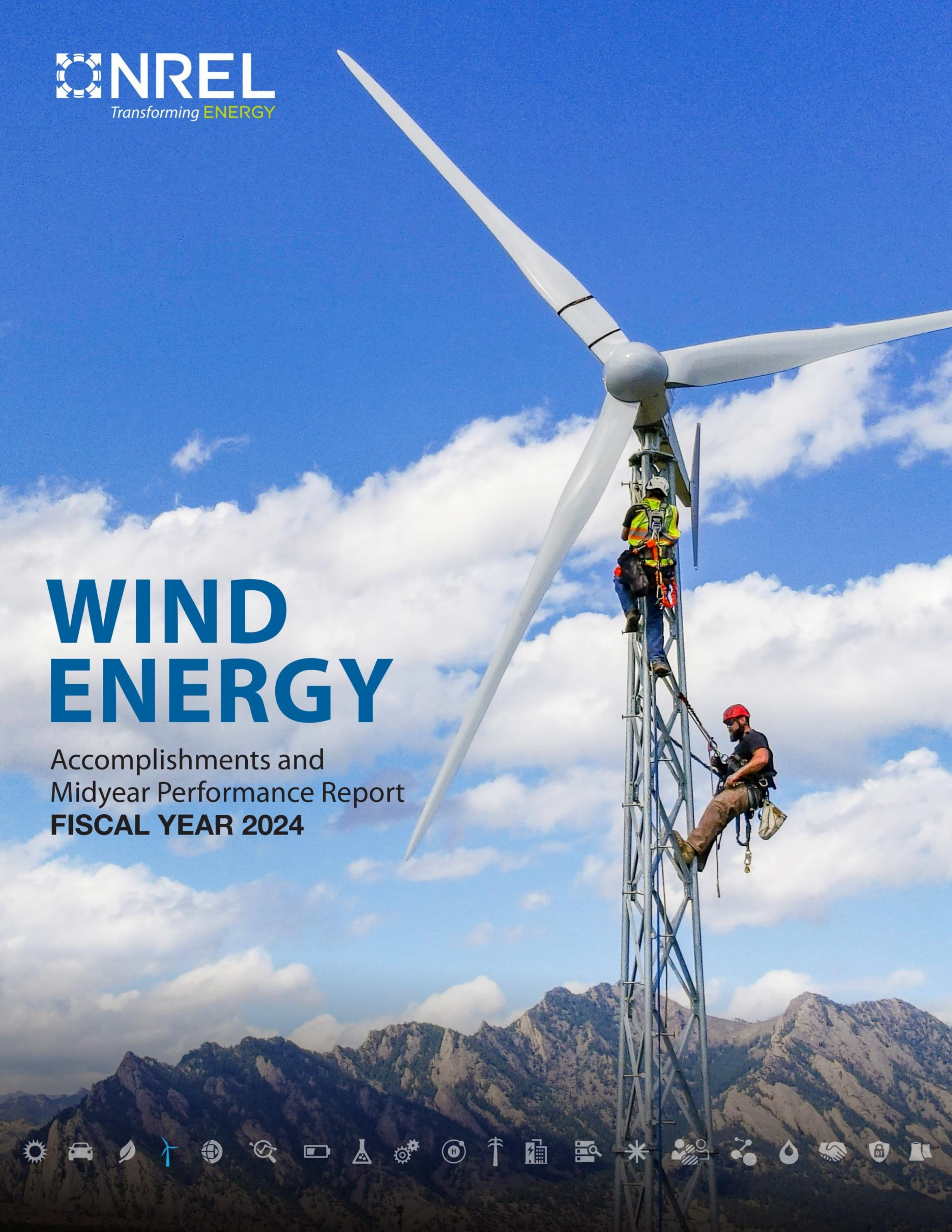

NREL
Transforming ENERGY

WIND ENERGY

Accomplishments and
Midyear Performance Report
FISCAL YEAR 2024

Notice

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Foreword

As one of the fastest growing energy sectors, wind energy is an essential source of clean, low-cost energy that supports the transition to a resilient and sustainable energy in the United States and beyond.

NREL's global leadership in fundamental wind energy research, development, and validation has played a leading role in propelling the industry forward.

To meet the growing national demand for wind energy advancement and deployment, critical challenges around the design, development, and deployment of land-based and offshore wind energy must be addressed.

The challenges facing wind energy cannot be solved alone or through one source of funding. Partnerships have always been pivotal to the success of the National Renewable Energy Laboratory (NREL) wind energy program's mission-driven work to take wind energy technologies to new heights.

During the first half of Fiscal Year (FY) 2024, NREL engaged with a robust array of partners across government, national laboratories, industry, academia, communities, and more—all in support of the U.S. Department of Energy's (DOE's) Wind Energy Technologies Office (WETO).

Working hand-in-hand with key partners, NREL researchers are helping hone the accuracy of tools that evaluate novel technologies related to the wind turbines and power plants under development. Through the NREL-led American WAKE experimeNt (AWAKEN), a multilab collaboration, researchers are studying atmospheric and wind turbine operational data to enhance modeling tools for large-scale wind power plants. In partnership with industry, NREL researchers are working to improve the accuracy of turbine performance and loads through the Rotor Aerodynamics, Aeroelastics and Wake Project (RAAW). Both projects enable industry to validate and improve their design tools while ensuring NREL research is relevant to the next generation of wind turbines to be deployed across the country.

In the offshore wind energy space, NREL researchers are collaborating with international scientists to refine modeling tools and methods that predict how offshore wind energy systems behave on floating platforms. The Atlantic Offshore Wind Transmission Study, a multilab collaboration, proposes transmission strategies for delivering electricity generated by offshore wind energy to land, where it can be equitably accessed. And NREL's first joint industry project is leveraging the expertise and insight of a broad and diverse set of corporate, government, and community partners to analyze plant-to-plant wake effects for wind farms off the U.S. East Coast.

In addition, researchers across the laboratory are working with partners on cross-cutting efforts to address gaps in wind energy modeling and analysis, deployment, and equity. The Wind Resource Database, an online platform that provides public access to more than a petabyte of detailed wind resource and climate data covering the United States and other countries, can help developers identify ideal sites for wind plants. NREL and Texas State University researchers studied how bats respond to ultrasonic signals to learn how to deter these creatures that are vital to the ecosystem from approaching wind turbines. And through the National Wind Workforce Assessment, NREL researchers established an innovative modeling effort to evaluate the root causes of the U.S. wind energy workforce gap and identify ways to close it.

NREL wind energy researchers also leveraged partnerships to make our research more accessible. The North American Wind Energy Academy (NAWEA)/WindTech 2023 conference, held near NREL's Flatirons Campus and cohosted by NREL and several Front Range research institutes and universities, gave NREL staff the opportunity to host a day of wind-energy-related workshops, tutorials, and project briefings for attendees.

NREL partners benefit from our accomplishments, too. Two new assets on NREL's Flatirons Campus are designed to support our research partners by answering critical questions about integrating large amounts of inverter-based resources on the grid. The recently commissioned, 20-megawatt (MW) Controllable Grid Interface (CGI-2) connects real energy systems, grids, and laboratories to simulate grid power events under safe conditions. Complementing this capability will be a 3-MW wind turbine, which will be installed on campus in 2025.

Thanks to the support of many sponsors and industry, academic, and community partners, NREL's work is reinforcing wind energy's role as a leading player in the race to meet the United States' clean energy goals.

The stories below highlight significant accomplishments NREL realized during the first half of FY 2024 (between Oct. 1, 2023, and March 31, 2024) with the robust support and collaboration of an outstanding lineup of sponsors and partners.

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People and Partnerships

Elevating the Staff who Propel NREL's Wind Energy Research and Development

The Behind the Blades series, launched in 2023, spotlights the NREL wind energy researchers who are advancing innovative solutions, pushing the boundaries of wind science, and making WETO's vision for wind energy a reality. Meet the NREL staff profiled thus far, and look for new profiles on NREL's wind energy website and in The Leading Edge, NREL's wind energy program newsletter.

Amy Robertson Takes On the Complexities of Floating Offshore Wind

As a child immersed in the science of NASA, Amy Robertson was bound to end up an engineer—an aerospace engineer, to be exact. At NREL, she's traded in her love of the cosmos for the delightfully challenging dynamics of floating offshore wind energy.

Amy Robertson joined NREL in 2010 to tackle the emerging field of offshore wind energy. *Photo courtesy of Amy Robertson; graphic by John Frenzl, NREL*

How Angel McCoy's Background in Meteorology Propels Offshore Wind Forward

Angel McCoy started her career as a meteorologist, which put her on the path that led to her current role at NREL, supporting the regulatory process for offshore wind energy in the United States.

Meet Angel McCoy, whose childhood fascination with earth science led her to her current role as an offshore wind energy regulation specialist at NREL. *Photo courtesy of Angel McCoy; graphic by John Frenzl, NREL*

Why Genevieve Starke Gave Up on Her Childhood Dream Job

As a kid, Genevieve Starke dreamt of becoming a con artist. Naturally, the little girl from Pennsylvania decided to pivot her dream to a field where rule following was a little more appreciated. She picked engineering.

Meet Genevieve Starke, a research engineer who helps determine how renewables can be safely and affordably integrated into the grid. *Photo courtesy of Genevieve Starke; graphic by John Frenzl, NREL*

Vahan Gevorgian's Three-Decade Clean Energy Odyssey

Twenty-nine years ago, Vahan Gevorgian was a postdoctoral researcher studying wind and hybrid energy systems at the State Engineering University of Armenia when a once-in-a-lifetime opportunity presented itself.

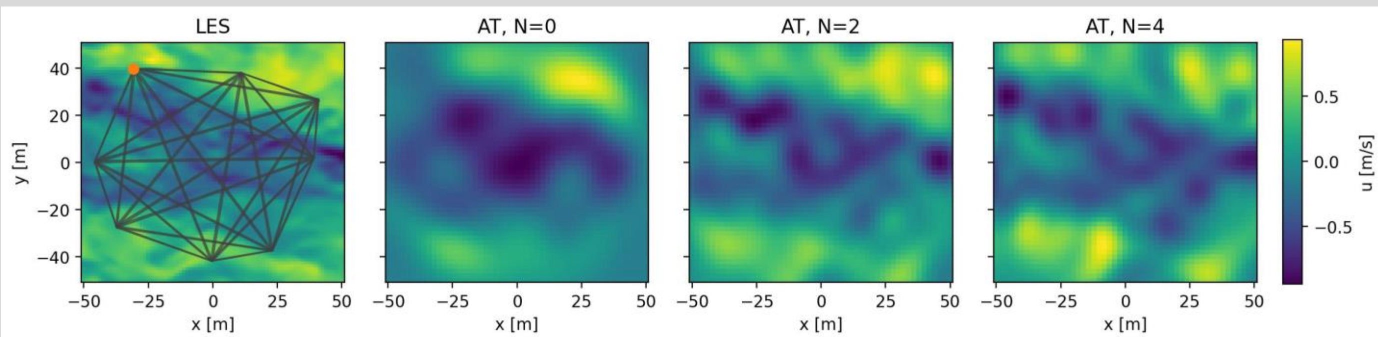
Meet Vahan Gevorgian, whose three-decade career at NREL has focused on integrating clean energy sources, like wind and solar energy, into the electric grid. *Photo courtesy of Vahan Gevorgian; graphic by John Frenzl, NREL*

Testing Infrastructure, Standards Development, and International Engagement

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

Acoustic Tomography Could Become a New Flatirons Campus Research Capability

Acoustic tomography, which measures turbulent velocity and temperature fields at an unprecedented resolution, could represent new technology and partnership pathways at NREL's Flatirons Campus. To better understand wind turbine response to turbulent inflows and facilitate high-fidelity model validation, NREL's acoustic tomography development team conducted a detailed sensitivity study of the accuracy of acoustic tomography measurements by performing large-eddy simulations using NREL's AMR-Wind. Funded by the WETO, this work quantifies the range of scales that acoustic tomography can resolve and highlights areas for improvement in turbulent flow-field retrieval, processing requirements for measured acoustic signals, and future system design considerations.



To understand the measurement uncertainty of acoustic tomography, reconstructions using successively larger ensembles of observations are compared to a large-eddy simulation of the turbulent atmospheric boundary layer was conducted with AMR-Wind, shown on the left with the travel paths of the virtual acoustic tomography array. *Image by Nicholas Hamilton, NREL*

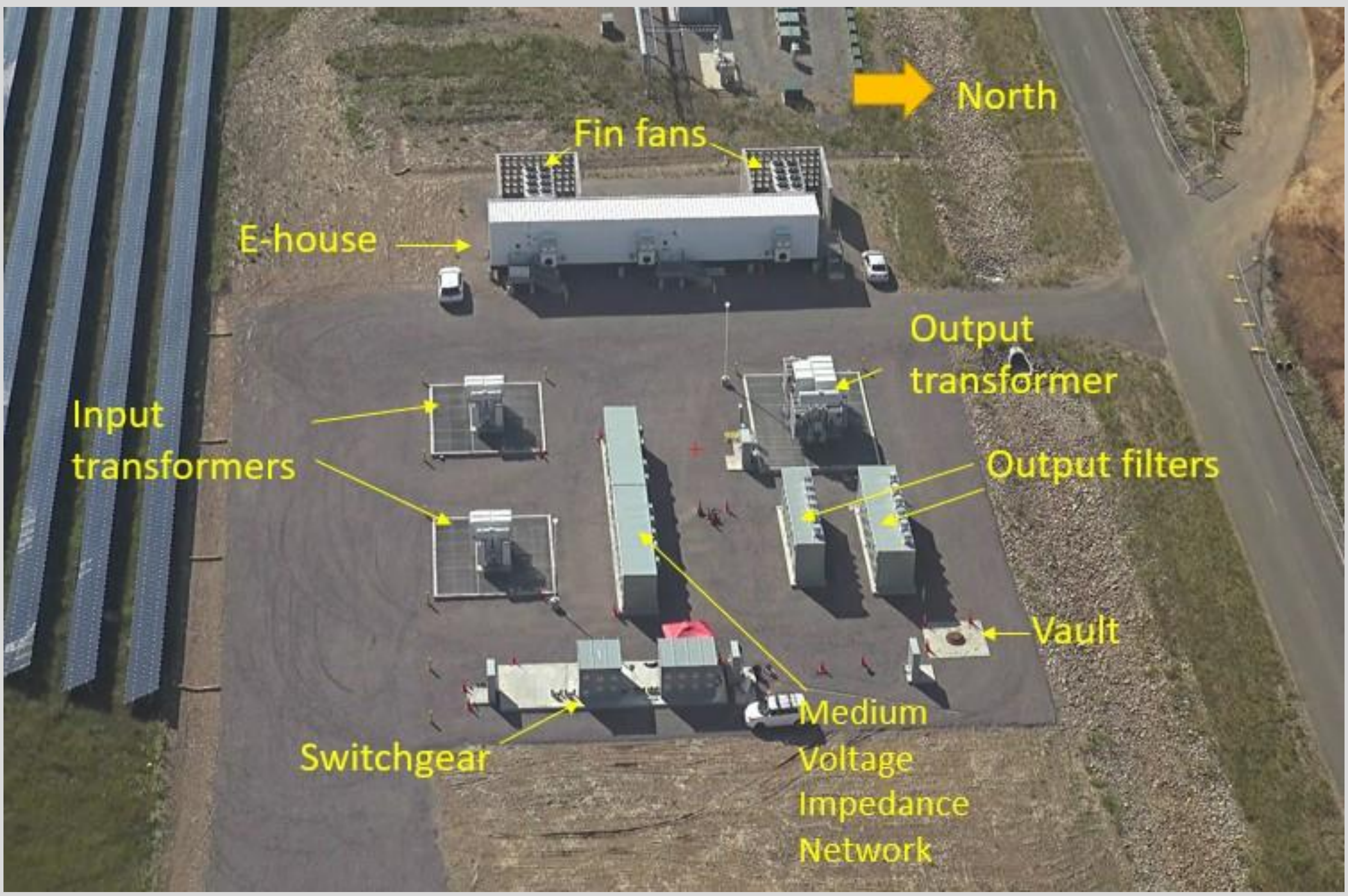
Flatirons Campus Expansion and Capability Enhancements

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

New Controllable Grid Interface Ready for Research

NREL's new, 20-MW CGI-2 is now research-ready. The second of its kind at the lab, CGI-2 complements the original 7-MW CGI by providing more power and capabilities: 20 MW (in addition to the CGI's 7 MW), a 34.5-kilovolt (kV) alternating current voltage level (in addition to the original 13.2 kV), and an additional 5-kV direct current voltage level. CGI-2 has been in development since 2018.

NREL's CGIs enable researchers to expose megawatt-scale electrical power devices to grid power events (such as grid faults and frequency fluctuations) under safe conditions isolated from the utility grid. This exposure helps validate and de-risk renewable energy technologies before deployment. The CGIs can also emulate devices (storage, generation, and loads) that are not physically on site.



NREL's second CGI comprises a variety of components, which are shown here, including fin fans on an e-house, an output transformer, output filters, a vault, a medium-voltage impedance network, a switchgear, and input transformers. *Photo and modification by NREL*

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

NREL Set To Elevate Wind Research With Cutting-Edge ≥3-MW Turbine Installation on Flatirons Campus

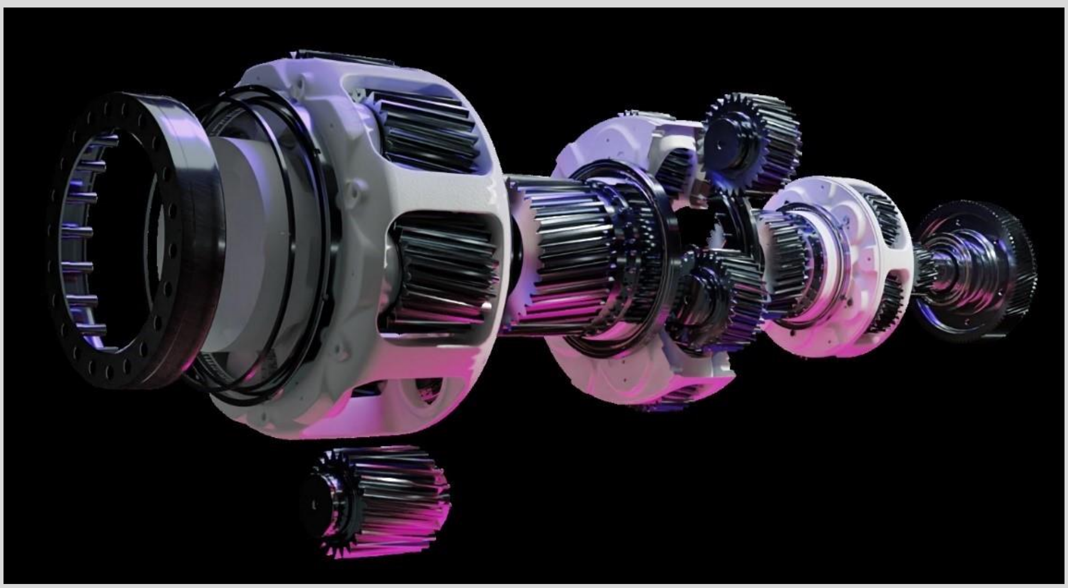
NREL is preparing to install a new wind turbine on the Flatirons Campus that could generate 3 MW and beyond. As part of the Advanced Research on Integrated Energy Systems (ARIES) platform, this modern turbine will help ensure NREL facilities support upcoming wind research and development (R&D) needs. The turbine will have a maximum tip height of 152 meters (m) and will be used in stand-alone and hybrid configurations. In addition, it will support many research areas, including industrial decarbonization, efficient electricity generation, and grid integration.

NREL's new wind turbine, capable of generating 3 MW and more, will provide a more current wind energy research platform than the General Electric 1.5-MW turbine, shown here, whose design is more than 20 years old. *Photo by Josh Bauer, NREL 61829*

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

Wind Turbine Gearbox Design Standard on Track for International Release

The International Electrotechnical Commission (IEC) 61400-4 standard, initially released in 2012, outlines design and verification criteria for wind turbine gearboxes. These standards serve as a practical application of wind energy research, minimizing risk and costs for wind turbine owners, operators, project financers, and the insurance sector. Given increases in wind turbine sizes and torque density in recent years, an international maintenance team within IEC was formed to address known limitations of the standard and upgrade it to include new technology such as plain bearings, knowledge of reliability improvements for failure modes such as white etching cracks, and revised design verification procedures—all elements of NREL's Drivetrain Reliability Collaborative research. The IEC Committee Draft for Vote of the newest version of IEC 61400-4 was recently approved by international committees, and the maintenance team has recently been addressing comments before final approval and publication. Approval and publication of IEC 61400-4 as an international standard should further improve the newest generation of wind turbine gearbox technology and help lower the levelized cost of energy from wind.



Exploded view of 7-MW high-torque-density gearbox with multiple planets and plain bearings. *Image by Gamesa Gearbox*

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

NREL Expands Research Arsenal: Negotiates Ownership of 2.3-MW Wind Turbine for Advanced R&D

NREL is negotiating with Siemens Gamesa Renewable Energy (Siemens Gamesa) to take ownership of its 2.3-MW wind turbine installed on NREL's Flatirons Campus. A change of turbine ownership would conclude a successful multiyear, multi-million-dollar R&D partnership with Siemens Gamesa and begin a new role for the turbine as an NREL/DOE research platform. Installed in 2009, the turbine was used for aerodynamics research as part of a collaborative R&D agreement. In 2023, Siemens Gamesa determined that the turbine was no longer critical to the company's R&D needs. This is similar to and will supplement the existing General Electric (GE) 1.5-MW turbine on NREL's Flatirons Campus.

NREL is negotiating with Siemens Gamesa to take ownership of the 2.3-MW wind turbine at NREL's Flatirons Campus shown here. *Photo by Werner Slocum, NREL*

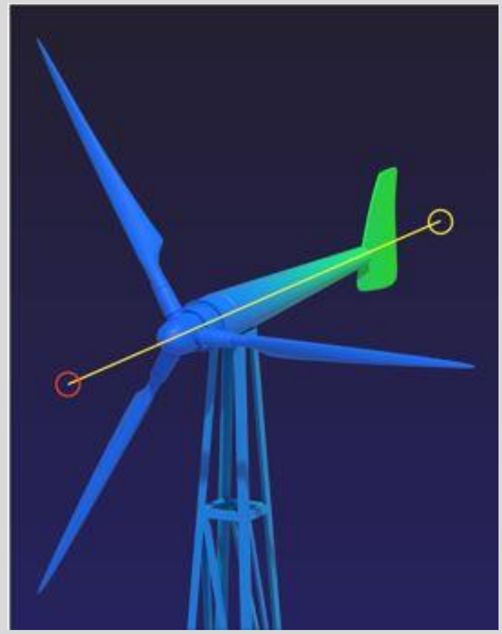
Distributed Wind Research and Development

Distributed Wind Aeroelastic Modeling (dWAM)

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

New OpenFAST Code Enables Modeling of Passive-Yaw Distributed Wind Turbines

NREL researchers on the Distributed Wind Aeroelastic Modeling (dWAM) project developed and implemented code to enable the OpenFAST wind turbine simulation tool to model designs for turbines that automatically adjust their direction to face the wind without needing an active control mechanism. Known as passive-yaw wind turbines, this type of technology is used by many distributed wind turbine designers to maintain rotor alignment with the wind. OpenFAST now includes code to simulate the resistance encountered when the passive-yaw turbine turns to face the wind—called yaw friction. It also now supports simulation of upwind, tail-vane controlled turbines. These updates have been validated using experimental wind tunnel data with further validation expected from field experiments planned later this year. With these updates, OpenFAST continues to serve as a useful tool for modeling, validating, and certifying distributed wind turbine designs.



