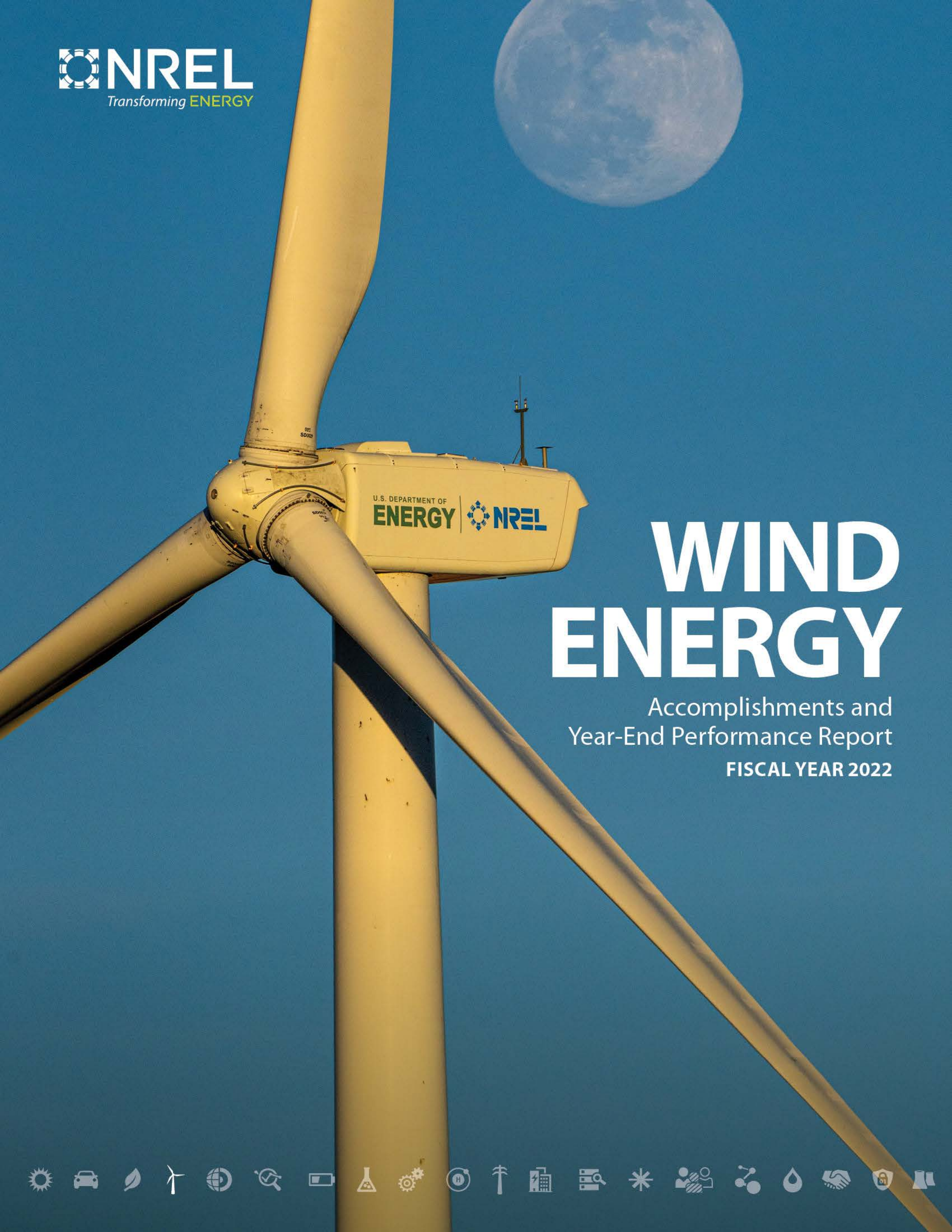
NREL
Transforming ENERGY



WIND ENERGY

Accomplishments and Year-End Performance Report

FISCAL YEAR 2022

Notice

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Foreword

Four decades ago, construction was just beginning on experimental turbines at the National Wind Technology Center (NWTC). Today, the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) facility is the centerpiece of the laboratory's Flatirons Campus, a world-class hub for renewable energy research.

The nation's shift to 100% clean electricity by 2035 will require a mix of renewable energy sources and strategies—and together, wind and solar energy could account for 60% to 80% of that clean energy resource. In Fiscal Year (FY) 2022, NREL scientists, engineers, and analysts contributed to these visionary goals through their wind energy research.

As wind innovations push into new areas, NREL continues to play a vital role in advancing technology and addressing deployment barriers in pursuit of more efficient, reliable, and predictable wind energy systems. FY 2022 wind research and development explored the potential for dramatic growth in land-based systems, the launch of the nation's first commercial-scale offshore installations, and transmission infrastructure buildout.

Land-based wind energy is one of the most cost-effective electricity supply options—but utility-scale deployment will require up to 10 times the current number of turbines. An NREL plan addressed this need to accelerate U.S. wind technology rollout at distributed and utility scales.

Another project conducted by NREL and the Pacific Northwest National Laboratory (PNNL) helps position the nation's first major offshore wind corridor for success. The WETO-funded Atlantic Offshore Wind Transmission Study is evaluating options for balancing electricity supply and demand, while supporting resilience of the grid and marine industries.

WETO, NREL, and other partners are working to enable the enormous supply chain and workforce changes the U.S. wind energy industry will need to meet net-zero-carbon-emissions targets. As part of a seminal series of DOE-funded supply chain studies, NREL analysts reported on the trade-offs involved in manufacturing large volumes of wind technologies, while addressing cost, workforce, and logistics issues.

All of this research is supported by NREL's outstanding research teams, tools, data, and facilities. A WETO-funded international wind energy field campaign, the American WAKE experimeNt (AWAKEN), has brought together experts from NREL, PNNL, and Sandia National Laboratories to create the world's most comprehensive set of high-resolution data on wind energy atmospheric phenomenon. This study could lead to more accurate predictions of losses from turbine-to-turbine wake interactions, eventually helping wind plants capture more energy and operators save millions of dollars.

In addition, NREL researchers developed testing, modeling, and analysis tools to improve the security of power grids by identifying wind power plant dynamic stability problems. A new Stochastic Soaring Raptor Simulator (SSRS) protects golden eagles from turbine encounters by predicting flight paths.

This report provides more detail on these top achievements and other accomplishments made by NREL and its partners during FY 2022 (between October 1, 2021, and September 30, 2022).

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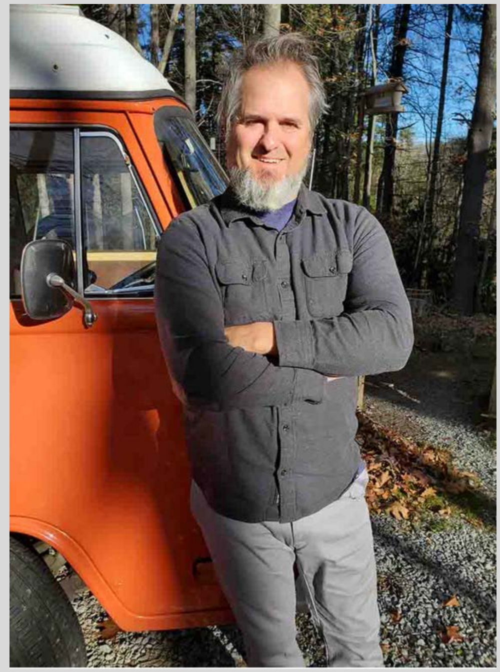
People and Partnerships

The People Behind NREL's Wind Energy Research Accomplishments

At the start of Fiscal Year 2022, NREL's wind energy communications team added a new feature to the monthly *The Leading Edge* newsletter: Behind the Blades. This feature directs the spotlight not just on the lab's invaluable research and development but also on the people working hard to realize those successes—offering first-hand insight into their careers, work at NREL, and the wind energy industry. Behind the Blades has proven to be one of the most engaging series in The Leading Edge, offering compelling stories about both NREL research innovations and the people behind them.



Brent Summerville joined the NREL wind energy team a year ago, but having worked with the lab in the past, he's already deeply involved in several projects. *Photo from Brent Summerville*

In December 2021, then-recent-hire Brent Summerville spoke about his path to wind energy and his work on the Competitiveness Improvement Project, Defense and Disaster Deployable Turbine project, and wind energy technology standardization. "I've had the pleasure of working with NREL staff and researchers throughout my career, and I am always impressed with the level of quality and impactful work from the lab," he said.

In summer 2022, the feature highlighted a joint appointee at the lab and the University of Colorado Boulder, Lucy Pao, her work on flexible wind turbine blades, and how important it is to expose students (or "future leaders to the field," as she called them) to the lab. "With NREL being so close by, I find that it is a tremendous recruiting tool in convincing prospective graduate students to come to UC Boulder," she said.

These popular articles have become a staple of the newsletters and a successful form of engagement on social media, revealing the faces, jobs, and work behind advancing wind energy.

Lucy Pao, a joint appointee at CU Boulder and NREL, stands next to a segmented ultralight morphing rotor wind turbine blade at NREL's Flatirons Campus shortly after the blade was manufactured and delivered to the lab for DOE-funded experiments in July 2018. The ultralight, flexible wind turbine rotor, designed by a multi-institutional team that included Pao and other NREL researchers, could lower wind energy costs. *Photo by Kathryn Johnson, Colorado School of Mines/NREL*

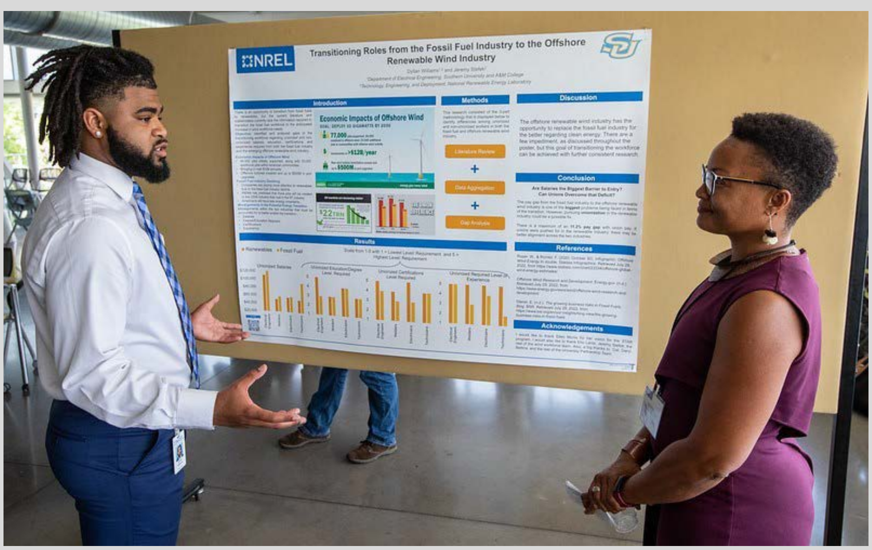
NREL Welcomes Next Generation of Wind Energy Workers

Each year, NREL researchers receive support from numerous interns who gain valuable hands-on experience and exposure through the lab's internship and fellowship programs.

In summer 2022, these six interns worked directly with NREL wind researcher mentors on ongoing projects as participants in DOE's Science Undergraduate Laboratory Internship and Research Participant Program. The next-generation researchers helped develop an open-source, real-time data analysis tool for wind farms; investigated levelized cost of energy under the Inflation Reduction Act; detected bats around wind turbines; and researched fishing industry concerns in relation to offshore wind energy—among other tasks.

NREL's Wind Program hosted three undergraduate students participating in the STAR program, which was designed to engage students from underrepresented backgrounds in becoming part of a research community early so they can begin to see themselves in similar roles. *Photo by NREL*

In FY 2022, NREL's Flatirons Campus participated in the inaugural year of the Student Training in Applied Research (STAR) program, which connects researchers with undergraduate students and faculty at minority-serving institutions. Campus researchers hosted three students who worked on projects such as automating the wind turbine finishing process and offshore wind energy workforce development.



NREL's Wind Program hosted three undergraduate students participating in the STAR program, which was designed to engage students from underrepresented backgrounds in becoming part of a research community early so they can begin to see themselves in similar roles. *Photo by NREL*

"Through the STAR program, our staff develop working relationships that can really transcend the year-long program and deliver research collaborations built on complementary roles," says Cat Dolezal of NREL's University Program staff, who led the program with colleague Ellen Morris. "We're really looking forward to seeing the difference this program makes, both for our researchers and for these incredible students."

Be sure to subscribe to NREL's *The Leading Edge* to read Behind the Blades features, the latest wind energy news, and more!

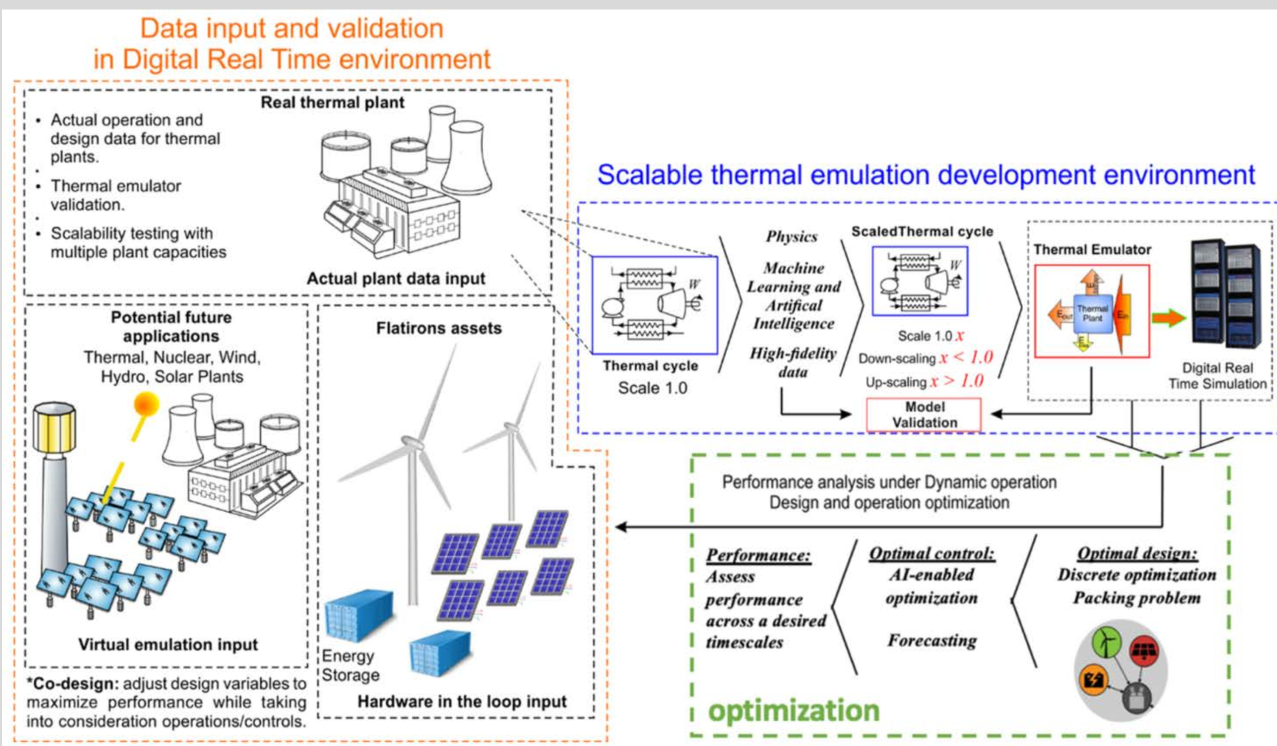
The Laboratory Directed Research and Development Program at NREL in FY 2022

Each year, NREL is a proud contributor of innovations built through the DOE's Directed Research and Development (LDRD) program. In FY 2022, three cutting-edge projects aim to shape the future of wind energy and wind energy deployment.

Pioneering the Grid of the Future

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

This project provides an opportunity to transition to dispatchable renewable generation to fully use the existing grid distribution infrastructure, minimize the risk for additional transmission capacity expansion, provide ancillary services not currently available, and unlock different end-use markets, such as hydrogen production. These end-use markets could be the key to achieving 100% clean energy across all sectors by 2050. By developing scalable models and optimization techniques that span subseconds to days ahead, we can enable optimal design and operation of hybrid power plants that will accelerate the development and deployment of clean energy.

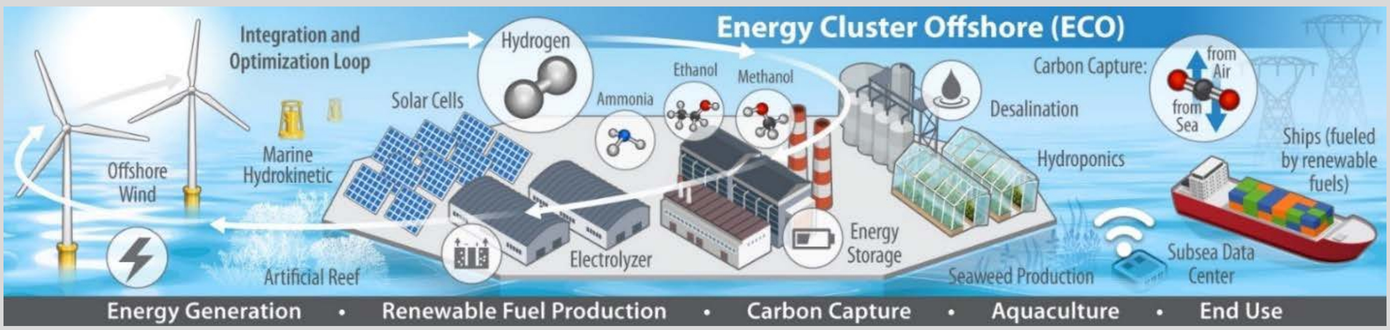


Coordination between real-world assets, scalable modeling, and co-design optimization. *Illustration courtesy of Julian Osorio and Jen King, NREL*

Optimal Design of Energy Clusters Offshore

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

NREL researchers started exploring the potential for energy clusters offshore. These clusters would be integrated and optimized systems of renewable electricity generation, storage, and fuel technologies paired with other complementary technologies, such as carbon capture and water desalination, and direct end uses, such as the production of renewable shipping fuels. An energy cluster offshore offers the potential to deliver the massive scale and flexibility necessary to transform the energy sector to achieve ambitious decarbonization goals. This project aims to establish the scientific basis and modeling, analysis, and optimization capabilities needed to quantify trade-offs between hybrid designs for different conditions and purposes to determine the technical and economic feasibility of an energy cluster. In FY 2022, the energy clusters offshore team assessed potential energy generation, storage, end use, and other complementary technologies and selected priority components for inclusion in the analysis and optimization of potential configurations. The team also started to modify and integrate existing NREL models, which included developing a cohesive interface between the models to be used in the optimization.

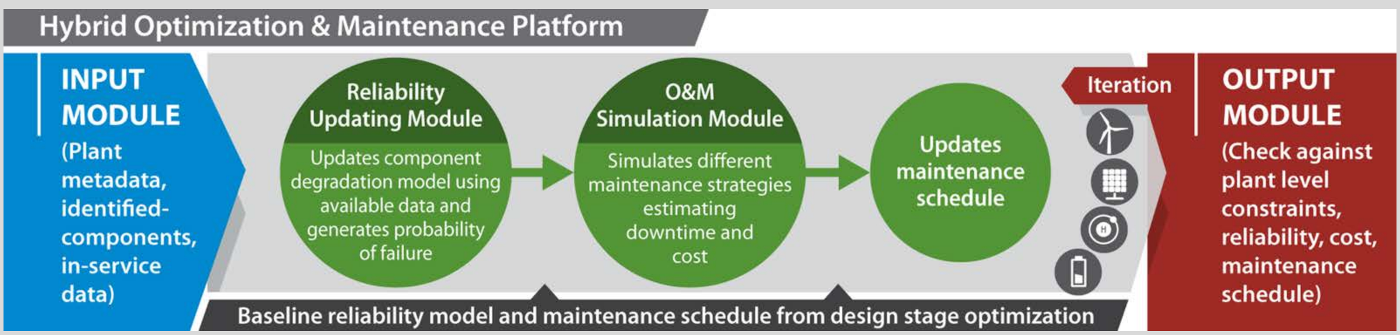


A nominal ECO design including the complementary technologies considered in the Optimal Design of Energy Clusters Offshore project.
Graphic by Alfred Hicks, NREL

Hybrid Optimization and Maintenance Platform - Concept Development and Demonstration

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

The ultimate objective of the Hybrid Optimization & Maintenance Platform project is to develop a framework for multiple-component reliability models across hybrid power plant technologies that accounts for degradation over time (from plant development to end of service life), mapping plant design configurations and operational decisions to reliability and operation and maintenance costs. This capability will enable stakeholders to balance potentially conflicting objectives (e.g., power production, loads, reliability, and costs) to optimize key plant design parameters, including generator and storage sizing, configuration, and operational strategies (e.g., charging and discharging cycles for battery storage). The team, which includes about a dozen members from various research centers at NREL and covering wind, solar, battery storage, and hydrogen four renewable technologies, focused on developing and demonstrating design-stage capabilities. They conducted 23 industry interviews and summarized the findings in a technical journal manuscript. They also integrated degradation, reliability, and dynamic operations and maintenance cost models into the Hybrid Optimization and Performance Platform for wind energy, solar power, battery, and hydrogen electrolyzer technologies, which enables optimal sizing of technologies for given effects of degradation and failure on levelized cost of energy/levelized cost of hydrogen, and a software record was filed. Follow-on work has been integrated in a hybrid power plants research project funded by the DOE Wind Energy Technologies Office.



