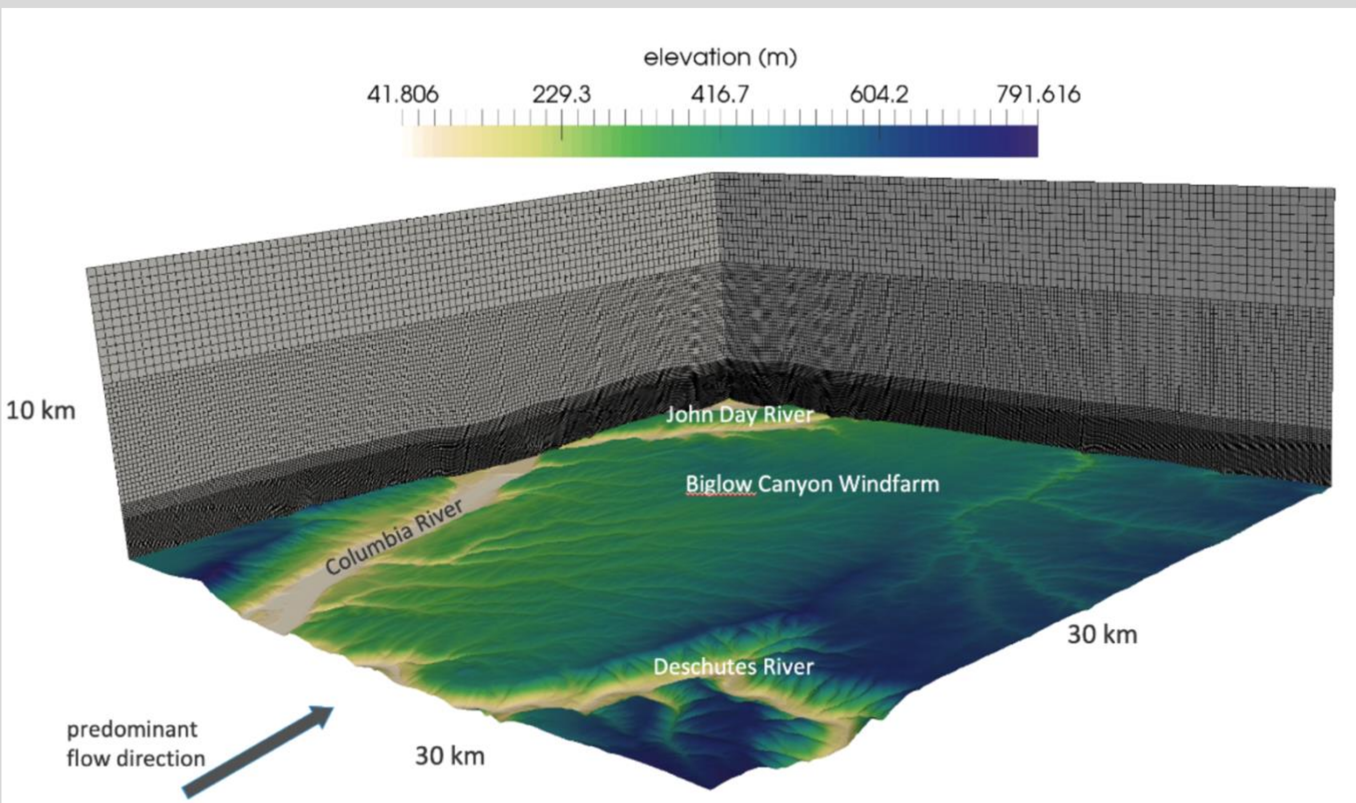


# Atmosphere to Electrons

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

# Multilab Team Creates Repository of Well-Documented Wind Flow Simulation Setups

A multilaboratory atmospheric flow modeling team consisting of NREL, PNNL, the Lawrence Livermore National Laboratory (LLNL), and the National Center for Atmospheric Research (NCAR) created a repository of highly detailed land-based and offshore wind flow simulation examples to share with the wind energy community. These example simulations are of the level of detail required to design wind turbines with the gusts and eddies of real wind. The well-documented examples will provide other researchers and engineers the directions and inputs required to simulate a variety of highly detailed atmospheric flow situations, enabling them to use advanced techniques and practices created by this multilaboratory team. Example cases include weather and wind flow modeling of the wind-power-plant-laden Columbia River area at the Washington-Oregon border in the U.S. Pacific Northwest region, which is characterized by complex terrain, and the U.S. Atlantic Coast, an important test case for large offshore wind turbines. Wind simulations like this can be used to develop improved wind turbine and wind plant designs.




The Biglow Canyon area of the Columbia River region at the Washington-Oregon border is provided as a case in a new publicly available repository of wind-flow modeling. Behind the terrain are two vertical planes comprising a mesh of black lines indicating the computational mesh used to solve the equations that govern the wind flow. *Illustration by Matt Churchfield, NREL*

| High-Fidelity Modeling | WETO.1.3.3.401 |
| --- | --- |

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

# High-Fidelity Modeling Team Adds Complex Terrain to ExaWind

Researchers at NREL and Sandia National Laboratories implemented the capability to simulate complex terrain in ExaWind: AMR-Wind through the immersed boundary method. Efforts included generating immersed-boundary-method representations of canonical cases and formulating a new large-eddy simulation wall model that can be applied along the immersed boundary method surface. Implementation of the wall model is nearing completion and will be followed by verification and validation of the method by comparing large-eddy simulation results against established literature for the canonical cases. The addition of complex terrain to AMR-Wind represents the completion of requirements for the code to serve as the background solver for blade-resolved simulations and as a stand-alone tool for actuator-line simulations for land-based wind power plant studies.

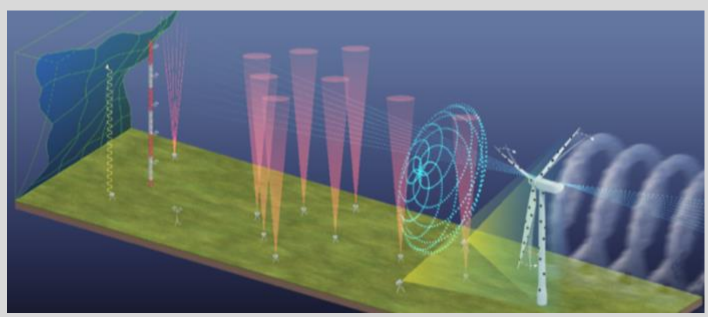
Visualization of cell velocities for a simulation of flow over a canonical-hill problem performed in ExaWind: AMR-Wind with the immersed boundary method. *Screenshot captured by NREL*

| Rotor Wake Measurements & Predictions for Validation | WETO.1.3.4.401 |
| --- | --- |

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

# Industry Partnership To Characterize Turbine Loading With Unprecedented Detail

NREL and Sandia National Laboratories have partnered with GE Renewable Energy on a 3-year project that includes a comprehensive field campaign and an array of modeling activities. The Rotor Aerodynamics, Aeroelastics, and Wake (RAAW) project seeks to determine whether computer simulation tools can accurately describe the behavior of ever-larger and ever-taller modern wind turbines as they respond to turbulent inflow. The team will collect detailed measurements of a 2.8-megawatt wind turbine in Texas and illuminate the inflow and loads in detail never attempted before. The wind around the rotor will be measured with 18 different sensors, and a high-resolution camera system will capture photos of the bending motions of the 200-foot-long blades. Ultimately, this comprehensive and unique data set will lead to improved computer models and more efficient designs, helping the United States reach its renewable energy goals.



The instrumentation layout and measurement design for the Rotor Aerodynamics, Aeroelastics and Wake project in Lubbock, Texas. The shape on the left side of the image represents turbulent wind entering the measurement site. The ground-based instruments include a microwave radiometer, a meteorological mast, a flux station, profiling lidars, and a camera system for photogrammetry. The turbine-mounted instrumentation includes a hub-placed spinner lidar, nacelle-placed scanning lidars, and a tower-blade laser clearance measurement. The spiral behind the turbine represents the wind turbine wake. The dots on the turbine represent stickers that will be placed on the blades for the photogrammetry measurements that will estimate blade bending and torsion. *Illustration by Besiki Kazaishvili, NREL*

American Wake Experiment (AWAKEN) WETO.1.3.4.404

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

# Final Preparations Underway for the International American WAKE experimeNt

Researchers across DOE-funded national laboratories NREL, PNNL, LLNL, and Sandia National Laboratories, in partnership with multiple universities and industry partners, completed the experimental design and acquired a majority of the hardware required for the long-term field campaign to better understand wind farm interactions with the atmosphere. Final preparations for the American WAKE experimeNt (AWAKEN) are nearly complete. Deployment will begin soon for this unique international wind farm observation campaign. In the coming months, advanced instrumentation will gather data to provide researchers with a better fundamental understanding of complex physical processes around wind farms. This understanding will translate into more accurate modeling tools used to predict wind farm performance and more optimal wind farm design and operation strategies.

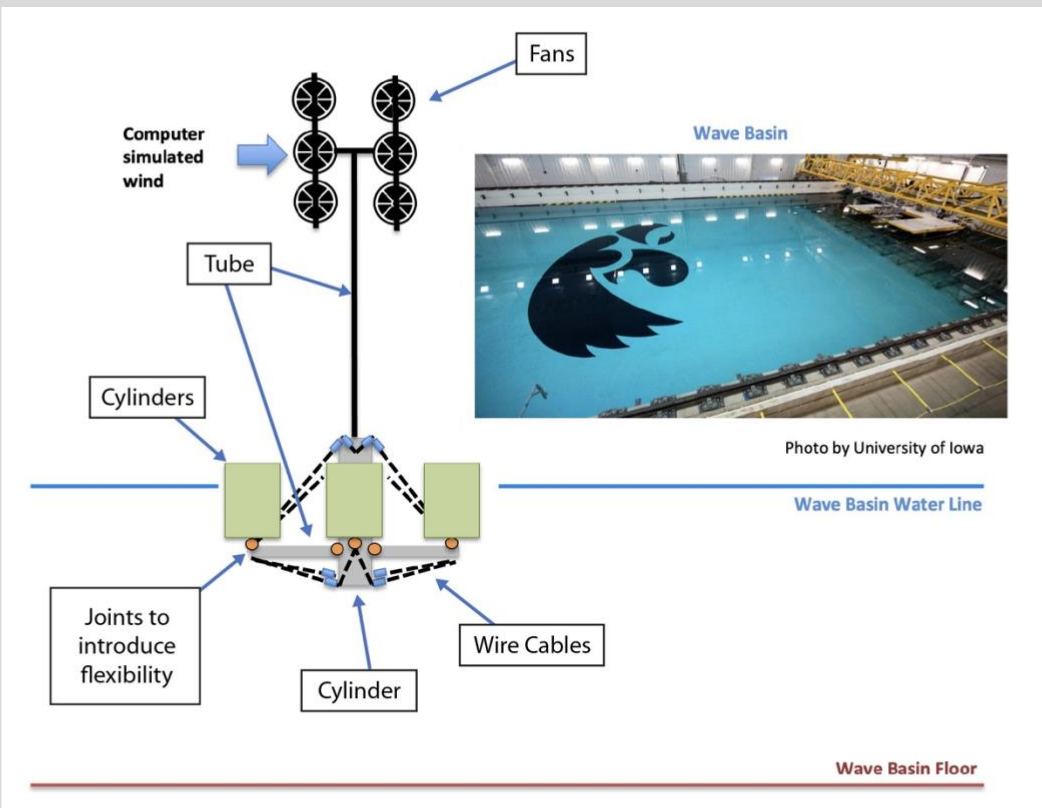
Turbines at the King Plains wind farm in northern Oklahoma where much of the American WAKE experimeNt project will take place. *Photo by Patrick Moriarty, NREL*

# Offshore Wind Specific Research and Development

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

# SpiderFLOAT Innovation To Improve Floating Offshore Wind Energy Performance

SpiderFLOAT is a scalable offshore floating wind turbine system developed in partnership with Equinor to improve performance by introducing flexibility to substructure design. The flexibility minimizes wave impact and maximizes power capture, challenging an existing paradigm of offshore wind energy production. The 1:52.5-scale model, based on a 10-MW offshore floating wind turbine system design, is being built, and the hybrid testing system—which generates wind loads via a smaller-scale set of fans from a computer simulation rather than a large physical fan system— is being developed at the University of Iowa to verify the design's performance. Most wave basins do not have the capability to simulate wind, and with this hybrid testing system, any kind of turbulent wind can be simulated in any wave basin. SpiderFLOAT's modular design and flexibility can significantly lower the levelized cost of energy for floating offshore wind energy technology.



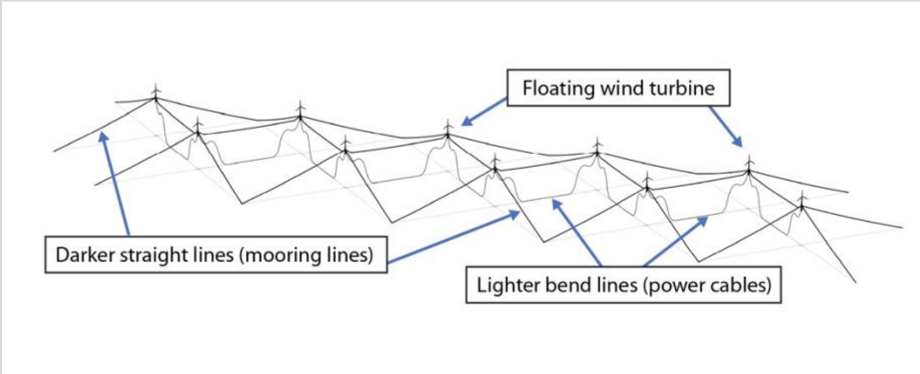

A 1:52.5-scale hybrid model test configuration (left) that uses fans to apply computer-simulated wind in the wave basin (right) that can generate waves to be applied to the hybrid model. *Graphic by Senu Sirnivas, photo from the University of Iowa*

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

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

## Shared Moorings Project Delivers a Cost-Effective Mooring Solution

The Shared Mooring Systems for Deep-Water Floating Wind Farms project team, in partnership with the National Offshore Wind Research & Development Consortium (NOWRDC), designed a first-of-its-kind floating wind farm with shared moorings. The 100-MW wind farm with 10 individual 10-MW wind turbines was designed for the Californian Humboldt Bay Call Area at a water depth of 600 meters. The design reduces the mooring cost by 25% compared to an individually moored system and is more robust against mooring line failures. This design demonstrates the potential for shared mooring systems and enables the offshore wind energy industry to lower the levelized cost of energy of offshore floating wind farms in deep waters.