NREL's OpenFAST wind turbine simulation tool now includes code for modeling tail-vane-controlled, passive-yaw wind turbines, like the one pictured here. *Graphic by Besiki Kazaishvili, NREL*

On-Site Wind for Rural Load Centers

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

NREL Releases New-and-Improved Hybrid Optimization and Performance Platform

NREL helped improve the efficiency and usability of the Hybrid Optimization and Performance Platform (HOPP), culminating in the release of version 2.0.0 and accompanying documentation to support the analysis and design of distributed-wind-energy-based hybrid systems. The team kicked off the release with an in-person workshop at NAWEA/WindTech 2023 in October 2023 and by recording a tutorial that shows how to use the platform.

New HOPP Capabilities Support the Design of Distributed Wind Energy Systems for Electric Vehicle Charging

To support stakeholders interested in installing distributed wind energy and hybrid systems in rural areas, an NREL team has integrated electric vehicle (EV) modeling capabilities into HOPP. As businesses in rural areas consider expanded electrification, EV charging models will help further demonstrate the value in behind-the-meter wind energy deployment. This value will be enhanced when EV charging capabilities are coupled with the advanced vehicle-to-grid services that are expected shortly from a number of American truck manufacturers—services that could greatly contribute to grid resiliency. NREL is using HOPP alongside accompanying control and design methods to support the design of on-site distributed wind energy and hybrid systems for EV charging. The team discussed this capability development, as well as the current landscape of EV charging needs in distributed grids, at the Distributed Wind Energy Association's Annual Business Conference in February 2024 and will present on it again at the Science of Making Torque From Wind (TORQUE) Conference in Italy in May 2024.

NREL Provides Technical Assistance for Lake Region Electric Cooperative

Project team members from NREL, the Idaho National Laboratory, and Pacific Northwest National Laboratory (PNNL) supported the analysis of hybrid power plant solutions for the Lake Region Electric Cooperative. The cooperative is looking to repower a wind energy facility to maximize renewable energy, resiliency, and other grid services. The team connected tools across the labs to devise recommendations for the cooperative's investments in renewable energy, which the cooperative will use to apply for federal funding and prioritize investments in local grid infrastructure. NREL team members simulated hybrid power plant options with varying capacities of wind energy, solar energy, and battery storage, which were then used to generate revenue estimates with PNNL's Energy Storage Evaluation Tool. The goal of this project is to serve as a functional example of the benefits of hybrid system development for energy cooperatives in many areas of the United States.

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

New Program Enables Early Review Process for Distributed Wind Turbine Certification

NREL is helping expedite the certification process for small- and medium-sized wind turbines used in distributed applications. Under the Competitiveness Improvement Project (CIP), NREL worked with the International Code Council's Small Wind Certification Council to implement an early review process for turbines initiating certification. The program removes a barrier to certification and enables distributed wind turbine companies to quickly engage with the council to gain a better understanding of their path to certification. In FY 2024, the program has funded four turbine reviews with more than 12 additional reviews expected before the end of FY 2024.

The Skystream wind turbine, shown here at a school in North Carolina, was the first turbine to use the NREL-funded preliminary review program, the first step to recertify the turbine model that is being put back into production. *Photo by Brent Summerville, NREL*

NREL Requests Proposals From U.S. Small and Medium Wind Energy Technology Manufacturers

NREL has issued a request for proposals under the CIP to support small- and medium-sized wind energy manufacturers to accelerate technology commercialization and market expansion. The request reflects the current needs of the U.S. distributed wind energy market by prioritizing topics that: provide distributed energy consumers with wind technology options that are tested and certified for performance and quality; address the need for inverters built specifically for distributed wind turbines and that meet national safety standards; and develop advanced manufacturing processes to reduce hardware costs and meet growing demand. Since the CIP began in 2012, NREL has awarded 64 subcontracts to 26 companies, totaling $15.4 million of DOE funding, and leveraged $7.9 million in additional private-sector investment.

NREL has issued a request for proposal under the 2024 CIP to U.S. manufacturers of small- and medium-sized wind turbines (such as this Bergey Windpower distributed wind turbine recently installed at NREL's Flatirons Campus). *Photo by Bryan Bechtold, NREL*

Strategize, Engage, Network, Deploy Distributed Wind

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

Guidelines Help U.S. Manufacturers Navigate Complex Certification Landscape

NREL managed the publication of the comprehensive *Distributed Wind Certification Best Practices Guideline*, which will help U.S. manufacturers achieve product certification and gain access to key U.S. and international markets. The report is the result of a recent collaboration between NREL and the distributed wind energy industry to revise U.S. and international standards for small wind turbines.

NREL's *Distributed Wind Certification Best Practices Guideline* offers comprehensive information and resources to help manufacturers of distributed wind energy technologies, like the Bergey Excel 15 wind turbine shown here, achieve certification so they can enter domestic and international markets. *Photo by Joe Del Nero, NREL 85094*

This timely guide offers information, tips, checklists, and references that help U.S. suppliers of distributed wind energy technology understand and work through complicated standards and certification requirements. For wind energy systems and components, the *Distributed Wind Certification Best Practices Guideline* also details National Electrical Code requirements that wind energy systems and their components must achieve to be listed to applicable electrical safety standards and obtain building permission for a proposed project.

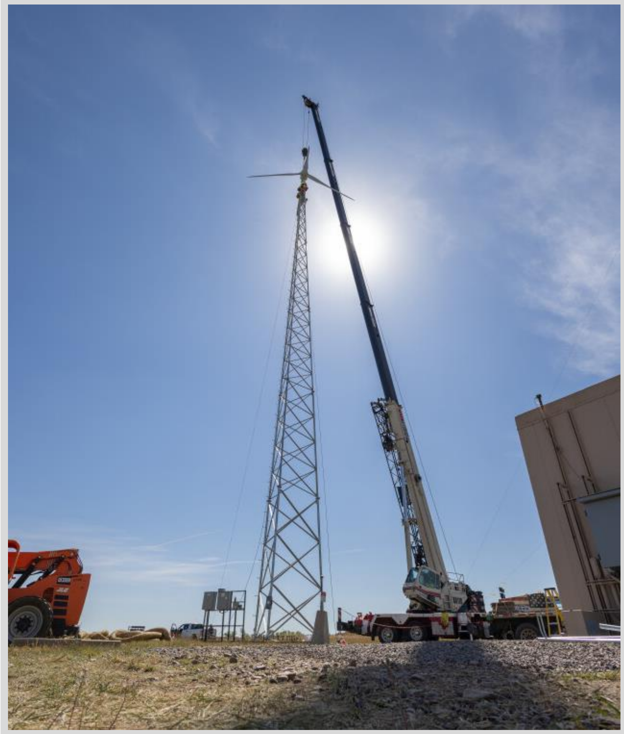
Strategize, Engage, Network, Deploy Distributed Wind (SEND)

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

Videos Communicate Role of Distributed Wind Energy

To communicate the importance of distributed wind energy and research concepts to an international audience, the International Energy Agency Wind Technology Collaboration Programme (IEA Wind) Task 41, Enabling Wind To Contribute to a Distributed Energy Future team produced three videos, which are available on the IEA Wind Task 41 website.

Co-led by NREL and PNNL, Task 41 coordinates international distributed wind energy research, facilitates collaboration on priority research topics, and increases the visibility of wind technology as a distributed energy resource. U.S. work performed under Task 41 is funded by DOE through the Strategize, Engage, Network, Deploy (SEND) Distributed Wind project. Designed to help enable more distributed wind energy deployment, SEND includes strategic and technical stakeholder engagement as well as information resource development and sharing.



Crews install a Bergey Windpower Excel 15 wind turbine at NREL's Flatirons Campus distributed wind energy site. *Photo by Joe DelNero, NREL*

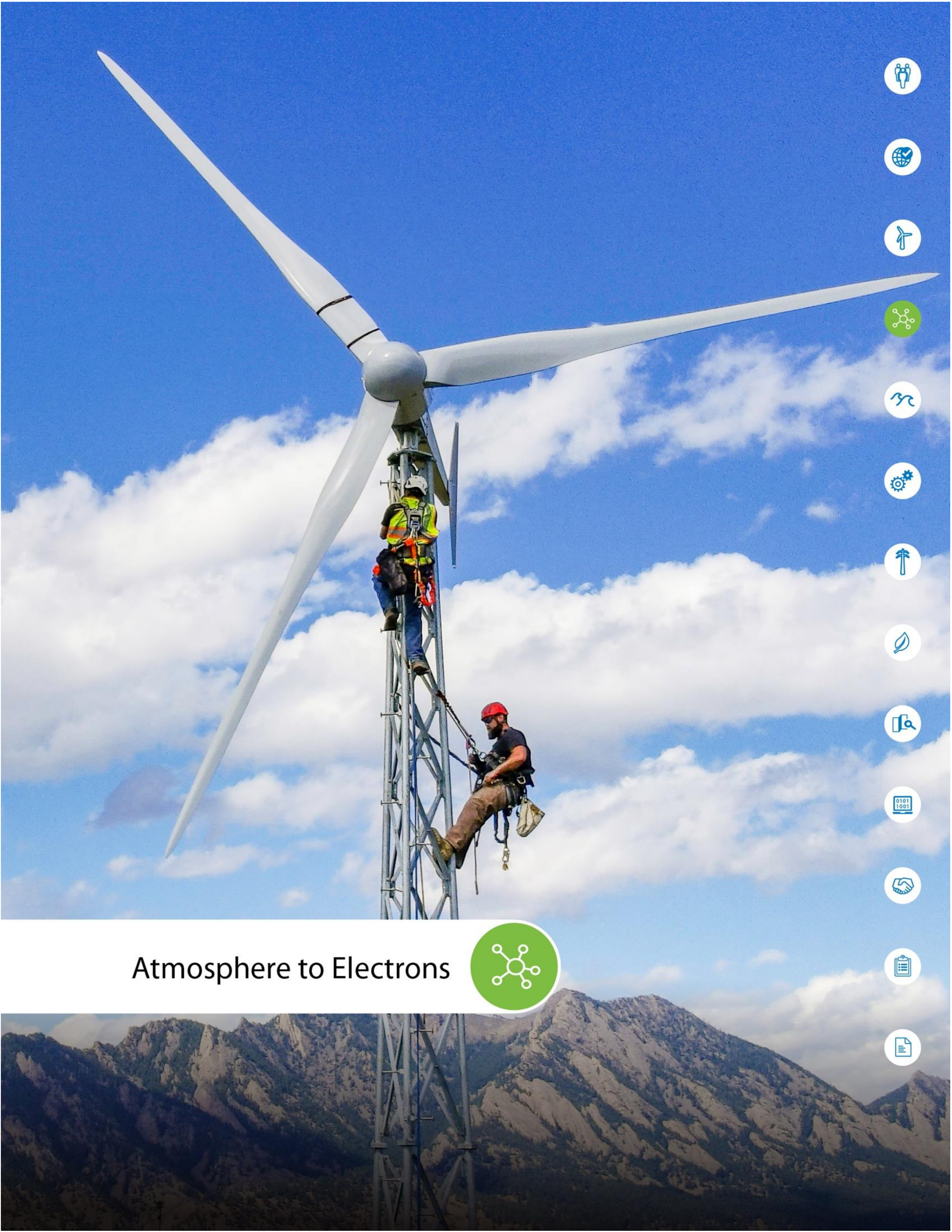
Strategize, Engage, Network, Deploy Distributed Wind (SEND)

Point of Contact: Suzanne MacDonald, suzanne.macdonald@nrel.gov

Initiative Empowers Communities To Seize On-Site Wind Energy Opportunities

NREL released two new resources that provide comprehensive information, tools, and support to anyone interested in installing distributed wind turbines and taking advantage of the benefits of on-site energy. The National Distributed Wind Network, which was created by NREL in partnership with PNNL and funded by WETO, offers extensive informational resources about distributed wind energy. The network and its complementary Distributed Wind Energy Resource Hub, hosted on WETO's WINDExchange resource website, will help farmers, municipalities, homeowners, and business owners navigate their decision making around distributed wind energy—with the ultimate goal of getting more distributed wind turbines deployed across the country.

Two new resources—a national network and resource hub—are designed to provide comprehensive information, tools, and support to anyone interested in deploying distributed wind turbines, like this 2.3-MW turbine that, along with a nearby 500-kilowatt solar photovoltaic array, provides power to a Minnesota electric cooperative. *Photo from Lake Region Electric Cooperative*



Atmosphere to Electrons

Offshore Wind Resources Sciences Work - WFIP3

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

First Large Offshore Wind Energy Field Campaign Begins

The first large field campaign focused on offshore wind energy in the United States began with NREL researchers deploying weather instruments off the Northeast U.S. Outer Continental Shelf. The 2-year Third Wind Forecast Improvement Project offshore field campaign will conduct comprehensive observational and modeling studies of wind resources closest to the ocean surface. Results of the study will dramatically improve offshore wind resource measurement and modeling.

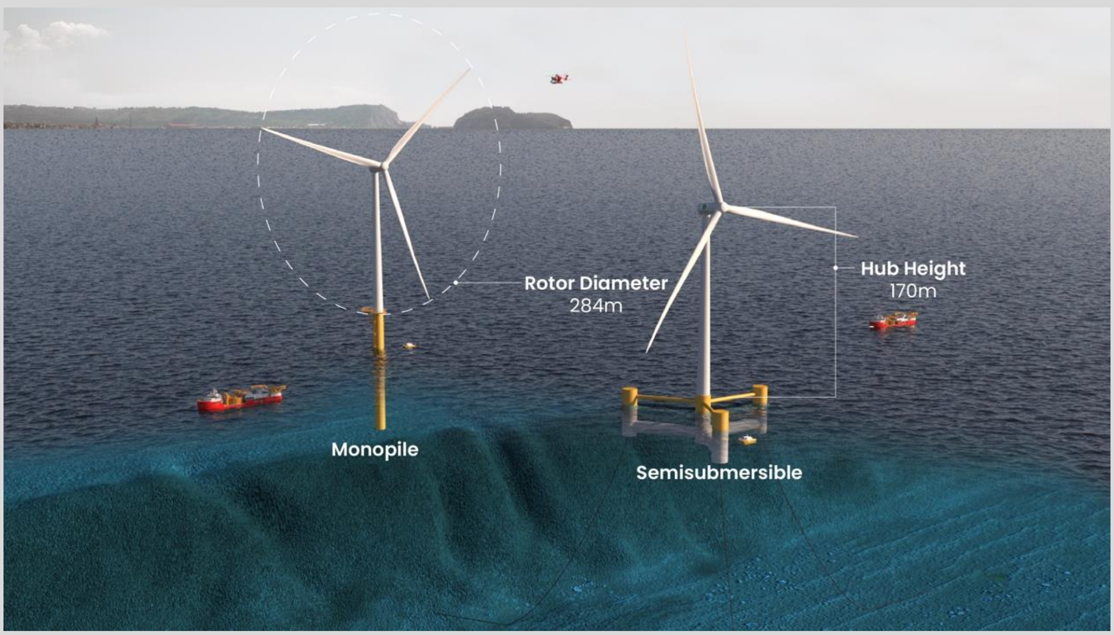
NREL and other institutions participating in the Third Wind Forecast Improvement Project field campaign deployed weather instruments designed to measure wind resources off the Northeast U.S. Outer Continental Shelf. *Photo by David Jager, NREL*

Holistic, Multi-Fidelity Wind Farm Design Optimization and Model Coordination

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

A Bigger Reference Model Helps Practitioners Keep Pace With Growing Offshore Wind Turbines

The offshore wind energy market has been dominated by a continuous upscaling of wind turbine power rating and rotor size, creating a need for models that can provide data representative of current turbine technology. To meet this need, NREL and the Denmark Technical University released a new offshore reference wind turbine model with a rating of 22 MW. The reference turbine, which is publicly available on GitHub, aims to model machines projected to be installed between 2025 and 2030. In addition, the reference turbine is a Class 1-B machine with a rotor diameter of 284 m, and a hub height of 170 m. The generator adopts the popular direct-drive configuration, which couples the rotor to a large generator bypassing the gearbox. The turbine can model operations with either fixed-bottom or floating support structures. The turbine will support practitioners in both academia and industry in a variety of purposes, including load and performance studies, techno-economic analyses, logistics planning, and investigations into manufacturing innovations. The new model will also inform decisions in the ongoing race among manufacturers to design, develop a prototype, and deploy ever-larger wind turbines.



A new 22-MW reference turbine model can model offshore wind turbine operations with either a fixed-bottom support structure or a floating support structure. *Image by Josh Bauer, NREL*

Advanced Control and System Design for Offshore Wind Turbines and Wind Plants

Point of Contact: Daniel Zalkind, Daniel.Zalkind@nrel.gov

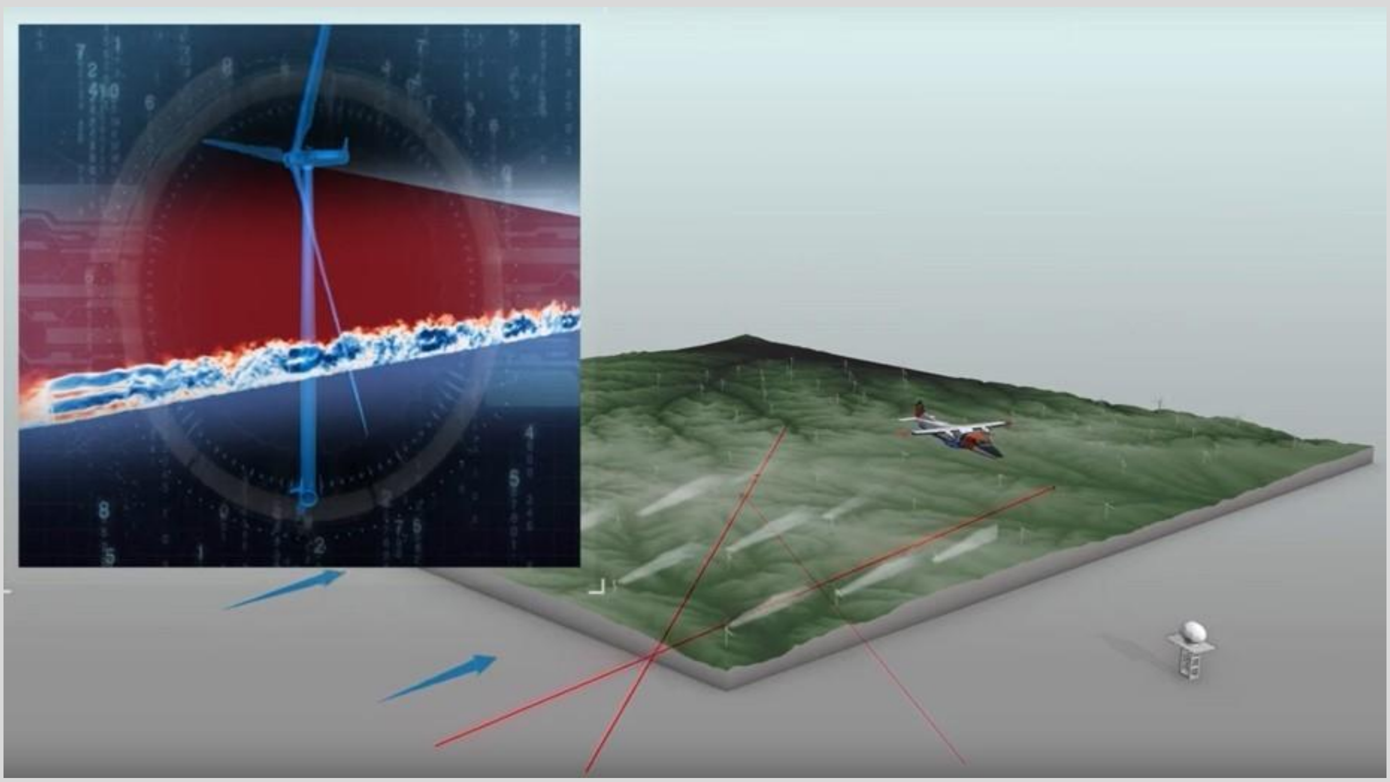
NREL Enhances Wind Turbine Control With Latest Release of Software

NREL recently released a new version of the Reference Open-Source Controller (ROSCO) for wind turbines. Manufacturers typically develop in-house software that controls turbines for optimal power production and safe operation. The ROSCO software brings similar capabilities to researchers, wind turbine manufacturers, floating platform designers, and wind power plant developers without these proprietary methods, easing collaboration among these stakeholders. The new version of ROSCO offers additional support for wind power plant control and features based on industry feedback, such as the ability to avoid rotor speeds that excite tower resonances, thereby reducing structural fatigue. NREL also added a method for safely controlling the rotor during high wind speeds, which reduces extreme loading on wind turbine components.

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

Study Unveils Key Insights for Predicting Wind Power Plant Performance

The AWAKEN research team, which is led by NREL, collected a year of atmospheric and wind turbine operational data from five wind power plants in northern Oklahoma. Collected from over 50 instruments, such as radar and lidar equipment, and nearly 600 wind turbines, this dataset is unique in its size and scope in the wind energy industry. These observations will be valuable for helping better understand how wind plants interact with the atmosphere in numerous different environments. The research team has begun processing these vast amounts of data and have observed wake behavior that can cause downwind wind power plants to lose energy. Although such impacts are not currently well understood, the AWAKEN data can help researchers validate and improve wind power plant modeling tools to better predict those losses in the future.