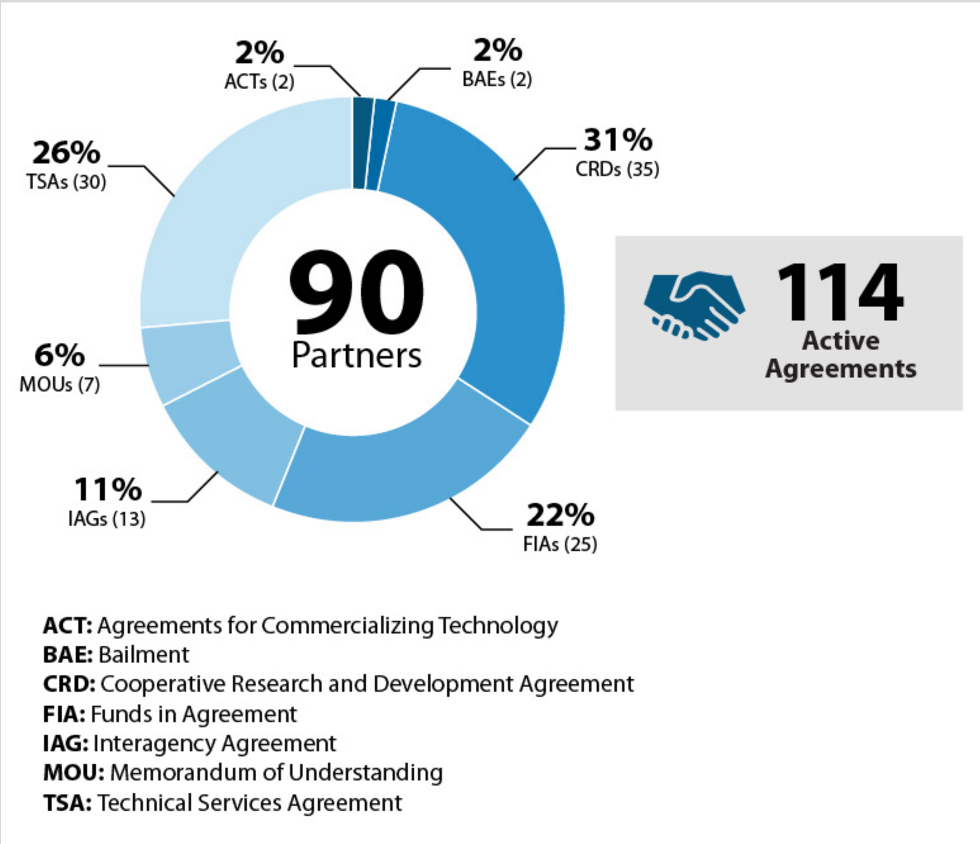
This graphic illustrates the Hybrid Optimization & Maintenance Platform. *Graphic by Alfred Hicks, NREL*

NREL Partners Help Accelerate Wind Energy

In FY 2022, NREL and the NWTC worked with 90 partners through 114 active agreements designed to advance wind energy science, streamline wind energy deployment, 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 90 partners, NREL's wind energy program participated in 114 various kinds of active agreements in FY22. *Graphic by NREL*

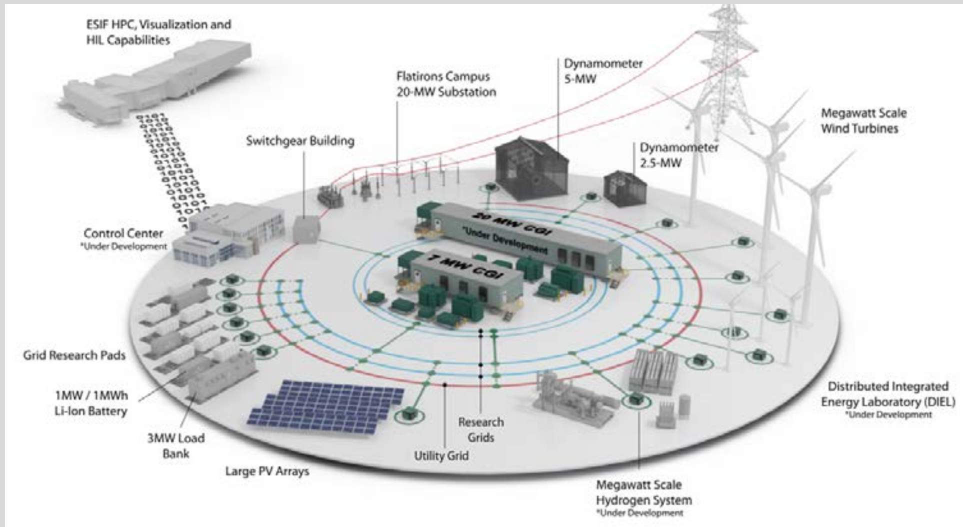
Testing Infrastructure, Standards Development, and International Engagement

Flatirons Campus Expansion and Capability Enhancements

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

Construction Begins on Second Controllable Grid Interface

The construction for the 20-megawatt (MW) controllable grid interface (CGI-2) at NREL's Flatirons Campus is underway with underground conduits being installed, foundation being poured, and installation of components on their foundations imminent. The construction will substantially be complete by the end of 2022, except the switchgear installation, currently expected in March 2023. Once that is installed, hot commissioning can commence. CGI-2 is currently expected to be "research ready" by mid-2023. At that time, 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 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*

Testing Facilities and Capabilities at National Wind Technology Center

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

Inventive Method Streamlines Microgrid Setup and Earns 2022 R&D 100 Award Finalist Status

When NREL experienced a surprise power outage, the lab had few options for recovery. Using the native controls of onsite battery, solar, and wind systems, NREL researchers quickly devised a solution that not only restored power to the NREL campus, but also demonstrated that relatively simple controls can enable power grids to operate with 100% renewable power—without the need for dedicated device-to-device communication. This communication-less method—honored as a 2022 R&D 100 Awards finalist for its entry titled *CommLess Microgrids: A Universal Design for Renewable Microgrid Resilience* —is the first step in a design that could become the standard for failsafe microgrids.

Testing Facilities and Capabilities at National Wind Technology Center

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

WETO Projects Soar With NREL's Eagle

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 DOE's Office of Energy Efficiency and Renewable Energy (EERE) program offices. In FY 2020, to ensure program success and continuity of research, 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 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 hardware ensured that over 40% of the year-to-date WETO workload ran at the highest priority, which is reflected in shorter wait times for WETO computing jobs. For example, in FY 2022, WETO computing jobs saw wait times 4–10 times shorter than the rest of Eagle's users.

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

Wind Standards Development

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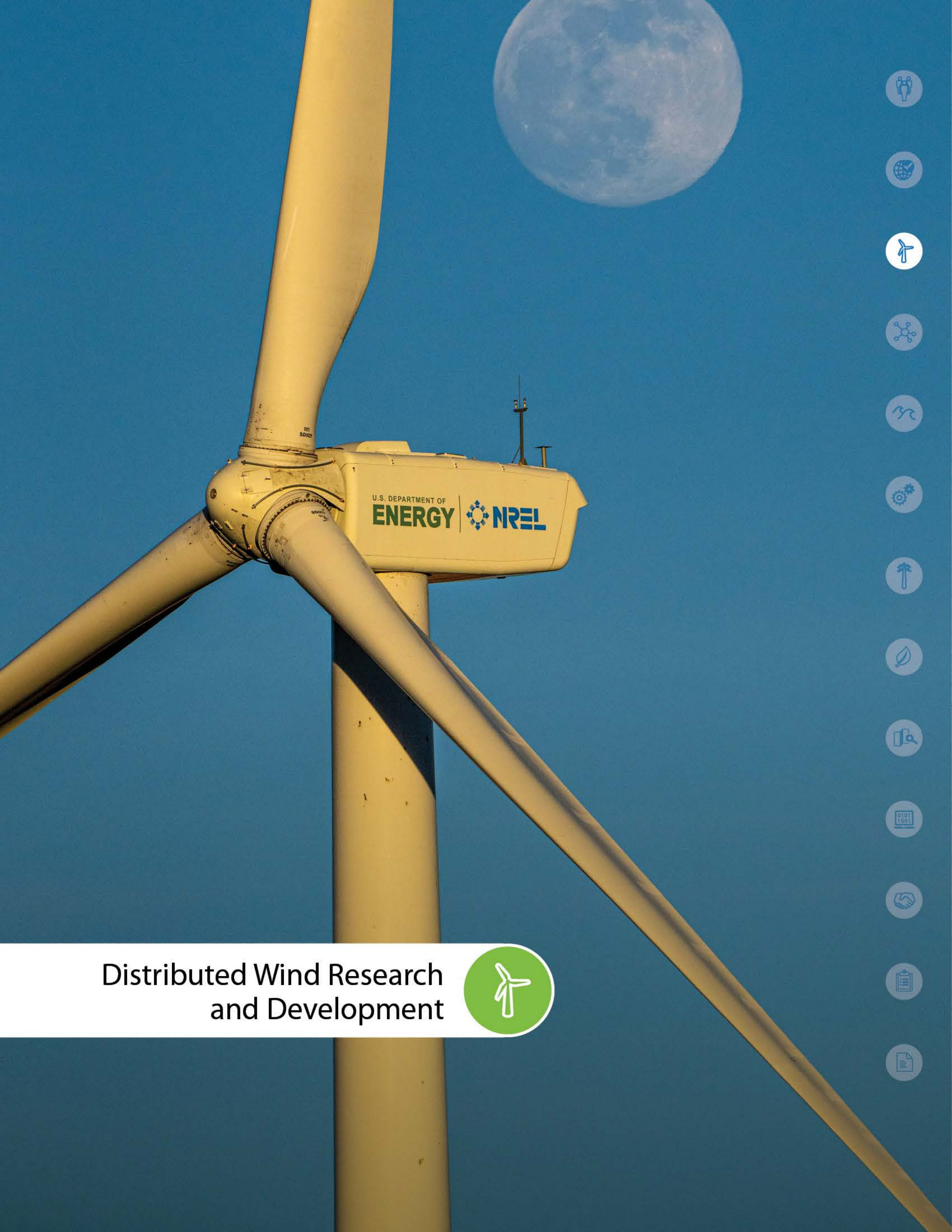
New Standard Approved for Offshore Wind Energy Project Compliance in U.S. Waters

The American National Standards Institute (ANSI) Board of Standards Review, working with the American Clean Power Association (ACP) and NREL, approved a new standard that is the overarching flagship for the offshore wind energy standards initiative. The standard was written by a broad, consensus-based group of more than 100 U.S. offshore wind energy industry leaders. ANSI/ACP OCRP-1-2022 is the culmination of a 5-year effort that is part of an industry-based standards initiative formed in 2017 under the ACP Offshore Wind Subcommittee, chaired by Walt Musial, the principal engineer and offshore wind energy research platform lead at NREL. The new standard can be officially recognized by regulators and referenced within the U.S. regulatory approval process. It is expected to become one of the primary guidance documents for the development of over 30 gigawatts (GW) of offshore wind energy on the U.S. Outer Continental Shelf. This long-awaited guidance will help provide transparency, consistency, and more certainty to the U.S. offshore wind energy regulatory process—and could lead to shorter regulatory timelines and increased worker safety.



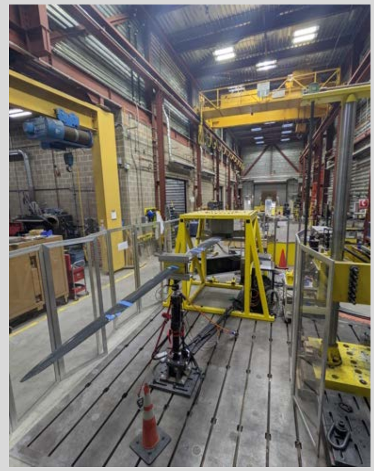
Distributed Wind Research and Development

Distributed Wind Research, Development, and Testing

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

NREL Provides Technical Support to Small Wind Turbine Manufacturers

Through the Competitiveness Improvement Project (CIP), NREL provided needed technical support to wind turbine manufacturers developing new, low-cost-and-reliable distributed wind turbine systems. CIP provides small, cost-shared technology development contracts to innovate new or existing technologies. Many CIP recipients are small companies that may not have deep technical expertise in all areas needed, which is why direct, laboratory-based technical support can be critical to the success of these projects. For example, NREL's support to CIP recipients in 2022 made way for improvements in aeroelastic models for vertical-axis wind turbines, which then allowed expanded modeling of the XFlow Energy 25-kW wind turbine. This year, NREL also initiated blade fatigue load testing for the new Bergey Excel 15 wind turbine at the NREL Flatirons Campus. Through these and other similar projects, NREL provided highly technical support to manufacturers who are unable to conduct such research on their own, making the small wind energy industry safer and more efficient.



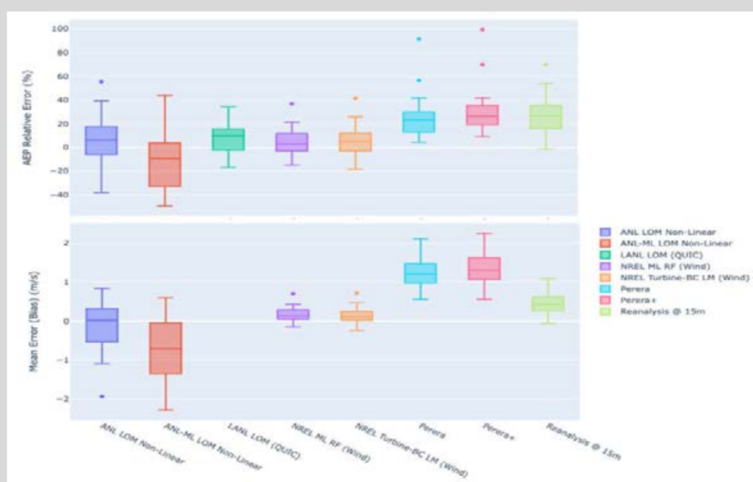
A 4.7-m blade from a Bergey Excel 15-kW wind turbine undergoes fatigue testing on a 135-kiloNewton-meter test stand at the NREL Flatirons Campus. *Image by NREL*

Tools Assessing Performance

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 for wind resource prediction 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*.

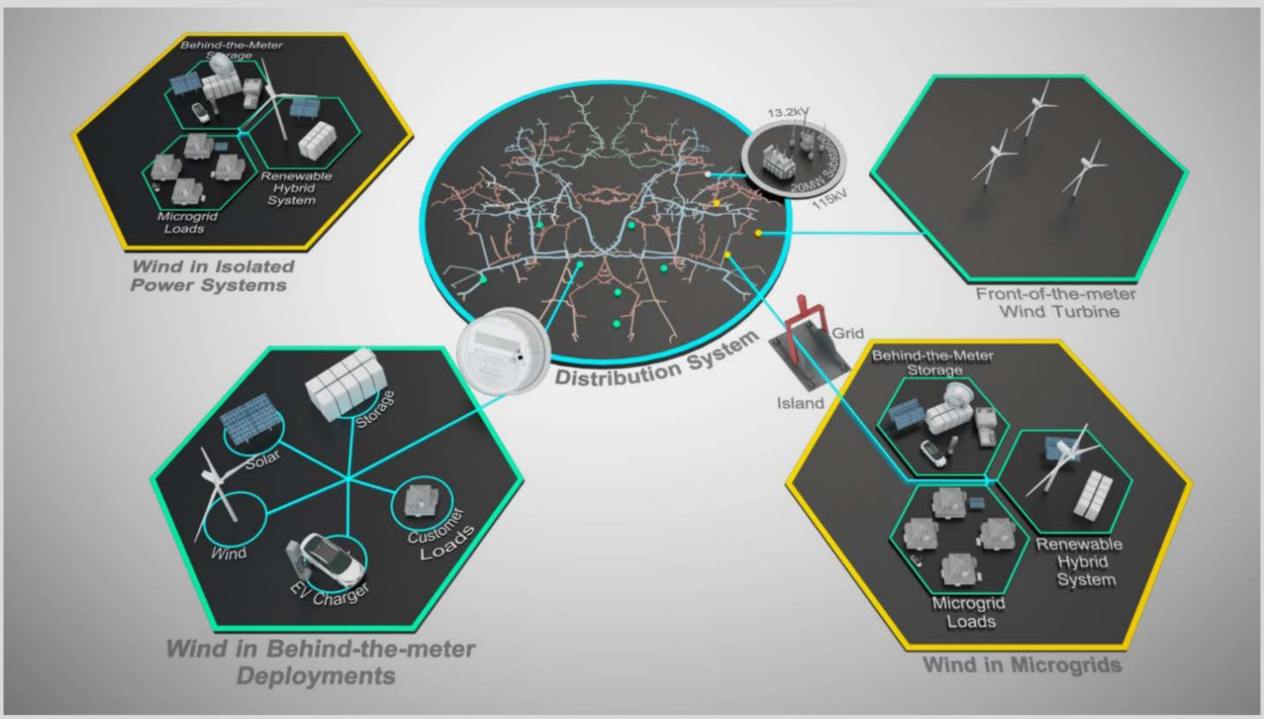


The mean error of seven wind turbine performance modeling approaches, alongside the raw reanalysis results for 300 distributed wind turbines in relatively consistent terrain, shows relatively large variations in model outputs with some quite close to actual performance. *Graph by NREL*

Point of Contact: Caitlyn Clark, Caitlyn.Clark@nrel.gov

MIRACL Team Built Simulation Capabilities of Distributed Wind Energy Assets

The multilaboratory Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) team culminated this 4-year project with the integration of a high-fidelity Simulink Advanced Research Turbine model into a wider model of NREL's Flatirons Campus. This model was then used to demonstrate the role that distributed wind energy can play in supporting a high renewable energy contribution, dynamic, distribution system of the future, which is being documented in the series of high impact publications. The new wind turbine model is equipped with a fault-impact reduction control module, which maximizes wind turbine power and safety in the presence of fault conditions, demonstrating how wind turbines of the future can work to support distribution networks and make them more resilient. The module communicates predictive information to the grid operator to give them time to react to potential wind turbine shutdowns. NREL's Flatirons Campus model includes a variety of elements that enable resilient, economic microgrid operation and participation in grid markets. These elements include advanced wind controls, forecasting, a battery with a smart inverter, and an autonomous microgrid controller to tie it all together. In addition, the NREL team is building high-fidelity Simulink models of the Bergey Excel 15, QED Wind Power Phoenix 20-kilowatt (kW), and Eocycle EOX M26 wind turbines, which are currently being installed at NREL's Flatirons Campus. In the future, these models may be validated with the physical machines and used for distributed wind energy hardware-in-the-loop experiments. The project produced several reports to be shared via a website launching in January 2023 showcasing all of the project's results.



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

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

Defense and Disaster Response Workshop Demonstrates Interest in Deployable Wind-Hybrid Solutions

The multilaboratory, DOE-funded Defense and Disaster Deployable Turbine (D3T) project team held a virtual workshop with stakeholders from defense and disaster response communities and technology developers to discuss the needs for demonstrating and deploying wind-hybrid deployable energy systems. About 90 participants joined the half-day workshop, which included: a project overview from the team; a lightning round of presentations by 11 suppliers of deployable wind, solar, and battery energy systems; a disaster relief discussion session with the Footprint Project; a defense industry discussion session with the Iowa National Guard; and a feedback/open-discussion session. The 4-year project ended in 2022, and this workshop clearly showed interest in this market space and a desire for continued collaborations dedicated to demonstrating and evaluating deployable hybrid wind energy solutions.

D3T workshop flyer with a 10-kW deployable wind turbine from Uprise Energy at the Idaho National Laboratory. *Flyer from Sandia National Laboratories*

Distributed Wind Research, Development, and Testing

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, Windward Engineering, and IEA Wind Task 41 (Enabling Wind to Contribute to a Distributed Energy Future), led a virtual workshop on distributed wind energy aeroelastic modeling. More than 45 industry participants, representing the global distributed wind energy industry, identified gaps and needs in aeroelastic modeling of distributed wind energy technology and detailed actions to advance this critical design tool. NREL will kick off a multilaboratory project in FY 2023 to implement a suite of improvements to the distributed wind energy aeroelastic modeling tools based on input from this workshop.