A simulation of a 100-MW, shared-mooring, floating wind farm configuration for the Humboldt Bay Call Area with a water depth of 600 meters. The 10 floating wind turbines are connected via shared mooring lines (darker straight lines) and power cables (lighter bent lines). *Graphic by Matthew Hall, NREL*

| Offshore Wind Resource Science | WETO.1.3.4.401 |
|---|---|

**Point of Contact:** Georgios Deskos, Georgios.Deskos@nrel.gov

## NREL Hosts Workshop Discussion of Air-Sea Interaction Research and Applications in Offshore Wind Energy

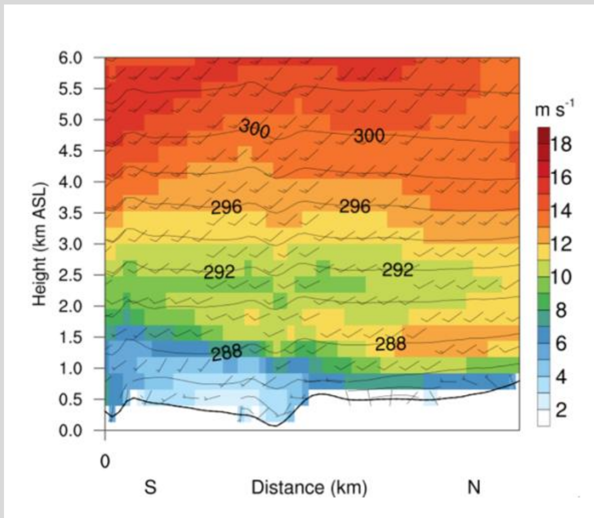
NREL led a workshop on air-sea interactions and implications for offshore wind energy together with PNNL, Argonne National Laboratory, and LLNL. The workshop convened experts from across disciplines and countries as well as industry and academia. With major developments of the U.S.-based wind energy industry moving offshore, opening a dialogue among engineers, atmospheric scientists, and oceanographers based on the practical use of the science of air-sea interaction is key to informing and optimizing offshore wind energy technologies. Participants discussed future pathways for computational modeling, the possibility of improved on-site measurements, and future steps needed for integrating these tools to optimize offshore wind power plants.

Offshore Wind Atmospheric Coupling WETO.1.4.1.402

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

# Multilab Team Surveys Wind Energy Mesoscale Modelers on Best Practices

A multilaboratory atmospheric-flow-modeling team comprised of NREL, PNNL, LLNL, and NCAR created and administered a survey to gather information about best practices for performing weather modeling and prediction for wind energy applications. This type of weather modeling uses high-performance supercomputers to simulate and predict regional-scale weather, a capability crucial to wind energy planning and operations. The team surveyed weather modelers from various national laboratories and academia. Survey responses were analyzed and included in a report to DOE, which will be released to the public. The aggregation of wind energy weather modeling practices into one place will better inform weather modelers and highlights where further research is required.



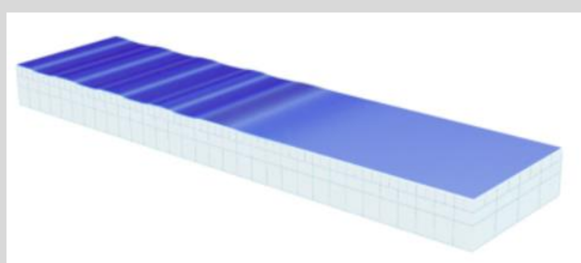

Typical output from a mesoscale weather model. This plot shows a cross section of the atmosphere above the land (land surface is indicated with the black line near the bottom). The colors indicate wind speed in meters per second (m $^{s-1}$), the barbed-shaped symbols indicate wind direction and magnitude, and the thin black lines and black numbers on the plot indicate temperature in Kelvin at different heights in kilometers above sea level (km ASL) and north-south location (km N, S) above the land. *Graphic by Caroline Draxl, NREL*

Floating Turbine HFM Simulation WETO.1.4.2.402

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

# ExaWind Numerical Wave Tank Provides Validation Platform for Floating Offshore Wind Energy

NREL's high-fidelity modeling team implemented a conceptual, numerical wave tank in AMR-Wind—a computational fluid dynamics solver in the ExaWind code suite. The numerical wave tank must resolve fluid dynamics at the air-water interface and provide a wavy environment, like a physical wave tank. This environment is key to validating models relevant to floating offshore wind energy, wherein the vast majority of validation data is from physical wave tanks—like that at the Maritime Research Institute Netherlands and used in the International Energy Agency Wind Technology Collaboration Programme (IEA Wind) Offshore Code Comparison Collaboration, Continued, with Correlation, and unCertainty project. Validation is key to establishing the predictive capabilities of the ExaWind code suite.



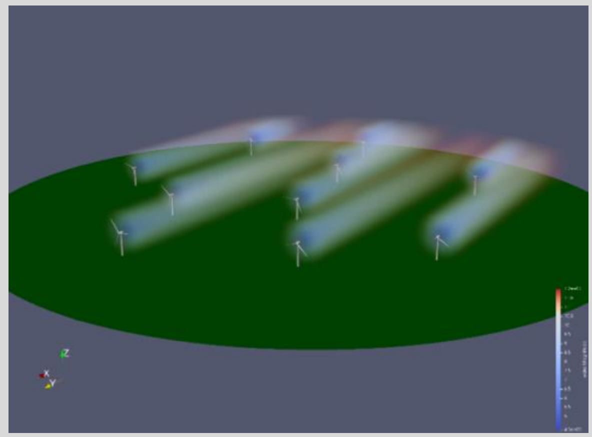
Demonstration of wave generation within the AMR-Wind numerical wave tank. Linear long waves are generated on the left side of the domain and absorbed on the right side, which prevents incorrect wave reflections. *Graphic by Georgios Deskos*

Offshore Wind Plant Control WETO.1.4.2.403

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

# FLORIS Release Results in Higher-Performing Code, Faster Speeds, New Features

The FLOw Redirection and Induction in Steady State (FLORIS) software framework, which provides models and tools for the design and analysis of wind farms and wind farm controllers, released Version 3.0 in collaboration with NOWRDC. The release involved major improvements, including a complete redesign of the software architecture, yielding much higher performance of the code. For example, computing the annual energy production for a 25-turbine wind farm is now 30 times faster than in the previous version. This release also includes new wake models calibrated for large offshore wind farms, which has shown more accurate prediction of power after comparing with data from three offshore wind farms. FLORIS continues to be updated; a future release will include such features as additional wake models, hybrid wind farm simulations, and three-dimensional visualizations.

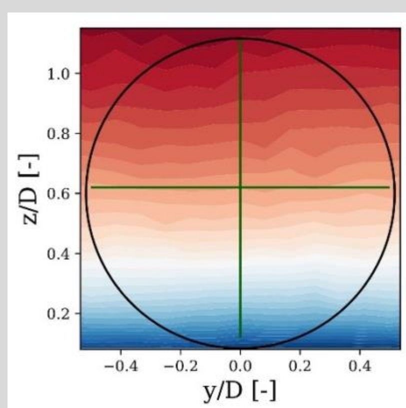


FLORIS is a software framework that provides models and tools to help stakeholders design and analyze wind farms and wind farm controllers. Version 3.0 included major improvements. A future release will include three-dimensional visualizations of FLORIS simulations, such as the one shown here. *Screenshot by P.J. Stanley, NREL*

Offshore Integrated Systems Engineering WETO.1.4.2.404

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

# Finding a New Way To Estimate Wind Turbine Loads for Optimized Power Production



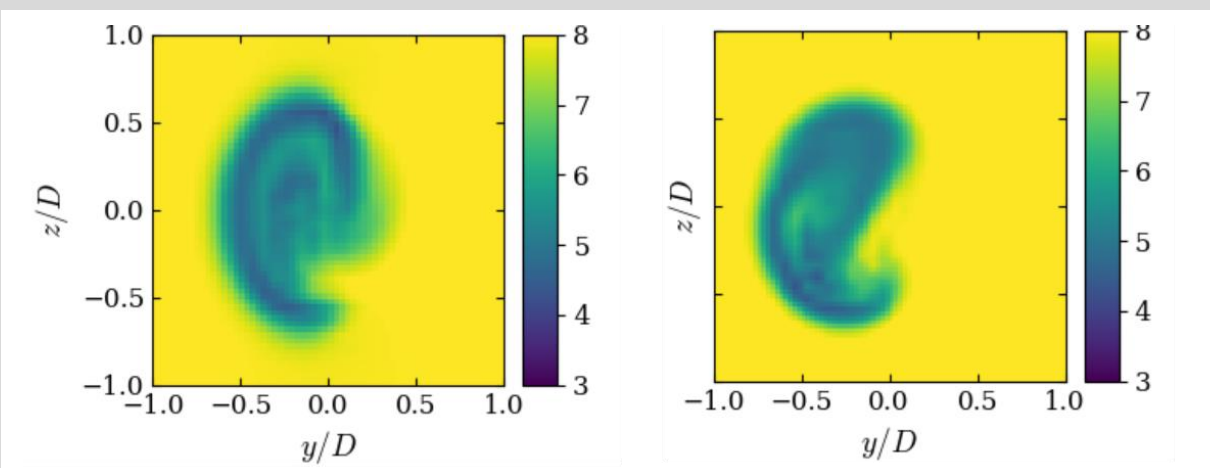

Velocity contours ahead of a wind turbine and the "slices" NREL researchers use to sample the inflow profile to generate turbine load estimates. *Graphic by NREL*

NREL researchers developed a novel method to estimate wind turbine loads without having to run complex simulations. The approach uses wind velocity profiles, such as the changes in velocity speed and direction from one part of the rotor blades to another, to capture many turbine load summary statistics. This method could also potentially be applied to any turbine in any position within an array under a wide variety of wind characteristics, such as different levels of shear or turbulence. If so, then combining this method with simple wake models, such as those used in the wind power plant optimization tool FLORIS, could lead to better understanding of extreme and fatigue load implications and turbine control and array layout for optimized power production.

**Points of Contact:** Jason Jonkman, Jason.Jonkman@nrel.gov; Amy Robertson, Amy.Robertson@nrel.gov

# New Engineering Model Developed for Assessing Structural Loads Impact From Wake Steering

Wake steering is an innovative wind power plant controls strategy to increase its energy yield by redirecting wakes away from downstream turbines by intentionally misaligning the rotor with the wind. Wind farm controls design typically relies on steady-state models with wake steering captured through a curled wake model, a model that captures the deformed shape of a wake resulting from skewed flow. However, steady-state models cannot predict the impact of such controls on wind turbine structural loads, which is an important consideration when implementing wake steering in real life. Now, this limitation has been solved by the development of a new time-varying formulation of the curled wake model, which has been introduced into an upgraded version of FAST.Farm, a midfidelity, physics-based engineering modeling tool (and offshoot of OpenFAST) that predicts the power performance and structural loads of wind turbines within a wind farm, including inflow, wakes, and turbine dynamic response. This new implementation of the curled wake model was validated against high-fidelity large-eddy simulation. The upgraded FAST.Farm model will enable the wind energy community to calculate the structural loads impact of wake-steering-based wind farm controls.




A comparison of FAST.Farm (left) and large-eddy simulation (right) of the curled wake 5 rotor diameters behind a wind turbine. The curled wakes capture the deformation of the wake resulting from skewed flow. The structural loading of downwind wind turbines is sensitive to this wake shape deformation. The upgraded FAST.Farm model enables wind energy stakeholders to calculate the structural loads impact of wake-steering-based wind farm controls. *Graphic by Emmanuel Branlard and Tony Martinez, NREL*

# Modeling the Aerodynamics of Floating Offshore Wind Energy Systems

Researchers working on Phase III of the NREL-led Offshore Code Comparison Collaboration, Continued, with Correlation and unCertainty project concluded an investigation into the accuracy of various modeling approaches to predict the wind loads on floating offshore wind turbines, which are impacted by the large motion that floating wind energy systems encounter due to wind and wave excitation. High-fidelity and mid-fidelity models were validated against measurements performed at Politecnico di Milano’s wind tunnel using a robotic system that moves a wind turbine independently in both the surge (forward/backward translational) and pitch (forward/backward rotational) directions. Results provide a better understanding of how to model the aerodynamics (wind loading) of floating wind energy systems, enabling the development of innovative, reliable, and optimized designs.

Experiments are conducted on a scaled version of a 10-MW reference wind turbine in Politecnico di Milano’s wind tunnel using a robotic system to mimic the motion of the wind turbine in the open ocean. This research provides a better understanding of how to model the aerodynamics of floating wind energy systems, enabling the development of more reliable and optimized designs. *Photo from Alessandro Fontanella, Politecnico di Milano*

| A Validated National Offshore Wind Resource Dataset with uncertainty Quantification (NOWRDC) | WETO.1.4.91.404 |
|---|---|

**Point of Contact:** Nicola Bodini, [Nicola.Bodini@nrel.gov](mailto:Nicola.Bodini@nrel.gov)

## Future Offshore Wind Energy Development Will Rely on NREL's Offshore Wind Resource Data

In collaboration with NOWRDC, NREL released new offshore wind data sets to provide wind energy stakeholders with accurate characterization of U.S. offshore wind resources on a geospatial basis. Additionally, NREL researchers partnered with the University of Colorado Boulder to analyze the impact that wakes from future wind power plants in the mid-Atlantic will have on expected power production. This reference data set will assist planners in the recently sold offshore lease areas in the U.S. mid-Atlantic region. Two publications summarizing the results of this analysis are in review in *Wind Energy Science* and *Nature Energy*.