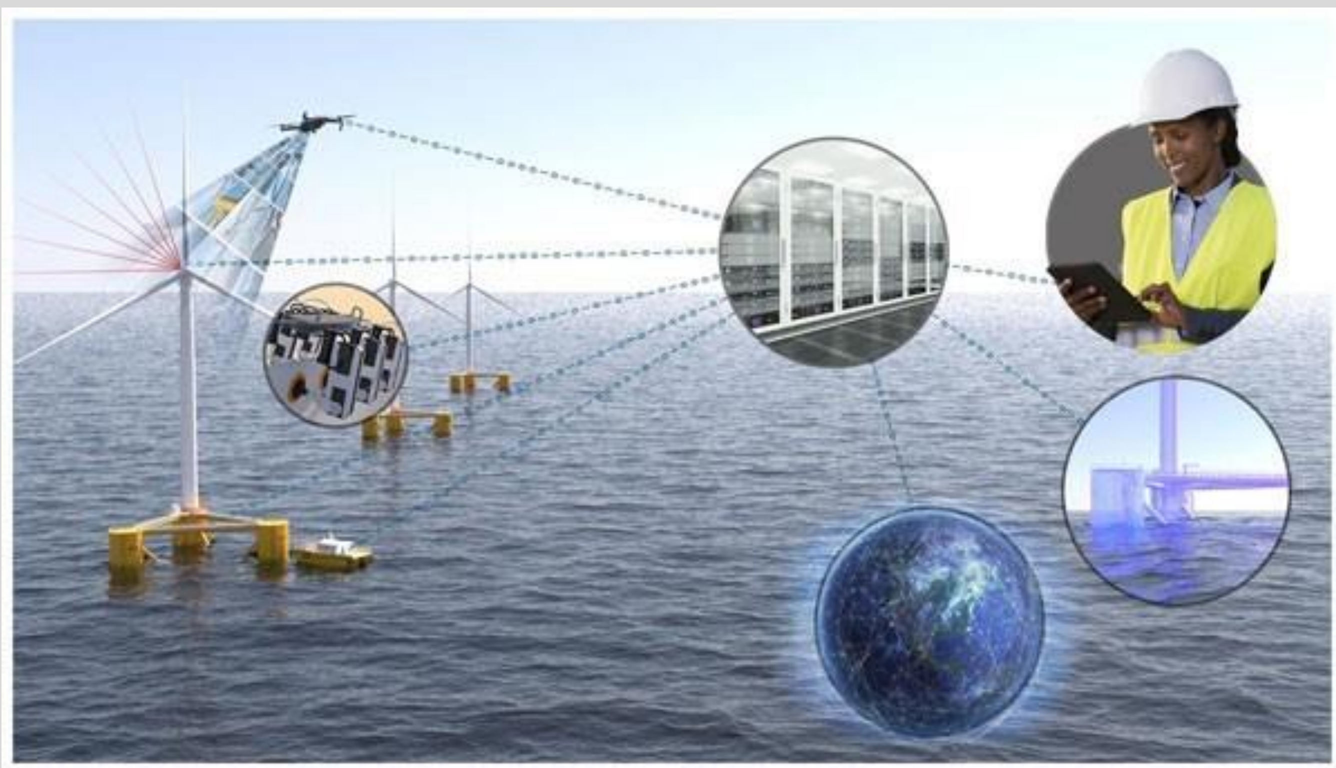


The AWAKEN research team has deployed unique instruments and tools, including lidar, radar, and aircraft, to observe atmospheric interactions at wind power plants. These observations will be used to benchmark and improve models used to predict wind farm performance. *Rendering and visualization by Josh Bauer, NREL*

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

Roadmap To Define Wind Industry Digital Transformation

Achieving aggressive wind energy deployment goals will require new digital tools that enable deployment and operations at an unprecedented scale. Funded by WETO and conducted by researchers from NREL, PNNL, and Idaho National Laboratory, a wind energy digitalization roadmap identifies top R&D topic areas and activities needed to achieve "Wind Industry 4.0." This concept, introduced by the research team, is like Industry 4.0, which defines manufacturing sector digitization. Wind Industry 4.0 features new technologies, such as sensors, that connect people and machines through an integrated digital physical ecosystem to enable data generation, analysis, and communication. Using feedback from stakeholder engagement events, extensive literature reviews, and lessons learned from other mature industries, the research team developed the wind energy digitalization roadmap. They released a draft roadmap that provides recommended R&D activities under different topic areas to help guide future wind energy digitalization R&D. The final roadmap is scheduled for release later in 2024.



A new digitalization roadmap project conducted by NREL researchers will help guide future wind energy digitalization R&D. In this illustration of a future floating wind energy plant, digitalization enables a plant manager to make data-based decisions in real time, increasing safety and reducing the cost of energy. *Image by NREL*

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

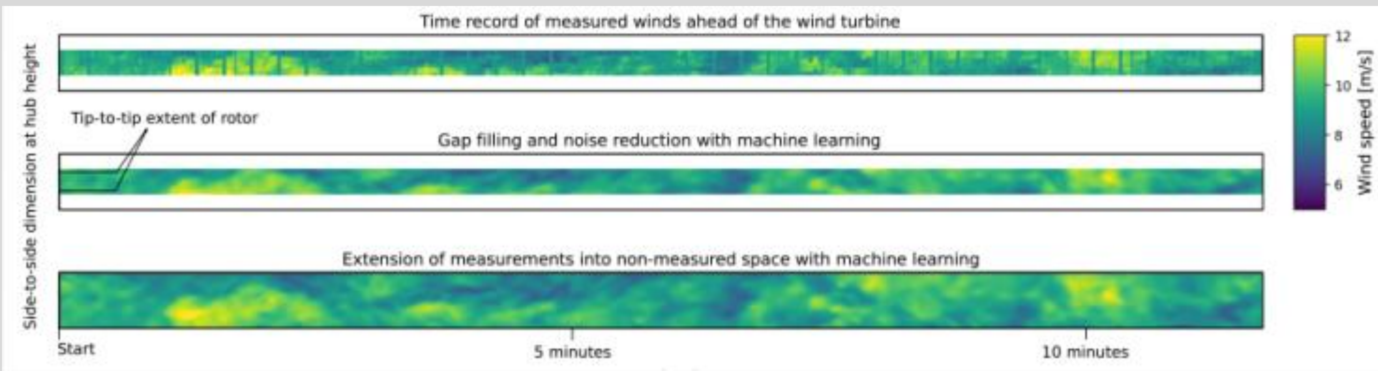
Unique Measurements To Improve Wind Turbine Safety

Data gathered during a 6-month measurement campaign in Texas reveals the close relationship between atmospheric turbulence and the structural response of multimegawatt wind turbines. In collaboration with GE, a team of NREL researchers employed traditional and novel instrumentation methods to capture detailed flow features and tower and blade motion. In addition to data gathered during periods of normal operation—when the wind turbine responds to the wind patterns as it is designed to—the team forced the rotor into stress states to measure large tower movements and blade vibrations. These unique measurements will be compared to computer simulations of wind turbine behavior to ensure that wind turbine design tools produce accurate structural load predictions, which are important for designing efficient and safe wind turbine technology.

NREL researchers triggered faults on this wind turbine in Texas caused by structural loads, resulting in the tower deflection shown here. The markers on the tower and blades were used to measure these motions. *Photo by Nicholas Hamilton, NREL*

Machine Learning Exposes the Wind Flow of Unmeasured Spaces

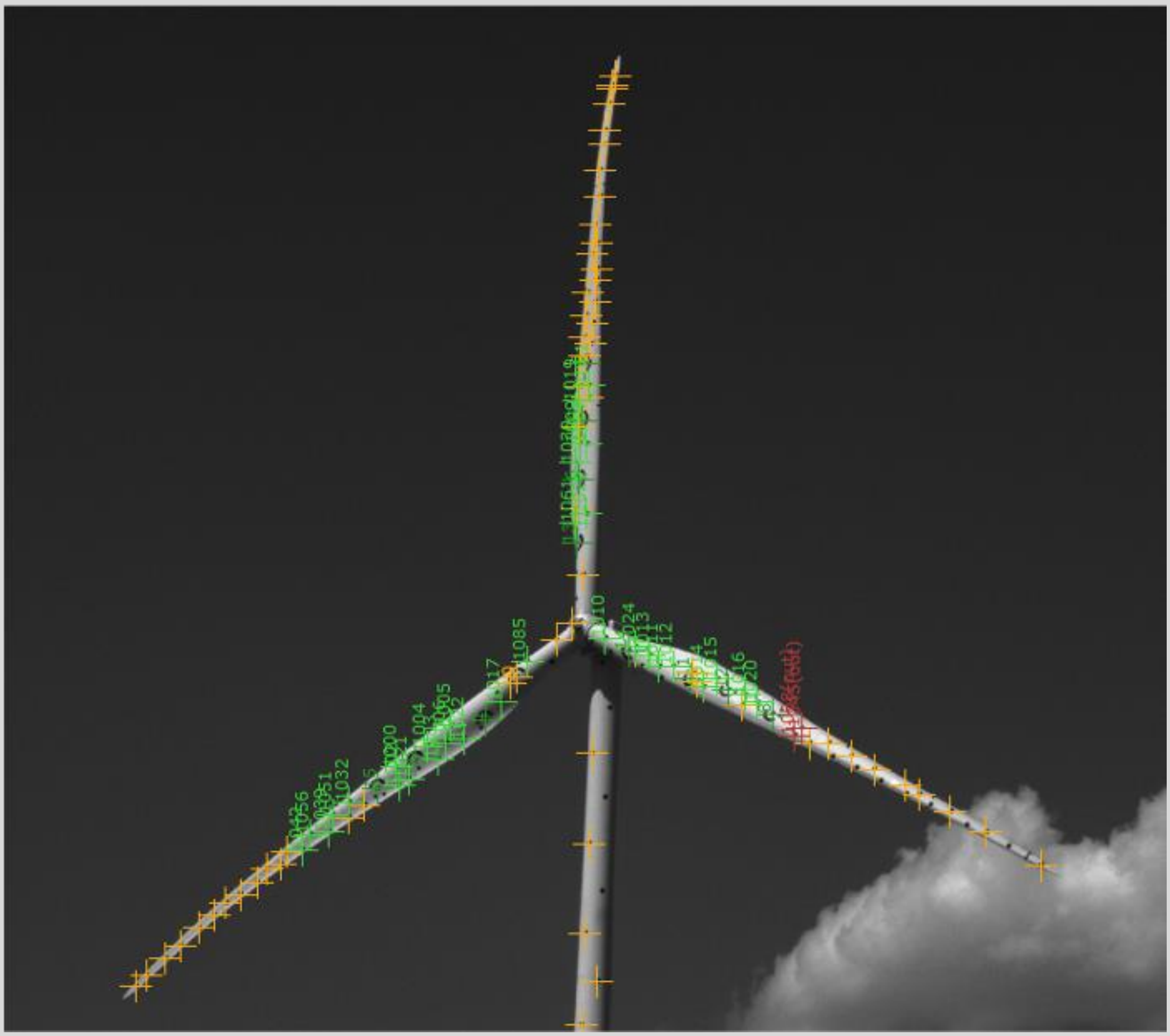
When using lasers to measure wind speeds, researchers often need to decide between focusing on a smaller area, and obtaining faster measurements, or expanding into a larger domain, which leads to a loss of time precision. Researchers at NREL have addressed this problem by combining measurements with flow simulations and machine learning models. With this combination of tools, wind measurements can be made on an area just large enough to cover a wind turbine rotor and fast enough to capture quick-changing turbulence. The unmeasured spaces around the observed points are then filled in with the computational tools, which also address data gaps introduced by field-of-view obstructions, such as blade passage in front of the laser beam. The higher-quality, expanded flow field obtained with this technique can then be used to drive simulations of wind turbine behavior under the highly specific wind patterns seen in the real world, enabling a one-to-one comparison between simulations and reality.



A scanning lidar placed atop a wind turbine nacelle, looking ahead into the incoming wind, measures wind speeds. These measurements, however, get regularly interrupted by blade passage. New tools devised by NREL researchers use machine learning to fill in these gaps in time and expand the measurement area to cover a wider field of view. *Graphic by Alex Rybchuk, NREL*

NREL Researchers and General Electric Make Progress Tracking Wind Turbine Motion

In partnership with GE, NREL researchers successfully applied photogrammetry to measure the motions of the blades and tower of a multimegawatt wind turbine. This technique uses photographs to capture the three-dimensional motion of an object. Applying photogrammetry to wind turbines faces a variety of obstacles: the target object is large, requiring the cameras to be far away from the turbine and far apart from each other; the blades are curved and rotate, with portions often disappearing from the field of view; winds may shift, causing the entire rotor to turn away from the cameras; lightning poses a threat to the sensitive electronics; and sunlight often saturates or obscures the images. Despite these complications, the team was able to obtain data covering several hours across different wind conditions. The team concluded that photogrammetry shows promise as a potential solution to the difficult problem of measuring the torsional movements of wind turbine blades.



The NREL team captured this image using a pair of ground-based cameras. The markers and numbers represent the stickers placed on the tower and blades for the purpose of motion tracking. *Photo captured using data analysis software by Nicholas Hamilton, NREL*

Floating Turbine High-Fidelity Modeling and Simulation

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

ExaWind Model Ready for Prime Time

The open-source ExaWind tool enables high-fidelity simulations of wind turbine designs on modern supercomputers that help developers simulate turbine geometry and rotor blades, down to millimeters of resolution, to optimize their designs for performance and efficiency. This novel approach, which leverages two solvers to model the flow around the blades and the background flow, was featured in the journal *Wind Energy*. ExaWind was also recently used to calculate the complete performance profiles of the NREL 5-MW and IEA Wind 15-MW reference turbine using a high-fidelity fluid-structure interaction capability. Now that these demonstrations are complete, ExaWind is ready for researchers to create the highest-fidelity wind power plant simulations and to better understand their complex fluid-structure interactions. Results from such simulations can be used to create next-generation data-driven engineering models and serve as a virtual environment to explore disruptive technology advances.

Researchers developed an ExaWind simulation of four NREL 5-MW wind turbines in a turbulent atmospheric flow, illustrated here. *Graphic by Nicholas Brunhart-Lupo, NREL*

Joint Industry Program (NOWRDC) - Interarray Wakes

Point of Contact: Georgios Deskos, georgios.deskos@nrel.gov

NREL Partners With Academia, Industry, and Government Agencies To Analyze Wind Plant-to-Plant Wake Effects off the U.S. East Coast

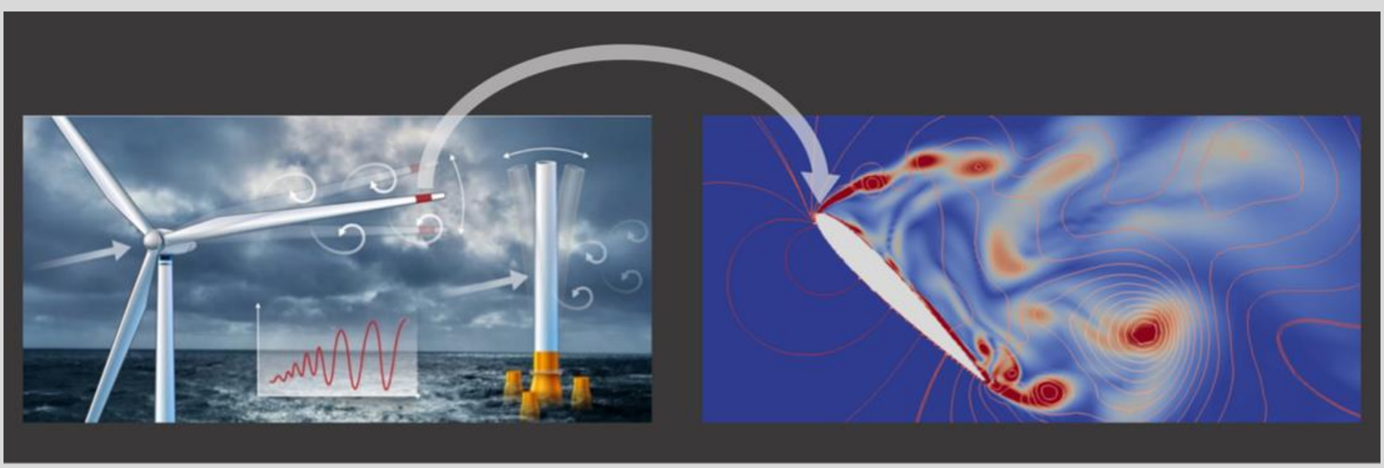
NREL researchers, in collaboration with the National Offshore Wind Research and Development Consortium and Cornell University, met with industry partners from Shell, RWE, TotalEnergies, and representatives from the Bureau of Ocean Energy Management (BOEM), DOE, and the State of Maryland in Washington, D.C., to kick off a joint industry project on interarray wake effects at wind power plants. The meeting elaborated upon the project's technical details and confirmed overall tasks, objectives, and deliverables. Administered by the National Offshore Wind Research and Development Consortium, the project will conduct state-of-the-art analysis of internal and plant-to-plant wake effects at planned wind power plants along the entire U.S. East Coast and assess suitable locations of future lease areas. This is NREL's first-ever joint industry project, which will open the door for similar projects in the future.

Stall/Vortex Induced Vibration Modeling and Validation

Point of Contact: Ganesh Vijayakumar, ganesh.vijayakumar@nrel.gov

Improved Computational Modeling Could Reduce Damage From Vibration in Wind Turbine Blades

As wind turbine blades get larger and become more flexible, the vortices generated behind them can make them vibrate—sometimes enough to cause permanent structural damage. As a result, researchers used the NREL-developed ExaWind software to demonstrate that turbine blade sections, commonly known as airfoils, create vibrations that overlap with the natural frequency of the blades under specific quantifiable conditions. These findings will ultimately help wind energy engineers design turbine blades that are both efficient and durable in extreme operating conditions.



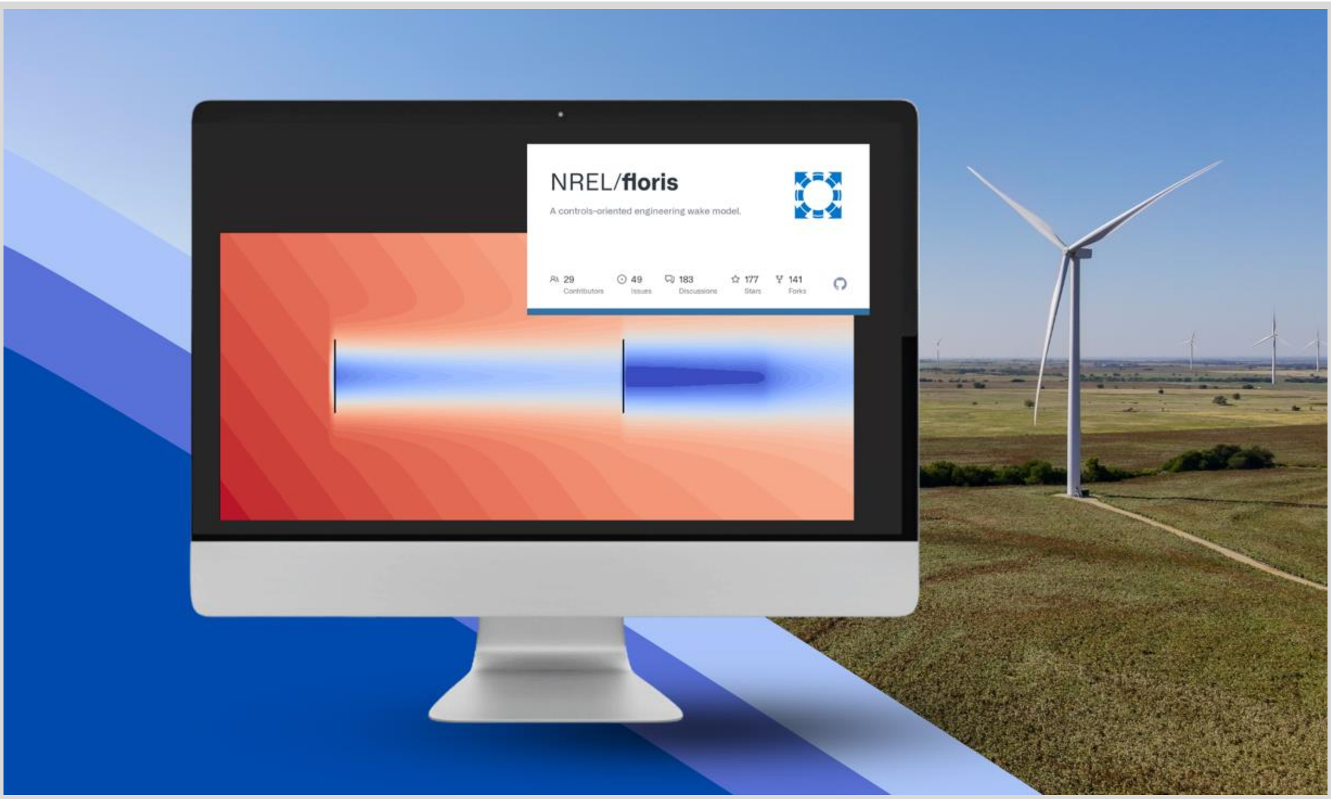
Research from NREL has improved understanding of turbulent airflow around wind turbine blades (shown as swirling colors in the cross section on the right) so that developers improve blade designs to prevent vibration-caused damages to wind turbines. *Graphics by Shreyas Bidadi, NREL*

Advanced Control and System Design for Offshore Wind Turbines and Wind Plants

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

FLORIS Version 4.0 Opens New Avenues for Advanced Wind Power Plant Control Studies

NREL's FLOw Redirection and Induction in Steady State (FLORIS) open-source software models the interaction between wind turbines in a wind power plant, which helps wind energy researchers, developers, and industry professionals improve energy capture and efficiency. The latest release, version 4.0, represents a comprehensive overhaul of the software's code base and application programming interface. This new version includes modes of operation beyond "nominal" and "wake steering." These modes allow for de-rating control, which involves intentionally reducing the power output to manage grid stability, protect the turbine from damage, reduce noise, or extend its life span; the implementation of control strategies that adjust the pitch angle of the turbine blades to improve overall wind power plant performance; and individual turbine shut-off. The FLORIS team also added the ability to evaluate the impact of different wind power plant control strategies and layouts on the market value of the energy produced. These updates enhance the software's code clarity—meaning they make the code more efficient and easier to understand and maintain. In addition, the updates provide additional avenues for studying new ways of controlling wind power plants. The updates expand FLORIS's capabilities, making it more user-friendly and facilitates easier integration with new features and modules.