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*

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

Based on NREL's ongoing collaboration with the Distributed Wind Energy Association (DWEA) on standards for small wind turbines, at the 2021 CIP informational workshop, NREL provided an overview of the new Small Wind Turbine Standard, ANSI/ACP 101-1-2021, including changes from the previous edition. ANSI/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 March 2022 DWEA conference. Participants provided input via real-time polling focused on what is needed to support successful implementation of the new 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 American Clean Power 101-1 standard. *Photo from David Carr, RenewTest*

Atmosphere to Electrons

WFIP II Extended Analysis

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

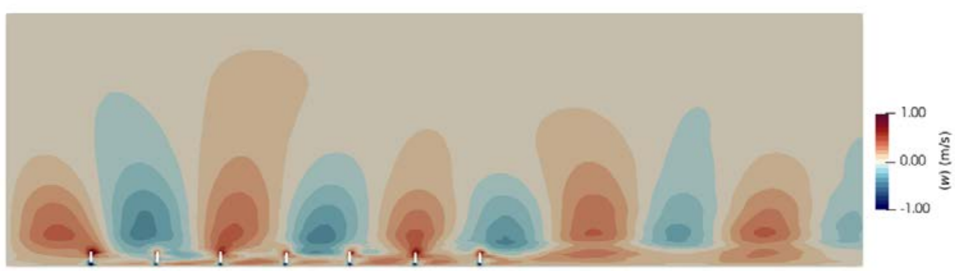
Open-Source and Systematic Validation Improves Wind Power Forecasts

Building on the work conducted under the Second Wind Forecast Improvement Project, NREL researchers demonstrated the value of using a consistent procedure to evaluate wind power forecasts. The researchers conducted a forecast evaluation benchmark exercise on two case studies using WE-Validate, an open-source Python code base tailored for wind speed and wind power forecast validation. WE-Validate evaluates model forecasts with observations in a coherent manner, which can be useful for the wind energy community when evaluating wind speed forecasts for various purposes. A research paper on this work emphasizes the importance of using statistically robust and resistant metrics as well as equitable skill scores in forecast evaluation.

MMC - Model Development & Validation

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

Successfully Simulating Atmospheric Gravity Waves Within High-Resolution Wind-Farm Flow Simulations



This is a side view of the vertical component of the atmospheric winds through and above a wind farm (with wind turbines indicated by small white bars). The atmospheric gravity waves are the alternating red and blue ripples above them. Wind flowing above the wind farm from left to right would be repeatedly pushed upward (red) and downward (blue) creating a wave pattern. *Graphic by Matthew Churchfield and Paul Fleming, NREL*

Like the ripples caused by tossing a stone into a pond, atmospheric gravity waves are ripples that propagate through the atmosphere, except these ripples are invisible and huge in scale. The stone, in the case of atmospheric gravity waves, can be mountains, thunderstorms, or even wind farms. Because of the high level of realism of high-fidelity wind farm/atmospheric flow simulations, users can now capture wind-farm- or terrain-induced atmospheric gravity waves and their feedback onto the wind farm. This is an important research topic because an increasing number of researchers are beginning to believe that wind-farm-induced atmospheric gravity waves are a component of a phenomenon known as wind plant blockage, which reduces a wind farm's power output. Properly simulating flows with atmospheric gravity waves is challenging because the waves tend to reflect off the simulation boundaries, causing unrealistic effects. The mesoscale-microscale coupling (MMC) and offshore wind atmospheric characterization (OWAC) projects have focused on finding robust ways to perform accurate wind-farm-atmospheric-flow simulations that contain atmospheric gravity waves.

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

A multilaboratory atmospheric-flow modeling team consisting of researchers from NREL, Pacific Northwest National Laboratory (PNNL), 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. 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 of the U.S. Atlantic Coast, which provides an important test case for large offshore wind turbines. Wind simulations like this can be used to develop improved wind turbine and wind power plant designs.

High-Fidelity Modeling

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High-Fidelity Wind Turbine Blade-Pitch Motion Modeling Enabled in ExaWind

The NREL and Sandia National Laboratories' high-fidelity modeling team enhanced the ExaWind simulation code to capture the pitch-controller movement of wind turbine blades in addition to large-deformation blade bending. They accomplished this by introducing model-mesh deformation near the blade root. The ability to model pitch motion is critical to enable ExaWind to model wind turbines operating in high winds where the pitch controller is active.

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*

High Fidelity Modeling Toolkit (TCF)

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

High-Fidelity Modeling Team Implements Proof-of-Concept Complex Terrain Model to ExaWind

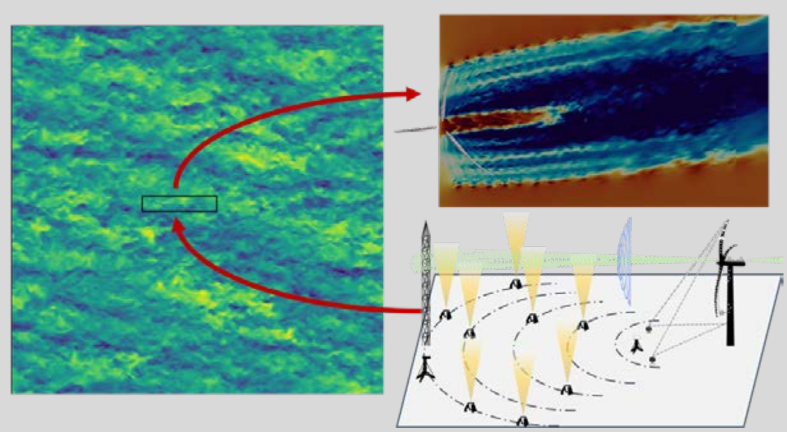
Researchers at NREL and Sandia National Laboratories implemented a proof-of-concept capability to simulate complex terrain in ExaWind: AMR-Wind through the immersed boundary method. Efforts included generating immersed-boundary-method representations of canonical cases and formulating a new large-eddy simulation wall model that can be applied along the immersed boundary method surface. Implementation of the wall model for production simulations is ongoing. The addition of complex terrain to AMR-Wind will be key to its impact 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.

Rotor Wake Measurements & Predictions for Validation (RAAW)

Points of Contact: Nicholas Hamilton, Nicholas.Hamilton@nrel.gov; Paula Doubrawa, Paula.Doubrawa@nrel.gov

New Simulation Capability Reduces Uncertainty and Opens Model Development Opportunities

NREL researchers working on the Rotor Aerodynamics, Aeroelastics, and Wake (RAAW) project are developing new methods for high-fidelity simulations of atmospheric flows to better understand wind turbines and their wakes. Using measurements from multiple remote-sensing and in situ instruments, one new capability ensures that simulations match observed atmospheric flow conditions and events as closely as possible, reducing model uncertainty and opening new pathways for model development and validation. By separating uncertainty from atmospheric modeling, wind turbine controls, and the structural response of the turbine, researchers will be able to quantify where to trust their models and where to focus future efforts in research and development.



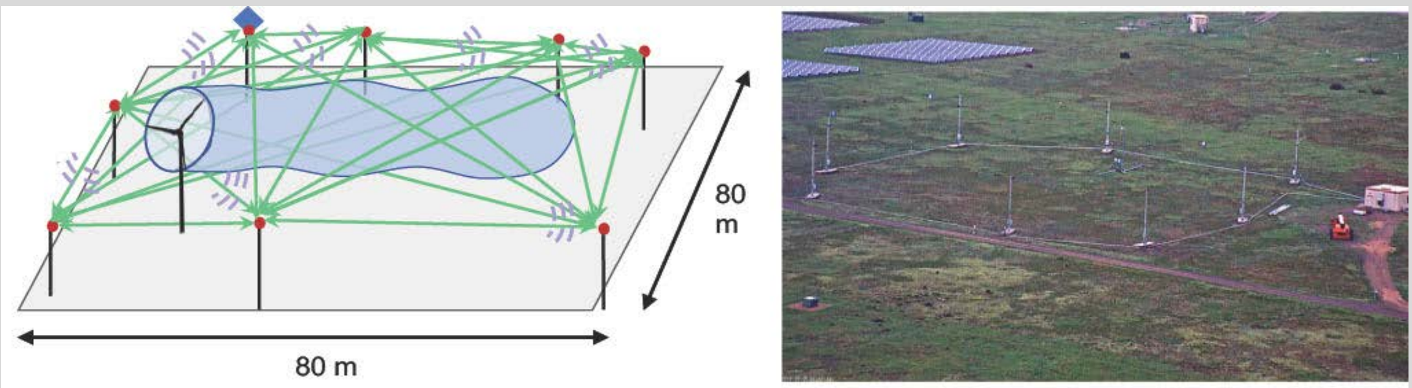
Time-series model validation though data assimilation drives simulated atmospheric flows (left) with a collection of observations from remote-sensing and in-situ instrumentation. The image on the left shows a plane at hub-height in a 5-kilometer-by –5-kilometer area with colors denoting streamwise velocity. NREL researchers are evaluating multiple methods to estimate the flow state in a large domain surrounding the virtual experiment, shown with a box encompassing the RAAW experiment area. The simulated atmospheric flow will then drive a wind turbine model, enabling researchers to focus on the wind turbine's aeroelastic response and the formation of coherent flow structures in the wake. The image on the top right shows the velocity field in the wake of a wind turbine where colors denote the magnitude of the streamwise velocity. *Images by Luis Martínez-Tossas, Alex Rybchuck, and Nicholas Hamilton, NREL*

Aeroacoustic Assessment of Wind Plant Control

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

Using Sound To Explore Wind Turbine Wake Dynamics

Researchers at NREL's National Wind Technology Center are using acoustic signals to develop new, remote-sensing measurement systems that explore the turbulent velocity and temperature fields in wind turbine wakes. Acoustic travel-time tomography characterizes bulk flow properties in a region of interest with the times of flight of acoustic signals. Theoretical advancements by the research team incorporates NREL's wake modeling tools into the velocity and temperature field-retrieval methods, opening new application spaces in renewable energy research and development.



The acoustic tomography array at the Flatirons Campus, including a subscale wind turbine. Red dots indicate acoustic transducer placement, and the blue diamond indicates the sonic anemometer and temperature/humidity probe. *Illustration courtesy of NREL*

American Wake Experiment (AWAKEN)

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

Final Preparations Underway for the International American WAKE experimeNt

NREL researchers finalized the logistical groundwork to launch the American WAKE experimeNt (AWAKEN), an international, multi-institutional wind energy field campaign funded by WETO. From September 2022 through October 2023, NREL researchers will use a variety of advanced sensors installed on the ground and in the sky to study how winds move through Oklahoma wind power plants. With that data, the team will create the highest-resolution measurements ever obtained of atmospheric effects in and around wind power plants. By detailing how these plants interact with the atmosphere, AWAKEN could help the plants increase energy production by 5% or more and capture revenues that are currently lost.

Wind turbines in the King Plains wind farm in Oklahoma will serve as the test bed for the AWAKEN project, helping researchers better understand how wind plants interact with the atmosphere. *Image provided by Patrick Moriarty, NREL*

Enabling Autonomous Wind Plants through Consensus Control (TCF)

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

Shared Control Experiment for Utility-Scale Wind Farms

Validating collective consensus control is now underway on a utility-scale wind farm. In collective consensus control, which was invented by NREL researcher Jennifer King and described in "Wind Direction Estimation Using SCADA Data With Consensus-Based Optimization" in *Wind Energy Science*, wind turbines cooperate by sharing information about wind direction with neighboring turbines. This shared information is incorporated into the turbine control decisions to enable better control over the turbines and improve performance. As a result of DOE's Technology Commercialization Fund (TCF) support and with industry partner RES, NREL researchers deployed the collective consensus control algorithm at a utility-scale farm.

Systems Engineering and Optimization

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

Wind Energy Systems Engineering Workshop Draws International Researchers

Through IEA Wind Task 37 (Systems Engineering), NREL and the Technical University of Denmark hosted the sixth Wind Energy Systems Engineering Workshop at the University of Colorado Boulder. More than 80 international researchers and industry practitioners who work in the development of design methods for wind turbines and power plants attended the 3-day event. The agenda featured technical talks, the Task 37 annual meeting, and tours of the Vestas Blades America, Inc. wind turbine blade factory and NREL's Flatirons Campus. The impressive strides in design tools across many institutions came through clearly in many presentations. The next frontier of design challenges was also presented, such as designing for industrial and sustainable manufacturing, achieving cost-competitive floating offshore wind energy, incorporating hybrid energy sources (including hydrogen), inherently protecting wildlife, and gaining greater acceptance from the public.

Wind Energy Systems Engineering Workshop participants tour the Vestas Blades Americas factory in Windsor, CO. *Image courtesy of Garrett Barter*

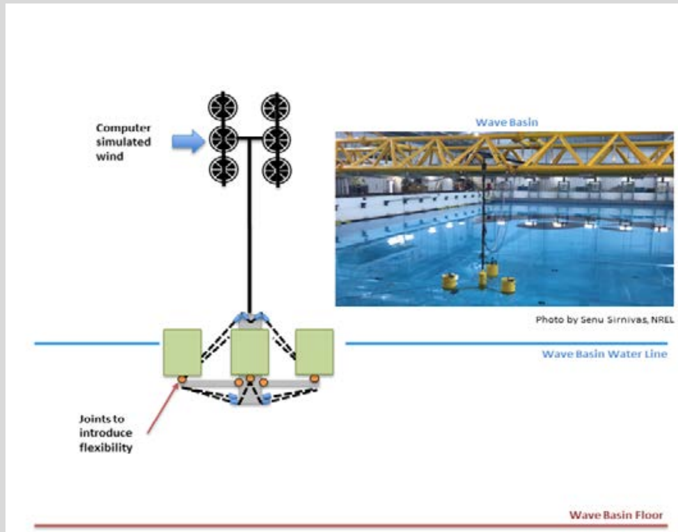
Offshore Wind Specific Research and Development

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

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

Flexible Floating Offshore Wind Platform Model Validated in Hybrid Wave System

A 1:52.5-scale model of SpiderFLOAT, NREL's patent-pending scalable floating offshore wind turbine system, moved closer to commercialization after NREL researchers validated the design's performance at the University of Iowa's wave basin. As most wave basins lack the capability to simulate wind, the university developed a hybrid wind-wave validation system that used a computer to simulate wind loads produced by a small-scale set of fans rather than using a large physical fan system. Results of the wave-tank research will inform design modifications that computer simulations alone cannot achieve. Developed in partnership with Equinor, owner of the world's first floating offshore wind farm in Scotland, and an Advanced Research Projects Agency-Energy (ARPA-E) Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control (ATLANTIS) Phase I project, SpiderFLOAT is designed 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. SpiderFLOAT's modular design and flexibility can significantly lower the levelized cost of energy for floating offshore wind energy technology. SpiderFLOAT began as an internal NREL Laboratory Directed Research and Development project, and it has also been funded DOE's Energy I-Corps and Technology Commercialization Fund programs.



A 1:52.5-scale hybrid model test configuration (left) for SpiderFLOAT uses fans to apply computer-simulated wind in a wave basin (right). *Graphic by Senu Sirnivas; photo from the University of Iowa*

Offshore Wind Resource Science

Points of Contact: Georgios Deskos, Georgios.Deskos@nrel.gov; Caroline Draxl, Caroline.Draxl@nrel.gov

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

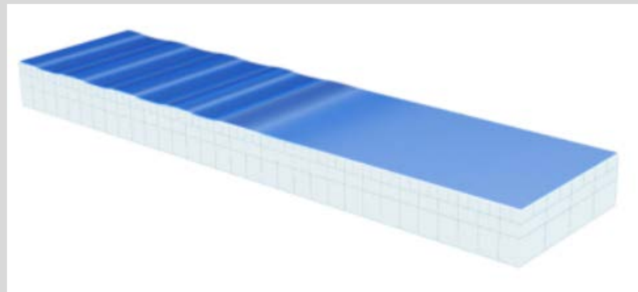
NREL led a workshop on air-sea interactions and implications for offshore wind energy with Pacific Northwest National Laboratory, Argonne National Laboratory, and Lawrence Livermore National Laboratory. The workshop convened experts from across disciplines and countries as well as industry and academia. With major developments in the United States-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.

Floating Turbine HFM Simulation

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.



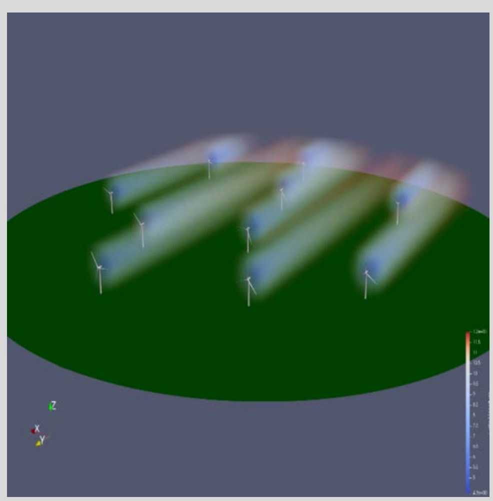
Demonstration of wave generation within the AMR-Wind numerical wave tank. Linear long waves are generated on the left side of the domain and absorbed on the right side, which prevents incorrect wave reflections. *Graphic by Georgios Deskos*

Offshore Wind Plant Controls

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

Major Redesign of Open-Source Optimization Tool Aims To Help Increase Productivity and Profits at Wind Energy Facilities

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. FLORIS continues to be updated; a future release will include such features as additional wake models, hybrid wind farm simulations, and three-dimensional visualizations.



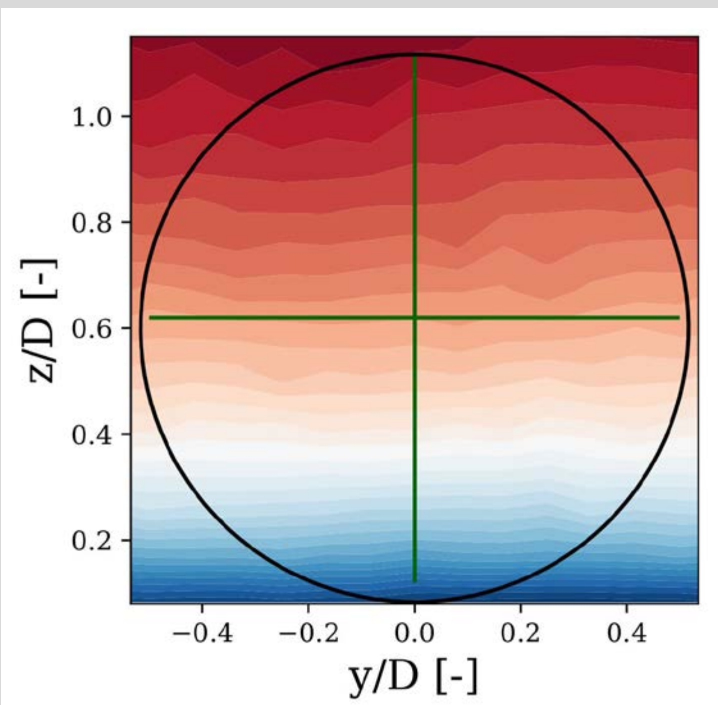
FLORIS is a software framework that provides models and tools to help stakeholders design and analyze wind farms and wind farm controllers. Version 3.0 included major improvements. A future release will include three-dimensional visualizations of FLORIS simulations, such as the one shown here. *Screenshot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

New ExaWind Capability Enables Study of Closed-Loop Wind Farm Controllers Under Realistic Atmospheric Conditions

Together, NREL teams working on wind farm controls and high-fidelity modeling tasks completed a major wind farm control simulation milestone. Based on the high-fidelity modeling team's AMR-Wind simulator, the group developed a dynamic simulation of a wind farm that captures wake interactions between turbines and incorporates embedded turbine- and farm-level controls. The simulation framework allows researchers to analyze in detail the performance of closed-loop wind farm controllers to mitigate wake effects in either realistic atmospheric conditions or useful test cases, such as step or ramp changes in wind direction. Rather than analyzing only the modeling results of a simulation after it has completed, researchers are now capable of analyzing performance while the simulation is running and adjusting interactively. The new capability is expected to be a major asset not only for research on closed-loop wind farm control, but for topics from grid services to hybrid plants to power forecasting.

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

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 wind 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.