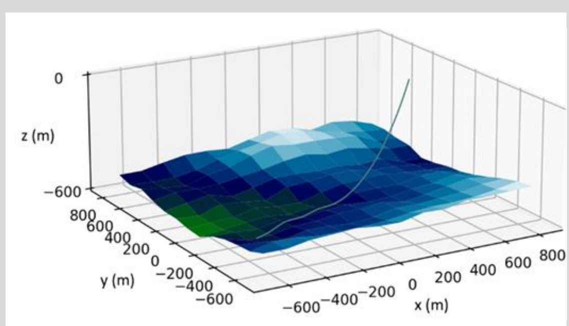
New offshore wind data sets from NREL will help offshore wind power plant planners accurately characterize offshore wind resources. *Image by Brent Rice, NREL*

| Innovative Deepwater Mooring Systems for Floating Wind Farms (DeepFarm) (NOWRDC - Principle Power) | WETO.1.4.91.402 |
|---|---|

**Point of Contact:** Matt Hall, [Matthew.Hall@nrel.gov](mailto:Matthew.Hall@nrel.gov)

## Mooring Dynamics Model Expands To Include Contoured, Three-Dimensional Seabed Surfaces

NREL researchers expanded the mooring dynamics model, [MoorDyn](), to simulate mooring lines interacting with contoured, three-dimensional seabed surfaces, done in partnership with NOWRDC. Forces on mooring lines from friction with the seabed and from water currents were also included. These new capabilities enable more realistic prediction of anchor forces, increasing the accuracy needed for sizing floating wind turbine anchors to be both cost effective and reliable.



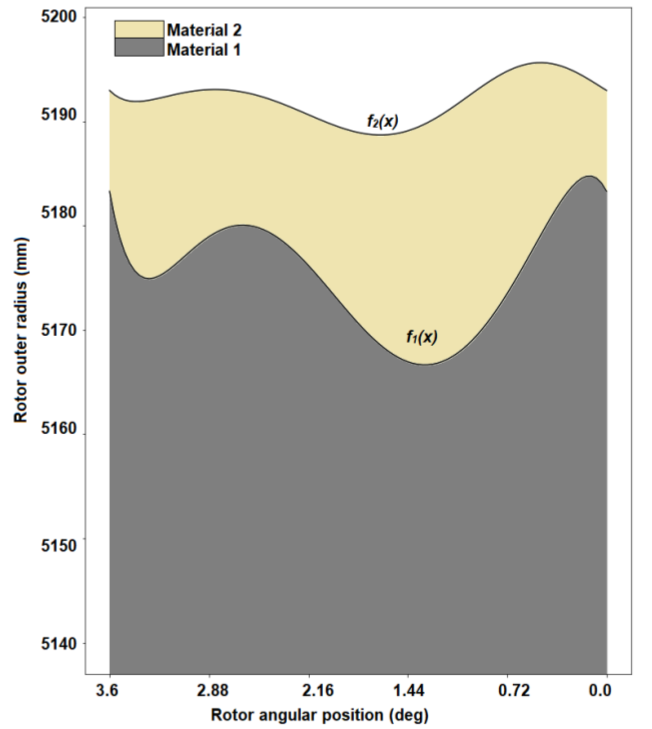

A mooring line moving over a three-dimensional seabed surface as simulated by the mooring dynamics model, MoorDyn. *Graphic by NREL*

# Materials, Manufacturing, and Design Innovation

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

# Adapting Blade Design Methods To Weight Reduction in Wind Turbine Generators

Topology optimization is a mathematical technique for optimizing material distribution within a design space. Traditional methods for weight reduction by using topology optimization for wind turbine generators require a grid-based solution that result in porous structures that require removing extraneous material even when using the most advanced techniques, such as three-dimensional printing. To overcome this design drawback and inspired by computer-aided geometric design of wind turbine blades, the NREL team implemented a novel, free-form boundary optimization technique wherein the outer shape of the magnets in the IEA Wind 15-MW direct-drive wind turbine generator was optimized. This research helped identify smooth and concise shapes that can be easily, additively manufactured with up to a 20-ton reduction in electrical steel mass. It also opens up a new opportunity for realizing multilayered designs with multiple materials whose distribution can be accurately controlled. The work was presented at the 2022 MMM-Intermag Conference in January 2022.

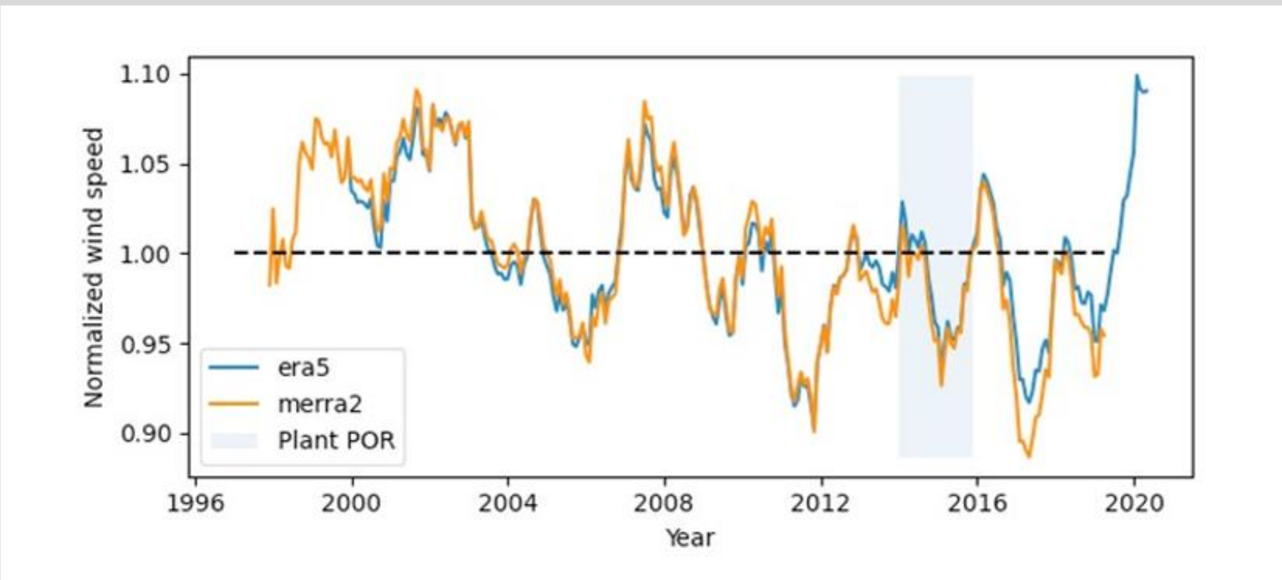



The dimensions in rotor design and new opportunities for realizing low-loss, light-weight generator design; for example, a shape-optimized rotor core section realized using two different types of electrical steel resulting in less material for manufacturing without the need to remove extraneous material. *Graphic by Latha Sethuraman, NREL*

**Point of Contact:** Eric Simley, Eric.Simley@nrel.gov

# Integration of PlanetOS Toolkit in OpenOA Software Allows Analysts To Easily Access Historical Weather Data

NREL, in partnership with the ENergy TRansition (ENTR) Alliance, a wind energy data standardization community, is developing an efficient wind power plant data analytics software environment combining the standard ENTR data model and reference operational data analysis methods from NREL's Open Operational Assessment (OpenOA) software. Many wind power plant operational assessment methods require historical weather data to estimate the long-term energy production of a wind plant during its expected lifetime. To help automate operational assessments in the ENTR/OpenOA software environment, NREL integrated Intertrust's PlanetOS weather data application programming interface in the latest release of OpenOA. This toolkit allows users to quickly download historical weather data from the European Centre for Medium-Range Weather Forecasts' ERA5 and the National Aeronautics and Space Administration's Modern-Era Retrospective analysis for Research and Applications, Version 2 global climate retrospective analysis (reanalysis) models, improving the efficiency of operational data analytics in the wind energy industry.

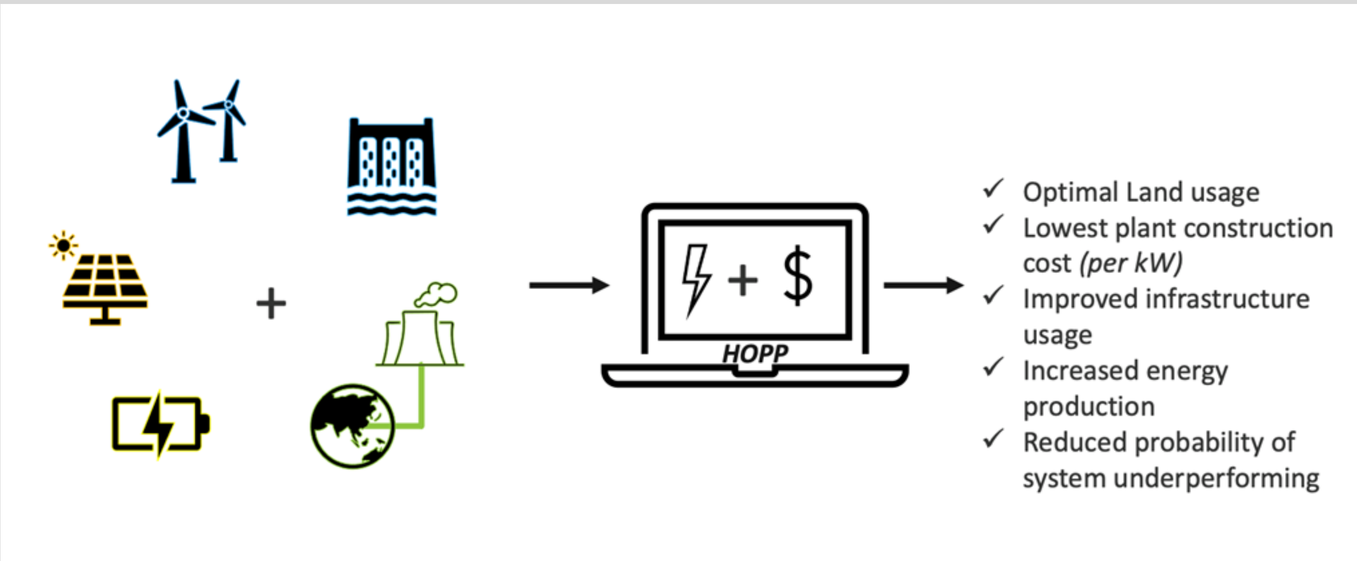



Historical wind speed data from global climate reanalysis models for an example wind power plant obtained using Intertrust's PlanetOS toolkit in NREL's OpenOA software. The historical wind data can be used to estimate the long-term energy production of a wind plant based on the measured energy production during a short operational period of record. *Graphic by NREL*

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

# NREL Partners With GE Global Research To Fast-Track Commercial Readiness of Hybrid Power Plant Technologies

NREL and GE Research are validating NREL's premier tool—Hybrid Optimization and Performance Platform (HOPP)—for designing and analyzing next-generation hybrid (wind-solar-storage) energy systems. The team developed a detailed, from-the-ground-up hydrogen electrolyzer model and integrated it into HOPP; the concentrated solar power technology is being added. Under GE Global Research's guidance and expertise, NREL is validating and field testing the models in HOPP and using HOPP to design wind-based hybrid power plants that are optimized for the highest-impact energy markets. This project will allow industry to use HOPP to design and develop bankable hybrid power plants, enabling higher renewable energy penetration in the grid while providing reliable power at a competitive cost.




A high-level schematic of NREL's HOPP model. This snapshot shows an overview of the workflow a user of the HOPP model follows, starting on the left with the icons of the various renewable energy generation technologies available for design and analysis in HOPP (wind energy, hydropower, geothermal, storage [batteries and hydrogen], and solar power [photovoltaic and concentrating solar-thermal power]). The plus sign in the middle of the icons shows that they can be mixed and matched together in any combination, after which the computer-based HOPP simulation software optimizes the design, performance, and economics of the user-defined hybrid energy system. The bullets to the right of the computer list the benefits of using HOPP to design a hybrid renewable energy system. *Graphic by NREL*

Wind Turbine Drivetrain Reliability WETO.1.5.2.401

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

## Joint Research Effort Helps Wind Energy Industry Improve Gearbox Failure Predictions, Optimize Operations and Maintenance

The wind energy industry is challenged by a lack of standardized reliability data collection and analysis practices as well as publicly available and up-to-date reliability statistics based on a meaningful sample size. A joint effort by NREL and the Electric Power Research Institute is helping the wind energy industry standardize data specifications and collection practices. Updated gearbox reliability statistics were released based on a larger population of failure records collected by NREL and the Electric Power Research Institute, reflecting more recent and accurate field experience by the U.S. wind energy industry. This project helps improve failure rate predictions and optimize operations and maintenance.

NREL and the Electric Power Research Institute are helping the wind energy industry standardize data specifications and collection practices that will improve gearbox failure-rate predictions and optimize operations and maintenance. Shown here is part of a 750-kilowatt wind turbine gearbox. *Photo by Dennis Schroeder*

Big Adaptive Rotor WETO.1.5.4.401

**Point of Contact:** Pietro Bortolotti, Pietro.Bortolotti@nrel.gov

# Improved Modeling Tools for Large, Flexible Rotors Ensure Accuracy, Reliability

Large rotors can increase a wind turbine's average capacity factor by 10% or more. The Big Adaptive Rotor project aims to reduce technological and scientific barriers to the adoption of large, flexible rotors. One major barrier is the inability to accurately predict the aeroelastic stability of these types of rotors. Recently, this multilab team from NREL, Sandia National Laboratories, Oak Ridge National Laboratory, and Lawrence Berkeley National Laboratory fixed several bugs in the modeling tools and completed a comprehensive code-to-code comparison. The modeling suite now yields accurate and reliable aeroelastic stability results.