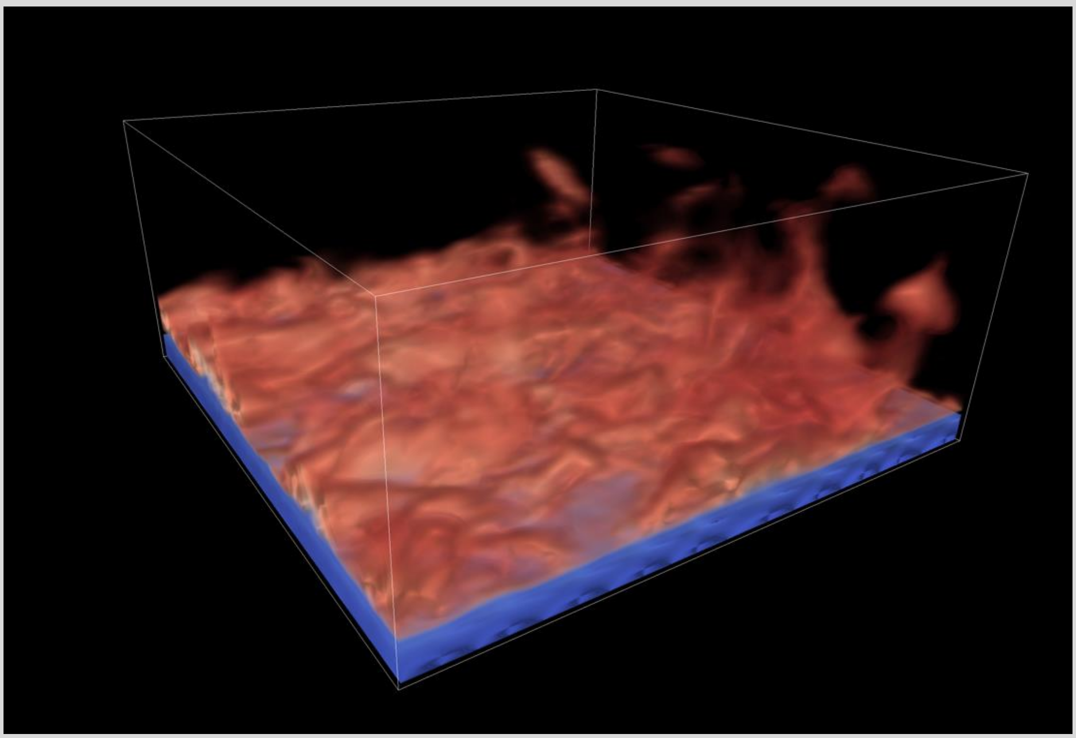
The latest version of NREL's FLORIS, which can be accessed publicly on GitHub, expands the software's capabilities and makes it more user-friendly. *Graphic by Christiann Vaughn and Misha Sinner, NREL*

Observationally driven Resource Assessment with CoupLEd models

Point of Contact: Geng Xia, GXia@nrel.gov

Project Enhances Offshore Wind Energy Forecasting

NREL's Observational drive Resource Assessment with CoupLEd models (ORACLE) project compares novel observational data and methods to detailed ocean-wave-atmosphere-coupled modeling techniques. By doing so, the ORACLE team aims to reduce uncertainty in offshore wind energy forecasting. Since the project's launch in 2023, the team has implemented a coupled mesoscale modeling framework at NREL that simulates the atmosphere, surface current, and ocean interaction. The team will use output from the coupled model to create detailed simulations of how the air and sea interact, especially near offshore wind turbines. By studying these interactions, they hope to make offshore wind energy more reliable and efficient, particularly along the Pacific Coast.



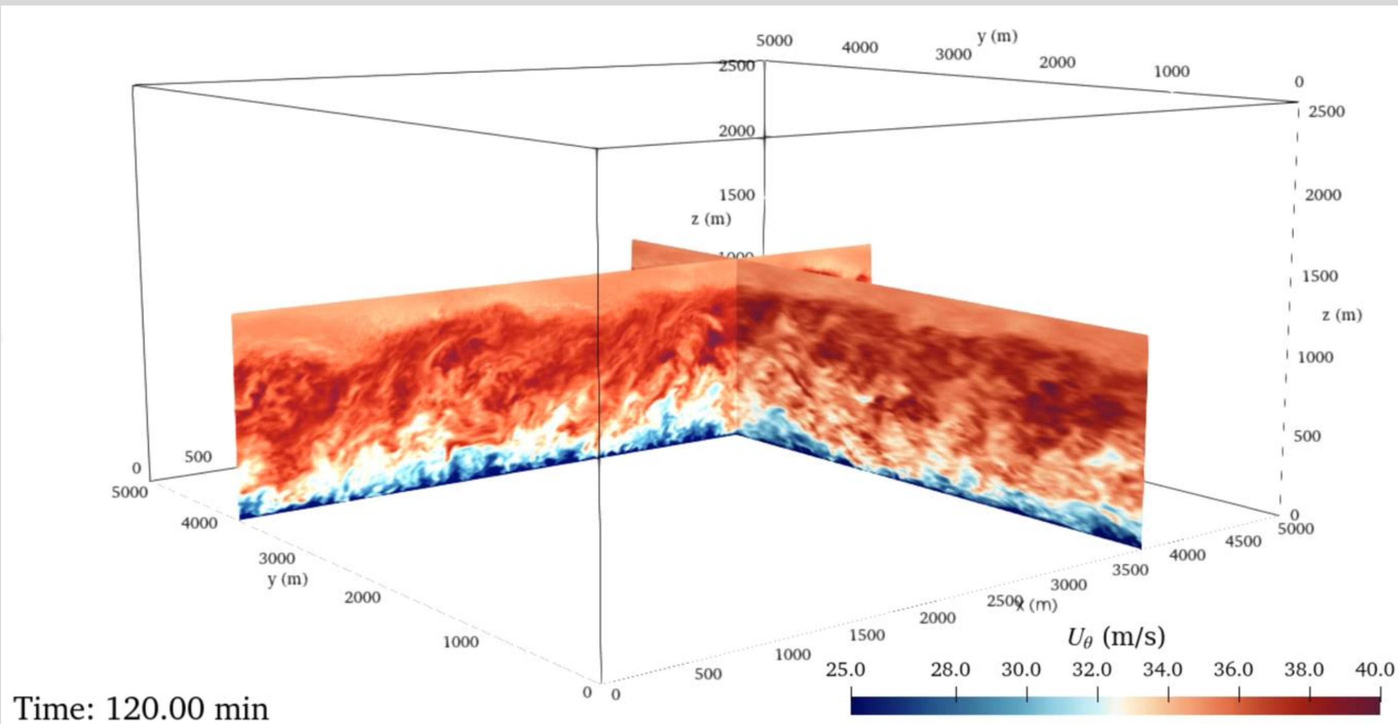
NREL's ORACLE project works to improve offshore wind energy by reducing forecast uncertainty, achieved through comparisons between novel observational data and detailed ocean-wave-atmosphere modeling.
Image by Tony Martinez, NREL

Influences of Future Tropical and Extratropical Storms on Wind Energy over the Eastern United States and Offshore (TREXO)

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

Simulations Provide Path to Offshore Wind Turbine Hurricane Resistance

NREL researchers are working on methods to simulate hurricane wind fields, better inform engineering approximations of wind fields, and assess the loads on wind turbines during hurricanes. As part of the WETO-funded TRopical and EXtratropical cyclone impacts on Offshore (TREXO) wind energy project, researchers successfully adapted ExaWind to simulate detailed turbulent wind fields, like those that offshore wind turbines would experience during a hurricane. Future work will refine this method and develop a method to simulate the wind fields in the particularly challenging region near the hurricane eyewall. TREXO's work will enable industry development of more hurricane-resistant offshore wind turbines.



A snapshot of a simulation of a hurricane's wind field using the high-fidelity ExaWind code. The color contours show the rotating wind speed approximately 40 kilometers east of the eye of the storm. Simulations, like this one, will enable industry development of more hurricane-resistant offshore wind turbines. *Graphic by NREL*

Offshore Wind Energy Research and Development

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

International Collaboration Will Support Floating Offshore Wind Design Innovation

IEA Wind has approved the Offshore Code Comparison Collaboration 7 (OC7) project as a new wind energy research task (Task 56), slated to operate from FY 2024 to FY 2027. Building on the successes of OC3–OC6 endeavors, OC7 aims to refine modeling tools and methods for offshore wind energy design, particularly emphasizing advancements in floating offshore wind energy structures. The project tackles three pivotal challenges: evolving hydrodynamic modeling and best practices for innovative designs, integrating structural flexibility into floater design frameworks, and enhancing predictive capabilities for wind turbine performance and loads to optimize floating wind power plant design. As an IEA Wind initiative, OC7 brings together more than 100 industry leaders worldwide, fostering collaborative innovation to overcome these challenges.

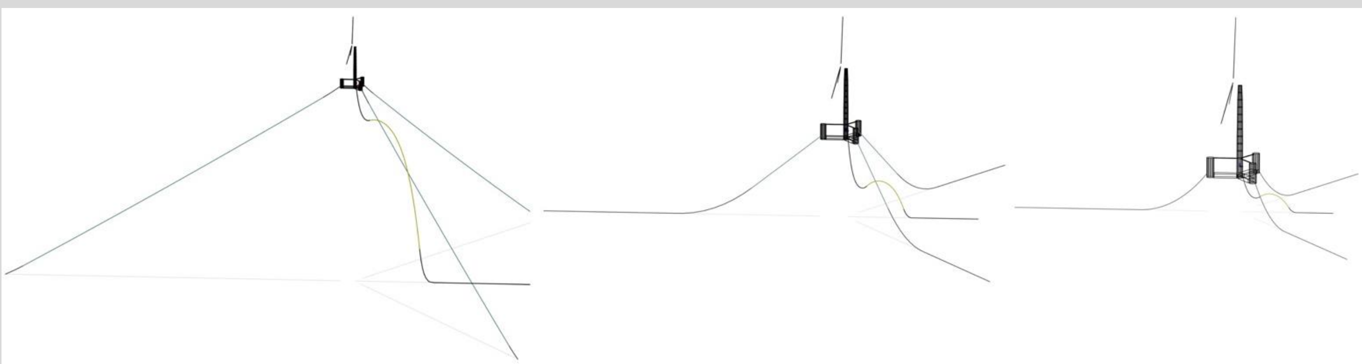
IEA Wind's Offshore Code Comparison Collaboration 7 project brings together over 100 industry leaders to refine offshore wind energy design modeling tools, with a focus on advancing floating offshore wind structures, like the ones shown here. *Image by Besiki Kazaishvili, NREL*

Floating Wind Array Design

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

New Mooring System and Power Cable Designs Extend the VolturnUS-S Reference Floating Wind Turbine Design

Large-scale floating offshore wind power plants will be key contributors to meeting offshore wind energy targets. In order to streamline R&D efforts, developers often use reference designs as a standard starting point. NREL researchers identified gaps in one common floating wind turbine reference, the VolturnUS-S 15-MW turbine, including a lack of power cable integration into the design and the fact that its mooring system was designed only for the Gulf of Maine. Through the Floating Wind Array Design project, researchers have developed reference site conditions for three U.S. regions—off the coast of northern California, the Gulf of Maine, and the Gulf of Mexico—and designed mooring systems and dynamic power cables for each. These new component designs will extend the capabilities of the VolturnUS-S reference turbine to allow for floating wind power plant analysis in a range of site conditions.



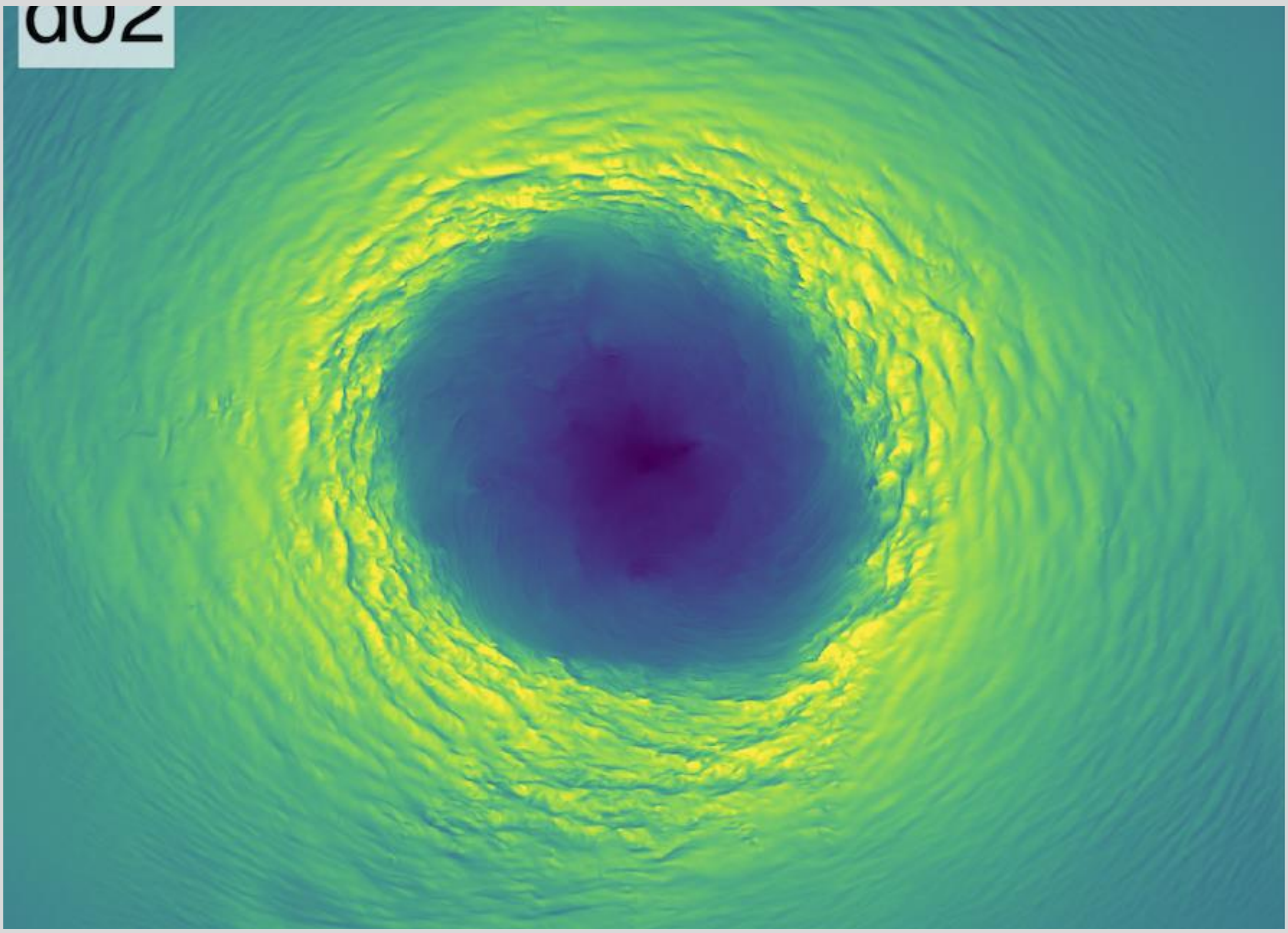
An NREL team created designs for mooring lines and dynamic power cables connected to a reference floating wind turbine at three different sites, which are visualized here from (shown left to right) deepest to shallowest depths. *Graphic by Matthew Hall, NREL*

STORM

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

Hurricane Simulations Highlight the Need for Enhanced Offshore Wind Turbine Design Standards

To assess whether existing wind turbine design guidelines adequately address the intense conditions of major tropical cyclones (those marked as category 3 or above), NREL’s Simulation-based Turbine design fOr hurricane Resilience and loads Mitigation (STORM) team conducted high-fidelity numerical simulations of category 1–5 hurricanes. Preliminary findings reveal that wind speed profiles and abrupt gusts within tropical cyclones exhibit features that are overlooked in offshore wind turbine design standards. These new discoveries emphasize the need to review and revise existing design standards and engineering protocols related to extreme wind conditions.



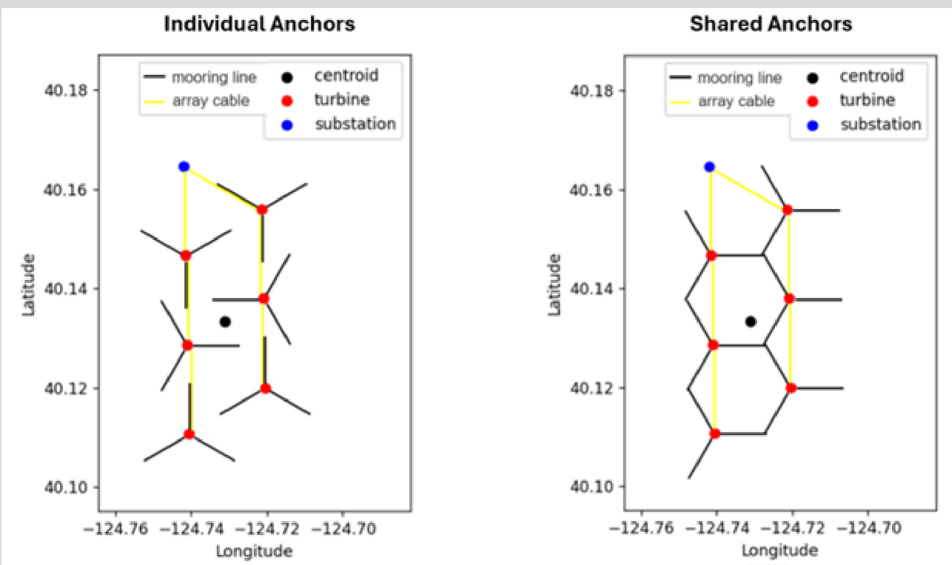
NREL’s STORM team simulated category 1–5 hurricanes to see how well the current wind turbine guidelines work in those storms. This image shows a simulation of the instantaneous horizontal wind speed at 100 m above the surface of a category 3 hurricane, which is representative of the design limit state for a tropical-class wind turbine design. *Image by Miguel Sanchez Gomez, NREL*

Innovative Deep-Water Mooring Systems for Floating Wind Farms (DeepFarm)

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

NREL Study Shows Shared Anchors Can Reduce Costs of Floating Offshore Wind Power Plants

In mooring systems for floating offshore wind power plants, shared anchors—where multiple mooring lines from various floating platforms attach to the same anchor—have become an interesting topic to consider, both technically and economically. To investigate their feasibility, as part of the DeepFarm project led by Principle Power, NREL performed a comparative analysis on the levelized cost of energy (LCOE) between a floating offshore wind power plant with individually moored anchors and one with shared anchors. They also compared two different plant sizes, a pilot-scale project comprising six floating wind turbines and a gigawatt (GW)-scale project with 100 floating wind turbines. The team used consistent water depths, distances from shore, turbine spacings, and mooring line types in both the individual and shared anchor wind power plants, as well as consistent adjustments to the shared anchor design and installation procedure in their analysis. They found that using shared anchors in the pilot-scale wind power plant contributed to a 3.8% reduction in LCOE to 155.6 $/megawatt-hour (MWh), and in the GW-scale wind plant, the LCOE reduced by 0.9% to 79.1 $/MWh. Using these assumptions, the team found that using shared anchors in a floating offshore wind power plant can decrease project costs, which is more noticeable in smaller plants, but absolute LCOE is still significantly lower in utility-scale plants.



The NREL team studied the economic impact of shared anchors on a pilot-scale floating offshore wind plant of six turbines, one with individually moored anchors (left) and one with shared anchors (right) with the same turbine layout, array cable layout, and distance from shore. *Graphic by Stein Housner, NREL*

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

Enhancements Improve OpenFAST Aerodynamic Modeling for Key Inflow Conditions

Upgrades to the OpenFAST model—NREL's open-source wind turbine simulation tool—will enable the wind energy community to better calculate wind turbine performance and structural loads when operating under complicated wind flow conditions. Recent work by the IEA Wind Task 47 and the RAAW experiment to validate OpenFAST demonstrated that the main aerodynamics model of OpenFAST did not accurately predict aerodynamic loading and turbine response under situations with misaligned (or skewed) wind flow and for situations where the wind speed changes with height (sheared). In response, NREL researchers changed how the main aerodynamics model of OpenFAST considers skew and shear based on an enhanced treatment of the underlying physics. The improved aerodynamics model was validated against reference solutions from a higher-fidelity, vortex-based method and resurface-resolved computational fluid dynamics.

Wake Effects on Fixed and Floating Offshore Wind Turbines Found To Be Similar

An NREL study of wake dynamics on floating offshore wind turbines revealed only subtle differences between fixed and floating systems, providing insight into the impact of floating offshore wind turbine wake interactions that will have growing importance as floating offshore wind energy advances. Wake effects reduce the power performance and increase the fatigue loading of land-based and fixed-bottom offshore wind turbines. Within a floating offshore wind power plant, increased motion and tilt of a floating wind turbine rotor could change wake deflection, evolution, and meandering compared to fixed-bottom offshore turbines. This new understanding will help improve the prediction of floating downstream wind turbines' motion, power, and structural loading. To conduct the study, NREL verified the engineering-fidelity FAST.Farm software for floating offshore wind turbine applications against high-fidelity modeling results. Researchers then used FAST.Farm to assess the impact of floating offshore wind turbine motion on wake dynamics and subsequent response of downstream turbines in a small floating offshore wind power plant relative to an equivalent fixed system. Next steps include further model improvements to FAST.Farm for floating offshore wind power plants and application of the tool to other floating wind turbines (including different turbine sizes and floater designs) and plant layouts.

Using FAST.Farm software, NREL researchers studied wake dynamics on floating offshore wind turbines, like the one shown here. The results will have growing importance as floating offshore wind energy advances.
Photo by Brent Rice, NREL 52798

Materials, Manufacturing, and Design Innovation

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

Program To Yield Pitch Bearing Reliability Insights

Industry interest in wind turbine drivetrain pitch bearing reliability is increasing as existing land-based wind power plants—with up to a 12% failure rate over a typical 20-year lifetime—age and new large offshore wind turbines—with high potential downtime for a bearing replacement—are installed. These reasons point to an increased need to describe the characteristics of pitch bearing operating conditions (such as deformations, load distributions, and contact stresses) and revise design and rating methodologies. NREL is taking a two-pronged approach to meet this need by a) installing instrumentation on a pitch bearing of the DOE 1.5-MW wind turbine and collecting operating data during the current wind season and b) working with Fraunhofer Institute for Wind Energy Systems and more than 20 wind turbine and pitch bearing suppliers to revise the original NREL-led pitch bearing design guideline.

Strain gauges installed on a pitch bearing of the DOE 1.5-MW wind turbine on NREL's Flatirons Campus will yield insights into pitch bearing reliability. *Photos from Jesse Graeter, Onyx Insight 85947 (left) and 85940*

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

Big Adaptive Rotor Program Offers New Insights on the Aeroelastic Modeling of Modern Wind Turbines

Modern wind turbines push the predictive capabilities of modeling tools used during design and analysis. The limitations of existing modeling tools can result in serious performance and safety issues for turbines. NREL's Big Adaptive Rotor project has focused on narrowing some of these modeling gaps. In the first half of FY 2024, researchers on the project concluded an experiment that aimed to accurately characterize the aeroelastic behavior of modern wind turbine blades. The team generated oscillations on a 2.8-MW land-based wind turbine and monitored the decay (gradual slowing and eventual ceasing) of the oscillations. The way blades oscillate informs the estimation of the turbine's structural damping, which refers to how much energy the wind turbine components absorb during movements. It is essential to quantify structural damping to successfully predict a turbine's aeroelastic behavior, or how turbines respond to the combination of aerodynamic forces from the wind and the flexibility of its components. The team observed that structural damping behaves differently than what common aeroelastic models predict. The team presented their findings at the TORQUE 2024 conference. The results of this experiment indicate that, moving forward, industry and academia will need to rethink mathematical formulations of structural damping and adopt more conservative approaches.

NREL researchers used the now-decommissioned GE 2.8-MW wind turbine to characterize structural damping of modern wind turbine blades. *Photo from GE Vernova*

MMDI Strategy Development

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

Roadmap Suggests Ways To Improve Offshore Wind Operations and Maintenance

Researchers from NREL and Sandia National Laboratories (Sandia) released the *Operations and Maintenance Roadmap for U.S. Offshore Wind Energy*, which highlights how U.S. offshore wind power plants can improve efficiency, cost-effectiveness, reliability, and performance. The roadmap was developed based on inputs collected through individual industry expert interviews, representing various sectors of the wind energy industry, and stakeholder engagement events, hosted in both the United States and Europe. Featuring topic areas such as digitalization, robotics and automation, and standards, the roadmap could help direct future offshore wind operations and maintenance research.