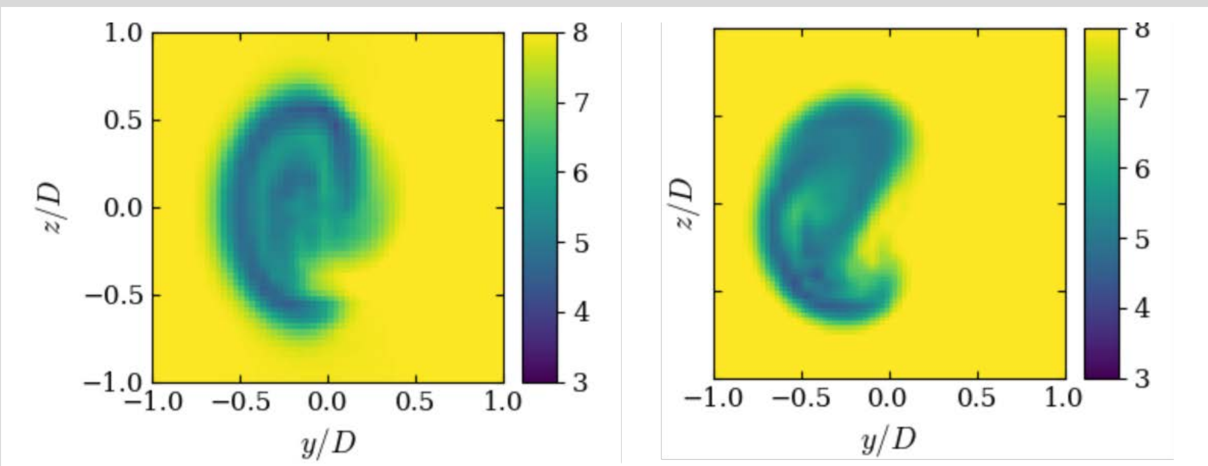
This graphic shows the velocity contours ahead of a wind turbine and the "slices" NREL researchers use to sample the inflow profile to generate wind turbine load estimates. *Graphic by NREL*

OSW System Design and Tool Validation

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

Engineering and High-Fidelity Models of Wakes and Turbine Response Validated With Experimental Field Data

Accurately predicting power production and structural loading of wind turbines within a wind farm using numerical tools is important to the design of wind energy technology. However, limited work to date has validated numerical tool predictions with realistic atmospheric conditions for wind farms with multiturbine interactions. NREL addressed this need by comparing numerical predictions from the engineering-fidelity tool FAST.Farm and the high-fidelity tool Simulator fOr Wind Farm Applications with measurement data taken from a field experiment. The experiment included five General Electric (GE) 1.5-MW turbines in a small wind farm and took place during night with intermittent turbulence. The simulations' wind inflow was generated using measurement-driven high-fidelity modeling techniques adopted from DOE's Mesoscale-to-Microscale Coupling Project. For generator power, rotor speed, blade and tower loads, and wake evolution, the numerical predictions and measurements generally agree well with each other. This provides further confidence that the numerical tools can be applied to wind farm design. A pair of companion journal papers detailing the measurement-driven inflow simulation and the numerical model validation have been submitted to *Wind Energy Science*.



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*

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

OC6 Project Validated Aerodynamic Modeling Approaches for Floating Offshore Wind Energy Design

Phase III of the international Offshore Code Comparison Collaboration, Continued with Correlation and unCertainty (OC6) project concluded an investigation into the accuracy of aerodynamic modeling approaches in predicting the loads in floating offshore wind energy systems, which undergo large motions caused by wind and waves. The team validated high-fidelity and mid-fidelity models against measurements from Polytechnic University of Milan's wind tunnel, where a robotic excitation system moved a wind turbine in both the surge and pitch directions independently. Findings from the project provide a better understanding of how to model the aerodynamics of floating offshore wind energy systems, which will enable the development of more 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*

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

New FLOWIN Prize to Accelerate Domestic Supply Chain for Floating Offshore Wind Energy

WETO launched the first-ever wind energy prize out of NREL: the FLoating Offshore Wind ReadINess (FLOWIN) Prize. This three-phase competition aims to pave the way for cost-effective domestic manufacture and deployment of commercial utility-scale floating offshore wind energy turbines in U.S. waters. About two-thirds of the nation's offshore wind energy resource potential can be found in deeper water—where building wind turbine support structures to the ocean floor is impractical and costly. Floating offshore wind energy can help unlock this potential. While no U.S. commercial-scale floating offshore wind projects have been constructed yet, mass-manufacturing capabilities and dedicated infrastructure development could make U.S. floating offshore wind energy a reality. The FLOWIN Prize will help designers, developers, engineers, fabricators, vessel operators, procurement and construction companies, logistics firms, and ports develop a supply chain and accelerate the market readiness of U.S. floating offshore wind energy designs. By doing so, FLOWIN Prize competitors will bring the United States closer to the goals of the new Floating Offshore Wind Shot™, one of DOE's Energy Earthshots™. These initiatives aim to reduce the cost of floating offshore wind energy by 70% by 2035.

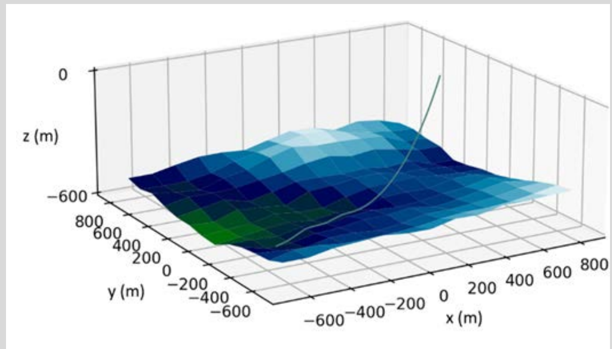
The FLOWIN Prize, announced as part of DOE's Floating Offshore Wind Shot, is designed to accelerate the market readiness of U.S. floating offshore wind energy technologies. With extensive experience managing American-Made Challenges competitions, NREL was selected to administer the prize. *Illustration by Besiki Kazaishvili, NREL*

Innovative Deepwater Mooring Systems for Floating Wind Farms (DeepFarm) (NYSERDA - Principle Power)

Point of Contact: Matt Hall, 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.



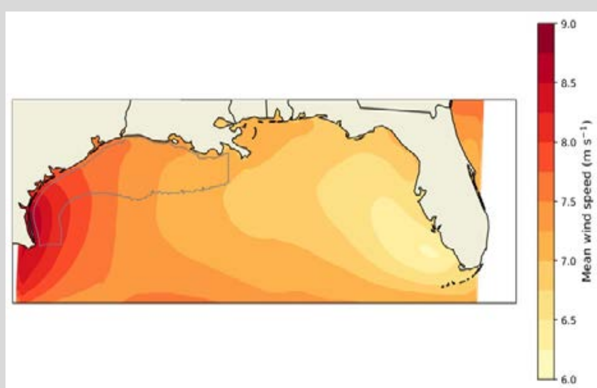
A mooring line moving over a three-dimensional seabed surface as simulated by the mooring dynamics model, MoorDyn. *Graphic by NREL*

A Validated National Offshore Wind Resource Dataset with uncertainty Quantification (NYSERDA)

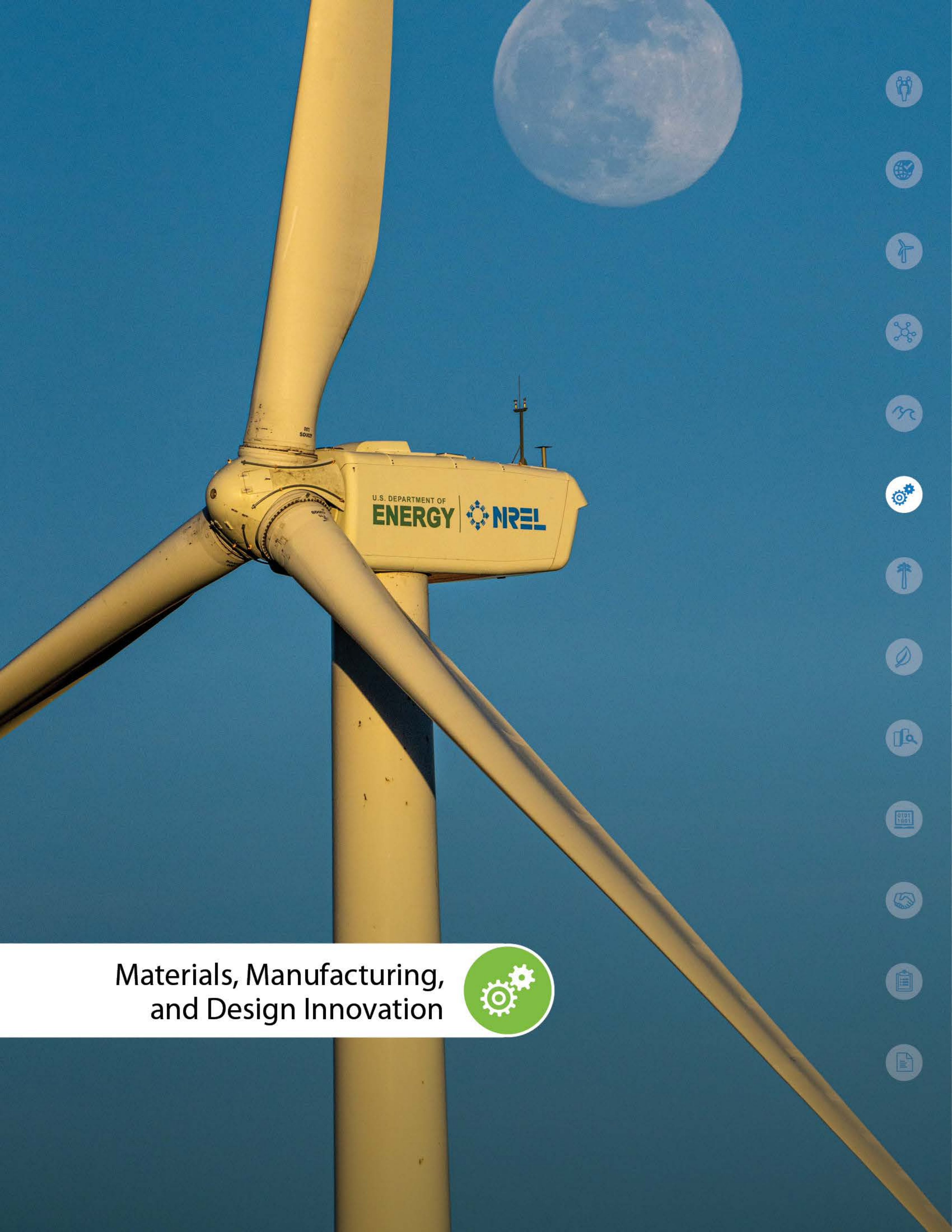
Point of Contact: Nicola Bodini, Nicola.Bodini@nrel.gov

Offshore Wind Resource Data To Foster Future Offshore Wind Energy Development

NREL In collaboration with the National Offshore Wind Research and Development Consortium (NOWRDC), NREL published new data sets covering the Gulf of Mexico and the North Atlantic that more accurately represent the U.S. offshore wind resource on a geospatial basis over a 20-year time frame. These data sets, developed using state-of-the-art numerical modeling approaches, will provide wind energy stakeholders with high-quality U.S. wind resource data that can foster the growth of offshore wind energy in the United States.



This map shows the 20-year average wind speed (in meters per second [m s^{-1}]) at 160 meters above sea level for the U.S. Gulf of Mexico. *Graphic by NREL*



Materials, Manufacturing, and Design Innovation

3D Printed Core Structures for Wind Turbine Blades

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

Multilab Team Sets Ambitious Goals To Develop Innovative Blade Core

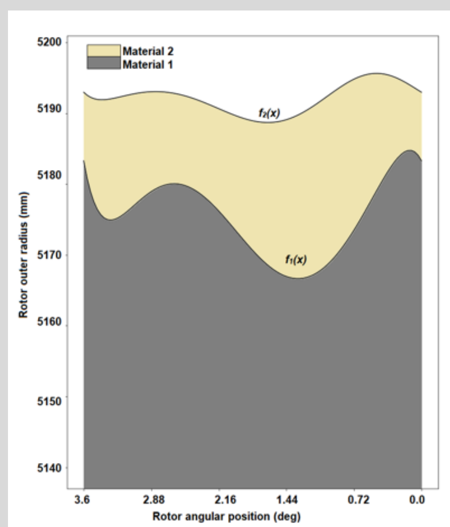
A multilaboratory industry advisory committee, convened in 2022, gathered information that highlighted the need for an innovative wind turbine blade core that is structurally sound, cost effective, and leverages the benefits of new manufacturing methods. To meet this need, the 3D Printed Core Structures for Wind Turbine Blades project research team, from NREL and Oak Ridge National Laboratory, established a risk-based project plan to research and develop innovative turbine blade core materials and manufacturing methods. The team also developed a techno-economic model to identify gaps that research can address and established processes to characterize the structural performance of the innovative blade core. The project represents a new approach to meeting DOE and administration goals of achieving broader deployment of next-generation wind energy systems by lowering the cost of energy, increasing domestic manufacturing, and improving U.S. supply chain resiliency of wind energy systems.

MADE3D

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 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.

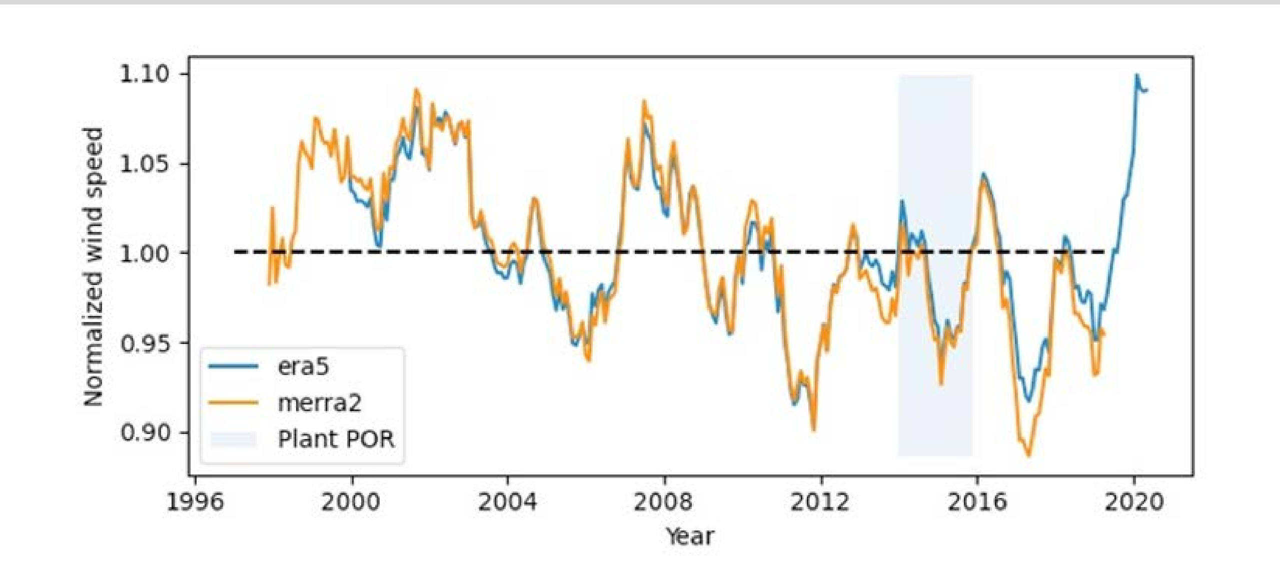


The dimensions in rotor design and new opportunities for realizing low-loss, light-weight generator design; for example, a shape-optimized rotor core section realized using two different types of electrical steel resulting in less material for manufacturing without the need to remove extraneous material.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

As part of TCF, 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

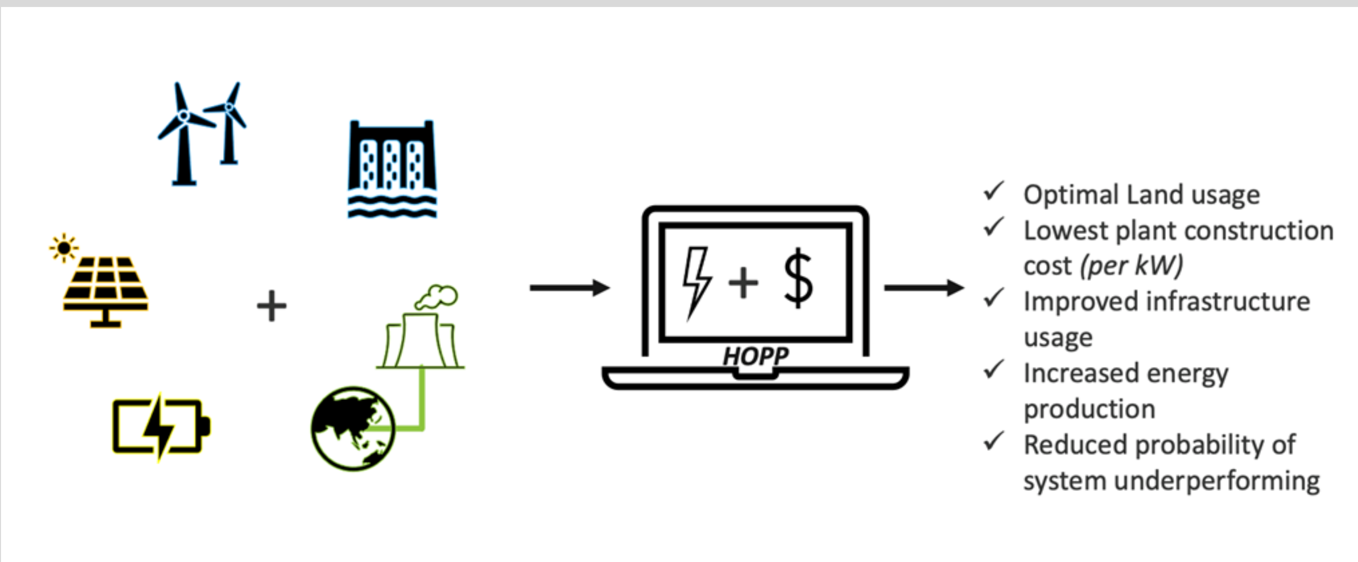


Historical wind speed data from global climate reanalysis models for an example wind power plant obtained using Intertrust's PlanetOS toolkit in NREL's OpenOA software. The historical wind data can be used to estimate the long-term energy production of a wind plant based on the measured energy production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

Point of Contact: Genevieve Starke, Genevieve.Starke@nrel.gov

NREL Collaborates With GE Global Research To Increase Commercial Readiness of Hybrid Power Plant Simulation Software

A TCF project, the Hybrid Optimization and Performance Platform (HOPP) is NREL's premier tool for designing, analyzing, and researching the next generation of renewable energy systems. NREL is collaborating with GE Global Research to improve the commercial readiness of HOPP and help elevate its status from a model used for research to a tool used by industry to design and develop optimal power plants. The enhancement of HOPP through consultation with industry will enable the design and development of bankable hybrid power plants. These plants could increase renewable energy penetration in the grid while providing reliable power at a competitive cost. The team has validated HOPP's performance models against real-world data from NREL's ARIES platform and used HOPP to develop and validate unique plant controls strategies for high-impact markets, like renewable-energy-based baseload generation, wind-energy-based hybrids that provide essential reliability services to the grid, and hybrid power-plant-generated electricity and hydrogen. Researchers are now implementing and validating these controls strategies in ARIES to validate and demonstrate HOPP's capabilities as one of the most advanced energy simulation software options in industry.



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

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

Can Gearboxes Be Lighter and More Reliable at the Same Time?

NREL, Siemens Gamesa Renewable Energy, and Sensing360 partnered to develop methods to improve continuous torque measurements and verify load-sharing characteristics in wind turbine gearboxes. As modern gearboxes increase in size and power rating, understanding their usage spectrum and these load-sharing characteristics is key to making the gearboxes as light as possible while also maintaining or even improving their reliability, both of which help to lower the cost of energy generated by wind.