A large downwind turbine with active aerodynamic devices. *Illustration by Besiki Kazaishvili, NREL*

**Point of Contact:** Pietro Bortolotti, Pietro.Bortolotti@nrel.gov

# Open-Access, Low-Temperature, Superconducting Wind Turbine Generator Model Supports the Next Generation of Offshore Wind Turbines

An NREL team is working with researchers at GE Research to optimize the design of low-temperature superconducting generators. This technology is a promising gateway to support the next generation of offshore wind turbines at nameplate powers between 15 and 25 MW. NREL developed an innovative magnetic and structural model to analyze and optimize superconducting generators. The open-source model is now available to the public within the NREL-developed systems engineering framework, Wind-Plant Integrated Systems Design & Engineering Model (WISDEM®).

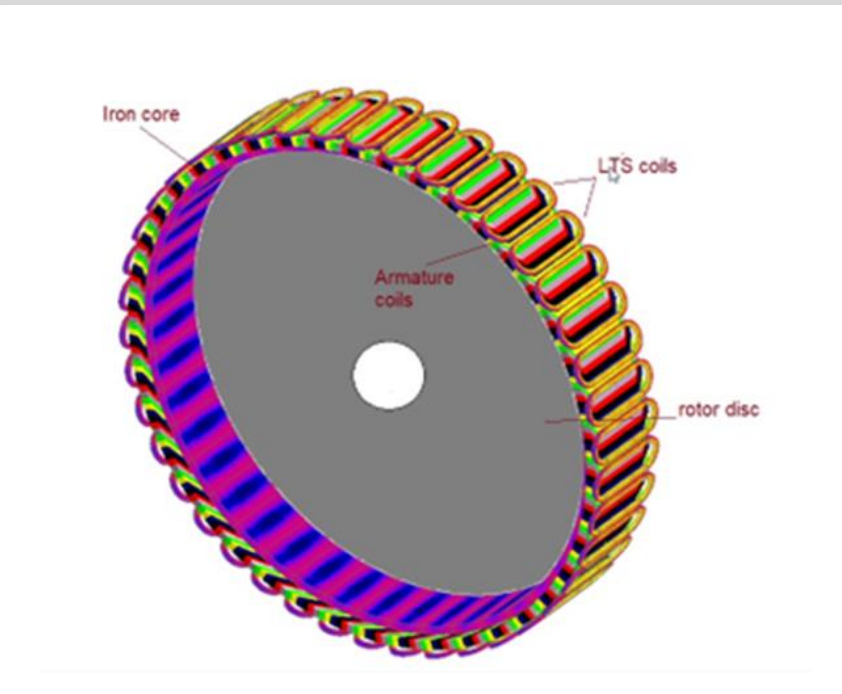
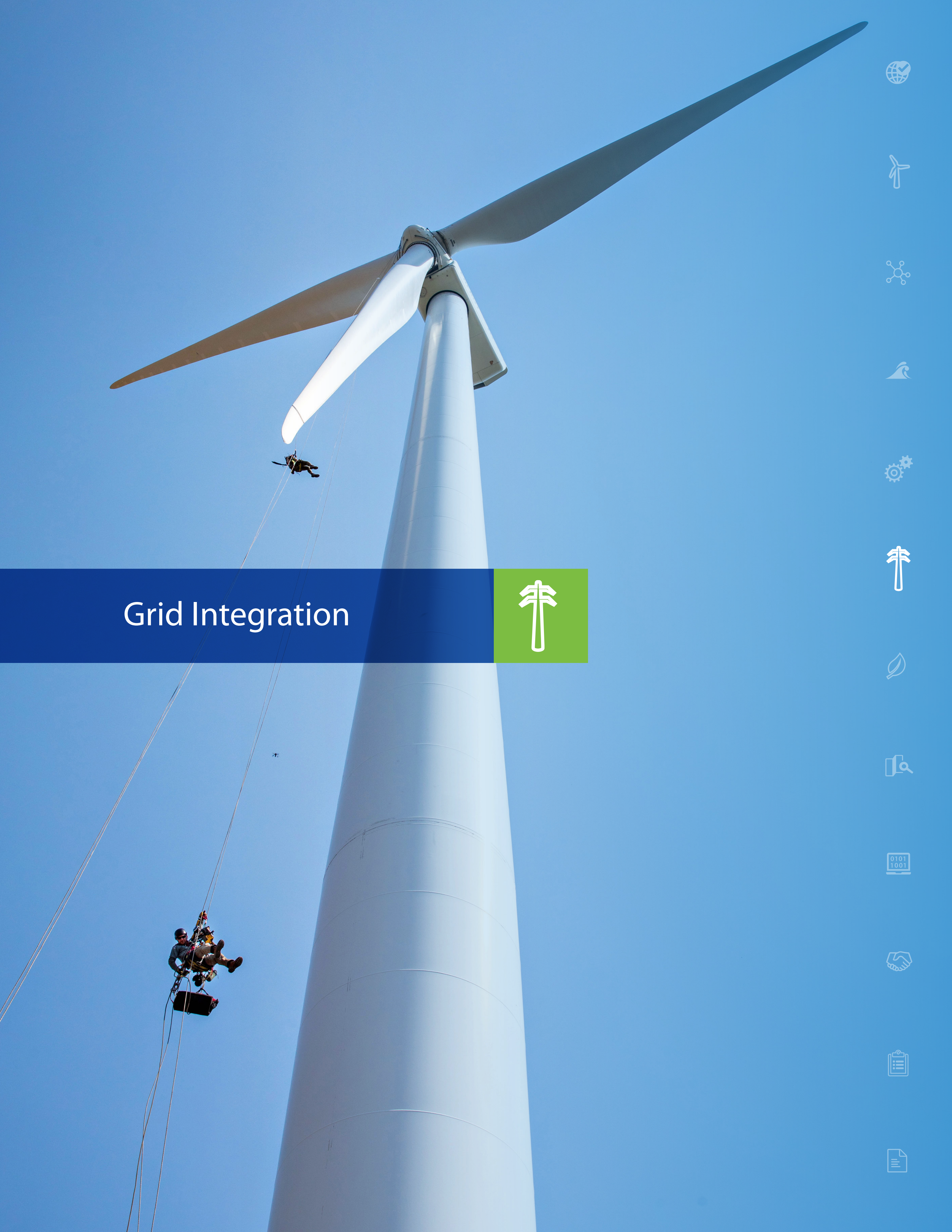



Illustration of a low-temperature superconducting generator model for offshore wind turbines. The technology is a promising gateway to support the next generation of offshore turbines due to its high efficiency and reduced mass. NREL researchers are optimizing the design of the generator by varying the parameters of the armature and the superconducting coils, the structure of the iron core, and macroparameters, such as the size of the rotor disc. *Graphic by Latha Sethuraman, NREL*

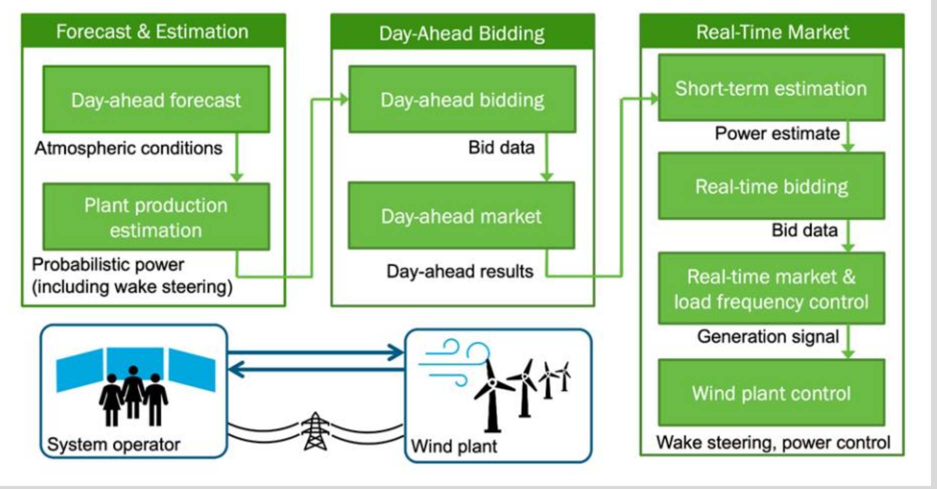
# Grid Integration



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

# New Platform Facilitates Supply of Grid Services by Wind Power Plants

In future power systems, wind power plants will need to provide grid services similar to conventional generators. The Atmosphere to Electrons to Grid platform integrates forecasting tools to account for weather uncertainty with aerodynamic models to account for wake dynamics and decision analysis models to account for delivery of grid services. Operators of wind power plants can use the platform to support their participation in markets for grid services and control their wind power plant in real time to deliver those services. Using the Atmosphere to Electrons to Grid platform, wind power plants can identify when it is economically viable to reliably provide grid services, thereby increasing their value streams.




The Atmosphere to Electrons to Grid framework takes wind power plant operators from forecasting day-ahead wind power plant behavior to receiving a real-time signal from the transmission system operator and responding to that signal. Implemented in Python, a programming language, the framework is modular, making it easy to exchange software components or run parametric studies to inform wind power plant operators. It also provides a control layer for real-time power estimation of the wind power plant. *Graphic by Misha Sinner, NREL*

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

**Point of Contact:** Shahil Shah, [Shahil.Shah@nrel.gov](mailto:Shahil.Shah@nrel.gov)

## NREL-Developed Impedance Measurement System Evaluates Dynamic Stability of Wind Power Plants

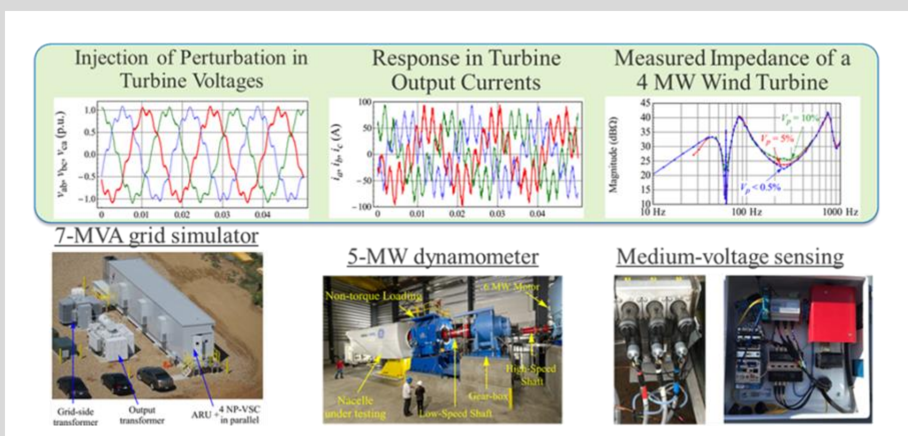
NREL developed an impedance scan software tool for wind power plants using power system simulation models to evaluate the plants' impact on grid stability. The software tool can scan the impedance response of vendor-supplied black-box simulation models without requiring internal proprietary information, enabling detailed stability analysis of power systems with high levels of wind energy generation. The tool was presented to several industry groups, including the North American Electric Reliability Corporation's Inverter-Based Resource Performance Working Group, International Wind Integration Workshop, and IEA Wind Task 25 Design and Operation of Power Systems with Large Amounts of Wind Power workshop. NREL received two requests from international transmission system operators to use the tool for evaluating the stability of their power grids during operation with high levels of wind energy and solar power generation.

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

**Point of Contact:** Shahil Shah, [Shahil.Shah@nrel.gov](mailto:Shahil.Shah@nrel.gov)

## NREL-Developed Impedance Measurement System Evaluates Dynamic Stability Problems in Wind Power Plants

An NREL team is developing impedance-based testing, modeling, and analysis tools to evaluate all types of dynamic stability problems involving wind power plants. Dynamic stability is a major concern in maintaining the security of power grids during operation with high levels of wind energy generation. The team developed a system for measuring the impedance responses of multimegawatt wind turbines and inverters. The system is being used by several DOE and industry-sponsored projects to evaluate stability impacts of wind turbine and inverter products. A journal article was published in *[IEEE Transactions on Energy Conversion](#)*.