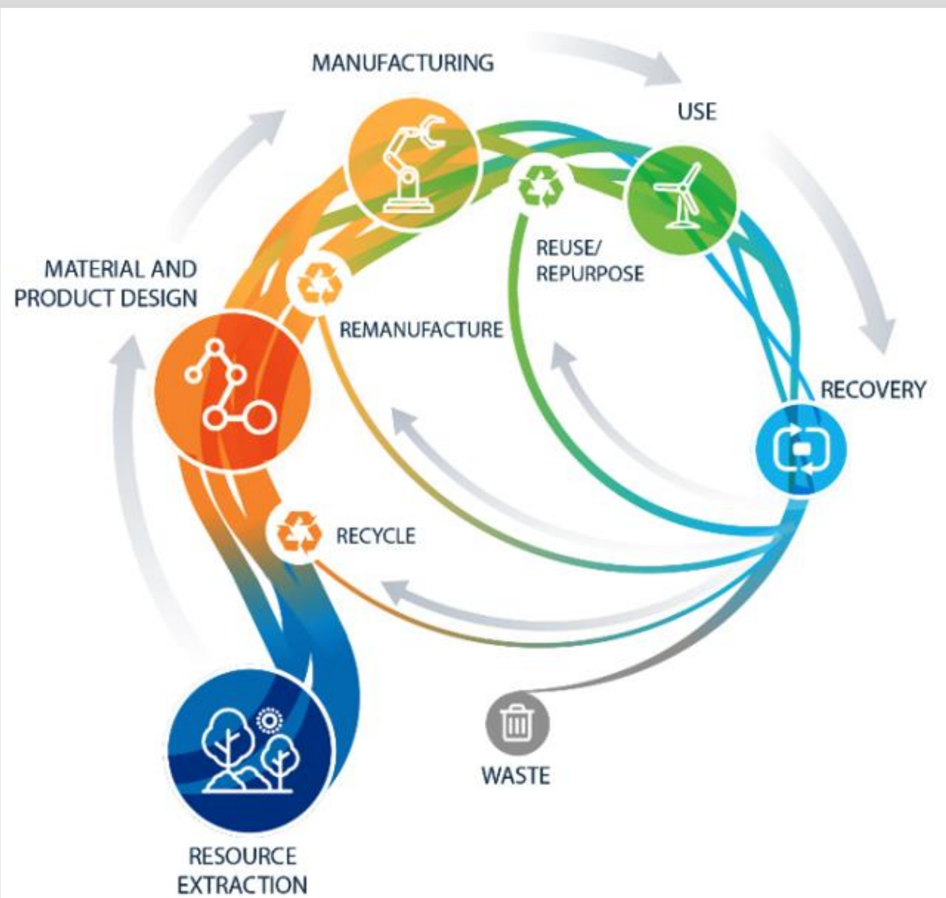
The *Operations and Maintenance Roadmap for U.S. Offshore Wind Energy* outlines ways the domestic offshore wind energy industry could improve operations and maintenance practices. *Photo from Lyfted Media for Dominion Energy*

Wind Technology Recycling Assessment

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

Enabling Future Wind Turbine Recycling Through Technology Assessment

A team of researchers led by NREL, and including Sandia and Oak Ridge National Laboratory researchers, are collaborating on DOE's Road Map for Recycling Wind Energy Systems in the United States, Part 1: Providing a Baseline for America's Wind Energy Recycling Infrastructure for Wind Turbines and Systems. The Wind Energy Recycling Assessment project performs strategic analysis to inform WETO of short-, medium- and long-term research, development, and demonstration recommendations along the life cycle of wind energy systems. These findings will help implement the $40 million Wind Energy Recycling Research, Development, and Demonstration Program under the Bipartisan Infrastructure Law. The research team interacted with a broad selection of U.S. and global wind energy industry partners to evaluate current industry practices and collect relevant data on materials, manufacturing processes, and infrastructure data that informed modeling and analysis efforts. In addition, this research project has helped identify opportunities for emerging recycling technologies that can provide the pathway to effective recycling of all wind turbine components in the near future. Part 2 of the recycling assessment report series is expected to be released by late summer 2024. The funding from this project also enables the United States to provide leadership on the IEA Wind Task 45 project, Wind Turbine Blade Recycling.



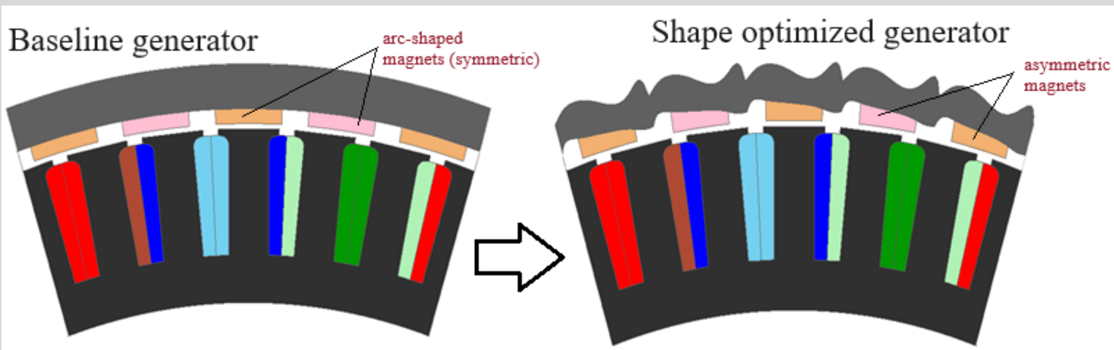
The Wind Energy Recycling Assessment project, led by NREL, and including Sandia and Oak Ridge National Laboratory researchers, provides research, development and demonstration investment recommendations to build a cost-effective, environmentally sustainable, and socially responsible U.S. wind energy recycling infrastructure. Assessment encompassed entire life cycles of wind energy materials. *Illustration by Alfred Hicks, NREL*

MADE3D

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

MADE3D Designs Could Reduce Dependence on Rare-Earth Minerals

Traditional design and manufacturing of wind turbine generators offer limited opportunities in reducing the use of rare-earth content. NREL's Manufacturing and Additive Design of Electric Machines enabled by 3-Dimensional Printing (MADE3D) team used Bezier curves to redesign the magnets for a 15-kilowatt baseline wind turbine generator. By experimenting with new shapes and arrangements, they found designs that performed better and could use up to 35% less rare earth element materials. These findings suggest that new, unexplored design freedom exists beyond the traditional limits of symmetry, which can be tapped by advanced manufacturing of wind turbine generators that are predominantly designed for unidirectional operation.



NREL researchers experimented with new magnet shapes and arrangements in a 15-kilowatt wind turbine generator magnets, finding designs that performed better and used fewer rare earth element materials.
Illustration by Latha Sethuraman, NREL

Wind Recycling Support Mod: 1

Point of Contact: Gunnar Tande, gunnar.tande@nrel.gov

Turbine Materials Recycling Prize Winners Pave a Path to a Sustainable Future

DOE announced the 20 winners of the first phase of the Wind Turbine Materials Recycling Prize, which is managed by NREL on behalf of DOE. The 20 winning teams, who represent 15 states, each received $75,000 and an invitation to advance to Phase 2, in which they will develop prototypes of their technologies and compete for the chance to win a cash prize of $500,000 and vouchers valued at $100,000 to work with DOE national laboratories. By awarding funding to designers of novel technologies and highly capable commercial entities, the Wind Turbine Materials Recycling Prize aims to:

- Extend the economic value of wind energy materials
- Accelerate development of a domestic recycling industry for key materials necessary for the clean energy transition
- Reduce waste from the wind energy industry
- Develop a recycling industry and workforce in an equitable and sustainable way.

The Wind Turbine Materials Recycling Prize, which ended its first phase with 20 awarded winners, aims to advance the development of a cost-effective and sustainable U.S. recycling industry for wind turbine materials. *Graphic by Joelynn Schroeder, NREL*

Grid Integration

Atlantic Offshore Wind Transmission Study

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

Researchers Identify Optimal Ways To Transmit Offshore Wind Energy to East Coast Communities

The Atlantic Offshore Wind Transmission Study is the most thorough analysis to date of how to bring offshore wind energy to areas of high demand along the Atlantic Coast via transmission lines. Considering the administration's goal of deploying 85 GW of offshore wind energy along the Atlantic Coast by 2050, the study identifies how to reduce grid congestion, increase reliability, maximize production, and lower costs for consumers while supporting a low-carbon future for East Coast communities from Maine to South Carolina. Developed over 2 years by NREL and PNNL researchers, the study also informed the concurrently released Atlantic Offshore Wind Transmission Action Plan, which was developed by the DOE's Grid Deployment Office and BOEM. The plan outlines immediate actions the United States can take to connect the first generation of Atlantic offshore wind power projects to the electric grid and how the country can increase transmission over the next several decades.

The Atlantic Offshore Wind Transmission Study evaluated multiple pathways and strategies for enabling offshore wind energy deployment along the U.S. Atlantic Coast, from Maine to South Carolina. *Photo from Getty Images*

WindVSG

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

Drivetrain Testing Highlights Potential for More Wind on Electric Grids

NREL and a team from GE conducted testing on a GE 2.5-MW wind turbine drivetrain installed on NREL's 5-MW dynamometer with the goal of estimating the loading and mechanical stress impacts on wind turbine drivetrain components when in grid-forming mode. Grid-forming mode is an operational state that can help provide stability to the grid as it transitions to 100% clean energy. The tests included demonstrating grid-forming wind turbine operation with modified controls under dynamic and transient conditions emulated by NREL's CGI. Researchers were able to characterize the performance of the components under various grid conditions imitated by the CGI, such as brief grid failures, and found that the drivetrain in grid-forming mode was able to operate stably. These tests show that wind turbines can successfully operate in grid-forming mode, paving the way to more reliably integrate high amounts of wind energy into the electric grid.

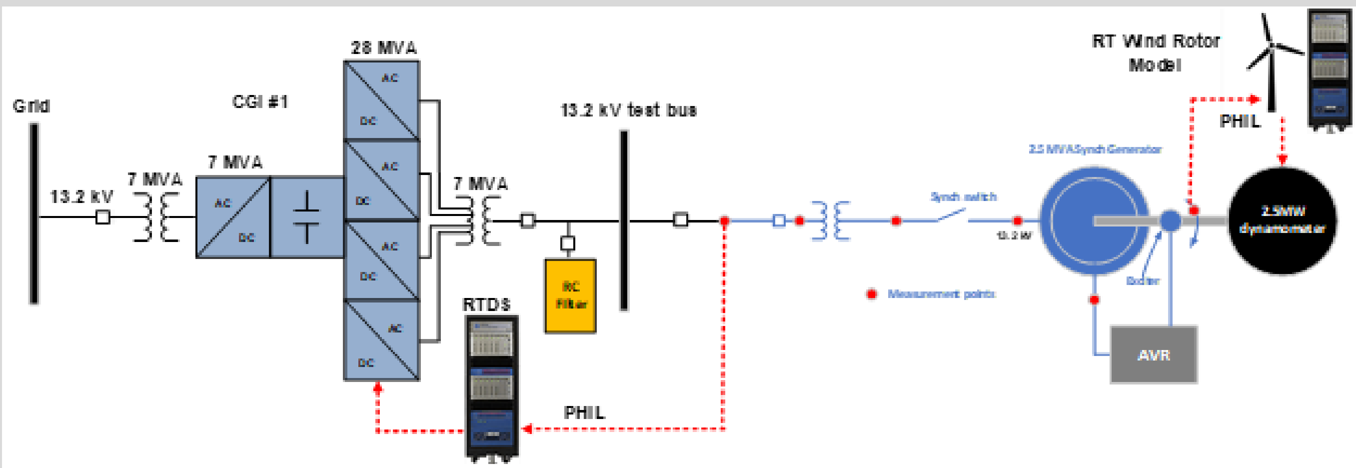
Researchers subjected GE's 2.5-MW wind turbine drivetrain, shown here attached to NREL's 5-MW dynamometer, to grid faults to test its stability in grid-forming mode. *Composite photo by Pat Corkery, Mark McDade, and Dennis Schroeder, NREL*

Wind as Real Synchronous Generator

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

Power-Hardware-in-the-Loop Testing Explores Type 5 Turbine Technology

A team of researchers from NREL and Idaho National Laboratory developed a real-time model of a full Type 5 wind turbine generator using a 2.5-megavolt-ampere synchronous generator installed on NREL's 2.5-MW dynamometer. Because the Type 5 wind turbine configuration has not been studied recently, the aim of this project was to demonstrate its potential to provide stability and resiliency to the power system when coupled with modern technology. The power-hardware-in-the-loop testing featured the real generator and excitation system paired with models of the wind rotor control and torque converter, and simulations from NREL's CGI. The project results are intended to demonstrate how Type 5 generators can offer an additional path to a more secure and reliable grid and to encourage wind turbine original equipment manufacturers to further investigate Type 5 turbine research and deployment.



The power-hardware-in-the-loop configuration, shown here, helped researchers demonstrate the benefits of the Type 5 wind turbine to the power system in terms of stability and resiliency. *Illustration by Vahan Gevorgian, NREL*

WindWEASEL

Point of Contact: Charlie MaGill, CMaGill@nrel.gov

Breakthrough Could Revolutionize Wind Energy System Security

Through the WindWeasel project, NREL, in collaboration with Sandia, has achieved 95% accuracy in detecting simulated wind energy system cyberattacks. This breakthrough has enormous significance for expanding wind energy nationwide. By providing technology to secure wind turbine controls and programmable logic controllers, NREL is enabling greater grid integration of intermittent wind resources. With stronger cybersecurity assurances, utilities can confidently deploy more wind energy capacity, and cyber-resilient wind power plants can take advantage of new revenue opportunities through secondary services, like frequency regulation. Hardening wind energy infrastructure against cyberattack intrusions directly supports DOE's vision of a flexible, resilient grid with high renewable penetration.

Point of Contact: Charlie MaGill, cmagill@nrel.gov

Tool Enables Precise Evaluation of the Wind Energy Industry's Cybersecurity Risks

NREL made a significant contribution to wind energy industry cybersecurity by establishing wind-energy-specific criteria within the Cybersecurity Valuation Framework. Through the WindSHIELD initiative, which is funded by WETO, NREL identified and incorporated the unique factors necessary for performing wind cybersecurity valuation, enabling more precise and relevant evaluation of wind energy industry cybersecurity risks. This achievement will not only improve the industry's understanding of cyberattack risks but also help develop effective mitigation strategies, furthering the project's goal of enhancing cybersecurity within the wind energy industry.

NREL researchers are improving wind energy industry cybersecurity through the WindSHIELD program. *Photo by Dennis Schroeder, NREL*

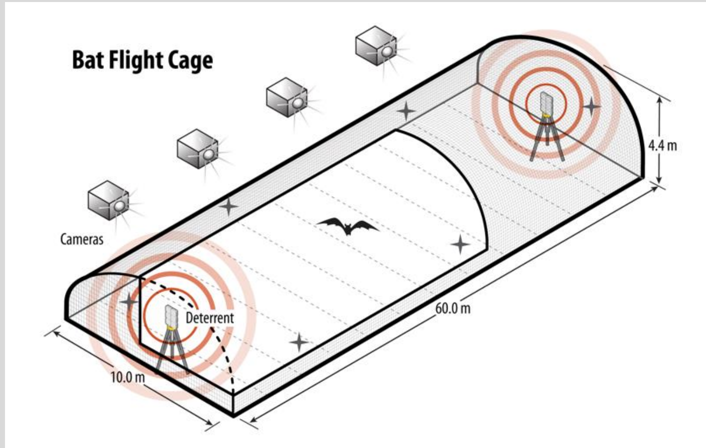
Environmental Research

Evaluating Advanced Ultrasonic Acoustic Deterrent (NREL)

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

Bats' Responses to Ultrasonic Signals May Enable More Effective Deterrent Technology

NREL researchers, in collaboration with Texas State University, Bowman Consulting, Wildlife Imaging Systems, and Western EcoSystems Technology, published a journal article on how bats respond to ultrasounic signals intended to deter them from approaching wind turbines. In the study, the research team released individual bats in a large flight cage and used thermal video cameras to observe the bats' flight response during trials of three different ultrasonic signals. The team observed that the five bat species responded differently to the ultrasonic signals. The results of this study may support the development of more effective ultrasonic deterrent technologies that can target specific species that are at risk of wind turbine collisions.



NREL researchers used a flight cage and thermal video cameras, illustrated here, to assess bat flight behaviors during three different ultrasonic signals. *Graphic by John Frenzl and Al Hicks, NREL*

U.S. Offshore Wind Synthesis of Environmental Effects Research (SEER)

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

New Tool Provides Insight Into Pacific Offshore Wind Energy Environmental Research

As the United States nears offshore wind energy deployment off the Pacific Coast, project developers, natural resource managers, and community leaders need to consider the potential environmental impacts of this development. To consolidate and track recently completed and ongoing wildlife research in this region, the U.S. Offshore Wind Synthesis of Environmental Effects Research team, a partnership between NREL and PNNL, released the Pacific Coast Offshore Wind Environmental Research Project Finder. The web-based tool provides key details on existing and upcoming research projects and includes links to reports and datasets.


A new tool from NREL and PNNL offers insight into research on the impacts of offshore wind energy on wildlife, like this northern gannet, off the U.S. Pacific Coast. *Photo from iStock 936363260*

Wind Operational Issue Mitigation

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

Webinar Series Tackles the Complexity of Compensating for the Environmental Impacts of Wind Energy

NREL, in partnership with the Renewable Wildlife Research Institute, hosted a four-part webinar series focused on the complexity of efforts to offset negative environmental impacts of wind energy development—a practice known as compensatory mitigation. Speakers, who included researchers, state and federal agencies, members of private industry, and nongovernmental organizations, discussed the latest research and effective strategies to offset the direct and indirect impacts of wind energy on wildlife and habitats. The series, which exceeded 700 attendees across all four webinars, reviewed the existing regulations and provided examples on how to apply compensatory mitigation in the context of wind energy development.

Some wind energy project developers use a practice called compensatory mitigation to counterbalance any negative impacts wind energy development may have on wildlife, like this greater sage-grouse. *Photo from LuRay Parker, Wyoming Game and Fish*

Stakeholder Engagement and Wind Energy Workforce

Wind Energy Equity Engagement Series (WEEES)

Point of Contact: Clara Houghteling, Clara.Houghteling@nrel.gov

Listening Sessions Elevate Community Perspectives on Wind Energy Equity

Energy equity and community engagement have gained increasing attention from wind energy developers, researchers, and policymakers in recent years, but understanding community members' lived experiences is essential to implementing these concepts in the real world. Through listening sessions held in the summer and fall of 2023 as part of the NREL-led Wind Energy Equity Engagement Series, NREL researchers collected diverse perspectives on wind energy equity in three communities across the country. More than 80 community members attended the listening sessions, which were co-designed and co-hosted with local organizations in Bloomington-Normal, Illinois; Elizabeth City, North Carolina; and Gallup, New Mexico. Attendees discussed their experiences with wind energy projects near them, sharing their perspectives as rural farmers, marine industry occupational trainers, local government workers, parents, environmental protectors, Indigenous elders, and community members. NREL has presented findings from the sessions at two conferences and in a published technical report on the project.

A group of community members discussed wind energy equity at a listening session in Bloomington-Normal, Illinois, in fall 2023. *Photo from Amanda Pankau, Prairie Rivers Network*

Point of Contact: Frank Oteri, Frank.Oteri@nrel.gov

Community Meetings Offer Perspectives About Wind Energy End of Service

After hosting community listening sessions in Lincoln, Nebraska; Woodward, Oklahoma; and Benton County, Indiana; NREL completed the final phase of its Community and Stakeholder Engagement End of Life perspectives project, funded by the Bipartisan Infrastructure Law. These listening sessions were focused on developing a better understanding of community perception and needs related to the decommissioning, repowering, and component processing of land-based wind energy projects. The events were organized with the help of Purdue Extension Services, the Oklahoma Renewable Energy Council, and Nebraska Extension Services, and covered more than 10 hours of in-person engagement. Along with the stakeholder interview and roundtable phases of the project, NREL spent more than 55 hours on direct engagement, the results of which were summarized for WETO to inform ongoing, community-focused end-of-service resource development and engagement efforts.

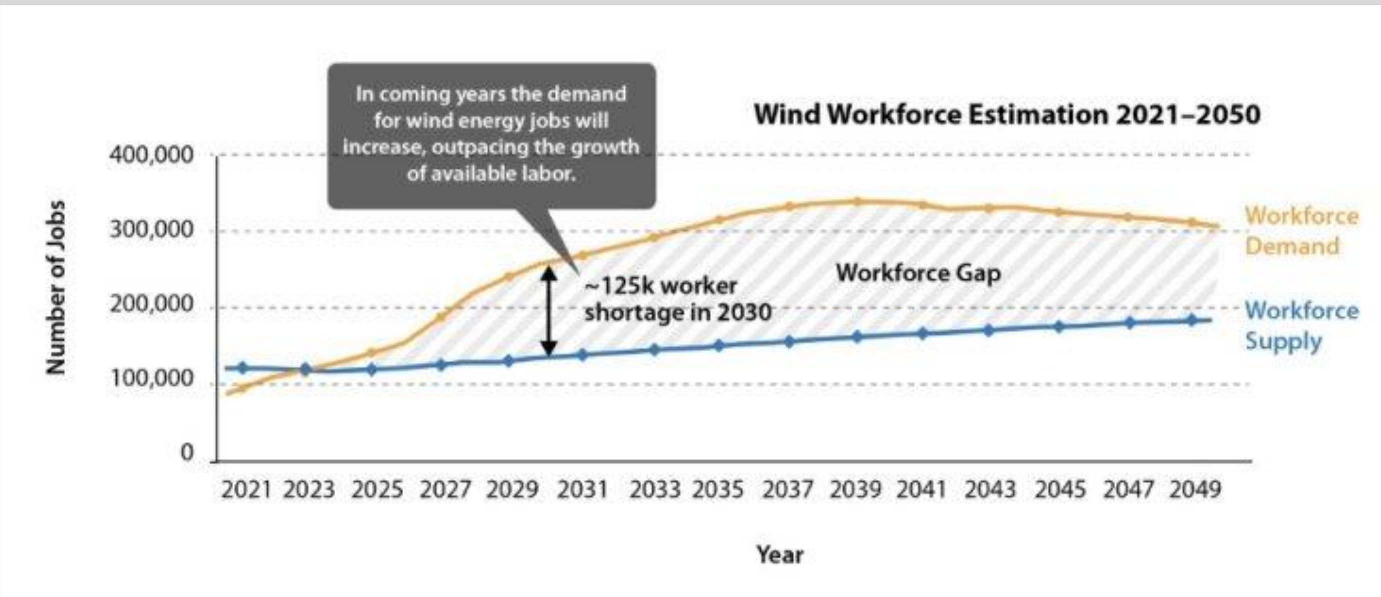
Community members participate in the Indiana End of Service listening sessions hosted by NREL and Purdue Extension Services. *Photo by Matilda Kreider, NREL*

National Assessment of Wind Workforce

Point of Contact: Brinn McDowell, bmcdowel@nrel.gov

Report Defines Ways To Bridge the Wind Energy Workforce Gap

Building on past research, NREL used an innovative system dynamics model to evaluate the root causes of the U.S. wind energy workforce gap and identify ways to close it. The *National Wind Workforce Assessment: Challenges, Opportunities, and Future Needs* report provides industry and educators with the information they need to develop the workforce and tackle hiring challenges. The report outlines and assesses dynamic scenarios stemming from a business-as-usual case to understand and evaluate how indirect effects of the Inflation Reduction Act and changing perceptions of the industry can impact the demand and supply of wind energy workers.