Instrumented gearbox in the SGRE G97 turbine. *Photo by Jerry Hur, NREL*

Big Adaptive Rotor

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

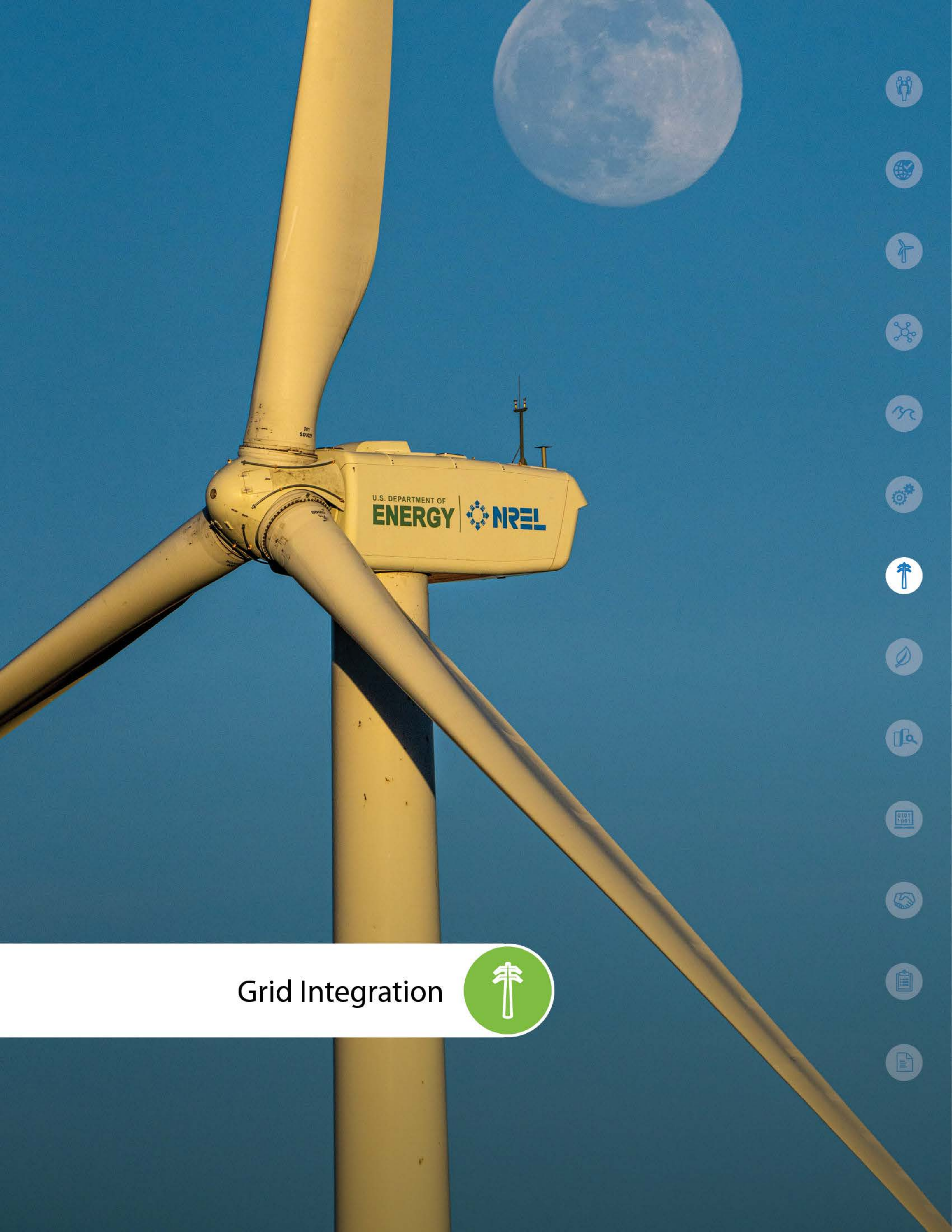
Improved Modeling Tools for Large, Flexible Rotors Ensure Accuracy, Reliability

Large rotors can increase a wind turbine's average capacity factor by 10% or more. The Big Adaptive Rotor (BAR) 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. A multilaboratory team from NREL and Sandia National Laboratories improved NREL's suite of modeling tools and completed a comprehensive code-to-code comparison. The models now yield accurate and reliable aeroelastic stability results. The models are being used within the experimental RAAW project, focusing on validation against experimental data sets obtained from a modern multimegawatt wind turbine.

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

Big Adaptive Rotor Project Forges Promising Pathway to Larger, More Flexible Rotors

The BAR project focuses on very large highly flexible rotors and, this year, concluded a detailed techno-economic analysis showing a promising pathway to increase the value of wind energy. An increasing share of wind energy users, namely wind farm owners and operators, is increasingly demanding the adoption of wind turbines characterized by lower values of specific power, which means larger rotor diameters. BAR researchers have shown that longer, slender, and more flexible blades can help overcome logistic constraints to better meet this demand by either implementing spanwise segmentation or by adopting controlled flexing during rail transport. The project has also shown that flexible rotors can fly in either a highly tilted upwind configuration or downwind. Within large wind farms, downwind rotors may return competitive advantages over upwind by redirecting the downstream wakes toward the ground, in turn increasing the farm power output. BAR has also shown that conventional numerical models struggle to accurately simulate large and flexible rotors, especially in the complex area of aeroelastic stability, which is an increasingly important analysis to design large wind turbine rotors. Researchers are busy improving the numerical models and are planning experiments to validate simulations and prove the technical viability of both upwind and downwind highly flexible rotors.

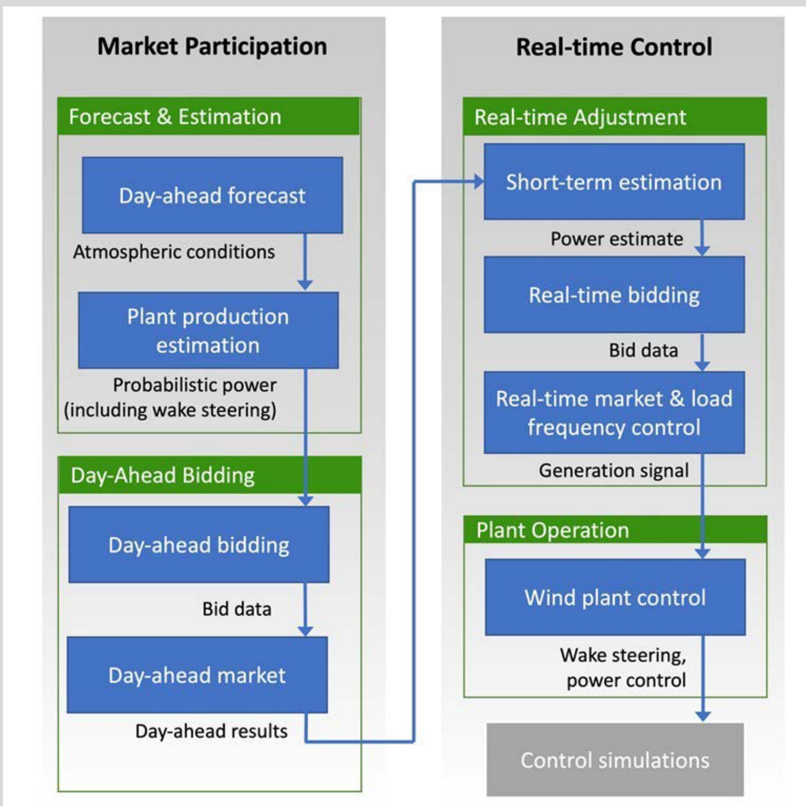


Grid Integration

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

Wind Plant Controller Increases Value of Wind Plant Grid Services

The Atmosphere to Electrons to Grid (A2e2g) project platform integrates forecasting tools that account for weather uncertainty, aerodynamic models that account for wake dynamics and wind power plant operation, and economic models that advise on bidding and operation for a wind power plant that offers ancillary services in addition to energy. The platform is a holistic Python tool with modules that can be run to advise on market participation as well as to control and operate a wind power plant in real time. The A2e2g platform can be used as a wind plant controller to maximize a wind power plant's value streams for energy and grid services, thereby providing optimized wind plant performance with a lower levelized cost of wind energy and more reliable grid operation.



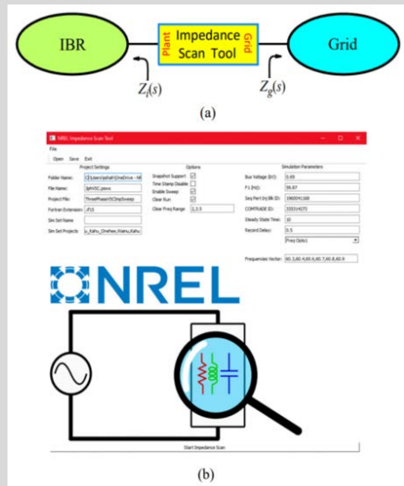
The Atmosphere to Electrons to Grid framework takes wind power plant operators from forecasting day-ahead wind power plant behavior to receiving a real-time signal from the transmission system operator and responding to that signal. The framework is modular, making it easy to exchange software components 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

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

NREL's Impedance Scan Tool Uses Simulation Models To Evaluate Wind Plant Impact on Grid Stability

NREL researchers 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. 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. The tool was also featured in a webinar organized by the Global Power System Transformation consortium.



This is an illustration and screenshot of the Grid Impedance Scan Tool (GIST), a software developed by NREL for evaluating stability impacts of inverter-based resources such as wind and solar power plants, high voltage direct current transmission, and distributed energy resources. *Graphic by NREL*

Wind Power as Virtual Synchronous Generation (WindVSG)

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

NREL and General Electric Demonstration for WETO Shows How Common Wind Turbines Can Provide Fundamental Grid Stability

A team from NREL and GE completed validation 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 was installed at NREL's 5-MW dynamometer facility. The experiment was conducted using NREL's 7-megavolt-ampere (MVA) CGI equipped with a power-hardware-in-the-loop capability (the portion of the system under example 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 validate 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 validation 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. In addition, the team demonstrated stable parallel operation of a 2.5-MW, type-3, grid-forming wind turbine with a 1.5 GE grid-following wind turbine installed at NREL's Flatirons Campus. They demonstrated stable parallel operation of 2.5-MW, grid-forming wind turbine with other grid-forming assets, such as NREL's 1-MW battery system and 2.5-MVA synchronous generator as well.

Wind Consortium Cyber Threat Model

Point of Contact: Zoe Dormuth, Zoe.Dormuth@nrel.gov

Wind Cybersecurity Workshop Addresses Cybersecurity Risks in Wind Energy Infrastructure

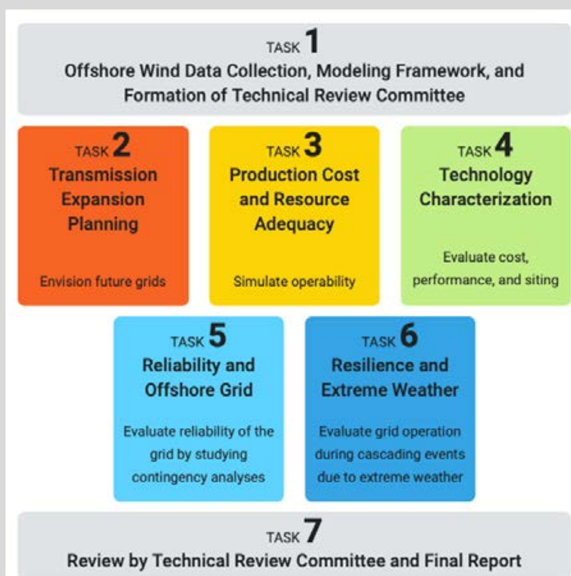
As an active member of the Wind Cybersecurity Consortium, which is a platform to improve wind energy threat intelligence and improve cybersecurity in the United States, NREL planned and hosted, with support from WETO, an in-person Wind Cybersecurity Workshop in Washington, D.C., at the Edison Electric Institute. This workshop brought together members from the Wind Cybersecurity Consortium, partner national laboratories, DOE, and individuals from the wind energy industry. Attendees collaborated on topics related to the cybersecurity of wind infrastructure—including wind threat intelligence, supply chain security, vulnerability management, and regulatory issues, certification, and standards—and on previous work completed by NREL in the past 2 fiscal years. The workshop provided an opportunity for stakeholders to identify, understand, and plan future projects to address cybersecurity risks in wind energy infrastructure.

Atlantic Offshore Wind Transmission Study

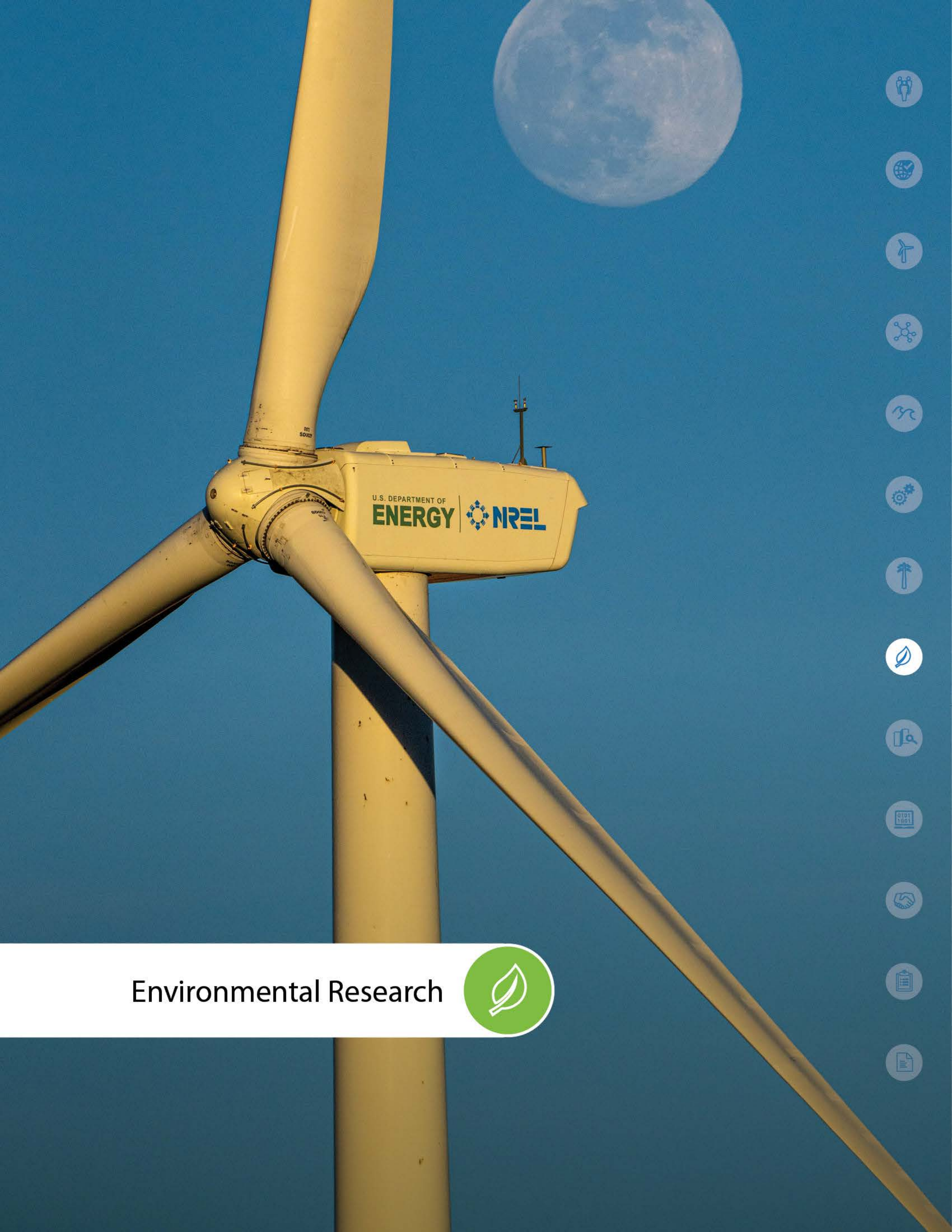
Point of Contact: Melinda Marquis, Melinda.Marquis@nrel.gov

NREL Evaluates Coordinated Transmission Solutions To Enable Offshore Wind Energy Deployment Along U.S. Atlantic Coast

The Atlantic Offshore Wind Transmission Study launched 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 address gaps in previous analyses. Researchers are comparing different transmission technologies and topologies, quantifying costs, assessing reliability and resilience, and evaluating key environmental and ocean co-use issues. A technical review committee of more than 100 members is focusing on four areas: generation and transmission planning; technology; environmental impacts and siting; and benefit quantification and cost allocation. The study considers transmission topologies—including radial lines, intraregional coordination, interregional coordination, and a backbone—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 / EcoWind

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

New Data-Driven Behavioral Model Enables Improved Wind–Wildlife Risk Assessment

NREL's Eagle Risk Modeling team finished developing a new data-driven behavioral model. The model is calibrated against telemetry data collected from golden eagles that have been tagged with global positioning system units. These movement data implicitly capture different eagle behavioral modes, including any changes to behavior that may arise from flying near wind turbines. The new model can be applied to predict the regions of a wind power plant that will have the highest eagle presence and therefore risk, which can inform preconstruction studies, siting, and postconstruction operations for wind energy projects.

Wind Operational Issue Mitigation / EcoWind

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

New Wind Energy Monitoring and Mitigation Technologies Tool

Under IEA Wind Task 34, NREL partnered with PNNL to develop the Wind Energy Monitoring and Mitigation Technologies Tool. The initial release of the tool, available via the Tethys database, highlights the research status of 60 technologies for both land-based and offshore wind energy and includes the most recent publicly available literature for each technology. Additional technologies will be added biannually.

WREN

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

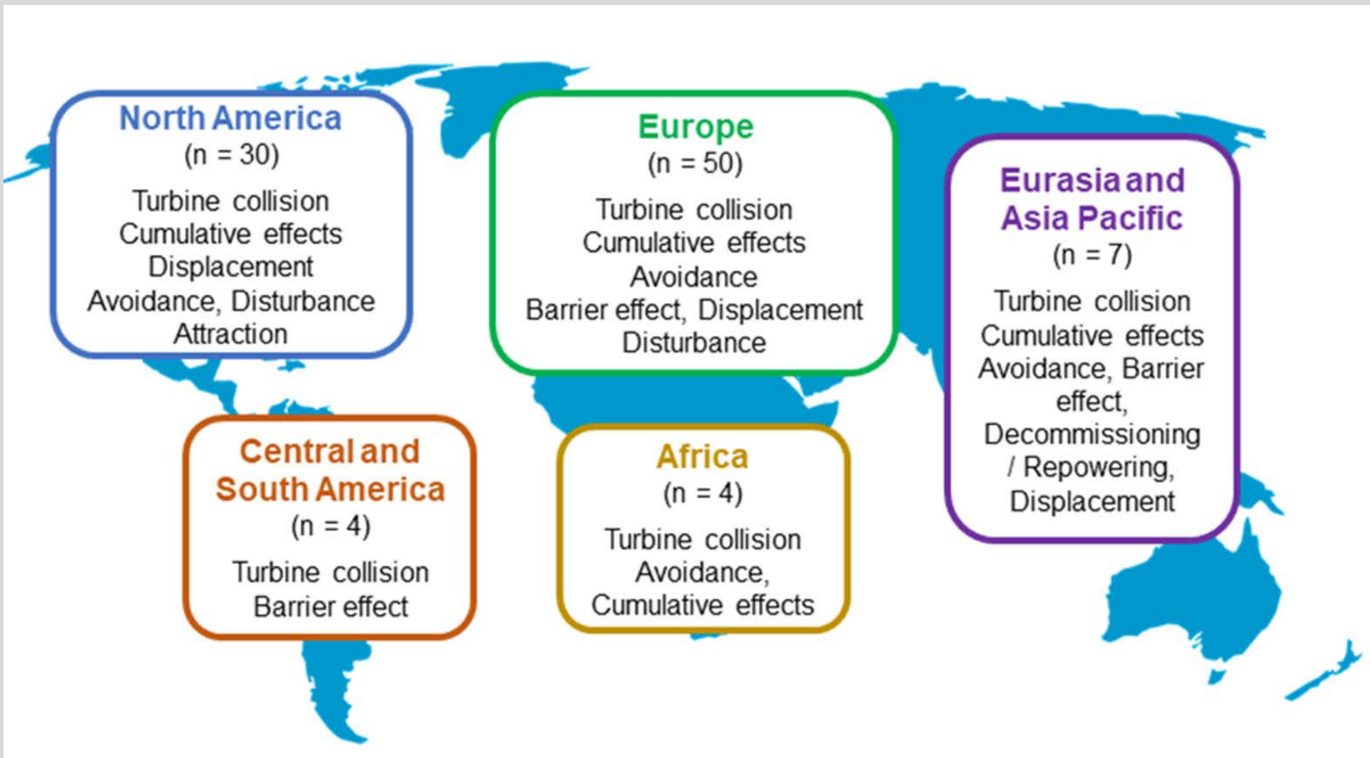
Research Awarded Funds To Study Bat Behavior at Wind Turbines

NREL's Enabling Coexistence Options for Wind Energy and Wildlife program selected three research teams through their first competitive request for proposals to receive funding for research on bat behavior around wind turbines. The awardees will receive a total of $1.1 million from WETO to track bat movements at operating wind energy facilities over the next 2 years. Findings from these studies will help the wind energy and wildlife community better understand and reduce bat interactions with wind turbines.

The three awardees will use NREL funding to observe bat behavior around wind turbines using methods that include thermal imaging, which can track the body heat. *Photo by John Yarbrough, NREL*

International Assessment of Environmental Priorities for Wind Energy Development Conducted

IEA Task 34, Working Together to Resolve Environmental Effects of Wind Energy (WREN), has served as the leading international forum for supporting the deployment of wind energy technology around the globe through a better understanding of environmental issues, particularly those related to wildlife, efficient monitoring programs, and effective mitigation strategies. As part of this task, NREL coauthored a publication in the journal *Global Sustainability*, assessing international priorities related to the existing and emerging environmental impacts of wind energy development. The assessment includes feedback from 294 responders from 28 countries. For land-based wind energy, the highest priorities included turbine collision for birds and bats and cumulative effects on species and ecosystems. For offshore wind energy, the highest priorities focused on cumulative effects on species and ecosystems, turbine collision risk for birds and bats, and underwater noise. Emerging issues were related to the implications of future turbine technologies (e.g., larger turbines and floating offshore platforms) and potential impacts on species and habitats in frontier regions. Resolving these priority issues will require collaborative engagement and research among the wind energy and wildlife communities.