A first-of-its-kind impedance measurement system for multimegawatt wind turbines and inverters developed at NREL. *Graphic by Shahil Shah, NREL*

| WindVSG | WETO.3.1.0.420 |
|---|---|
| **Point of Contact:** Vahan Gevorgian, Vahan.Gevorgian@nrel.gov | |

# NREL Demonstrates the Ability of a Typical Wind Turbine Generator to Form the Grid

A team from NREL and General Electric completed testing of a 2.5-MW type-3 wind turbine drive operating in grid-forming mode (i.e., establishing the voltage and frequency of the grid, a job usually done by conventional large thermal generation plants). The drivetrain is installed at NREL's 5-MW dynamometer facility. The experiment was conducted using NREL's 7-megavolt-ampere (MVA) controllable grid interface equipped with a power-hardware-in-the-loop capability (the portion of the system under test uses real hardware and the other portion uses virtual real-time setup) to emulate strong and weak grid conditions and with a 3-MVA load bank to test islanded operation. The 2.5-MW wind turbine demonstrated stable grid-forming operation under all scenarios. The transient model of the system was validated through testing as well. This testing demonstrates that Type-3 wind turbine generators can stably operate in grid-forming mode, thereby helping stabilize electric grids with high shares of inverter-based resources.

| Wind Consortium Cyber Threat Model | WETO.3.1.0.420 |
|---|---|
| **Point of Contact:** Zoe Dormuth, Zoe.Dormuth@nrel.gov | |

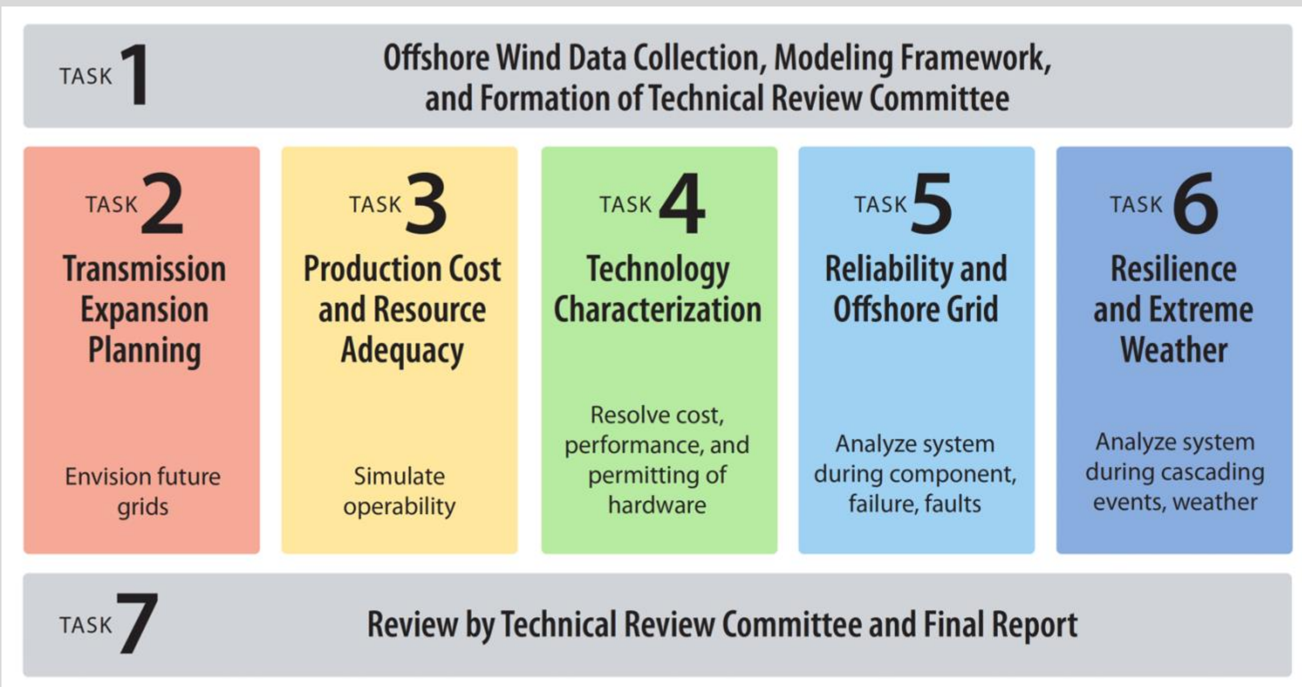
# NREL Teams Study Potential for Cyberattacks on Wind Energy Infrastructure—and How To Mitigate Them

NREL's wind energy and cybersecurity teams are collaborating with wind energy industry partners in NREL's Wind Cybersecurity Consortium to identify and mitigate potential cyber risks on wind energy infrastructure. The team identified two cyberattacks and developed mitigation strategies to understand cyber risks and prevent future attacks from affecting wind turbine infrastructure. In addition, NREL hosted a virtual, half-day wind cybersecurity seminar to increase collaboration in this field. Participants, such as original equipment manufacturers and owner operators in the wind energy industry, national labs, DOE, and other wind energy stakeholders focused on wind power plant architectures, risk management, and cyber insurance. These topics provide more security to wind energy infrastructure. Future opportunities were presented, such as research to support standards (National Institute of Standards and Technology, International Society of Automation/International Electrotechnical Commission 62443), analyzing third-party device security, and understanding how a cloud environment could integrate into wind power plant architecture.

**Point of Contact:** Melinda Marquis, Melinda.Marquis@nrel.gov

# Multiple Pathways to Offshore Wind Energy Goals Along U.S. Atlantic Coast

The Atlantic Offshore Wind Transmission Study was formed in 2021 to evaluate multiple pathways to offshore wind energy goals through coordinated transmission solutions along the U.S. Atlantic Coast—in the near term (by 2030) and long term (by 2050)—under various combinations of electricity supply and demand while supporting grid reliability, resilience, and ocean co-use. NREL and PNNL are conducting the 2-year study to evaluate coordinated transmission solutions and addressing gaps in previous analyses. Researchers will compare different transmission technologies and topologies, quantify costs, assess reliability and resilience, and evaluate key environmental and ocean co-use issues. A technical review committee of more than 100 members is focusing on three areas: generation and transmission planning, technology, and environmental impacts and siting. The study will consider transmission topologies—including radial lines, backbones, and meshed networks—to inform decision making and offer feasible solutions, data, and models that will benefit offshore wind energy stakeholders in their planning processes.



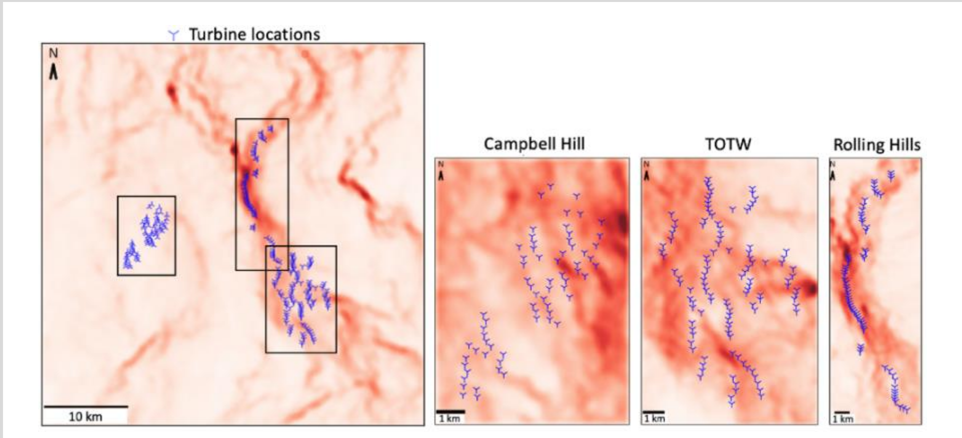

Seven tasks comprise the Atlantic Offshore Wind Transmission Study, which will evaluate multiple pathways to offshore wind energy goals through coordinated transmission solutions along the U.S. Atlantic Coast in the near term (by 2030) and long term (by 2050). *Figure by John Frenzl, NREL*


Environmental Research

| Wind Operational Issue Mitigation | WETO.3.3.0.401 |
|---|---|
| **Point of Contact:** Eliot Quon, Eliot.Quon@nrel.gov | |

## Modeling Flight Behavior of Eagles May Predict Collision Risk

NREL's atmospheric scientists published the Stochastic Soaring Raptor Simulator to model eagle flight behavior during migration in relation to updrafts. The predictive model simulates thousands of soaring eagles to produce a density map that quantifies the relative probability of eagle presence. During development, the model was validated using actual flight data from Global-Positioning-System-tagged eagles. The model offers a predictive tool to assist wind energy developers, ecologists, and wildlife managers in estimating the potential for conflict between soaring birds and wind turbines.




The Stochastic Soaring Raptor Simulator models eagle flight behavior during migration in relation to updrafts. These four outputs show the relative density of eagles (in red) during migration at four wind energy facilities in the United States. Darker shading represents a higher-density presence. Wind turbine locations are marked with blue icons. *Screenshots by NREL*

| WREN | WETO.3.3.0.403 |
|---|---|
| **Point of Contact:** Cris Hein, Cris.Hein@nrel.gov | |

## NREL Engages With Offshore Wind Energy Community Concerning Key Environmental Effects Topics

NREL, in partnership with PNNL, organized and hosted four webinars on key environmental topics related to offshore wind energy as part of the U.S. Offshore Wind Synthesis of Environmental Effects Research project. Each of the four webinars included two topics: 1) noise and entanglement, 2) benthic disturbance and fish ecology, 3) bat and bird interactions with wind farms, and 4) vessel collision and electromagnetic fields. Live attendance ranged from 168 to 298 people and included stakeholders from state and federal agencies, the wind industry, academia, research organizations, and nongovernmental organizations. Webinar recordings can be accessed on PNNL's Tethys website.

FOA 1924 - OSW Autonomous Monitoring System (OSU) WETO.3.3.0.409

**Point of Contact:** Jason Roadman, Jason.Roadman@nrel.gov

# NREL Team Completes Field Testing With Custom Launcher and Projectiles To Minimize Wind Energy's Impact on Birds and Bats

NREL completed a field campaign in partnership with a team from Oregon State University in which they tested bird and bat strikes on a wind turbine. Oregon State University developed a sensor network that could be installed on the wind turbine blades and used to detect collisions. NREL developed a custom simulated wildlife launcher to shoot projectiles that realistically simulate birds and bats in terms of mass and makeup. In validating a system that can accurately detect these strikes, the team produced technology that is one step closer to helping determine the timing and conditions of collision events.

NREL completed a field campaign in partnership with a team from Oregon State University in which they tested bird and bat strikes on a wind turbine. These tests simulated bird and bat strikes on a wind turbine using a custom launcher and projectile. *Photo by Werner Slocum, NREL*

FOA 1924 - Advanced Bat and Bird Collision Detection System (WEST) WETO.3.3.0.410

**Point of Contact:** Sam Rooney, Samantha.Rooney@nrel.gov

# Validation Study Performed of Improved Wind Turbine-Bird Collision-Detection System

NREL performed a validation study of the wind turbine-bird collision-detection (WT-Bird) system using the DOE 1.5-MW turbine at NREL's Flatirons Campus. The project team simulated bird and bat collisions on the wind turbine blades using a custom-made wildlife launcher and projectiles. Collisions of 8-gram (g), 25-g, and 250-g projectiles were recorded by the NREL team and validated by project partners, Netherlands Organisation for Applied Scientific Research and Western EcoSystems Technology, Inc., to assess the accuracy of the system in detecting bird and bat collisions with a wind turbine blade. The data collected from this project will be used to further refine the WT-Bird system and to better quantify and understand the timing and conditions when bird and bat collisions might occur.

NREL engineers launch a small projectile at moving wind turbine blades to validate a collision-detection system. The purpose of the study was to assess whether the detection system could register collision events of projectiles that resemble small birds or bats, helping advance species protection. *Photo by Werner Slocum, NREL*

# STEM and Siting Research and Development

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

# New Collegiate Wind Competition Registration Process Fosters Reach and Accessibility

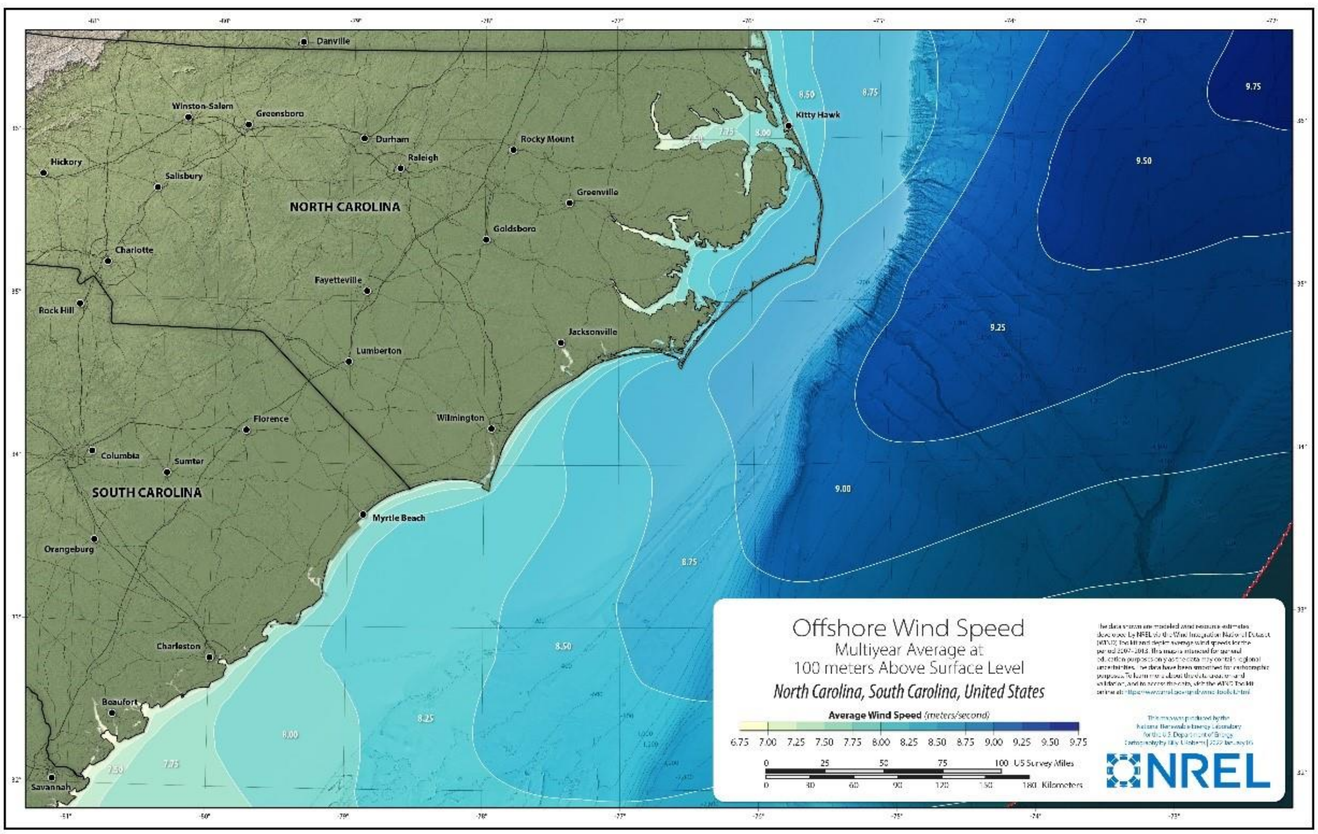
Organizers of the Collegiate Wind Competition (CWC) increased accessibility to schools that have not participated in the past and thus broadened the competition's reach and impact. For the 2023 competition, organizers developed a simple application process for teams interested in participating in the CWC. This process allowed teams to participate in the culminating event based on assessment of midyear deliverables, thereby choosing teams based on performance as well as passion. In the past, organizers released a request for proposals in the fall inviting interested teams to apply to participate in the competition. This new CWC application process was amplified broadly, including to Minority Serving Institutions (MSI) through the MSI STEM Research and Development Consortium and other similar avenues. The competition itself hosted the largest group of collegiate teams in its history, with 12 officially competing and four learn-along teams. This competition also featured the establishment of the first-ever panel of industry experts and CWC alumni.