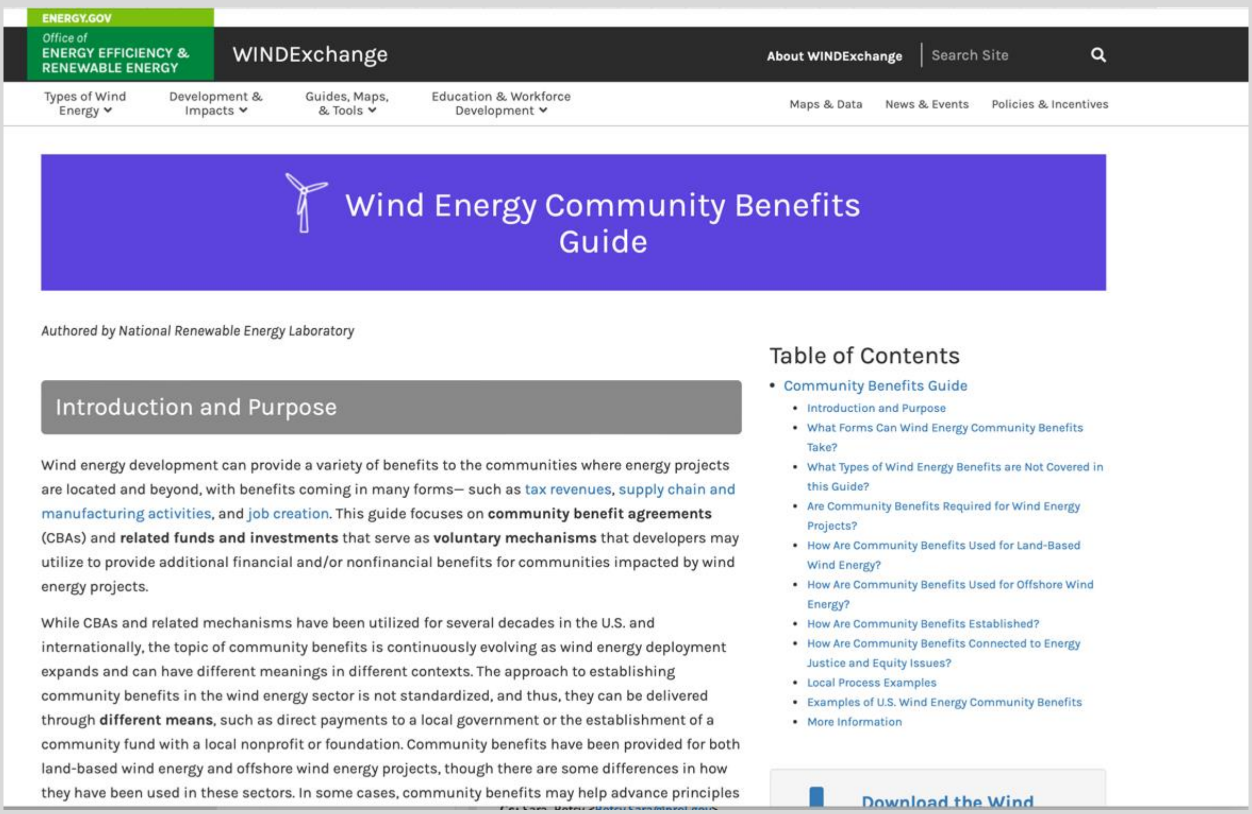


A graphic from the *National Wind Workforce Assessment: Challenges, Opportunities, and Future Needs* report highlights how the demand for wind energy jobs from 2021 to 2050 is expected to outpace the supply of wind energy jobs, resulting in a workforce gap. *Graphic by John Frenzl, NREL*

Point of Contact: Matilda Kreider, mkreider@nrel.gov

Guide Helps Communities Understand Wind Energy Benefits

NREL's Wind Energy Community Benefits Guide on DOE's WINDExchange platform is designed to help communities better understand how they can benefit from and become involved with wind energy. The guide provides information about land-based and offshore wind energy community benefits, such as tax revenues, supply chain and manufacturing activities, and job creation. NREL developed the guide by conducting a series of interviews with community and industry members, government and nongovernment officials, and researchers; collecting examples of community benefit agreements across the United States; reviewing literature; and hosting a peer exchange workshop convening 20 community and Tribal leaders and other interested parties working on community benefits for offshore wind energy. Following the publication of this guide, NREL hosted a community benefits webinar in February 2024 and launched a study exploring national community benefit use trends, which will be conducted throughout 2024.



The Wind Energy Community Benefits Guide offers information about how communities can benefit from land-based and offshore wind energy. *Screenshot by Matilda Kreider, NREL*

Collegiate Wind Competition

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

Collegiate Wind Competition Helps Prepare College Students to Breeze into the Clean Energy Workforce

In FY 2024, the Collegiate Wind Competition, which NREL manages on behalf of DOE, continued to help college students prepare for jobs in wind and renewable energy through hands-on, real-world experience. The competition organizers selected 12 multidisciplinary student teams to represent their colleges and universities at the competition's 11th annual final event, which was held in conjunction with the American Clean Power Association's CLEANPOWER Conference and Exhibition in Minneapolis. At the event, the teams tested model wind turbines in an onsite wind tunnel; presented wind turbine designs, wind energy project development plans, and outreach efforts to panels of wind industry experts; and connected with members of the renewable energy industry who attended the conference. The event culminated with an awards ceremony, where California State University Maritime Academy claimed awards for first place overall and for the Turbine Testing Contest. Over 150 students participate in the competition each year, collaborating across disciplines and gaining valuable experience with wind energy technology, project development, and outreach, which they can apply to their future careers. Since the competition's 2014 launch, over 40 U.S. colleges and universities have participated in the event, hundreds of companies have partnered with the competition to provide mentorship and support, and over a hundred competition alumni have landed jobs in the renewable energy sector.

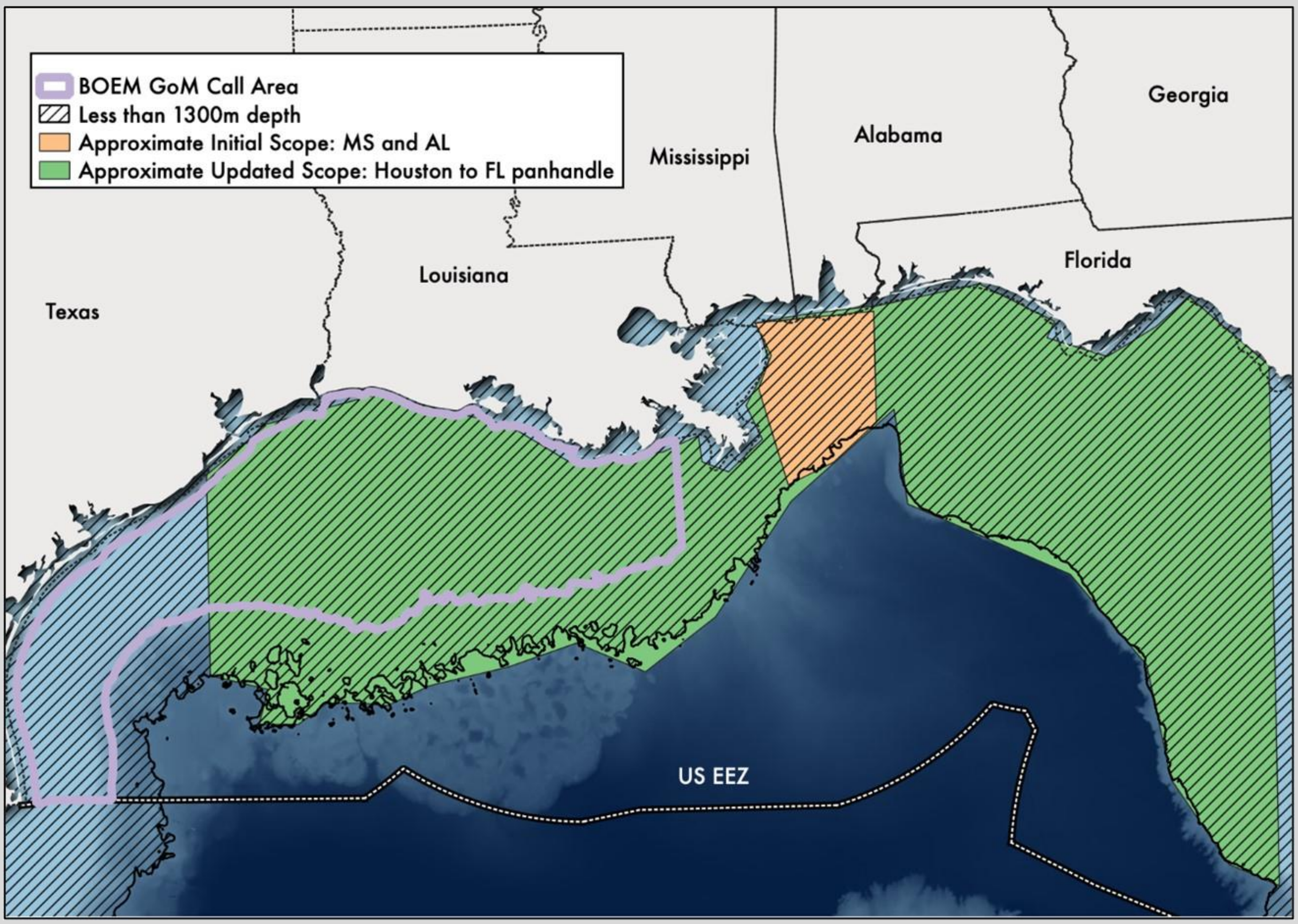
The Collegiate Wind Competition continues to prepare participants for jobs in clean energy through hands-on, real-world experience. The California State University Maritime Academy (pictured above) won awards for first place and for the Turbine Testing Contest at the competition's 2024 final event. *Photo by Mark McDade, NREL*

Modeling and Analysis

Point of Contact: Owen Roberts, Owen.Roberts@nrel.gov

NREL Performs Techno-Economic Assessment of Offshore Wind Energy Potential in the Gulf of Mexico

NREL researchers developed a techno-economic assessment for deploying offshore wind energy in waters in the Gulf of Mexico, spanning coastline from Houston to the Florida Panhandle. The analysis was performed on behalf of energy utility Southern Company Services (SCS) to help them identify ways to meet their goal of achieving net-zero greenhouse gas emissions by 2050. The assessment aimed to characterize the spatial variations of offshore wind power plant costs and performance, potential siting constraints, and costs to connect the plants to the grid. In coordination with SCS technical staff, the NREL team took a wide variety of variables into account to create scenarios that employ offshore wind energy technologies that are projected to be available by either 2030 or 2035. The resulting data were provided to SCS for use in their planning and capacity expansion models. This work was modeled after a previous effort between NREL and SCS that resulted in an offshore wind techno-economic analysis of the federally controlled waters off the coast of Georgia.

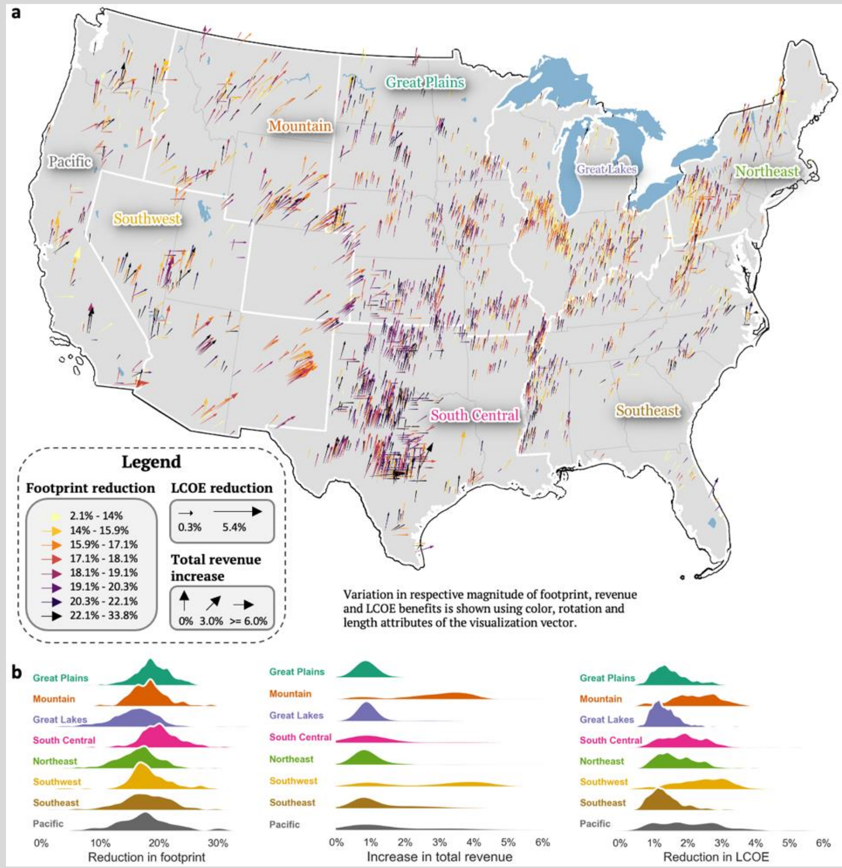


A map of the area in the Gulf of Mexico covered in this techno-economic assessment by NREL researchers. *Image by Gabriel Zuckerman, NREL*

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

Study Employs Artificial Intelligence To Identify Substantial Benefits of Wake Steering

As soon-to-be documented in a publication accepted to *Nature Energy*, NREL researchers used artificial intelligence to evaluate the benefits of wake steering at more than 6,800 plausible land-based wind energy locations in the United States. Their scalable approach for plant-level optimization considered an array of objectives, including land use, LCOE, and net revenue. Using the artificial intelligence model to compare controls co-design (i.e., joint-layout and wake-steering optimization) to a reference design (i.e., layout only), researchers found that wake-steering strategies can reduce land requirements by an average of 18% per plant, with site-specific benefits ranging from 2% to 34%. They also found that wake steering is predicted to increase power production during high-value (often low-wind) periods, boosting individual plant annual revenue by up to $27,000/MW of installed capacity. Importantly, this artificial-intelligence-based approach provides national-scale insights for the potential impact of wake-steering technology while maintaining a granular perspective that can reveal the regional variability of these benefits (e.g., while the western United States demonstrates the greatest potential benefit for wake steering to lower costs, the central region could see significant land savings.)



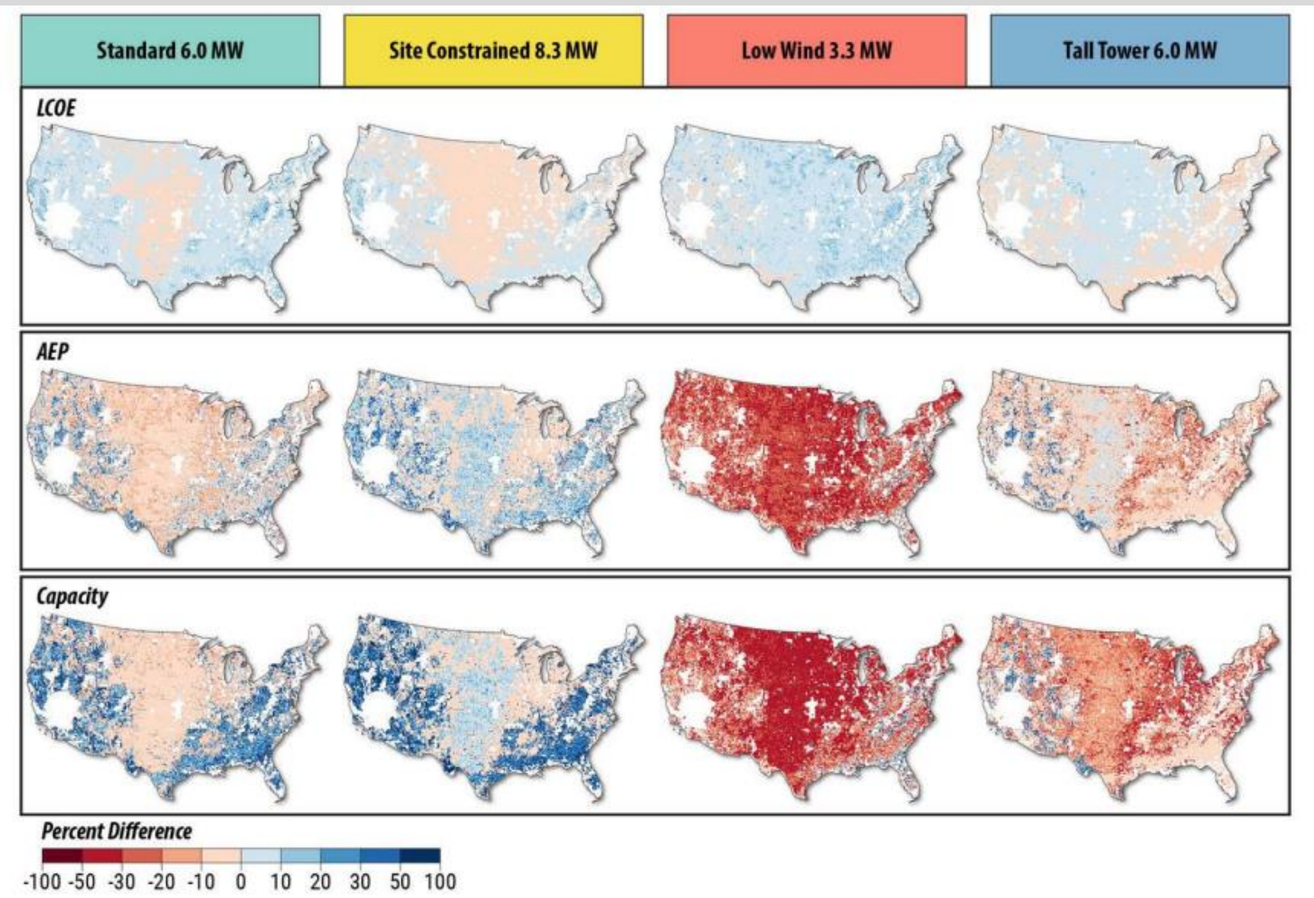
Researchers used artificial intelligence to identify how use of wake-steering technologies could reduce a wind power plant's footprint, decrease the LCOE, or increase the plant's revenue. *Graphic by Dylan Harrison-Atlas, NREL*

Wind Plant Technology Characterization, Spatial Analysis, Energy Sector Modeling and Analysis

Point of Contact: Annika Eberle, Annika.Eberle@nrel.gov

New Modeling Approach Facilitates Location-Specific Turbine Choices To Increase Deployment

NREL researchers developed a wind potential assessment for the United States using a new methodology that spatially optimizes wind turbine placement by considering technology design, plant layout, and the vast array of regulatory, land use, and infrastructure conflicts that exist in today's environment. This project highlights wind technology's unique ability to be sighted in and among the built and natural environments while acknowledging the substantive constraints that siting challenges impose. The new methodology shows that current wind energy technology has a capacity potential of 7.8 terawatts across 3 million square kilometers (km^2) of land, which could grow to 11.9 terawatts on just 2.6 million km^2 of land with modest continued technology improvements. But uncertainty in siting could reduce developable land down to 0.76 million km^2—potentially reducing wind energy's potential role as a backbone of the zero-carbon energy system.

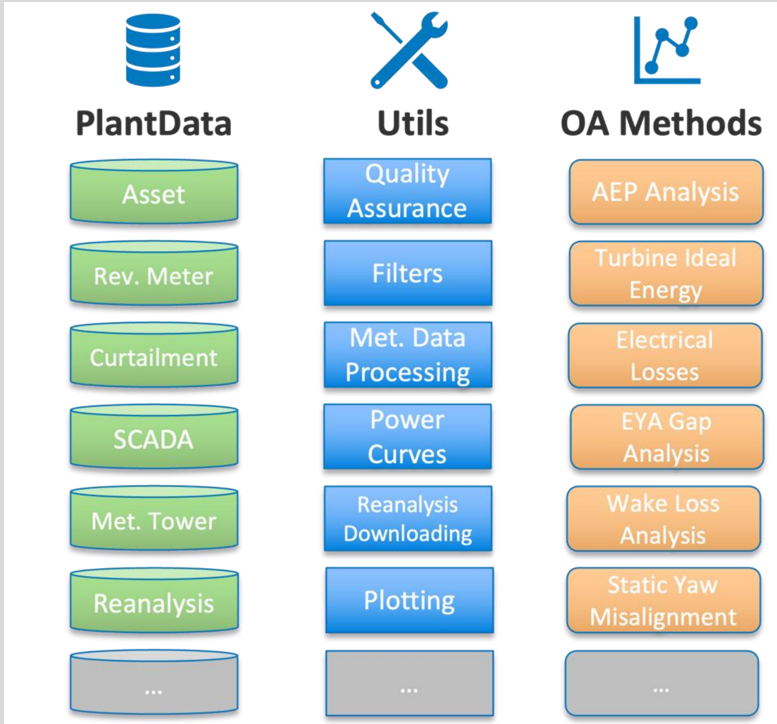


NREL's updated modeling tools demonstrate the differences in capacity, annual energy production, and LCOE in 2030 of a common turbine technology relative to a customized turbine choice scenario. *Graphic by Billy Roberts, NREL*

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

New Capabilities Added to Wind Power Plant Operational Assessment Software

NREL's Open Operational Assessment (OpenOA) software is an open-source tool for assessing the performance of wind power plants using operational data. The code was developed to support the NREL-led Wind Plant Performance Prediction Benchmark project, which focuses on quantifying differences between the expected and actual energy production of wind power plants in North America. OpenOA contains a library of analysis methods that can help users estimate the expected long-term operational energy production from wind power plants and identify causes of gaps between expected and actual energy yield. In fall 2023, NREL released version 3 of OpenOA, which includes several new analysis capabilities and makes the code more user-friendly. Specifically, the new version includes methods for estimating the operational wake losses experienced by wind plants and the amount by which individual wind turbines are misaligned with the wind. In response to feedback from industry stakeholders, the newest version of OpenOA also features a simplified process of importing and validating the operational data needed to assess wind plant performance. These improvements will help OpenOA continue to provide reference implementations of important operational assessment methods for the wind energy industry.