Environmental priorities and number of responses (n), by global region for land-based wind energy development. *Graphic by Rebecca Green, NREL*

STEM and Siting Research and Development

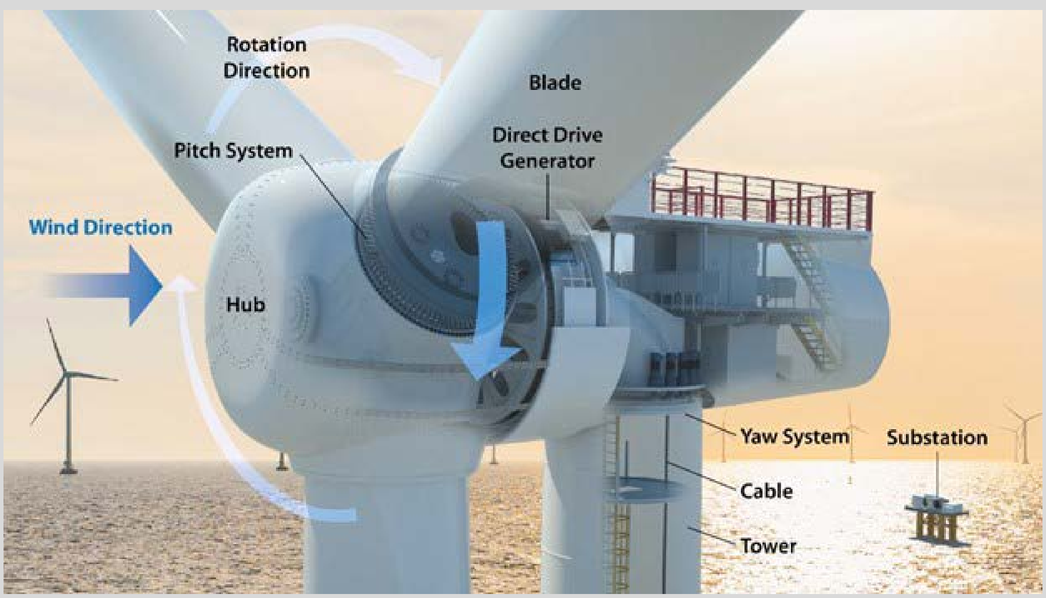
Point of Contact: Elizabeth Gill, Elizabeth.Gill@nrel.gov

NREL Works To Advance Wind Energy Equity Through Engagement Series

As wind energy development grows, community considerations and impacts are of growing importance to ensure deployment are both equitable and meet community values. Through the Wind Energy Equity Engagement Series project, NREL is gathering information from stakeholders and communities that host wind energy to define and study the equity implications of wind energy. The NREL team designed and deployed a questionnaire to stakeholders who have participated through DOE's WINDExchange initiative to gather baseline data and understand their perspectives on energy equity and fairness in wind energy development. The team then interviewed 13 subject-matter experts from academia, government, and nonprofit organizations to complement the questionnaire results and will host a workshop in the fall of 2023 to bring together diverse stakeholders to discuss wind energy equity. Given the growing need for community engagement in wind energy development, the project team also worked with an equity consultant to determine best practices for equitably engaging with wind energy communities. The outcomes of the project will be compiled into a publicly available resource and used to inform engagement and research moving forward.

WINDExchange Webinar Series Grows Awareness of Offshore Wind Energy Technology

The NREL Stakeholder Engagement and Outreach team conducted the two final webinars in the ongoing Offshore Wind Technology Basics Webinar Series. The first webinar, Offshore Wind Technology Above the Water, featured NREL offshore wind energy expert Walt Musial. The second webinar, Offshore Wind Technology Below the Water, featured geotechnical expert Sanjay Arwade (University of Massachusetts Amherst) and NREL's offshore wind energy expert, Amy Robertson. The webinar series is increasing awareness of offshore wind energy technology basics as the industry scales in the United States. These webinars were recorded and are accessible publicly, an important aspect as the offshore wind energy industry continues to grow and there is limited information on the technology generally available from independent, trusted sources.



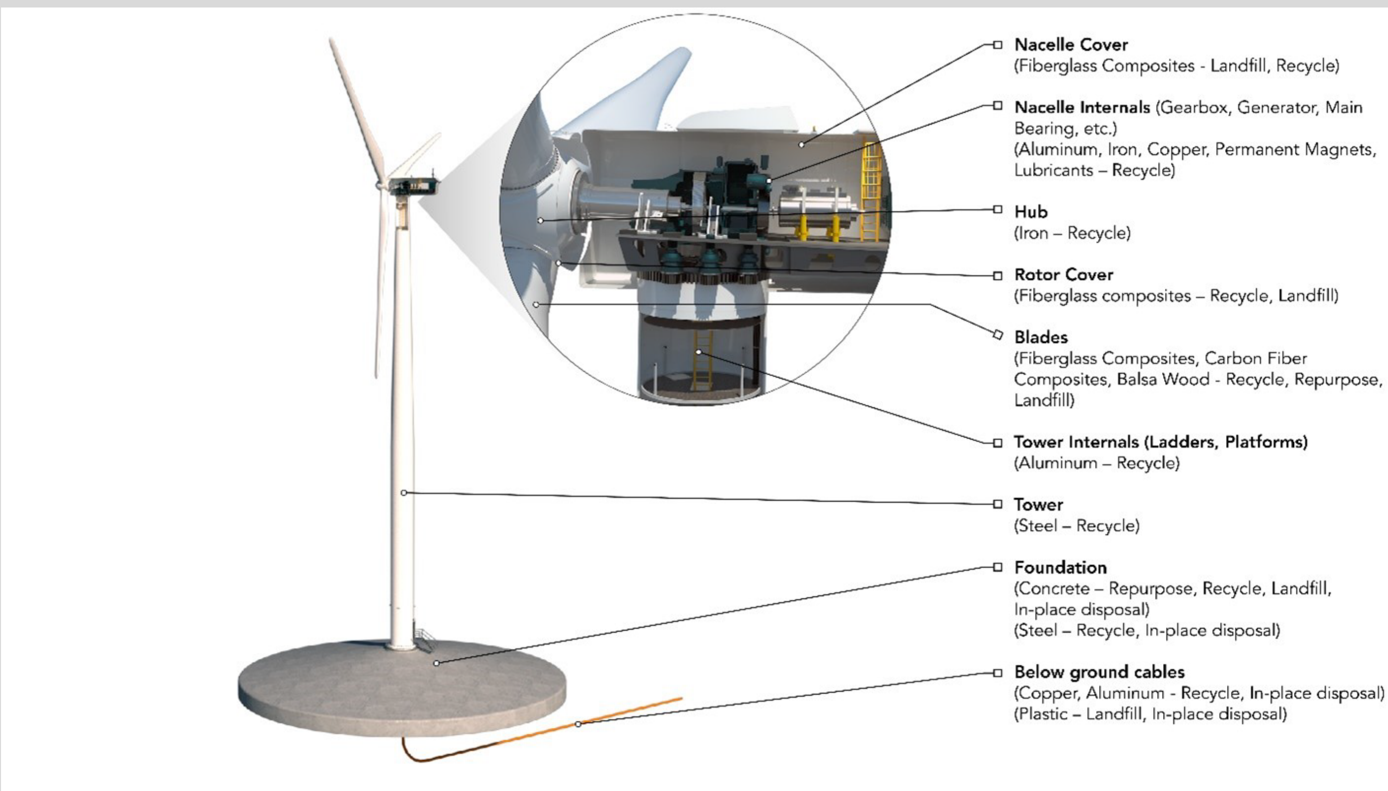
This graphic shows a cut-through of an offshore wind turbine nacelle and was used in the WindExchange Offshore Wind Technology Above the Water webinar. *Graphic by Joshua Bauer, NREL*

WINDExchange Stakeholder Engagement and Outreach - End of Service Guide

Points of Contact: Chloe Constant, Chloe.Constant@nrel.gov; Frank Oteri, Frank.Oteri@nrel.gov

New Informational Guidelines Address End of Service for Wind Energy Facilities

Although wind energy market growth continues rapidly, some project owners are already making end of service decisions by either decommissioning or repowering wind energy projects. NREL's wind energy Stakeholder Engagement and Outreach team completed content development of a guideline that defines end-of-service activities for land-based wind energy projects. The *Wind Energy End of Service Guide* includes information on full and partial repowering, decommissioning, and component processing, typically through recycling, repurposing, landfill or in-place disposal. Many of the aging wind energy projects are expected to make end-of-service decisions in the near future while communities are increasingly concerned with understanding how wind power plants that are now being installed will be decommissioned when that time comes. With that in mind, the *Wind Energy End of Service Guide* resource, which will be posted publicly on WETO's WINDExchange platform, will be an important tool that will help state and local decision makers and planners better understand what happens to turbine components and project infrastructure when they reach their end of service.



This diagram identifies different wind turbine components and infrastructure, what materials they are made from, and how they are processed when a wind energy project reaches the end of its service. *Graphic by Josh Bauer, NREL*

Collegiate Wind Competition (Competition FY22)

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

Collegiate Wind Competition 2023 Application Process Creates Opportunities for 30 Teams

In 2022, DOE's Collegiate Wind Competition transitioned to an application-based process, enabling 30 teams from 34 schools to compete in Phase 1 of the 2023 competition. Schools were allowed to partner with international institutions as well as community colleges, which adds breadth to participants' collective experience as well. By January 2023, 12 schools that are selected from the initial 30 based on work to date will be invited to compete in the full event at ACP's CLEANPOWER 2023 Conference and Exhibition in New Orleans, Louisiana, in May 2023. Schools not selected for the event will be invited to continue their learning as learn-along (noncompeting) teams.

This photo shows the 2022 Collegiate Wind Competition University of Colorado Boulder Wind team. Back row: (left to right): Graham Blanco, Alec Kostovny, Aaron Schwan, Erik Feiereisen, Simon Grzebien. Front row: Anika Levy, Charles Candon, Claire Isenhart, Luke Walker. *Photo courtesy of the University of Colorado Boulder Wind Team, University of Colorado Boulder*

Wind Workforce Analysis and Roadmap

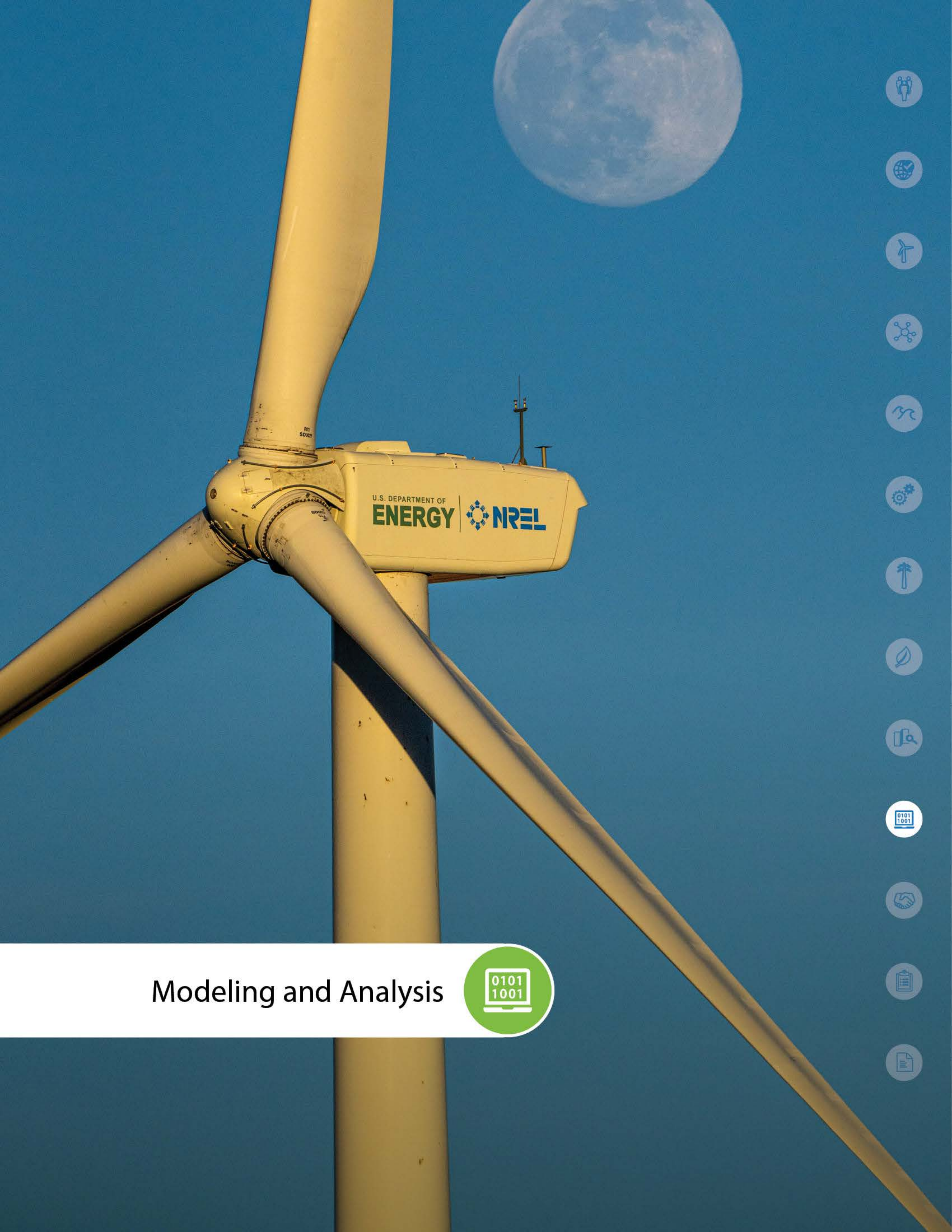
Point of Contact: Jeremy Stefek, Jeremy.Stefek@nrel.gov

Assessment for Workforce Development To Provide Estimates for Supply, Demand for Offshore Wind

The U.S. offshore wind energy industry is expected to grow exponentially over the next decade. Over the last year, NREL researchers have been synthesizing analysis and stakeholder feedback to develop an assessment of workforce development in the offshore wind energy industry. This report provides an estimate of the current and future workforce needs of the industry (demand) and identify existing relevant occupations and requirements, emerging educational institutions, training programs, and initiatives that can contribute to meeting workforce needs (supply). The report then recommends actions to bridge workforce gaps and support key stakeholders—industry organizations, state and local governments, educational institutions, and unions—in their efforts to attract, educate, train, and retain a domestic workforce to support this burgeoning industry. This cornerstone report, the first of its kind looking at offshore wind energy development across the nation, has been called for and supported by the offshore wind energy industry and will provide needed insight as the industry grows.

A framework for the offshore wind workforce roadmap. An assessment is being conducted to understand the offshore wind workforce demand and supply, and gaps and opportunities to align and connect initiatives and stakeholders. *Graphic by NREL*

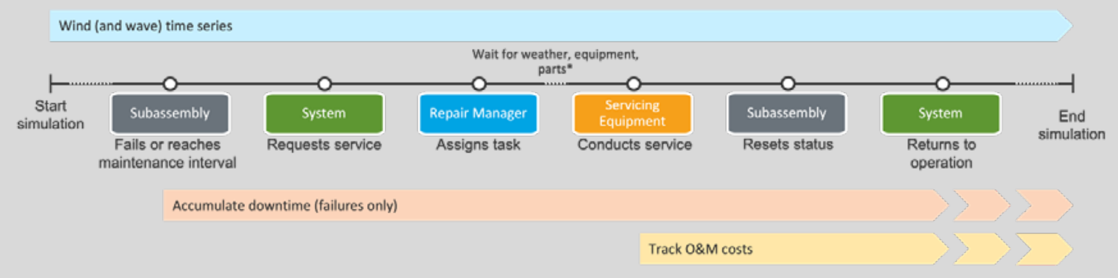
Modeling and Analysis



WOMBAT—Wind Plant Technology Characterization

Point of Contact: Rob Hammond, Rob.Hammond@nrel.gov

NREL Completes State-Of-The-Art Capability Advancement Through Its Windfarm Operations and Maintenance Cost-Benefit Analysis Tool



A conceptual overview of a single event within the simulation architecture of WOMBAT. *Illustration courtesy of Rob Hammond, NREL*

NREL released an open-source, process-based operations and maintenance model for land-based and offshore wind energy and published a technical report that provides underlying documentation for the model. The Windfarm Operations and Maintenance cost-Benefit Analysis Tool provides a flexible platform to evaluate the impacts of different technologies or process innovations on downtime, cost, and reliability metrics. The model was used to conduct a preliminary assessment of the tradeoffs between tow-to-port and in situ repair for floating offshore wind energy systems.

Wind Analysis for Priority Needs

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

Securing the U.S. Supply Chain for the Wind Energy Industry

In collaboration with WETO, researchers at NREL conducted research and analyses that characterize supply chain strengths, weaknesses, opportunities, and threats within the wind energy industry, including land-based and offshore wind energy. As part of the research, the team also conducted interviews with industry stakeholders and subject matter experts. The resulting report documents the team's findings and explores critical vulnerabilities today and in the future as technology evolves and as the industry scales to serve the Biden administration's goal of net-zero carbon emissions by 2050.

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

Wind Analysis For Priority Needs - Blade Recycling Analysis

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

Analysis Considers Strategies To Increase Wind Turbine Blade Recycling

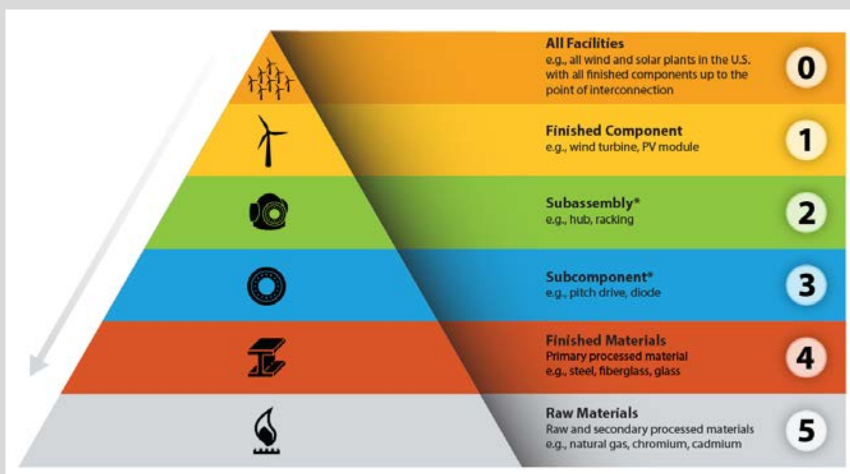
NREL researchers used the [Circular Economy Wind Agent-based Model]() to understand the behavioral aspects of wind power industry stakeholders' recycling decisions. The research indicated that among the factors impacting wind turbine blade recycling are high transportation costs, lack of regulations that incentivize recycling, and the number of recycling facilities for wind turbine blades. The research is summarized in an *iScience* article, "[Regional Representation of Wind Stakeholders' End-of-Life Behaviors and Their Impact on Wind Blade Circularity]()."

Wind Analysis For Priority Needs - Blade Recycling Analysis

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

NREL Builds Renewable Energy Materials Properties Database: A Foundation for Work in Sustainability, Civil Engineering, and the Supply Chain

Researchers created the Renewable Energy Materials Properties Database (REMPD), which contains: (1) information on the amount of each material that goes into wind and solar power plants; (2) descriptions of the relevant material properties; and (3) the primary countries of origin for each material. The database identifies vulnerable materials, which are defined as critical minerals (per the United States Geological Survey) or any nonfuel mineral, element, substance, or material that EERE determines has a high risk of supply chain disruption and serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy. The database can be used to assess the types and quantities of materials required for the wind and solar power plants associated with future deployment scenarios. It allows public and private-sector organizations to identify and mitigate risks associated with obtaining sufficient quantities of materials to deploy a given level of wind and solar power capacity. Products include a web platform with visualizations; an open-source version of the database; an accompanying summary report; a technical report on hubs and bedplates, which are components of wind turbines made from heavy cast iron; and full technical report that analyzes material quantities and availability for two future U.S. wind energy scenarios. This work provides a foundation for continued research and knowledge development around wind energy materials requirements and sustainability.