Undergraduate students from the University of Maryland assisted KidWind students with the building of their own miniature wind turbine as part of the Collegiate Wind Competition. *Photo by Dennis Schroeder, NREL*

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

# WINDExchange Publishes Additional 100-meter Wind Energy Resource Maps

NREL continued producing and publishing 100-meter wind energy resource maps across the country. Offshore wind maps were produced for Texas, Louisiana, and Mississippi; North and South Carolina; and Alabama, Florida, and Georgia. Land-based wind maps were produced for Missouri, Tennessee, Arkansas, Wyoming, Iowa, Kansas, Utah, and Arizona. These maps provide wind energy developers and community leaders with tools to help assess and characterize a region's available wind resources, which will support the development, siting, and operation of wind energy projects around the United States. Wind resource maps and other information are available through the WINDExchange platform.




Through the WINDExchange program, NREL engaged stakeholders by creating 100-meter wind resource maps, including the offshore wind speed map of North and South Carolina. These maps give wind energy developers and community leaders tools to help assess and characterize a region's available resources. *Map by NREL.*

# Modeling and Analysis

Wind Analysis for Priority Needs WETO.4.1.0.402

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

# Deep-Dive Report Assesses State of U.S. Wind Energy Supply Chain

In close coordination with WETO staff, NREL researchers delivered a report highlighting strengths, weaknesses, opportunities, and vulnerabilities of the U.S. wind energy sector supply chain. The work explored critical vulnerabilities today and in the future as the industry scales to serve the Biden Administration's goals and technology evolves. The report was used to inform the WETO deliverable in response to Executive Order 14017: America's Supply Chains. Along with 12 other deep-dive assessments conducted by DOE and its national laboratories on specific technologies and crosscutting topics, the report identifies strategies and recommendations that could help the United States move toward a secure and equitable clean energy future.

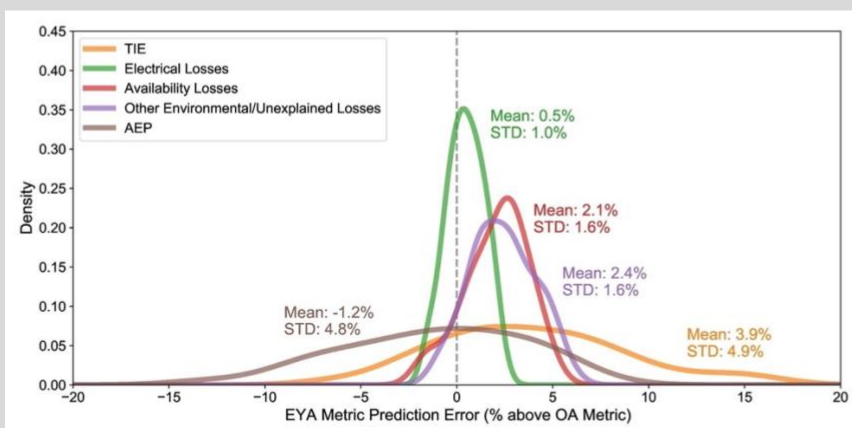
Trucks transport wind turbine blades to their final destination. *Photo by Lee Fingersh, NREL.*

Wind Plant Performance Benchmarking (PRUF) WETO.4.1.0.406

**Point of Contact:** Jason Fields, Jason.Fields@nrel.gov

# NREL Team Identifies Sources of Wind Plant Energy Prediction Errors

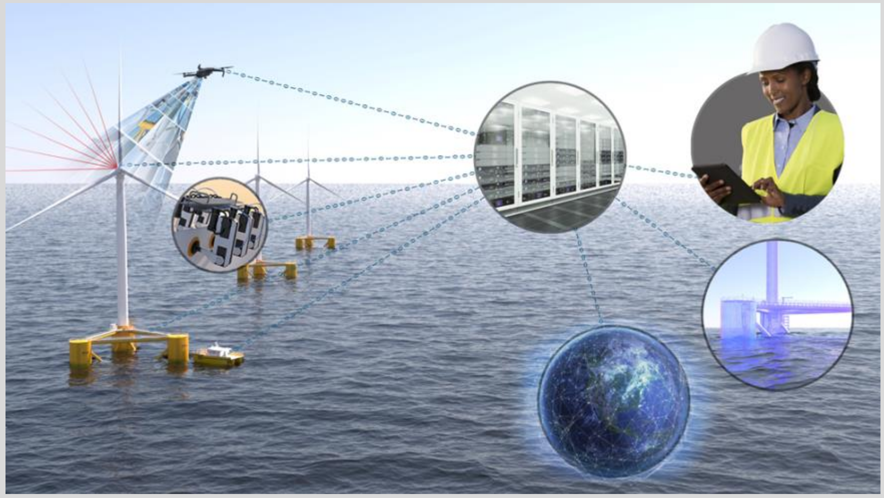
The Wind Plant Performance Prediction project is a multistakeholder, data-sharing and benchmarking initiative focused on improving the industry's ability to predict and quantify wind power plant performance. The Performance Risk, Uncertainty and Finance (PRUF) Focus Area team developed an approach for understanding the difference in predicted energy versus measured energy from a wind power plant. It also analyzed data from the Wind Plant Performance Prediction benchmark project, which suggests that the wind energy resource is broadly overestimated but compensated by a corresponding overestimation of energy losses. The article is currently in peer review in the open-access journal *Wind Energy*.




The distribution of prediction errors (in density) for each step of the energy yield assessment (EYA) process based on 68 submissions from wind power plants in Phase 1 of the Wind Plant Performance Prediction benchmark project (obtained using Gaussian kernels). Percentages indicate the mean and standard deviations of the prediction bias relative to the corresponding metric calculated from the operational data. This demonstrates a tendency for wind resource overprediction that is countered by a countervailing overprediction of wind energy losses. *Graphic by NREL*

# NREL and International Collaborators Identify Digitalization as a Grand Challenge in Wind Energy

Wind energy digitalization represents a unique opportunity to accelerate wind energy deployment, reduce costs, and improve industry collaboration. As part of IEA Wind Task 43, the PRUF project team published a discussion article in *Wind Energy Science* that details the three grand challenges of wind energy digitalization—data, culture, and “coopetition.” Data refers to the need for findable, accessible, interoperable, and reusable data. Culture is the need to address organizational, people-centric approaches for adopting digital technologies and data- driven decision making. Lastly, “coopetition” refers to collaboration among competitors, with the goal of realizing mutually beneficial outcomes. In the article, the authors recommend potential solutions and research needed to achieve a new digital wind energy industry, with expected gains in plant performance, reductions in costs, and shorter innovation and deployment timelines.

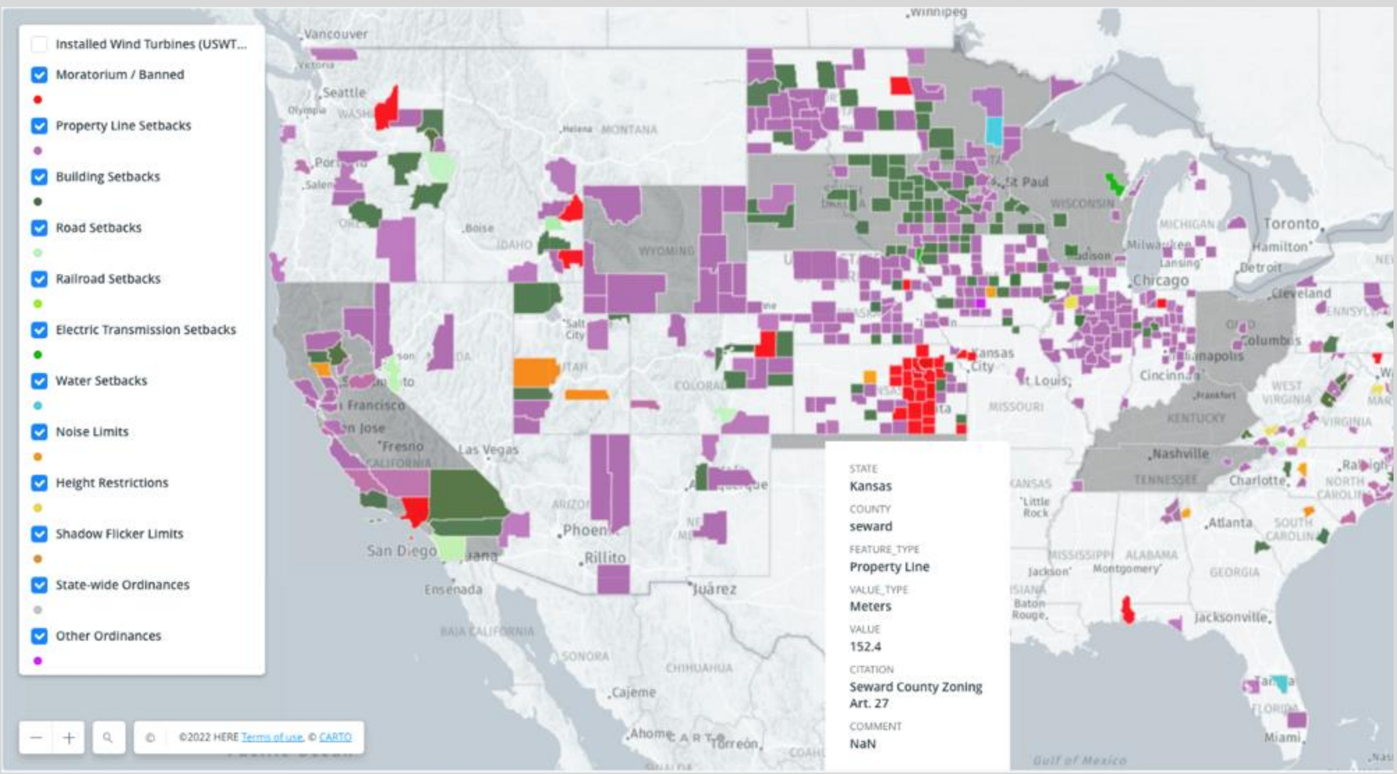


Digitalization in action. In this future floating wind energy plant, digitalization enables a plant manager to make data-based decisions in real time, increasing safety and reducing the cost of energy. The image also demonstrates the concepts of robotic inspections and transportation as part of a fully autonomous wind power plant. *Graphic by NREL.*

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

# Database of Wind Energy Ordinances Increases by 400% in 4 Years

In the United States, ordinances pertaining to wind energy are typically established and regulated at the county level. In 2018, the NREL spatial analysis team sought to collect and spatially model all existing wind energy ordinances across the contiguous United States. At that time, the team collected roughly 300 ordinances and demonstrated the potential implications for wind energy deployment. This year, the team executed another data-collection drive, amassing more than 1,500 ordinances—a 400% growth in 4 years. This soon-to-be-published database provides critical insight into the growth, types, and scale of local regulations—pertinent information for developers, policymakers, decision makers, land managers, and energy modelers. Next, the team will spatially model these local regulations to quantify national wind potential impacts.

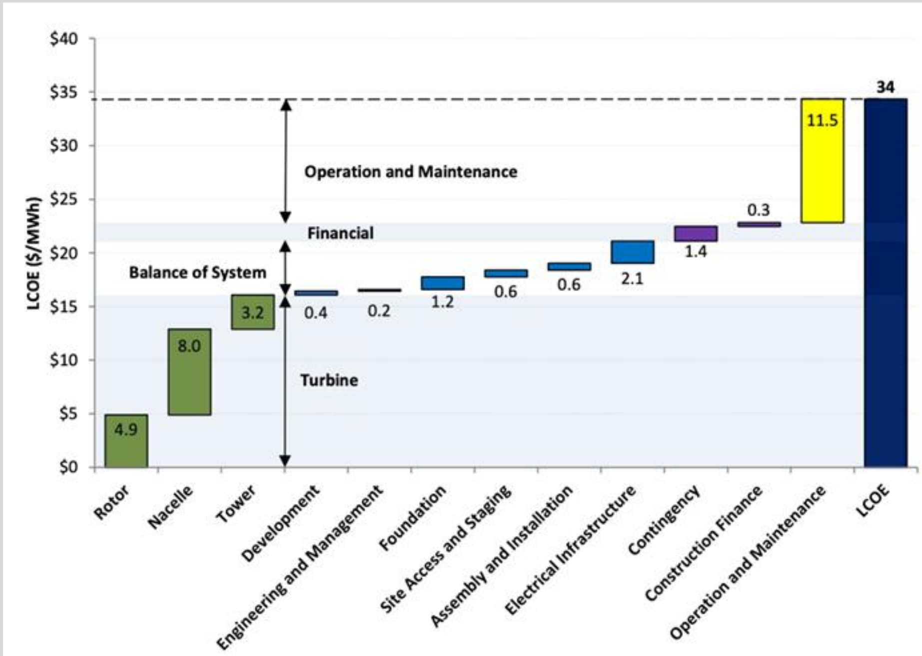



The spatial distribution of existing county wind energy regulations as captured in the ordinance database. Users can hover over a county to display the details of an ordinance. *Screenshot by Anthony Lopez, NREL*

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

# NREL Researchers Estimate Cost of Wind Energy in 2020 Annual Report

The *2020 Cost of Wind Energy Review* provides estimates by NREL researchers on the levelized cost of energy for representative land-based and offshore wind power plants and residential- and commercial-scale distributed wind energy projects in the United States. Levelized costs of energy estimates are based on U.S. commissioned wind power plants and wind resource information from 2020, along with the aid of state-of-the-art modeling capabilities and data accumulated throughout the global wind energy industry. Results of this report provide cost data to DOE to meet the annual reporting requirements set by the Government Performance and Results Act and offer component-level costs that aid researchers, developers, investors, and utilities.