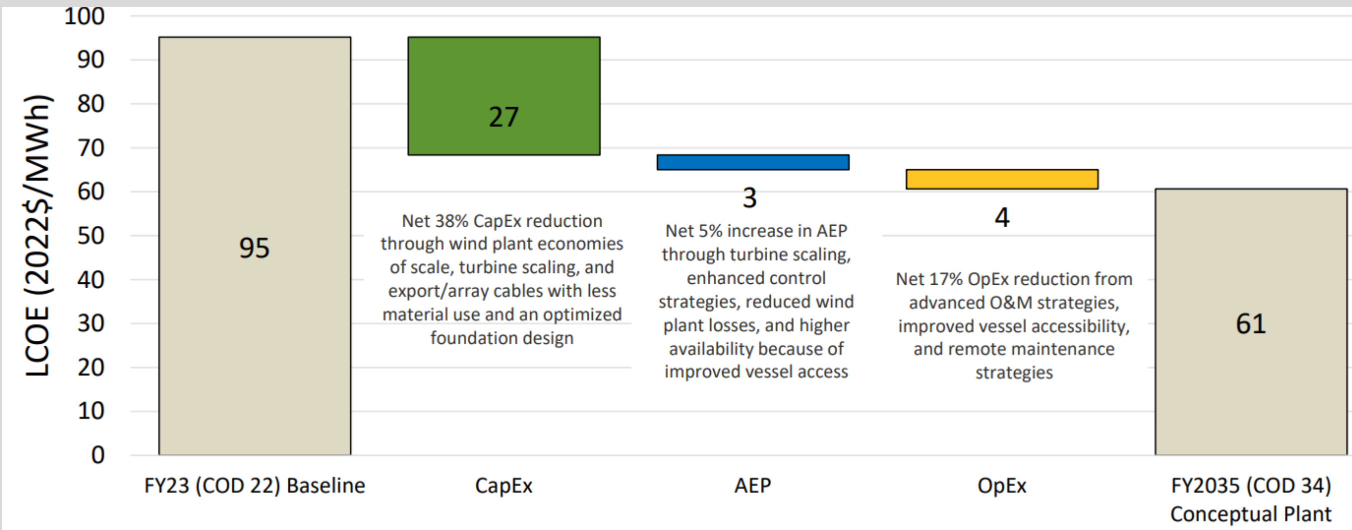
The OpenOA software features a variety of operational wind power plant data, utilities toolkits, and core operational assessment (OA) methods, which now include wake loss and static yaw misalignment. *Graphic by Eric Simley, NREL*
Note: SCADA = supervisory data and acquisition; met = meteorological; AEP = annual energy production; EYA = Energy Yield Assessment

Data Collection and Annual Reporting

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

NREL Updates Annual Cost of Wind Energy Review

NREL published the 2023 Cost of Wind Energy Review, which estimates LCOE for representative land-based wind and offshore wind energy projects. These estimates are widely used throughout the wind community to understand key cost factors. The LCOE estimates include insights based on software development, model improvements, and bespoke wind plant and annual technology baseline project efforts, and will provide new insights into the relative cost values of components needed for projects to qualify for domestic content bonuses from the Inflation Reduction Act.

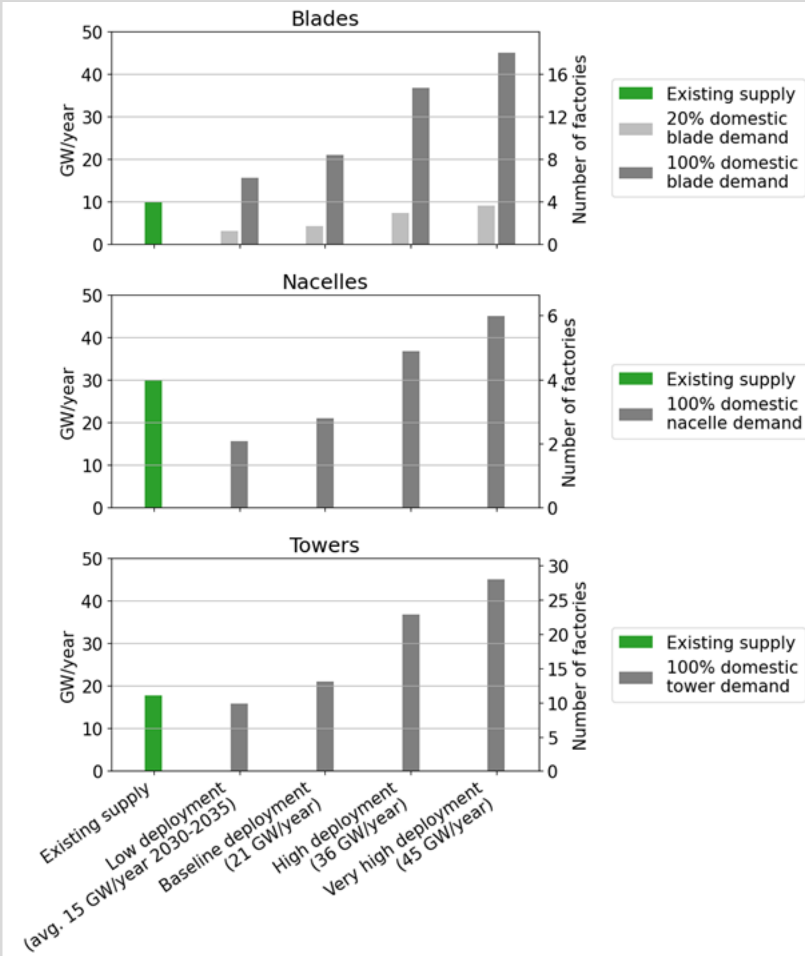


The 2023 Cost of Wind Energy Review demonstrates how LCOE of fixed-bottom offshore wind energy, including capital expenditures (CapEx), annual energy production (AEP), operational expenditures (OpEx), and commercial operations date (COD), are projected to decrease from $95 per megawatt-hour (MWh) in 2022 to $61/MWh in 2034 based on 38% reductions in capital costs, 5% increases in annual energy production, and 17% decreases in operational expenditures. *Graphic by Tyler Stehly, NREL*

Point of Contact: Owen Roberts, Owen.Roberts@nrel.gov

NREL Analyzes the Impact of the Inflation Reduction Act on Land-Based Wind Energy Cost and Domestic Manufacturing

Embedded in the Inflation Reduction Act was the creation of two incentives designed to accelerate domestic production and procurement of wind turbine components. The domestic content bonus rewards wind project developers that acquire 40%–55% of qualifying components domestically, whereas the advanced manufacturing production tax credit provides a tax credit to the manufacturer of qualifying components. An NREL study found that the advanced manufacturing production tax credit could lead to a 15%–33% reduction in the cost of domestic components, potentially making them more cost competitive with imported components. Under baseline deployment scenarios (21 GW/year), manufacturers could likely obtain the domestic content bonus using components from existing manufacturing facilities in the United States. The study found, however, that increasing deployment to 36–45 GW/year could require an additional one to two nacelle manufacturing facilities, 12–17 tower facilities, and 10–14 blade facilities.

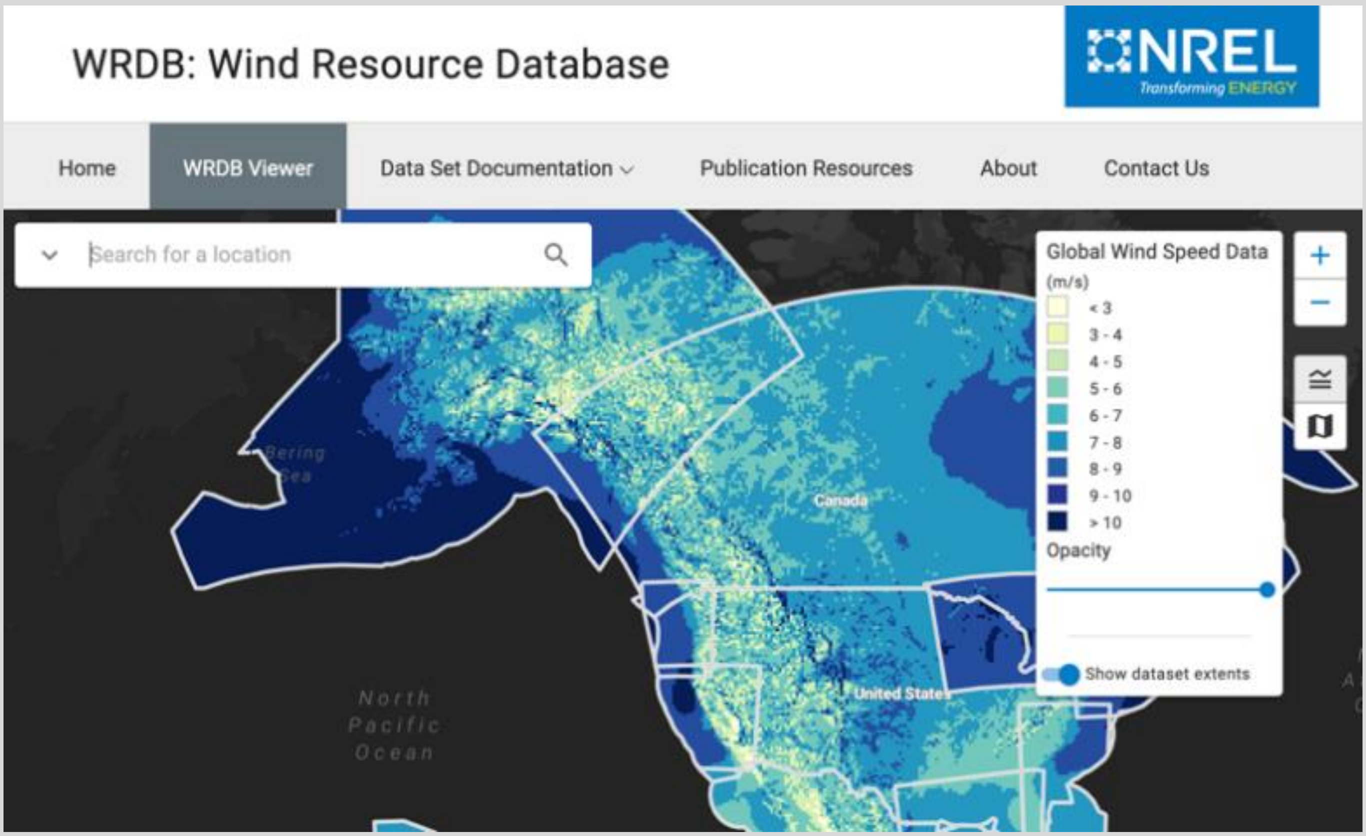


An NREL study mapped out average 2030–2035 component supply and demand for deployment scenarios ranging from 15–45 GW/year. New manufacturing facilities would be required for most projects to obtain the domestic content bonus from the Inflation Reduction Act for high or very high deployment rates. *Graphic by Paula Perez, NREL*

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

Public Wind Resource Database Offers Key Data for Developers Around the World

NREL launched the Wind Resource Database, an online platform that provides public access to massive amounts of data on the atmospheric forces that affect wind turbine performance, informs wind power plant development, and increases energy capture. The platform offers more than a petabyte of detailed wind resource and climate data covering the United States and other countries, which can help developers identify ideal sites for wind power plants. Designed for a diverse audience, the Wind Resource Database includes interactive maps and a simplified data retrieval process, providing a user-friendly experience—all at no cost. NREL also hosted a workshop with key stakeholders and experts to discuss next steps for continuing to improve the capabilities and applicability of the database.



The new, easy-to-use Wind Resource Database offers public access to more than a petabyte of detailed wind resource data in the United States and other countries. *Screenshot by Caroline Draxl, NREL*

Programmatic Support

NREL Technology Management and Support

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

Effective Programmatic Support Enhances Wind Energy Research Impacts

NREL's wind energy program actively manages a diverse project portfolio that advances technologies for offshore, land-based, and distributed wind energy, as well as wind energy's integration with the electric grid. NREL supports WETO's main objectives of achieving aggressive cost reductions, addressing environmental and siting challenges, providing grid services, ensuring cybersecurity, and advancing hybrid systems. To help the United States meet the significant acceleration and scale-up of wind energy deployment needed to achieve carbon-free electricity by 2035 and net-zero greenhouse gas emissions 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:

- Coordinating development of international research strategies through the IEA Wind Executive Committee and accelerating national renewable energy goals through DOE's Floating Offshore Wind ReadINess Prize and the Wind Turbine Materials Recycling Prize
- Increasing the impact of WETO's mission through strategic engagement with key wind energy stakeholders, fostering innovative and integrative programs, and establishing a unique, portfoliowide perspective
- Managing high-level executive outreach and engagement efforts to amplify the office's research and development portfolio
- Leading technology-to-market initiatives that create pathways for market readiness and resource access, including supporting projects funded through DOE's Technology Commercialization Fund, and providing three NREL research teams opportunities to strengthen U.S. competitiveness through the Energy I-Corps program
- Providing support to NREL's Flatirons Campus and NREL's ARIES research platform through the development of state-of-the-art equipment and facilities that enable fundamental wind energy research and innovative, integrated renewable energy solutions.

Editorial Support

Point of Contact: Pardeep Toor, Pardeep.Toor@nrel.gov

Editorial Support

In FY 2024, the NREL wind energy program's communications team collaborated with the WETO communications team to produce editorial content, including "Three Reasons Our Team Loves Wind Energy," "Wind Farms of the Future Will Be More Powerful and Quieter," and "Make Wind Energy a Community Affair this Holiday Season." Additionally, the communications team is working on completing articles for the Spring 2024 R&D Newsletter.

Non-AOP

BOEM HQ Interagency Agreement: Vessel Supply, Demand Analysis, and Tracking

Point of Contact: Daniel Mulas Hernando, Daniel.MulasHernando@nrel.gov

NREL Tracks Vessel Gaps To Help Chart a Course for U.S. Offshore Wind Energy Industry Growth

NREL researchers analyzed the supply and demand for U.S. offshore wind energy construction vessels based on empirical industry data. The team presented these estimates at the American Clean Power Association's 2023 Offshore WINDPOWER Conference. As of September 2023, the Vessel Tracker forecasted gaps of three to four wind turbine installation vessels, three to four service operation vessels, and seven to 11 crew transfer vessels by the beginning of 2026. In recent months, the U.S. offshore wind energy pipeline has seen several changes, necessitating an ongoing effort to update estimates for the demand of these vessels. NREL developed these estimates in collaboration with the BOEM. The insights developed by NREL could help the industry plan for the number of additional U.S.-built or international offshore wind vessels needed to meet the projected demand for the pipeline of projects during the 2020s and 2030s.

At the American Clean Power's 2023 Offshore WINDPOWER Conference, (from left to right) NREL researchers George Hagerman and Daniel Mulas Hernando, along with Brigitte Hagen-Peter of New Wave Offshore Energy and Jonathan Lints of Clarksons Offshore & Renewables, presented supply and demand forecasts, which were found using NREL's Vessel Tracker tool, for offshore wind energy construction vessels. *Photo by Megan Eddings, New Wave Offshore Energy*

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

WAVES Software Illuminates the Life Cycle Costs of Offshore Wind Energy Projects

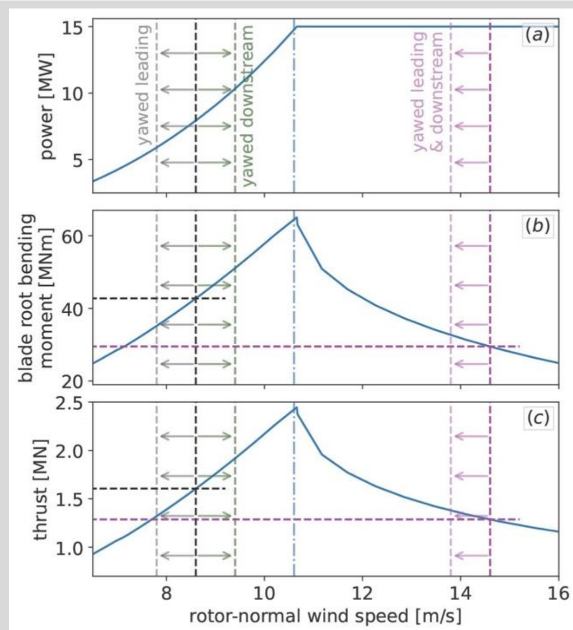
NREL researchers unveiled the Wind Asset Value Estimation System (WAVES) tool, which helps users estimate the life cycle costs and generation performance of offshore wind energy projects. Developed with support from BOEM, WAVES integrates other NREL techno-economic models for capital expenditures, operational expenditures, and annual energy production estimates, like the Offshore Renewables Balance-of-system and Installation Tool, the Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT), and FLORIS, respectively. WAVES enhances NREL's modeling suite by enabling users to quickly estimate the LCOE for diverse offshore wind energy project scenarios without the need for complex and error-prone processes.

Shell Offshore Wind

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

Study Investigates Use of Wake Steering for Wind Turbine Load Reduction

Wake steering is the act of deflecting a wind turbine's yaw setting away from the incoming wind direction to steer the wake away from downstream turbines in the array. Wake-steering technology, which is typically implemented when wind speeds are below the rated speed of the turbine, can increase power production of a wind power plant at the cost of increased load cycles or oscillations that shorten the total lifetime of the turbine and, therefore, plant. In this study, NREL researchers investigated if using wake steering at higher wind speeds—above the rated wind speed of the turbine—could reduce load cycles on the downstream turbines when power production is maximized for every wind turbine in the plant. Researchers simulated a sweep of wind directions and yaw misalignment angles, ranging from negative to positive values. The team found that load oscillation could be reduced by up to 5% (depending on the component) by yawing the turbine toward negative angles. However, other yaw angles, which would naturally occur during operation, could instead increase the load oscillations, making this an undesirable operational strategy. This result differed from the original hypothesis, which anticipated load oscillation reductions for all angles, and is therefore a helpful guide to inform wind power plant operation. The results of the study were presented at the TORQUE conference in May 2024.



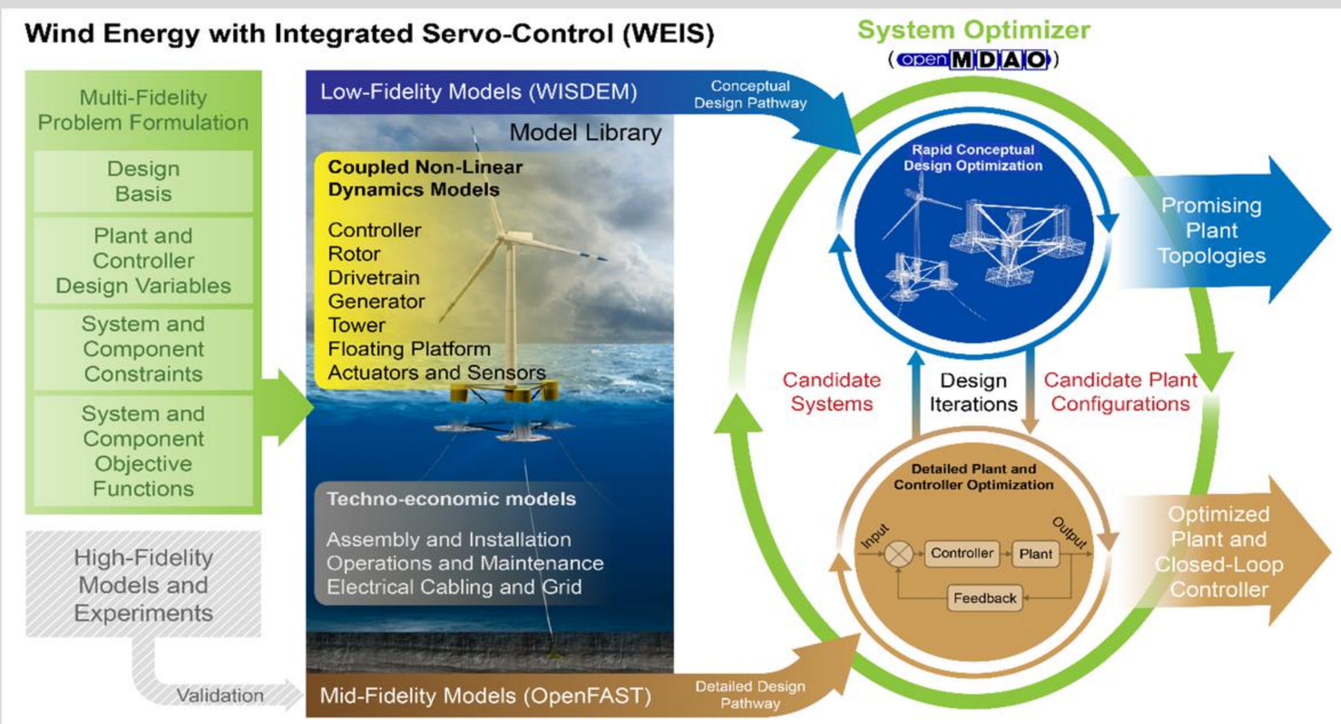
An NREL team studied the performance curves for the IEA Wind 15-MW reference turbine and identified the effects of wake steering via yaw misalignment on downstream turbines. *Graphic by Regis Thedin, NREL*

Wind Energy with Integrated Servo-control (WEIS): A Toolset To Enable Control Co-Design of Floating Offshore Wind Energy Systems

Point of Contact: Daniel Zalkind, Daniel.Zalkind@nrel.gov

Updates to the Wind Energy With Integrated Servo-Controls Program Expand the Tool's Capabilities

The Wind Energy with Integrated Servo control (WEIS) program began a new phase of development on its user-friendly, open-source, flexible, and modular toolset that enables the design, simulation, and analysis of floating offshore wind turbines. Initial efforts are aimed at improving the user experience, expanding the tool's modeling capabilities and adding modularity so that users can adapt WEIS to their existing workflows. To understand potential users' needs, the WEIS team interviewed representatives from 15 companies, including wind turbine manufacturers, plant developers, floating platform designers, consultants, and certification agencies. The findings from these interviews will be used to guide WEIS development priorities and demonstrate how the tool can be used to enable collaboration, shorten project timelines, and design cost-effective floating offshore wind turbines.