Taxonomy used to organize data in the REMPD. Asterisks note that not all components in the database have data. *Illustration by Nicole Leon, NREL*

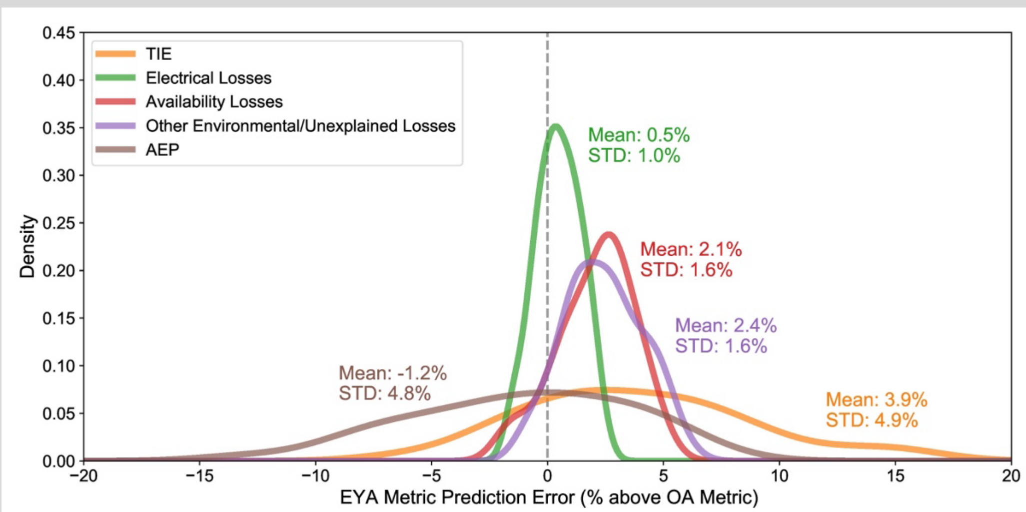
Point of Contact: M. Jason Fields, Michael.Fields@nrel.gov

NREL Researchers Identify Gaps in Consultants' Estimates of Energy Yield Assessment at Wind Power Plants

The wind energy industry has lacked an independent analysis of bias investigated across multiple consultants to identify the greatest sources of uncertainty and variance in the energy yield assessment process and the best opportunities for uncertainty reduction. NREL researchers addressed this gap in the Wind Plant Performance Prediction Benchmark Gap analysis. The research team benchmarked consultant methodologies against each other and against operational data at a scale not seen before in wind industry collaborations. The team considered data from 10 wind plants in North America and evaluated discrepancies among eight consultants in the steps taken from estimates of gross energy to net energy. In general, consultants tend to overestimate the gross energy produced by wind turbines, then compensate further by overestimating downstream losses. These overestimations can lead to what is known as the P50 bias—a comparison made between the 50% probability of exceedance (P50) value of the energy yield assessment and the long-term corrected operational annual energy production. Researchers found significant variability among the individual wind power plants. Within NREL's data sample, the consultant estimates of all loss categories, except environmental losses, tend to reduce the project-to-project variability of the P50 bias. Differences in consultants' estimates of project performance can lead to differences of up to $10 per MWh in the levelized cost of energy for a wind power plant. Results of this research were published in the *Journal of Wind Energy*.

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 was published in the open-access journal *Wind Energy*.

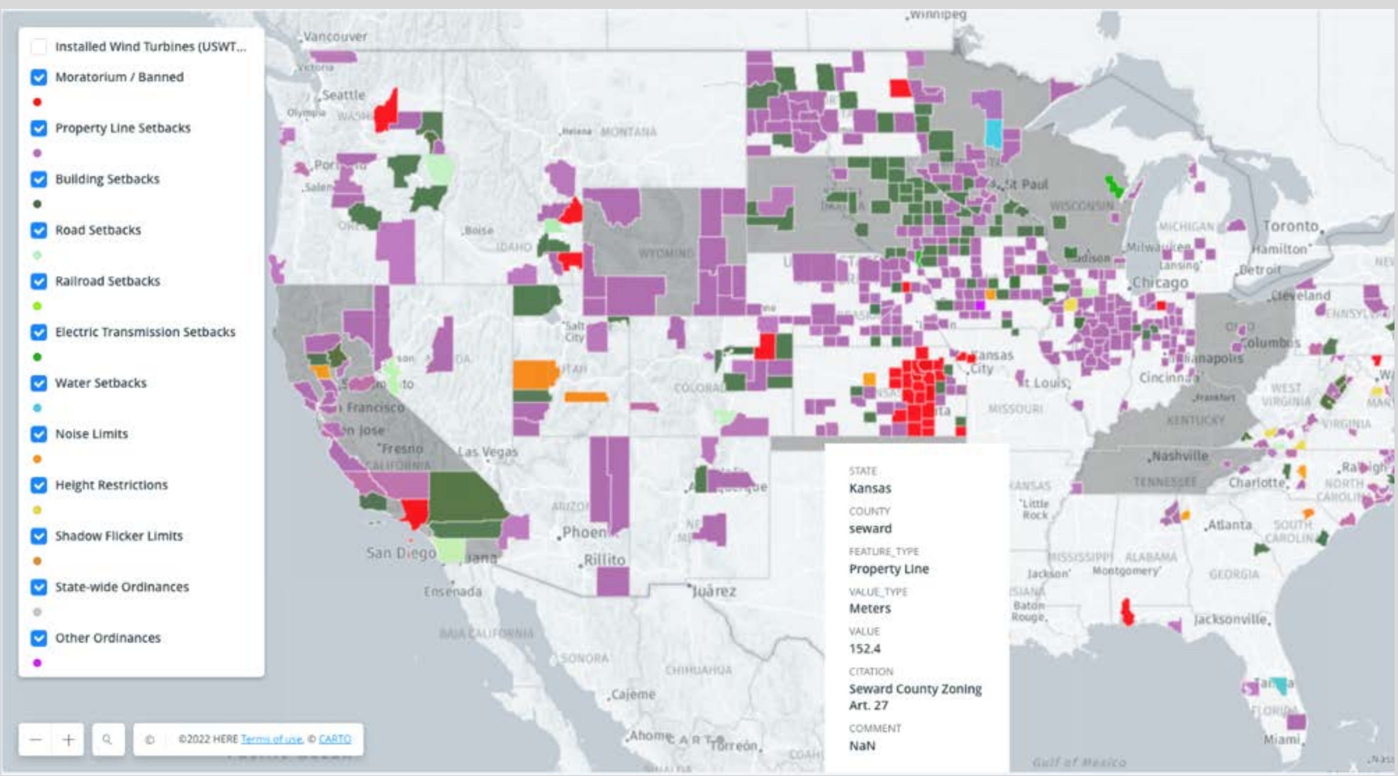


The distribution of prediction errors (in density) for each step of the energy yield assessment (EYA) process based on 68 submissions from wind power plants in Phase 1 of the Wind Plant Performance Prediction benchmark project (obtained using Gaussian kernels). Percentages indicate the mean and standard 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*

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

Database of Local Ordinances Informs Planning for Clean Energy and Decarbonization Goals

NREL released a comprehensive database of more than 2,000 ordinances at the state, county, township, and city levels for siting wind energy projects. The new machine-readable data set compiles these regulations in a format that is easy to access and analyze, with the goal of informing planning for clean energy and decarbonization goals. These data can also inform technology development and narrower analysis needs. This material includes setbacks—or the required boundaries around infrastructure where wind turbines cannot be installed—for property lines, buildings, roads, railroads, electric transmission lines, and bodies of water. Because setbacks are influenced by wind turbine tip heights—the taller the turbine, the larger the setback—the data set also includes height and rotor size restrictions. Other ordinances, like noise limitations, shadow flicker limits, and utility-scale wind bans or moratoriums, are also included. This work is part of ongoing research at NREL to explore the dynamics of land use and clean energy deployment, and provides critical insight into the growth, types, and scale of local regulations—pertinent information for developers, policymakers, decision makers, land managers, and energy modelers. Thus far the database has been well received by key stakeholder groups in clean energy. ACP and the American Council on Renewable Energy took particular interest. Researchers, including those at academic institutions, have also expressed enthusiasm and appreciation for the data set.



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*

Data Collection and Annual Reporting

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

Offshore Wind Market Report Showcases Latest in Global and Domestic Offshore Wind

In partnership with WETO, NREL developed the Offshore Wind Market Report: 2022 Edition, showcasing the progression of the offshore wind energy industry, how DOE is addressing challenges unique to offshore wind energy, and how to benefit the industry and its key stakeholders by providing detailed up to date information. Key highlights include information about the levelized cost of energy for U.S. fixed-bottom projects and its decline to an estimated $84 per megawatt-hour (MWh), showing a cost reduction of more than 50% since 2014. In addition, the U.S. offshore wind energy industry continues to expand with a pipeline of 40,083 MW in various stages of development, representing a 13.5% growth between 2021 and 2022. Ultimately, this market report serves as the primary source of information that the offshore wind energy industry and government organizations around the world use to inform their decisions, especially about the U.S. market.

Distributed Wind Analysis

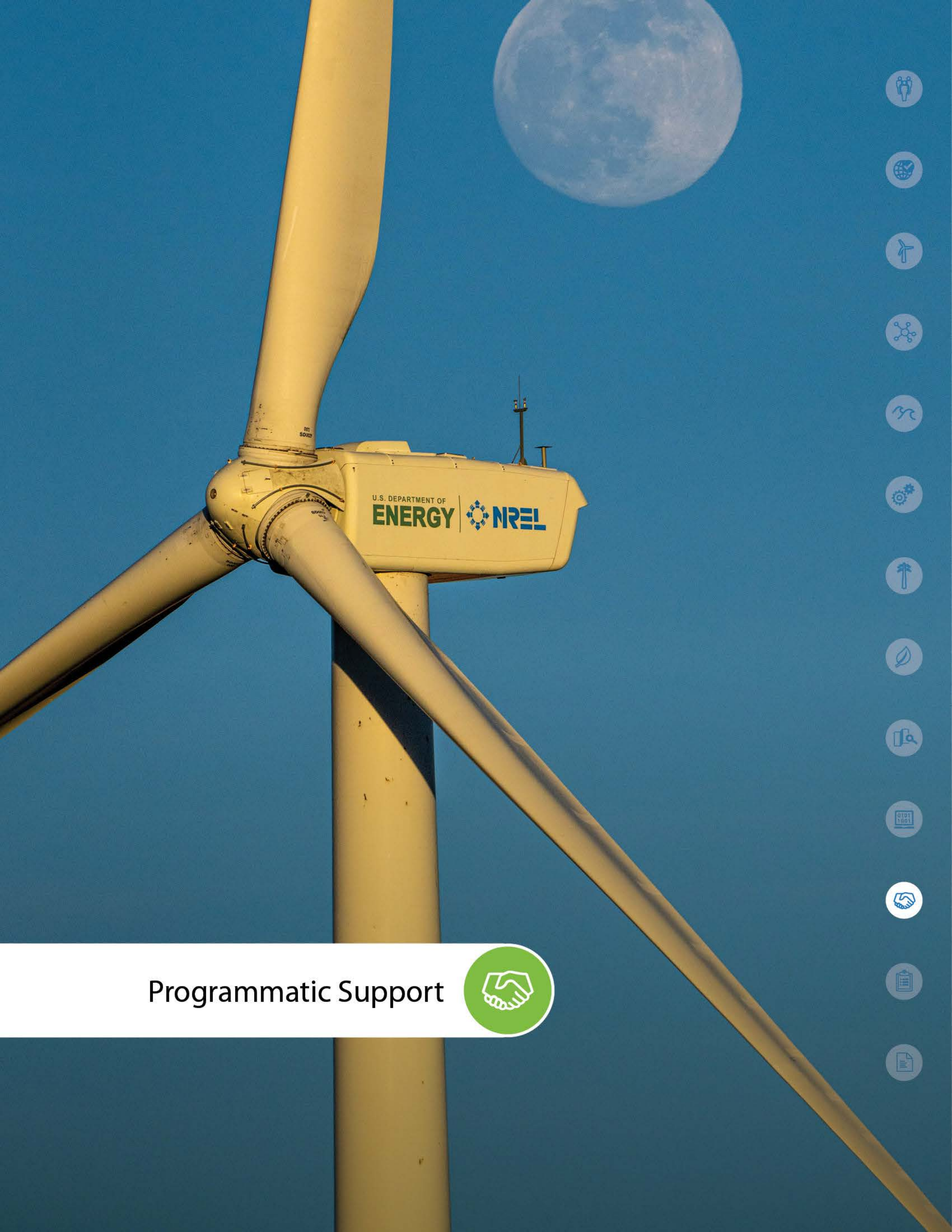
Point of Contact: Kevin McCabe, Kevin.McCabe@nrel.gov

The Future of Distributed Wind in the United States: Considerations for Unlocking Terawatt-Level Potential

Nearly 1,400 GW of distributed wind energy capacity could be accessed today and bring clean power to millions of American households, according to NREL's *Distributed Wind Energy Futures Study*. That is enough energy to supply more than half of current U.S. annual electricity consumption.

Distributed wind could play a meaningful role in the U.S. energy future. *Photo from David Nevala Photography for CROPP Cooperative*

Funded by WETO, the comprehensive analysis explores potential opportunities for U.S. distributed wind energy in 2022 and 2035. New, high-resolution data and modeling techniques from dWind, a model within the Distributed Energy Market Demand Model (dGen™) suite, identified the best locations for distributed wind of all forms—including special consideration for distributed wind energy in underserved communities. Results reveal large areas of the country that provide economic power today and in 2035. But the right technology, cost, siting, and policy conditions are key to unlocking this potential. Select results from the study are available on the dWind open-source Github repository, in addition to code and inputs for a reduced-form model.



Programmatic Support

NREL Technology Management and Support

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

Wind Research Impact Cultivated Through Sound Programmatic Support

NREL's wind energy program actively manages a diverse 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 energy deployment needed to achieve carbon-emission-free electricity by 2035 and net-zero greenhouse gas emissions across the economy by 2050, NREL wind energy 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, which includes supporting the growth of projects with a high potential of impact funded through TCF; a nearly $30 million funding opportunity that leverages funding in the applied energy programs to mature promising energy technologies with the potential for high impact across DOE's Research, Development, Demonstration, and Deployment (RDD&D) Continuum; and providing researchers an opportunity and a framework for industry engagement to guide future research and inform a culture of market awareness through the Energy I-Corps program
- Serving in a strategic leadership role of IEA Wind
- Providing support to NREL's Flatirons Campus and NREL's Advanced Research on Integrated Energy Systems (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.

NREL Researchers Lead International Wind Collaborations

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, 13 NREL researchers led these individual tasks as Operating Agents, and NREL communications staff wrote the U.S. chapter of the 2021 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 2022 participation in IEA Wind tasks. *Graphic by John Frenzl, NREL*

NREL Technology Management and Support

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

NREL Develops a DOE Action Plan To Meet 2035 Clean Electricity System Using Wind Energy

Achieving a 100% clean electricity system in the United States by 2035 will require a broad approach encompassing all sources of renewable energy and new thinking around how our electricity system is designed and operated. However, analysis from multiple sources makes one thing clear: technological advancements and continued deployment of land-based, utility-scale wind energy will support wind energy as being one of the most cost-effective forms of energy in many parts of the country. Historically, WETO has focused on the technical innovations to lower wind turbine system costs but has not conducted a systematic assessment of actions DOE would need to implement the deployment of up to 10 times the current number of wind turbine installations. As a result, NREL developed a multidimensional plan of action to accelerate the deployment of land-based wind energy in the United States, considering wind technology at distributed and utility scale on private and public lands, covering five defined development challenge areas.

Communications Support

Point of Contact: Jen Grieco, Jen.Grieco@nrel.gov

Outreach Amplifies Key Impacts of WETO-Funded Research

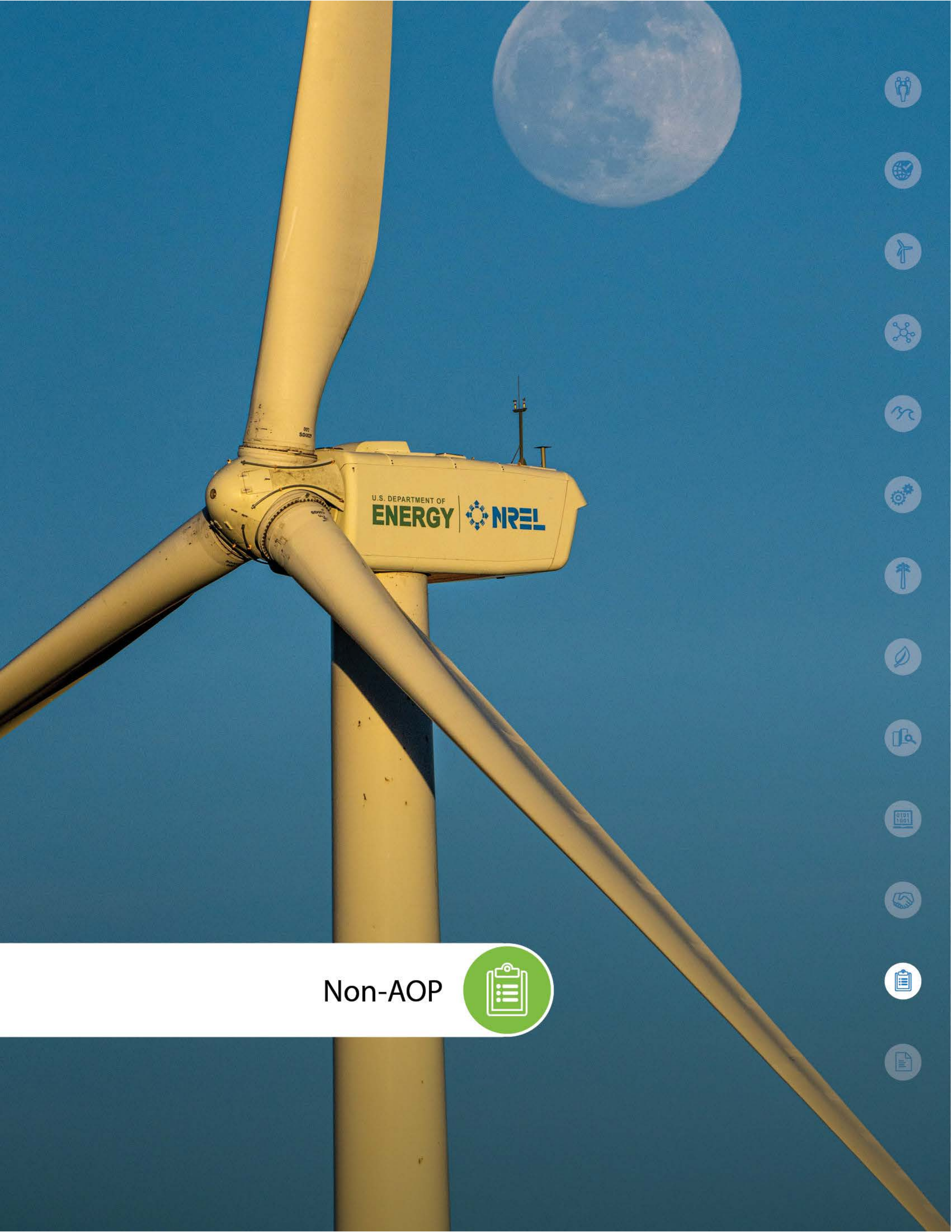
NREL Wind Program's communications team delivers comprehensive communications products across a variety of platforms—from social media and websites to online newsletters and news articles—to inform thousands of stakeholders and members of the general public about the impact of NREL's WETO-funded research. 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 to repackage the publication to improve audience engagement, increase opportunities for article amplification by releasing articles throughout the year, and reduce costs.

M&O Support

Points of Contact: Alexsandra Lemke, Alexsandra.Lemke@nrel.gov; Mike Robinson, Mike.Robinson@nrel.gov; Richard Tusing, Richard.Tusing@nrel.gov; Ian Baring-Gould, Ian.Baring-Gould@nrel.gov

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

NREL's Alexsandra Lemke, Mike Robinson, Rich Tusing, and Ian Baring-Gould 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 Land-based Wind Deployment Action Plan, Renewable Energy Materials Properties Database (REMPD), WETO Strategic Vision Report to Congress, provided timely and effective management of analytical and technical support activities, and exhibited strong leadership in targeted areas (early-stage research and development, HPC, technical and economic analysis, technology to market, external affairs, and communications) with high market impact.



Non-AOP

Wind Technology Partnership Program (TPP) Portfolio

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

Strategic Partnership Agreement Portfolio Continues To Grow and Support Nation's Offshore Wind Deployment Goals

NREL's National Wind Technology Center continues to grow its portfolio of strategic partnership agreements, executing about 40 new contracts and contract modifications in 2022—worth approximately $6 million. The main business development focus areas were offshore wind energy, ARIES, and wind power plant controls, all utilizing the unique capabilities and facilities at NREL. Several projects support efforts by the U.S. Department of the Interior's Bureau of Ocean Energy Management and the Bureau of Safety and Environmental Enforcement to reach the Biden administration's offshore wind energy deployment goals. Covered topics include lease area delineation, resource assessment, programmatic support, risk analysis, and cost modeling.