The component-level cost breakdown shown as levelized cost of energy (LCOE; in $/megawatt-hour [MWh]) for the land-based wind reference project based on U.S.-commissioned wind power plants and wind resource information from 2020, with the support of state-of-the-art cost models. Starting from left to right, the green bars (rotor, nacelle, and tower) represent the wind turbine components, the lighter blue bars (development, engineering and management, foundation, site access and staging, assembly and installation, and electrical infrastructure) signify balance of systems components, the purple bars (contingency and construction finance) denote financial components, the yellow bar represent operations and maintenance, and lastly, the darker blue bar reports the total system levelized cost of energy. *Image by NREL*

# Programmatic Support

| NREL Technology Management and Support | WETO.5.1.0.401 |
|---|---|
| **Point of Contact:** Brian Smith, Brian.Smith@nrel.gov | |

# Wind Research Impact Cultivated Through Sound Programmatic Support

NREL's Wind Program actively manages a diverse wind portfolio that advances technologies for offshore, land-based, and distributed wind energy, as well as its integration with the electric grid. NREL supports WETO's main objectives of aggressive cost reduction, scaling and light-weighting, environmental and siting challenges, grid services, cybersecurity, and hybrid systems. To meet the significant acceleration and scale up of wind deployment needed to achieve carbon emissions-free electricity by 2035 and net-zero greenhouse gas emissions across the economy by 2050, NREL wind research includes workforce development and education, social science and acceptance, analysis and modeling, and energy equity and environmental justice.

Achievements include:

- Increasing the impact of WETO's mission through strategic engagement, fostering innovative and integrative programs, and ensuring a unique, portfolio-wide perspective is established.
- Leading high-level executive outreach and engagement to amplify the office's research and development portfolio.
- Leading technology-to-market initiatives that create pathways for market readiness and resource access. This includes supporting the growth of projects with a high potential of impact funded through the Technology Commercialization Fund and providing researchers opportunities to prioritize latest needs of the market through the Energy I-Corps program.
- Serving in a strategic leadership role of the IEA Wind Technology Collaboration Programme.
- Providing support to NREL's Flatirons Campus and NREL's ARIES program, promoting the development of state-of-the-art equipment and facilities that support fundamental wind energy research and forward-thinking, integrated renewable energy solutions.

| M&O Support | WETO.5.1.0.403, WETO.5.1.0.404, WETO.5.1.0.410, WETO.5.1.0.412, WETO.5.1.0.413 |
|---|---|
| **Point of Contact:** | Alexsandra Lemke, Alexsandra.Lemke@nrel.gov |

# NREL Advisors Provide Guidance and Support to Help Execution of Research

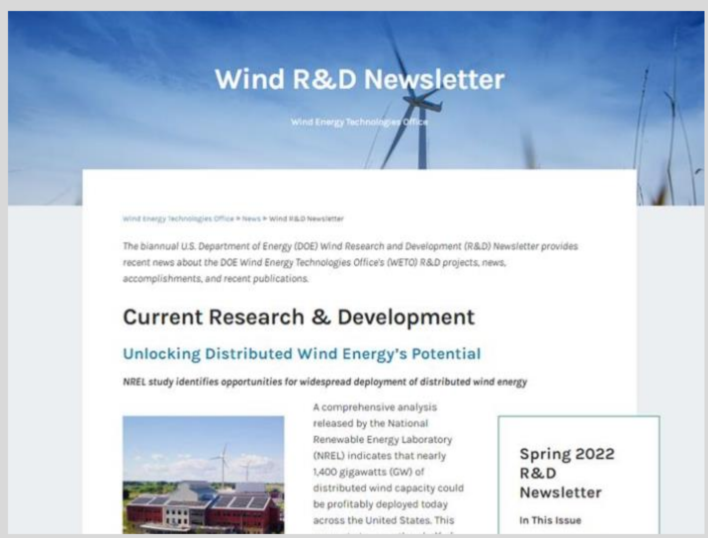
NREL's Ian Baring-Gould, Alexsandra Lemke, Mike Robinson, and Rich Tusing provided strategic guidance, subject matter expertise, and technical assistance in developing new strategic initiatives and opportunities in support of amplifying the WETO's research, contributing to program collaboratives consisting of multiple national laboratories, universities, and industry players. This support consisted of strategic 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. These advisors played a crucial role in contributing to high-quality, industry-leading long-term wind energy research development and deployment strategies, and supported wind-hybrid technologies, wind-storage technologies, wind-circular economy technologies, and Small Business Innovation Research and Small Business Technology Transfer programs.

| Communications Support | WETO.5.1.0.402 |
|---|---|
| **Point of Contact:** | Amy Howerton, Amy.Howerton@nrel.gov |

# Content Optimization Amplifies Key Impacts of WETO-Funded Research

NREL Wind Program's communications team delivers comprehensive communications products across a variety of platforms—from social media and websites to online newsletters and news articles—to inform thousands of stakeholders and members of the general public about the impact of NREL's WETO-funded research. Informed by audience metrics, the communications team continues to refine its strategies, resulting in increased readership and audience engagement.

For example, as managing editor of WETO's Wind Research and Development Newsletter, NREL worked with WETO staff to repackage the publication to improve audience engagement, increase opportunities for article amplification by releasing articles throughout the year, and reduce costs.




WETO's Wind Research and Development Newsletter is one of the many ways the NREL Wind Program's communications team harnessed audience metrics and expert communications strategy counsel to foster improved audience engagement, providing key updates to stakeholders and members of the general public about the impact of NREL's WETO-funded research. *Screenshot by NREL*

# Non-AOP

Wind Farm Control and Layout Optimization for U.S. Offshore Wind Farms

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

# FLORIS Wake Model Shows Improved Accuracy for Large Offshore Wind Farms

In collaboration with NOWRDC, NREL engineers developed and validated a new model of wind turbine wakes and wake steering. The Cumulative Curl model, implemented in the updated version of FLORIS Version 3.0, improves the accuracy of the model when compared to large offshore wind farms, wherein a turbine can be in the wake of many others upstream. This improvement was demonstrated in a recent paper that compared this new model to data collected from three offshore wind farms. The paper shows that the model, compared to previous ones, greatly improves the prediction of reduced power production of turbines located in the wake of many upstream turbines. The model improvements will enable the design of wind farm controllers for U.S. offshore wind farms to enhance electricity generation at no additional capital cost.

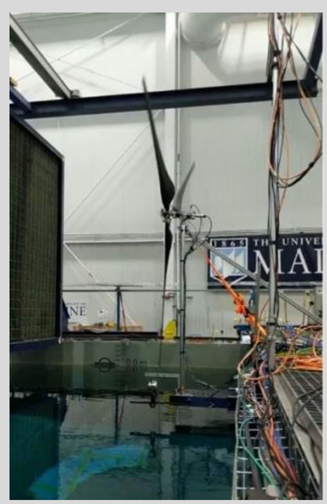
In collaboration with the National Offshore Wind Research & Development Consortium, NREL engineers developed and analyzed a new model of wind turbine wakes and wake steering through FLOw Redireciton and Induction in Steady State (FLORIS) software (Version 3.0), improving accuracy of the model when compared to large offshore wind farms. *Photo by Dennis Schroeder, NREL*

ARPA-E ATLANTIS FOCAL Project

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

# ATLANTIS FOCAL Project Completes Design and Testing of Scaled Wind Turbine With Active Control

The Floating Offshore wind and Controls Advanced Laboratory (FOCAL) project, run under the Advanced Research Projects Agency-Energy Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control (ATLANTIS) program, completed a model experiment focused on controlling the aerodynamic response of wind turbines through active blade pitch and torque control. This is the first of four experimental campaigns demonstrating the impact that controls can have on steadying dynamic floating offshore wind turbine behavior. The data set will be shared publicly through the Data Archive and Portal to validate several offshore wind modeling tools that aim to capture the impact of advanced controls on reducing the motions and loading on floating wind turbines. The FOCAL project showed that the controller can be used to dampen the motion of the floating wind system and lessen the loading on the structure, allowing for cheaper, lighter-weight floating support structures to be designed.



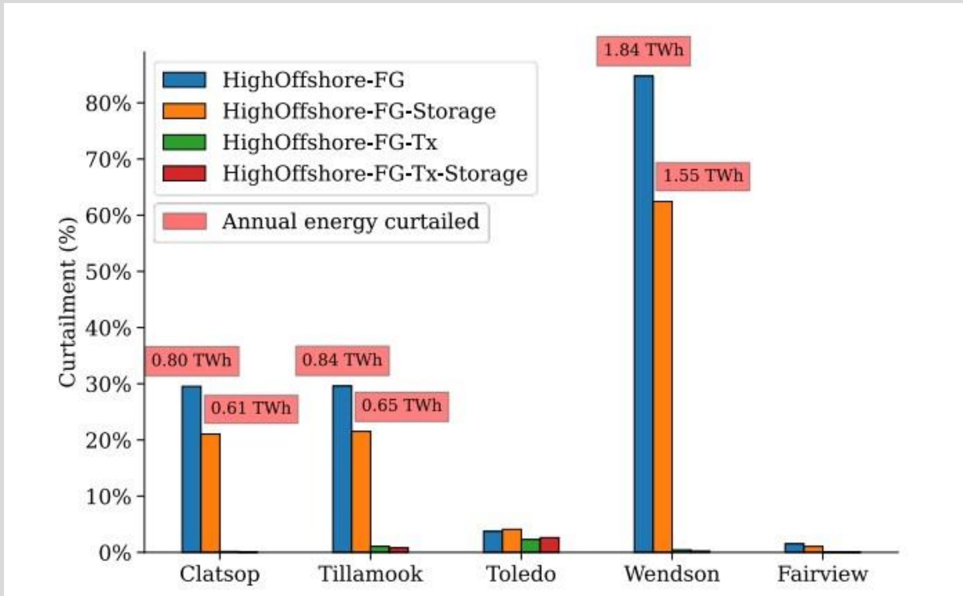
A 1:70-scale model of the International Energy Agency's 15-MW wind turbine undergoes validation of aerodynamic loading while under active turbine control in a water tank. *Photo by Matt Fowler, University of Maine*

Evaluating the Grid Impact of Oregon Offshore Wind (funded by the Bureau of Ocean Energy Management (BOEM))

**Point of Contact:** Marty Schwarz, Marty.Schwarz@nrel.gov

# BOEM-Funded Work Analyzes the Power Grid Value of Oregon Offshore Wind Energy

NREL used a production cost model of the full Western Interconnection to analyze the impact of integrating up to 5 GW of offshore wind energy along the Oregon coast. The study, executed in partnership with the U.S. Department of the Interior's Bureau of Ocean Energy Management (BOEM), determined the existing coastal transmission system could accommodate about 2.6 GW, if spread across the five major points of interconnection, without leading to significant congestion or curtailment. It also found the total system value to be greater than the estimated cost of offshore wind energy in 2032 on a megawatt-hour (MWh) basis in all scenarios studied. Since it was published in October 2021, the work has directly helped the Oregon Department of Energy strategize its grid planning and several other government agencies move forward to identify call areas for possible offshore wind energy development.

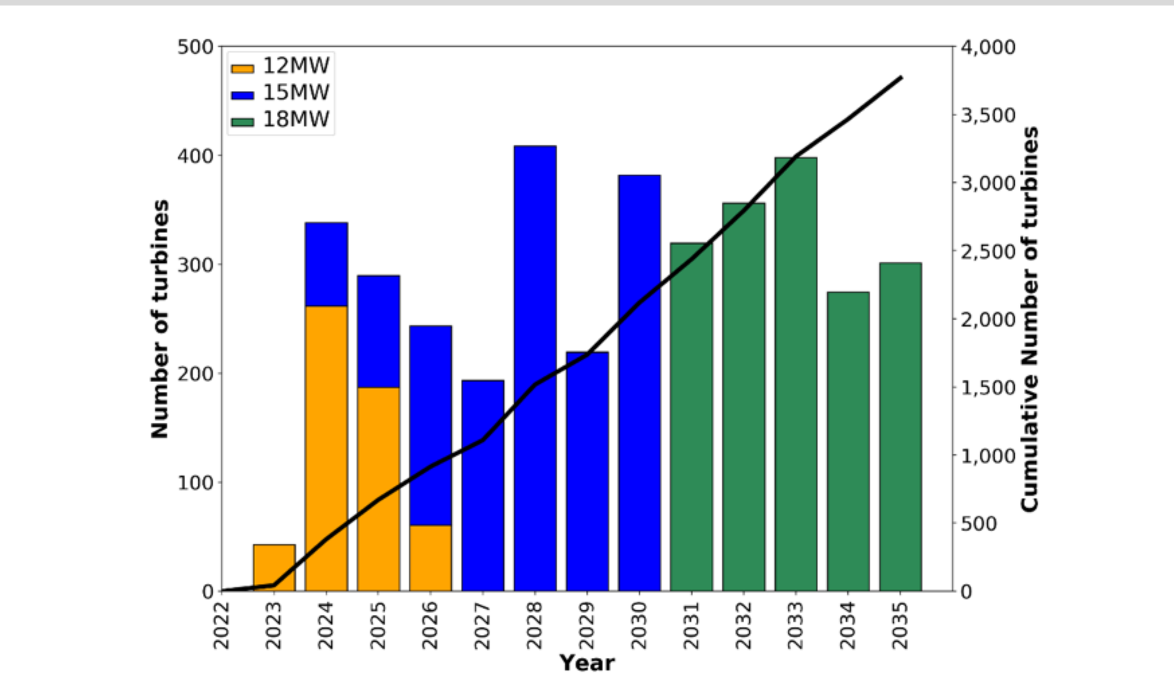



The curtailment of offshore wind energy (in terawatt-hours [TWh]) at each point of the five (left to right representing northern to southern) points of interconnection along the Oregon Coast for the four high offshore wind penetration scenarios. HighOffshore-FG and HighOffshore-FG-Storage refer to scenarios without any coastal transmission expansion and without or with, respectively, storage deployment; HighOffshore-FG-Tx and HighOffshore-FG-Tx-Storage refer to scenarios with coastal transmission and without or with storage deployment, respectively. Coastal transmission upgrades mostly eliminate curtailment, whereas small energy storage systems only reduce curtailment by about 15%. *Graphic by Marty Schwarz, NREL*

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

# Analysis Characterizes the Demand for a Domestic Offshore Wind Supply Chain

The offshore wind energy industry in the United States aims to develop a domestic supply chain to help achieve a target deployment of 30 GW installed by 2030 while also creating local jobs and economic benefits. NREL is leading a study funded by NOWRDC to characterize what the supply chain could look like in 2030 to realize this achievement. The first report from the study was published in March 2022, outlining the high-level demands the supply chain will need to support, including over 2,100 wind turbines and foundations, 6,800 miles of cable, 5–6 wind turbine installation vessels, and 12,300–49,000 manufacturing jobs. Understanding these resource demands will inform the study's next phase and help the industry develop a domestic supply chain by 2030.