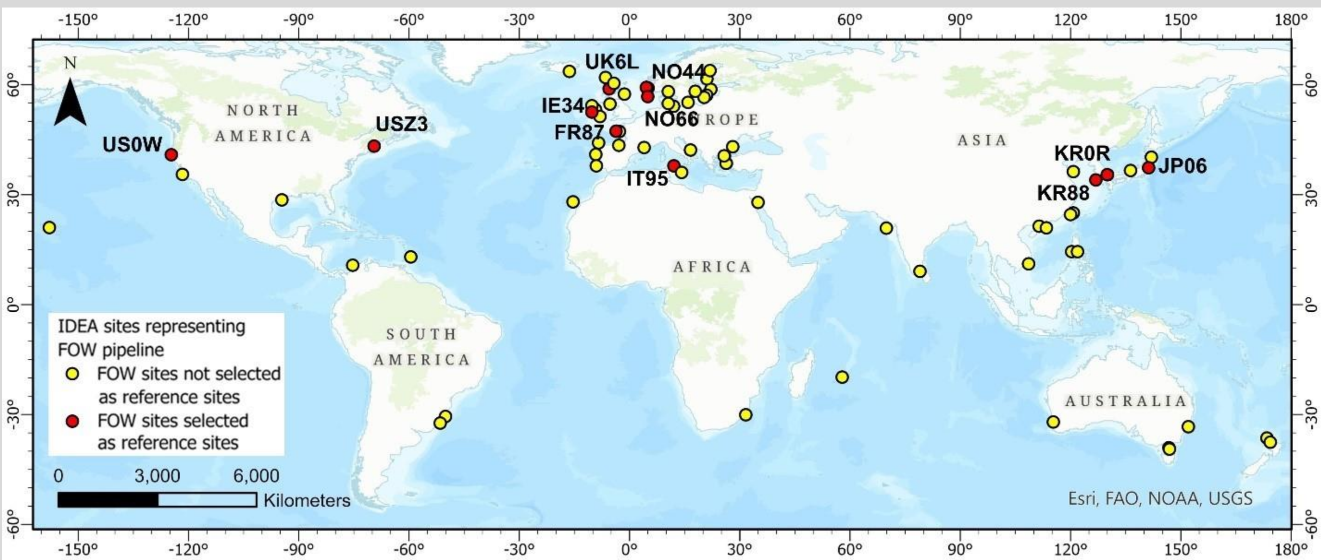


The WEIS toolset combines multiple modeling fidelity levels (such as the Wind-Plant Integrated System Design & Engineering Model [WISDEM] on the high end and OpenFAST on the low end) into an integrated design environment, in which floating offshore wind turbines and their controllers can be fine-tuned and optimized. *Illustration from WEIS team, NREL*

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

NREL Contributes Floating Wind Power Plant Reference Site Conditions and Design Considerations to Task 49

IEA Wind Task 49 aims to advance the global development of floating wind energy technology by addressing challenges and opportunities that arise when designing multiple-turbine power plants. Members of the task are gathering data and developing benchmark designs for floating wind energy development that will facilitate future research. The task has assembled a global collection of reference site conditions including from NREL researchers who contributed data for Humboldt Bay and the Gulf of Maine, which can be used for floating wind turbine research projects. NREL researchers also coordinated inputs from a broad international group of technical experts to create a document that outlines key engineering considerations when designing floating wind power plants. That document, which will be published and made available for use by offshore wind energy researchers and technology developers, provides the foundation for ongoing efforts to develop three reference floating wind power plant designs.



An NREL team gathered wind, wave, and water depth data for the two North American sites, included in those shown here, which will be part of IEA Wind Task 49's floating wind power plant site condition dataset. *Graphic from Shauna Creane, Gavin & Doherty Geosolutions*

Removal of G97 Wind Turbine From NREL Flatirons Campus

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

Wind Turbine Leaves a Research Legacy

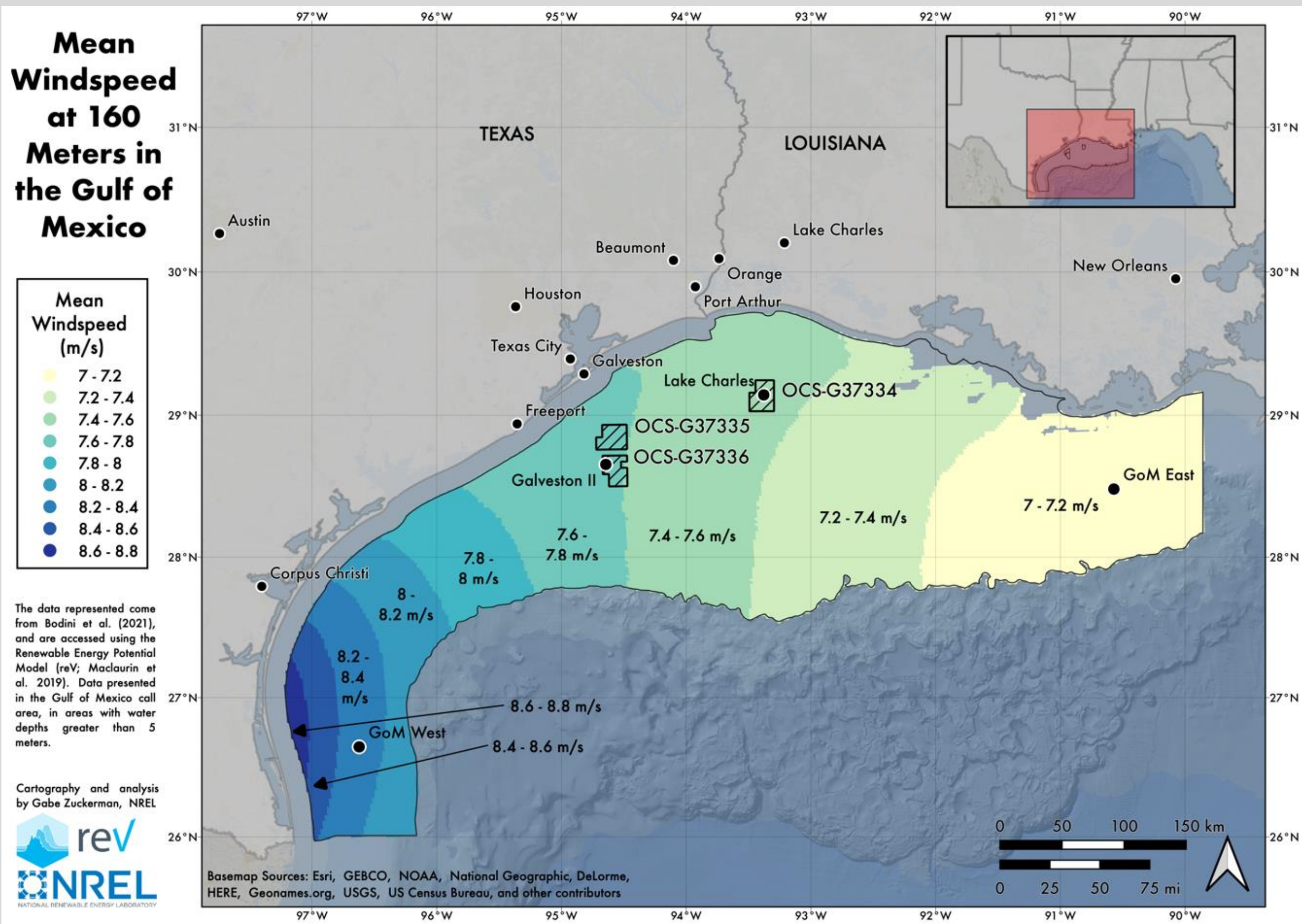
In late 2023, Siemens Gamesa removed its 2-MW G97 wind turbine from NREL's Flatirons Campus. Installed in 2011, the prototype wind turbine was used to study controls, drivetrains, and grid integration, which resulted in several publications. After the turbine's removal, Siemens Gamesa remediated the site and recycled or repurposed the turbine components.

After 12 years of controls, drivetrain, and grid integration research, the Siemens Gamesa 2-MW G97 wind turbine was removed from NREL's Flatirons Campus. *Photo by Jeroen van Dam, NREL*

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

U.S. Gulf of Mexico Study Verifies Offshore Wind Energy Potential

An updated assessment of the U.S. Gulf of Mexico shows that this region has the potential to be a viable clean energy option to help the United States achieve carbon neutrality by 2050. NREL's new offshore wind resource dataset, developed specifically for this region, shows that the likelihood of hurricanes necessitates the use of wind turbine designs that are able to withstand extremely high winds, but low-specific-power rotors may be needed to optimize energy capture with the area's common low wind speeds. Battery backup systems during loss-of-grid events (e.g., hurricanes) are recommended to maintain yaw control. Because of experience in the Gulf of Mexico with offshore industrial activities, developing an offshore-wind-specific infrastructure could be easier than in regions that are new to offshore construction.



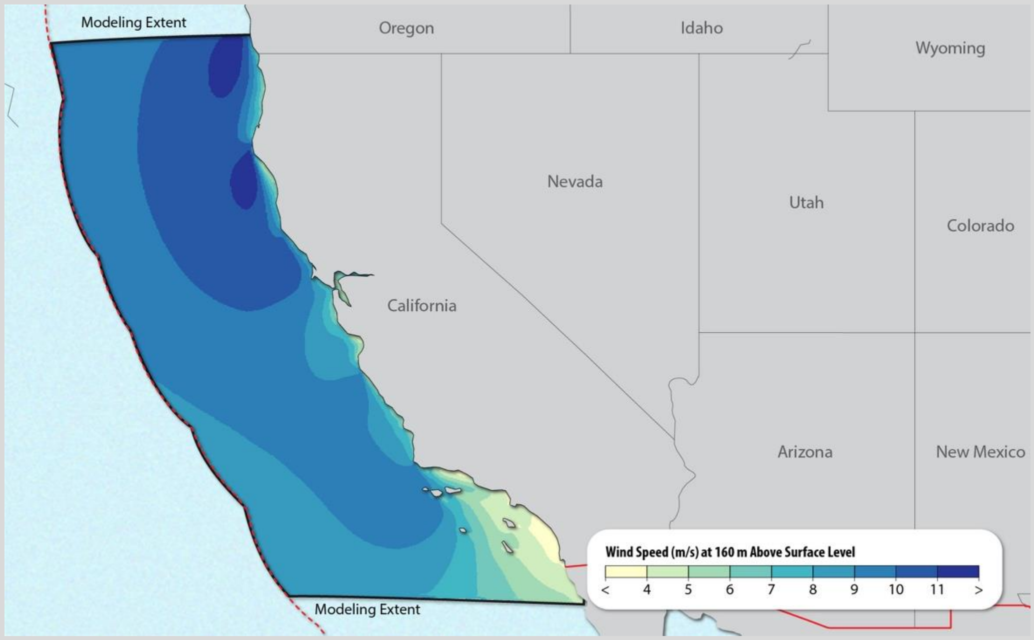
Mean wind speeds in the Gulf of Mexico are low, with the highest winds (8–8.8 m/s) found in a small region in the western side. *Graphic by Gabe Zuckerman, NREL*

BOEM California Wind Resource Assessment

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

Updated California Wind Resource Assessment

As part of its state-of-the-art 2023 National Offshore Wind dataset, NREL released an updated offshore wind speed dataset for waters off the coast of California. This new dataset characterizes offshore wind speed and critical atmospheric variables over a span of more than 20 years and supersedes the previous version of the California dataset, named "CA20." The data are publicly available at no cost.



NREL released an updated wind speed dataset for offshore California. In this map, the red dashed line indicates the Exclusive Economic Zone, the outer edge of where the U.S. government has jurisdiction for wind power plant construction. *Graphic by Billy Roberts, NREL*

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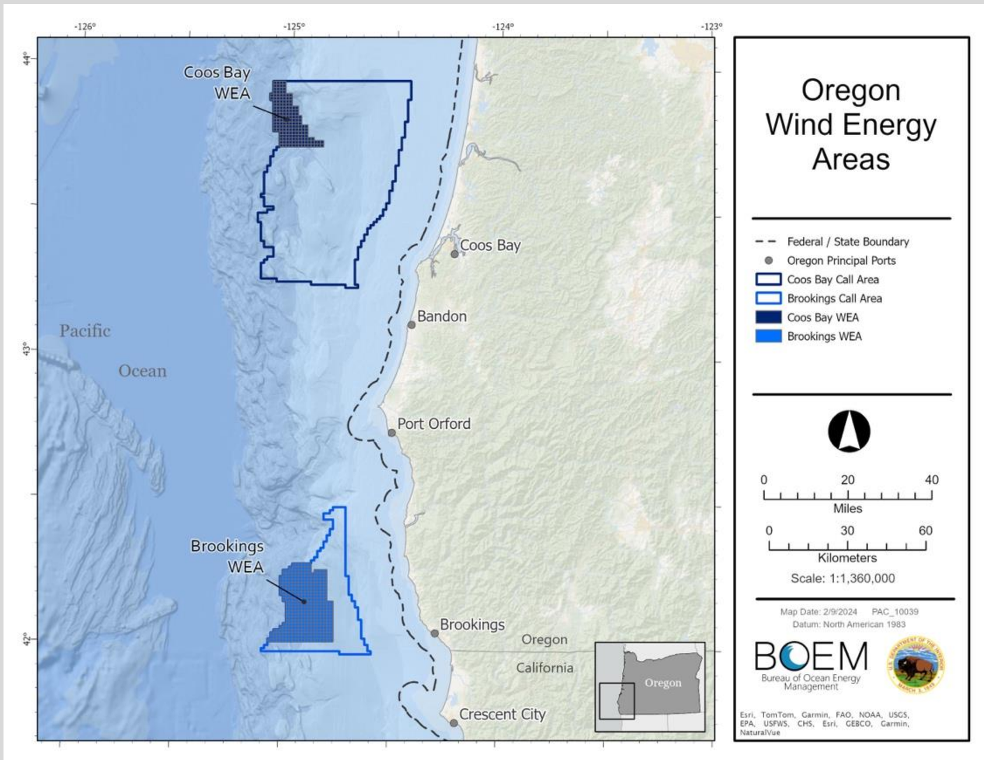
Research Could Unlock Oregon Floating Offshore Wind Energy Opportunities

By providing scientific and technical assistance to BOEM, NREL is enabling deployment of floating offshore wind energy projects along the U.S. West Coast, from California to Washington. In Oregon, NREL is analyzing wind speed, water depth, and distance to land-based infrastructure within two BOEM-designated wind energy areas. If leases are issued, offshore wind energy projects in these areas could produce more than 3 GW of power.



NREL is developing options for dividing the southern Brookings wind energy area off the Oregon coast into two lease areas with potential for more than 3 GW of offshore wind energy. *Image from BOEM*

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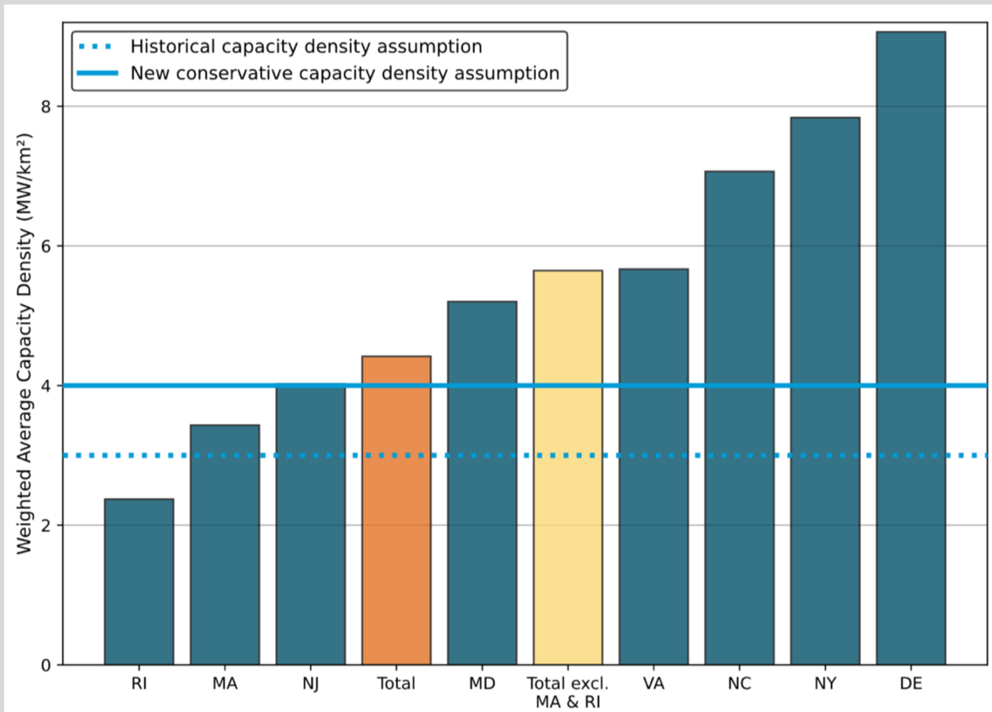
Report Establishes a More Realistic Offshore Wind Capacity Density Metric



This plot shows the variability of capacity density by state, from smallest capacity density (Rhode Island [RI] at just over 2 MW/km^2) to largest (Delaware [DE] at 9 MW/km^2). The dotted blue line indicates the historical capacity density assumption of 3 MW/km^2, and the solid blue line indicates the new capacity density assumption of 4 MW/km^2. The states with the lowest densities (Massachusetts [MA] and RI) are constrained by U.S. Coast Guard 1-nautical-mile spacing requirements. For this reason, the plot shows the total U.S. weighted-average capacity density of 4.4 MW/km^2, and the U.S. weighted average, excluding MA and RI projects, of 5.6 MW/km^2. *Graphic by Daniel Mulas Hernando, NREL*

Capacity density plays a crucial role in estimating the electric-generating capacity potential of existing offshore wind energy lease areas. NREL researchers reviewed the documentation for U.S. projects in progress and analyzed the anticipated capacity density values of those projects. The team published their findings in the report *Capacity Density Considerations for Offshore Wind Plants in the United States*, which describes in detail the primary factors influencing capacity density. Although precise predictions are challenging, this report shows that the weighted-average capacity density for U.S. offshore wind energy projects is 4.4 MW/km^2. This average value challenges the conservative capacity density assumption of 3 MW/km^2, which has historically been used in DOE wind energy market reports and by BOEM. These findings also provided the basis for the authors of DOE's *Offshore Wind Market Report: 2023 Edition* to increase the report's capacity density assumption by 33%. This increase has important implications for the estimated pipeline capacity and the amount of ocean space needed to achieve national renewable energy targets. This finding also influences the estimates from supply chain and workforce assessments.

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Interagency Project Supports Rural Communities

NREL provided technical assistance that helped rural communities and farmers accelerate the clean energy transition and expand opportunities for economic development and energy equity. *Photo from Eocycle*

NREL researchers completed 14 technical assistance requests submitted by grant reviewers for the U.S. Department of Agriculture's Rural Energy for America Program (REAP). The assistance included several in-depth reviews to assess the technical merits of applications to install underutilized renewable technologies such as biomass, solar power, and energy storage, as well as distributed wind turbines on rural farms and businesses. This interagency project leverages NREL's scientific expertise and the U.S. Department of Agriculture's connection with rural communities and farmers to accelerate the clean energy transition and expand opportunities for economic development and energy equity. NREL expects to provide webinars in spring 2024 to educate REAP staff and applicants on the benefits of distributed wind energy for rural communities as well as best practices for evaluating distributed wind energy's applications. Providing a direct line of communication between NREL's subject-matter experts and REAP grant reviewers maximizes the quality of applications and helps ensure that allocated funds are well placed.

North American Windy Energy Academy/Wind Tech Conference

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Educational Workshops Define National Wind Conference

The NAWEA/WindTech 2023 conference, held near the Flatirons Campus and cohosted by NREL and several Front Range research institutes and universities, gave NREL staff the opportunity to hold educational workshops, tutorials, and project outreach meetings. These included a day of tutorials on how to use NREL research tools, such as OpenFAST, FLORIS, WOMBAT, and AMR-Wind. Project briefings on AWAKEN and RAAW and IEA Wind task workshops rounded out the offerings. More than 100 people attended these side meetings, which complemented the record-setting attendance at the conference of 375, up from the previous high of 250 attendees.

NREL partnered with Front Range research institutes and universities to deliver the NAWEA/WindTech 2023 conference. Along with the conference, NREL researchers hosted educational meetings, tutorials on NREL software tools, and project briefings for conference attendees. *Photo by Josh Bauer, NREL; banner by Jennifer Breen Martinez, NREL*

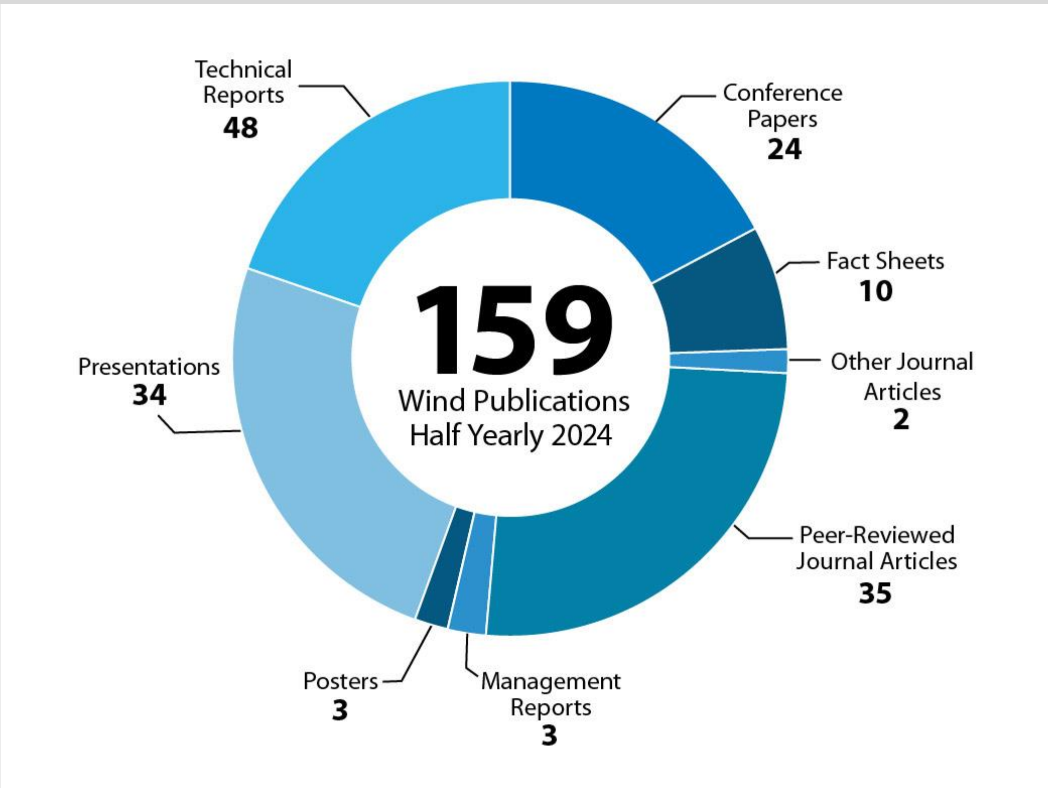
Publications Overview

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 the first half of FY 2024, NREL researchers published their latest scientific findings and breakthroughs in 191 technical reports, peer-reviewed journal articles, conference papers, fact sheets, and other publications.

Fiscal Year 2024 NREL Wind Energy Publications as of March 31, 2024

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 2024, as of March 31, 2024, NREL published 159 wind energy documents. *Graph by NREL*

Notable Publications

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View all wind energy-related journal articles and technical reports published in the first half of FY 2024.

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NREL/MP-5000-90028 • May 2024

Front cover photo by Josh Bauer and Brian Bechtold, NREL. Back cover photo by Werner Slocum, NREL.