California Lease Areas

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

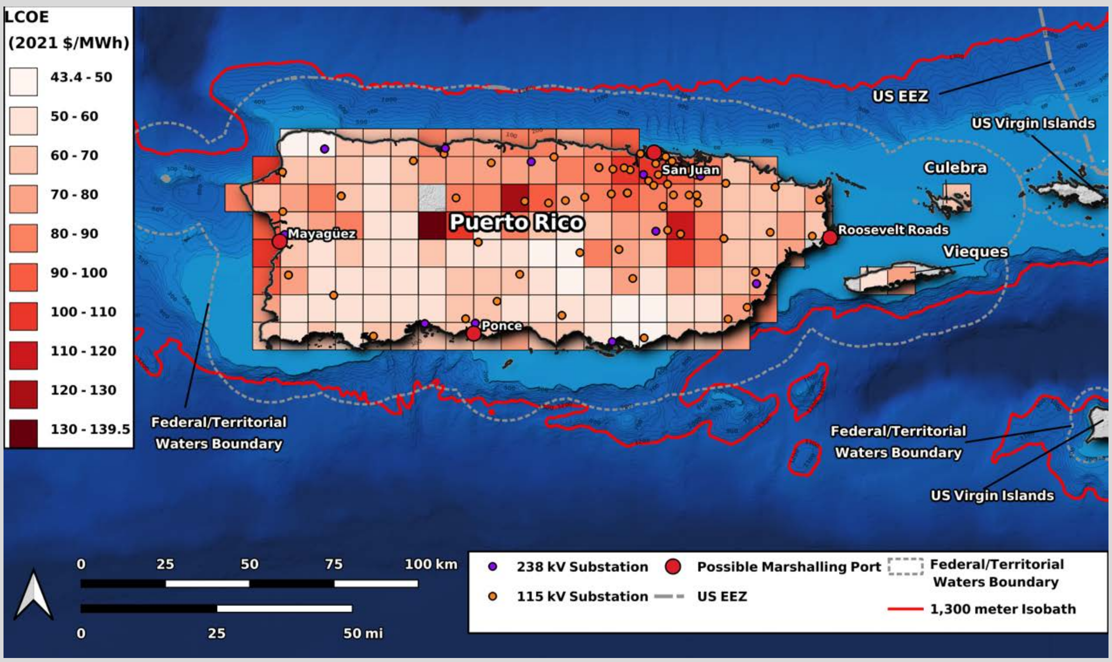
NREL Analyzes Layouts for the First Floating Offshore Wind Energy Lease Areas on the West Coast

Researchers worked with the U.S. Department of the Interior's Bureau of Ocean Energy Management to develop and compare options for new offshore wind energy lease areas in California. These lease areas are the first in the deep waters off the Pacific Coast, where developers will need to deploy floating wind turbines. NREL's analysis considered the spatial requirements of several different mooring types as well as other factors, including wind resource and access to infrastructure, to delineate lease areas of equal value. After publication, the report and related analysis informed the California Energy Commission's decision to set offshore wind energy deployment targets of 2–5 GW by 2025 and 25 GW by 2045.

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

Wind Energy Cost Assessment Supports Grid Planning in Puerto Rico

NREL analysts leveraged new wind resource data to assess the costs and feasibility of wind energy projects in Puerto Rico and better understand how wind can play a key role in meeting a target of 100% clean electricity by 2050. The spatial cost assessment included evaluating the financial impacts of insuring and operating typhoon-class wind turbine designs in hurricane-prone regions. Decision and policymakers in Puerto Rico will use this data set to inform their upcoming integrated resource plan, and NREL will build on this analysis in DOE and NREL's Puerto Rico Grid Resilience and Transition to 100% Renewable Energy Study.



Projected levelized cost of energy (LCOE) for offshore wind around Puerto Rico in 2035. Possible development exclusion areas are shown in black, representing military areas and environmental protected areas, including national marine sanctuaries. This map suggests that wind energy can play a key role in helping Puerto Rico meet its goal of 100% renewable electricity by 2050. *Screenshot by NREL*

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 NOWRDC, NREL engineers developed and analyzed a new model of wind turbine wakes and wake steering through FLORIS software (Version 3.0), improving accuracy of the model when compared to large offshore wind farms. *Photo by Dennis Schroeder, NREL*

Wind Energy Science Journal Leadership

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

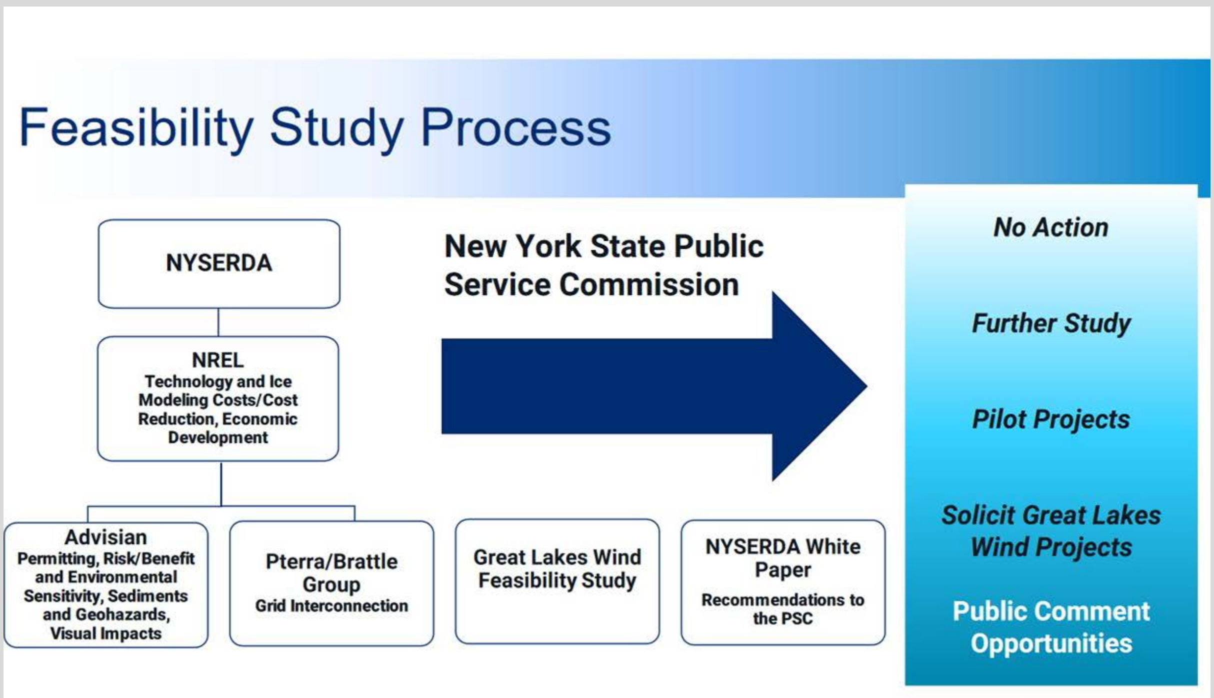
NREL Researchers Appointed Editors of Wind Energy Journals

NREL wind energy researchers Paul Veers, Paul Fleming, and Amy Robertson have been named chief and associate editors of *Wind Energy Science*, an international scientific journal focusing on studies that provide an interdisciplinary perspective on fundamental or pioneering research in wind energy. Veers previously served for 12 years as chief editor of *Wind Energy*, and Fleming has authored or coauthored 20 papers for the journal. Their appointments began September 2022. Robertson has been renewed for another term as associate editor for the *Journal of Offshore Mechanics and Arctic Engineering*, a position she's held for 4 years.

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

Great Lakes Wind Energy Feasibility Assessment for Lake Erie and Lake Ontario

NREL worked with two partners—Advisian and Brattle/Pterra—to lead the Great Lakes Wind Feasibility Study for the New York State Energy Research and Development Authority, conducting various analyses between February 2021 and May 2022. The study focused on the New York portions of Lake Erie and Lake Ontario. The team gathered data, synthesized information, performed technical analysis, and developed recommendations to help New York achieve the goals of its Clean Energy Standard. This research and analysis considered existing and emerging technologies for fixed-bottom and floating wind turbines, taking into account icing conditions unique to the Great Lakes, new technology development timelines, geospatial conditions, resource assessment, regulatory processes, permitting requirements and risks, potential conflicts, costs and economic opportunities, electrical infrastructure, and overall cost-reduction pathways. The New York State Energy Research and Development Authority facilitated public engagement throughout the study, which included public webinars and a public forum in 2021. This study is as an important step toward assessing the overall value and viability of this potential resource for helping New York achieve Climate Leadership and Community Protection Act goals.



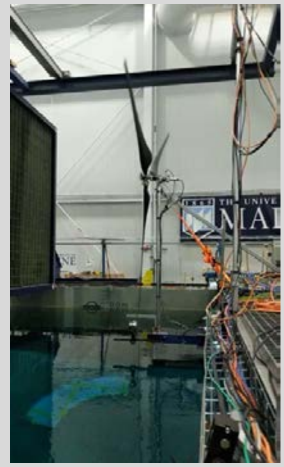
This graphic shows the feasibility study process for the Great Lakes Wind Feasibility Study, led by NREL for the New York State Energy Research and Development Authority. *Graphic courtesy of New York State Energy Research and Development Authority*

ARPA-E ATLANTIS FOCAL Project

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

ATLANTIS FOCAL Project Experimental Campaign Evaluated Impact of Tuned-Mass Dampers on Loads in Floating Offshore Wind Energy Semisubmersibles

The team behind the [Floating Offshore-wind and Controls Advanced Laboratory]() (FOCAL) experiment, run under DOE's ARPA-E ATLANTIS program, has completed a scaled experimental campaign evaluating how tuned-mass dampers placed on a floating offshore wind energy platform can help reduce system motion and loads. The semisubmersible design is a 1:70-scaled version of the IEA Wind reference VolturnUS-S floating offshore wind energy platform design, which supports a 15-MW wind turbine. Only the platform and flexible tower were tested, but an upcoming campaign will combine this floating platform design with a scaled model of the 15-MW wind turbine. The findings from this project indicate that tuned-mass dampers can effectively reduce the pitch motion of a floating platform, but only at a specific frequency. The final campaign will investigate how to use tuned-mass dampers in conjunction with floating offshore wind turbine controls to optimize system performance and loads.



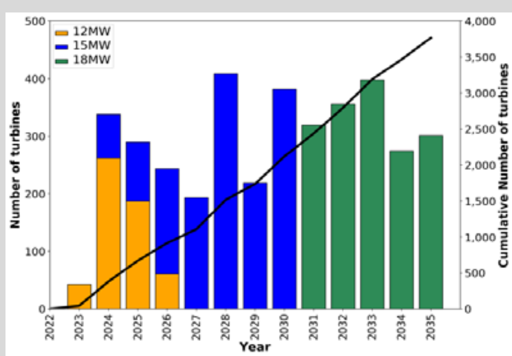
A 1:70-scale model of the IEA Wind's 15-MW wind turbine undergoes validation of aerodynamic loading while under active turbine control in a water tank. *Photo by Matt Fowler, University of Maine*

30 GW by 2030: A Supply Chain Roadmap for Offshore Wind in the United States

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

Researchers Build Supply Chain Roadmap for Offshore Wind Energy

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.



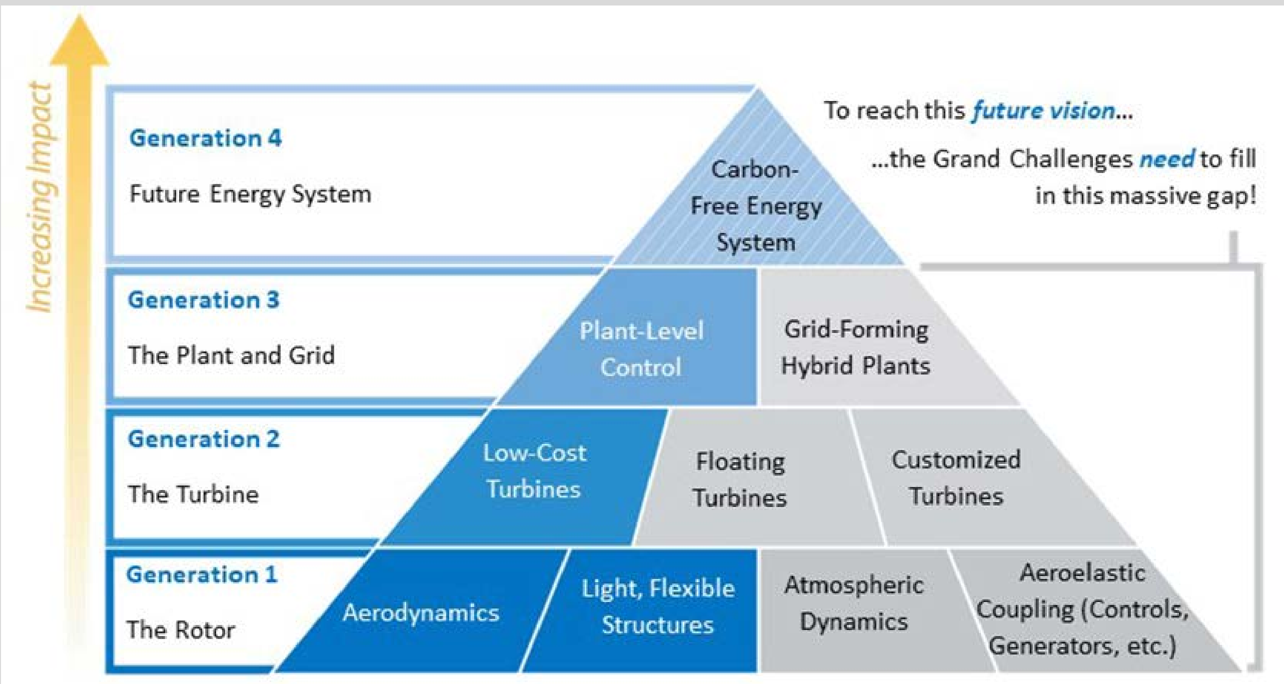
Annual deployment of offshore wind turbines required to reach a cumulative deployment of 30 GW by 2030. *Image by Matt Shields, NREL*

NREL co-hosted a workshop in July 2022 that brought together key stakeholders from the industry and state and federal government to build off the results from the March 2022 report, inform the next phase of the study, and encourage collaboration between these key groups to develop supply chain solutions. This workshop supported the Biden administration's [Federal State Offshore Wind Implementation Partnership]().

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

NREL Leads Grand Challenges of Wind Energy Science Article Series To Review Wind Energy Research Needs and Propose Actions To Help Reach Worldwide Decarbonization Goals

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* publication, which outlined 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. 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.



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*

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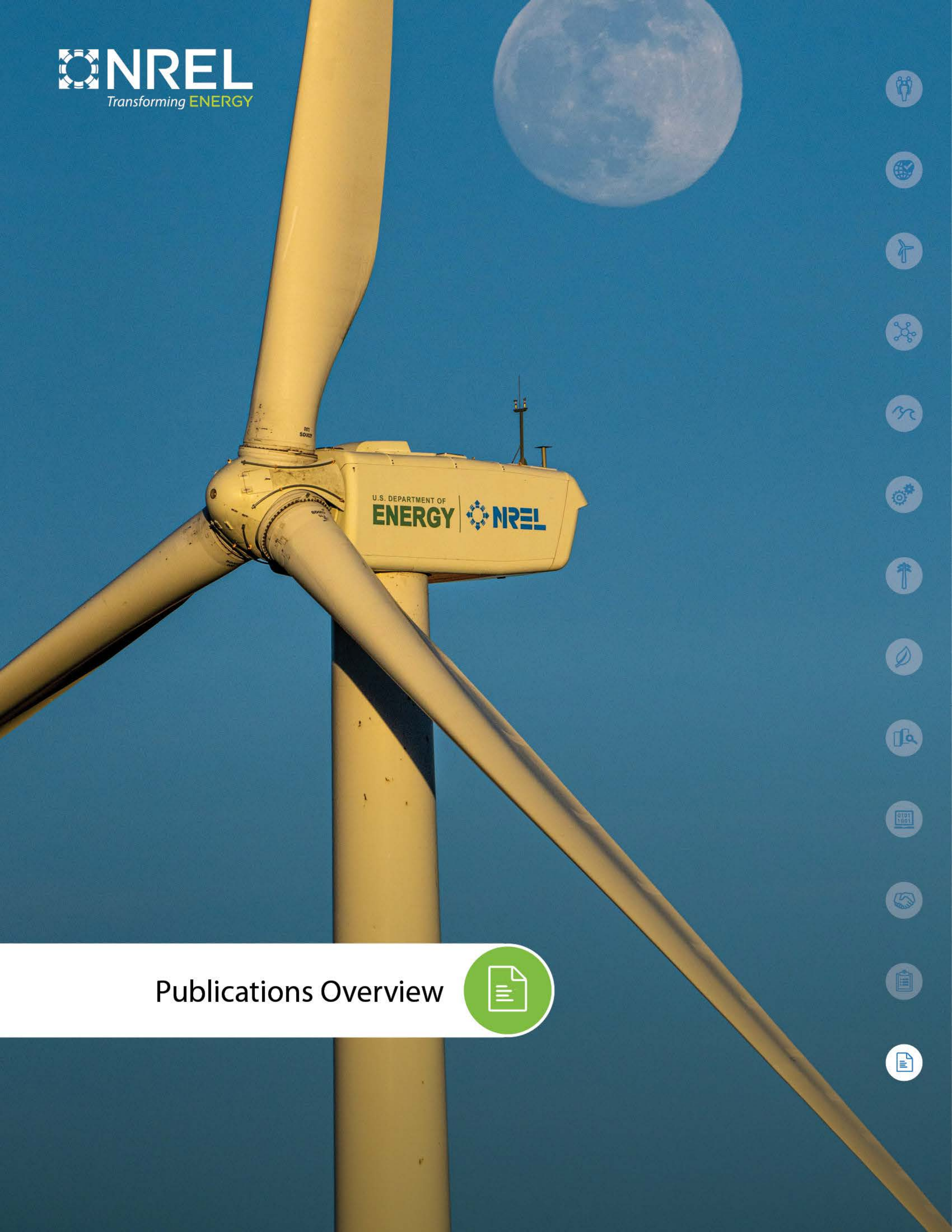


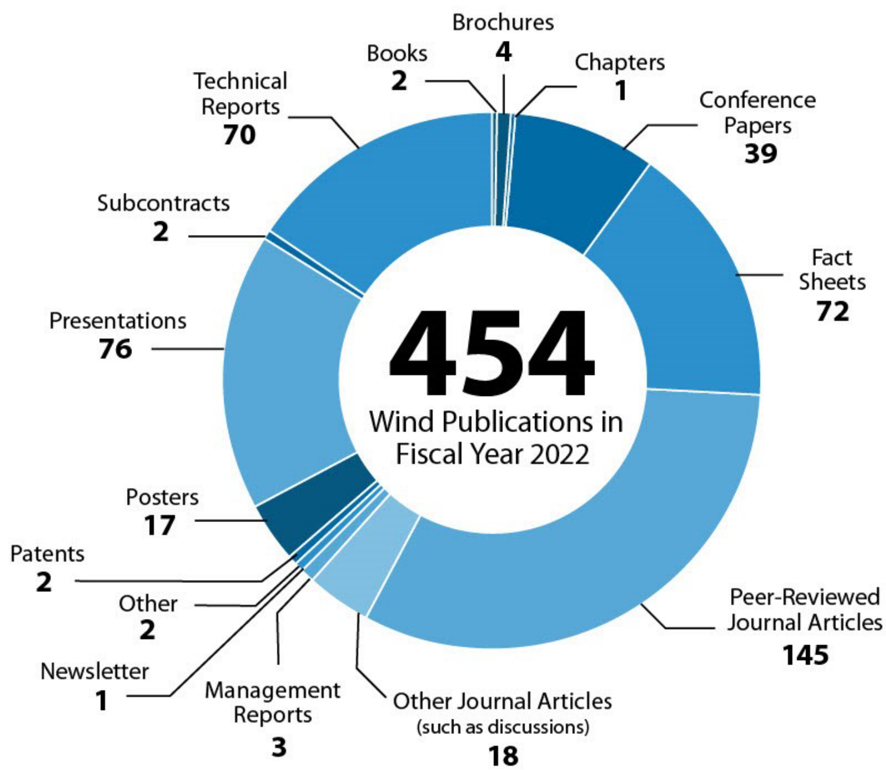
Publications Overview

Publications Overview

Publications produced by NREL Wind Energy Program staff provide information about the many areas of wind energy research conducted at the lab. In FY 2022, NREL researchers published their latest scientific findings and breakthroughs in 454 technical reports, peer-reviewed journal articles, conference papers, fact sheets, and other materials.

Fiscal Year 2022 NREL Wind Energy Publications

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 FY 2022, the National Renewable Energy Laboratory (NREL) Wind Energy Program published 454 publications processed through the Communications Office Publication Tracker. *Graphic by NREL*

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View all wind energy-related journal articles and technical reports published in FY 2022.

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