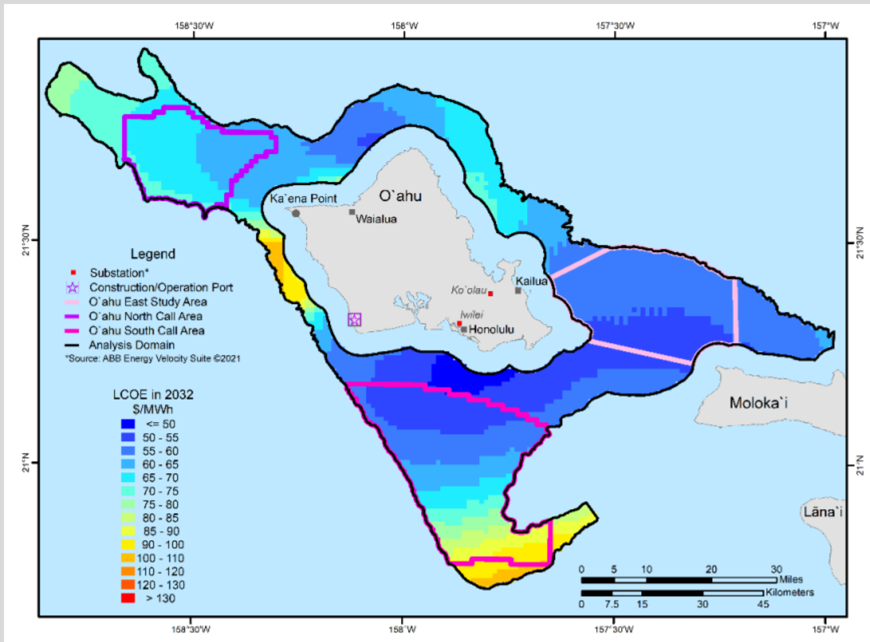



Annual deployment of offshore wind turbines required to reach a cumulative deployment of 30 GW by 2030. *Image by Matt Shields, NREL*

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

## NREL Conducts Cost and Feasibility Study for Offshore Wind Energy in the Hawai`i Region With Promising Results

Offshore wind energy has the potential to be deployed in Hawai`i to address the state's current high electricity prices, heavy reliance on imported fossil fuels, and favorable wind resources. NREL conducted a feasibility study for BOEM to evaluate how costs, infrastructure, logistics, and public perception may evolve for offshore wind energy in the region surrounding O`ahu. NREL determined that, by the early 2030s, the levelized cost of energy could be as low as $56/MWh to $66/MWh in likely deployment zones surrounding the island. Despite Hawai`i's remote location, these costs can be similar to those of global offshore wind energy projects, if sufficient investments in infrastructure (e.g., ports, workforce, and grid connections on O`ahu are developed in time.



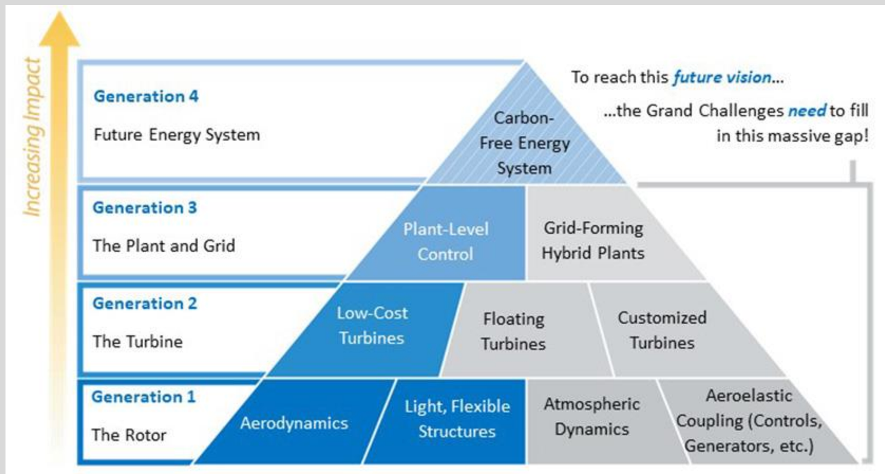

Heat maps of offshore wind energy's potential levelized cost of energy (LCOE in $/MWh) in the O`ahu region in Hawai`i for commercial operation dates in 2032. Costs are lower in the southern and eastern regions of the analysis domain because of favorable wind resources, benign wave and current conditions, and close proximities to ports and grid infrastructure. *Map by Donna Heimiller, NREL*

Wind Energy's "Grand Challenges"

**Point of Contact:** Paul Veers, [Paul.Veers@nrel.gov](mailto:Paul.Veers@nrel.gov)

# NREL Leads Effort To Define Wind Energy "Grand Challenges" Roadmap

NREL is leading an international effort to describe the critical research needed to meet wind energy's "Grand Challenges," initially introduced in a 2019 *Science* article outlining the progress, potential, and high-level scientific gaps in wind energy. With the support of the European Academy of Wind Energy and IEA Wind, a series of 10 papers is being published in *Wind Energy Science*. The series, written by wind energy researchers worldwide, reviews the breadth of wind energy research needs and proposes actions to help reach global decarbonization goals.




NREL is collaborating with international partners to develop a series of journal articles that define the wind energy research needed to reach a carbon-free energy future. *Image by Paul Veers, NREL*

Although wind energy has grown from virtually nothing to supplying 9.2% of total U.S. electricity in just 20 years, there remains crucial work to be done for wind energy to become a significant contributor to the future carbon-free energy system.

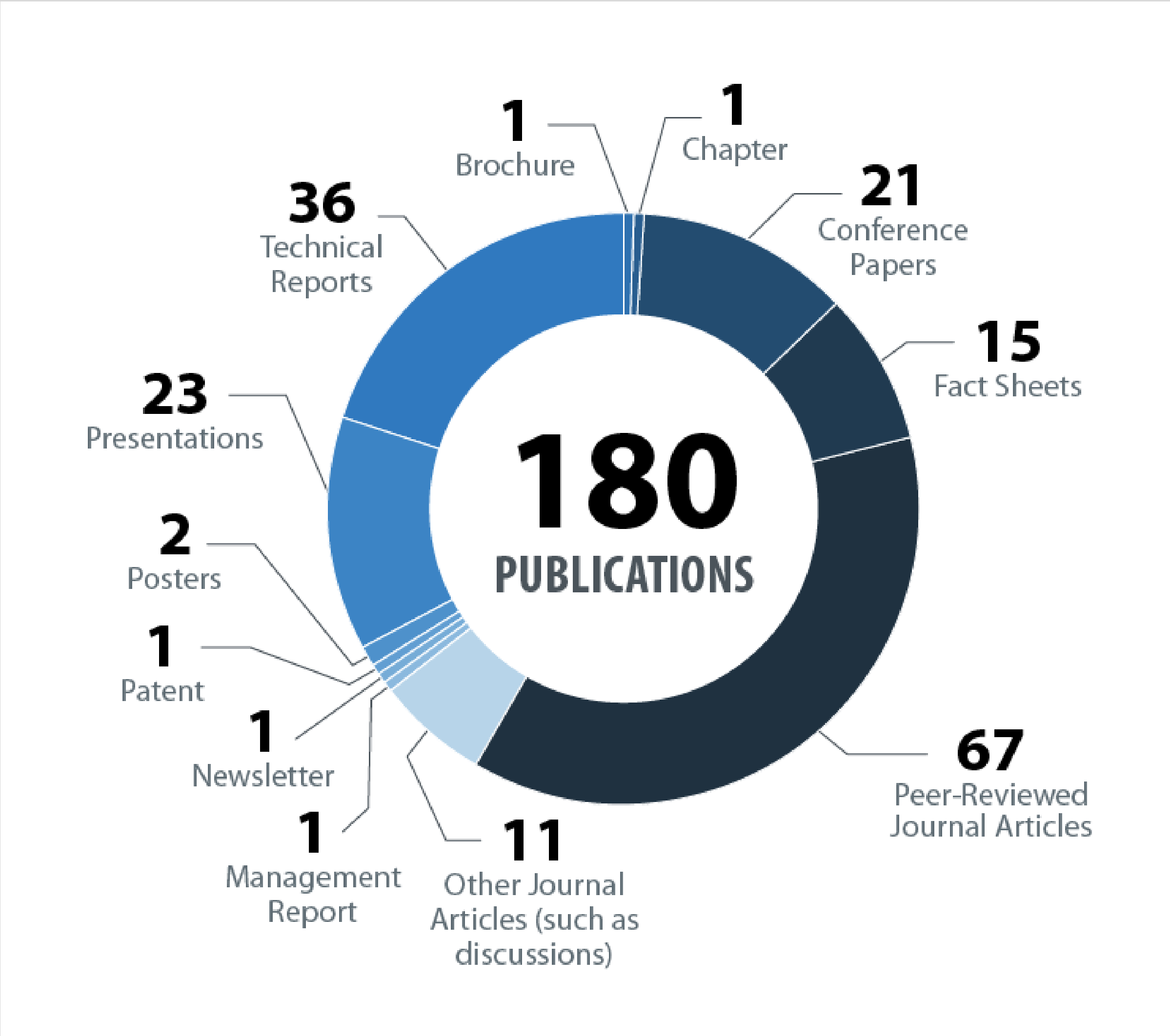
# Publications Overview

# Publications Overview

Publications produced by NREL Wind Energy Program staff provide information about the many areas of wind energy research conducted at the lab. As of the midyear point in FY 2022, NREL researchers published their latest scientific findings and breakthroughs in 180 technical reports, peer-reviewed journal articles, conference papers, fact sheets, and other materials.

### Fiscal Year 2022 NREL Wind Energy Publications as of March 31, 2022

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.




In Fiscal Year 2022, as of March 31, 2022, the National Renewable Energy Laboratory (NREL) Wind Energy Program published 180 publications processed through the Communications Office Publication Tracker.

# Notable Publications

Abbas, Nikhar J.; Zalkind, Daniel S.; Pao, Lucy; Wright, Alan. 2022. "A Reference Open-Source Controller for Fixed and Floating Offshore Wind Turbines." *Wind Energy Science.* https://dx.doi.org/10.5194/wes-7-53-2022.

Allen, Jeffery; Young, Ethan; Bortolotti, Pietro; King, Ryan; Barter, Garrett. 2022. "Blade Planform Design Optimization To Enhance Turbine Wake Control." *Wind Energy.* https://dx.doi.org/10.1002/we.2699.

Bodini, Nicola; Lundquist, Julie K.; Moriarty, Patrick. 2021. "Wind Plants Can Impact Long-Term Local Atmospheric Conditions." **Scientific Reports**. https://dx.doi.org/10.1038/s41598-021-02089-2.

Harrison-Atlas, Dylan; King, Ryan N.; Glaws, Andrew. 2021. "Machine Learning Enables National Assessment of Wind Plant Controls With Implications for Land Use." *Wind Energy*. https://dx.doi.org/10.1002/we.2689.

Nejad, Amir R.; Keller, Jonathan; Guo, Yi; Sheng, Shawn; Polinder, Henk; Watson, Simon; Dong, Jianning; et al. 2022. "Wind Turbine Drivetrains: State-of-the-Art Technologies and Future Development Trends." *Wind Energy Science.* https://dx.doi.org/10.5194/wes-7-387-2022.

Sandhu, Rimple; Tripp, Charles; Quon, Eliot; Thedin, Regis; Lawson, Michael; Brandes, David; Farmer, Christopher J.; et al. 2022. "Stochastic Agent-Based Model for Predicting Turbine-Scale Raptor Movements During Updraft-Subsidized Directional Flights." *Ecological Modelling.* https://dx.doi.org/10.1016/j.ecolmodel.2022.109876.

Shaw, William; Berg, Larry; Debnath, Mithu; Deskos, Georgios; Draxl, Caroline; Ghate, Virendra; Hasager, Charlotte; et al. 2022. "Scientific Challenges to Characterizing the Wind Resource in the Marine Atmospheric Boundary Layer." *Wind Energy Science Discussions* [preprint]. https://doi.org/10.5194/wes-2021-156.

Stanley, Andrew P. J.; Roberts, Owen; Lopez, Anthony; Williams, Travis; Barker, Aaron. 2022. "Turbine Scale and Siting Considerations in Wind Plant Layout Optimization and Implications for Capacity Density." *Energy Reports.* https://dx.doi.org/10.1016/j.egyr.2022.02.226.

Wang, Lu; Robertson, Amy; Jonkman, Jason; Yu, Yi-Hsiang. 2022. "OC6 Phase I: Improvements to the OpenFAST Predictions of Nonlinear, Low-Frequency Responses of a Floating Offshore Wind Turbine Platform." *Renewable Energy.* https://dx.doi.org/10.1016/j.renene.2022.01.053.

Wilson, Samuel; Hall, Matthew; Housner, Stein; Sirnivas, Senu. 2021. "Linearized Modeling and Optimization of Shared Mooring Systems." *Ocean Engineering*. https://dx.doi.org/10.1016/j.oceaneng.2021.110009.

View all journal articles and technical reports published in FY 2022 as of March 31, 2022.

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

NREL/MP-5000-83261 • June 2022

Photo Credits:
Front cover photos by Werner Slocum / NREL (65539)
Back cover photo by Werner Slocum / NREL (66537)