NREL
Transforming ENERGY

WIND ENERGY

Accomplishments and Year-End Performance Report

FISCAL YEAR 2024

Notice

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Foreword

As the largest source of clean, renewable power generation in the United States and one of the fastest growing sources of new electricity supply, wind energy will play a large role in the nation's energy future. In Fiscal Year (FY) 2024, scientists, engineers, analysts, and support professionals at the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) worked to accelerate the pace of innovation in wind energy science and technology, advance grid systems integration, and develop sustainable solutions to deployment challenges.

Much of NREL's research, development, and deployment work aligns with addressing the Grand Challenges of Wind Energy. Beginning in 2019, DOE's Wind Energy Technologies Office partnered with the International Energy Agency to identify the barriers to greater wind energy deployment and related research gaps. The world's leading wind energy scientists and engineers identified five research areas as critical to advancing wind energy deployment: wind atmospheric science, wind turbine systems, wind plants and grid, environmental co-design, and social science. In FY 2024, NREL's accomplishments helped narrow the research gaps in these critical areas. This report provides details on those accomplishments.

Wind Atmospheric Science. According to researchers, improving understanding of the physics of atmospheric flow in wind power plant operation is necessary to expand deployment into new and challenging onshore and offshore areas. FY 2024 NREL research accomplishments that help narrow the research gap related to wind atmospheric science include:

- Reducing uncertainty in offshore wind energy forecasting and investigating wake steering and wake mixing, two wind farm control strategies, to assess their effect on power production and turbine lifetime
- Coordinating international research in wind flow, wind turbines, and wind farm simulations via International Energy Agency Wind Technology Collaboration Programme Task 57: Joint Assessment of Models
- Partnering with academia, industry, and government agencies to analyze wind plant-to-plant wake effects off the East Coast.

Wind Turbine Systems. Researchers agree that addressing unanswered wind turbine research and development questions requires improving our understanding of materials and system dynamics of wind turbines to develop innovative, custom solutions. FY 2024 NREL research accomplishments that help narrow the wind turbine systems research gap include:

- Publishing an operations and maintenance roadmap for offshore wind energy to highlight ways to improve efficiency, cost effectiveness, reliability, and performance
- Upgrading wind turbine gearbox design standards
- Developing new design and 3D-printing capabilities to reduce the weight of wind generator components.

Wind Plants and Grid. Researchers have identified improved optimization and control of fleets of wind plants as necessary to address challenges around grid stability, electrical transmission, and wind energy technology. FY 2024 NREL research accomplishments that help narrow the research gap related to wind plants and the grid include:

- Analyzing how to bring offshore wind energy to areas of high demand along the Atlantic Coast and publishing the *Atlantic Offshore Wind Transmission Study*, which addresses reducing grid congestion, increasing reliability, maximizing production, and reducing costs for consumers. The study also informed the Atlantic Offshore Wind Transmission Action Plan, which outlines immediate actions the United States can take to connect the first generation of Atlantic offshore wind projects to the electric grid and increase transmission.

- Enhancing wind energy cybersecurity by developing a standardized framework to help protect essential wind infrastructure from cyber threats and researching cybersecurity evaluation tools to determine their effectiveness in the wind energy sector.
- Characterizing a GE 2.5-megawatt wind turbine drivetrain to highlight the potential for more wind energy on electric grids.
- Developing models to demonstrate how Type 5 generators can offer an additional path to a more secure and reliable grid and to evaluate performance and stability of offshore wind integration with the onshore grid.

Environmental Co-Design. Researchers determined that co-designing wind turbines and wind energy projects with environmental considerations can streamline project development and reduce wind turbine-related impacts that may delay or hinder deployment. FY 2024 NREL research accomplishments that help narrow the environmental co-design research gap include:

- Developing more effective ultrasonic deterrent technologies that can target species at risk of wind turbine collisions
- Educating state agencies from Colorado, New Mexico, Texas, Utah, and Wyoming and other stakeholder groups on current practices for monitoring and mitigating wind energy and wildlife interactions
- Developing a framework to validate technologies that can detect whales and track their movement around offshore wind energy construction activities.

Social Science. Social science plays a crucial role in understanding and addressing social, cultural, and behavioral aspects associated with wind energy deployment. Researchers have determined that focusing more on social science and integrating it across wind energy projects can improve outcomes. FY 2024 NREL research accomplishments that help narrow the social science research gap include:

- Collecting diverse perspectives on wind energy equity in communities in Illinois, North Carolina, and New Mexico, as well as presenting findings from the sessions at two conferences and in a published technical report
- Launching a first-of-its-kind community of practice to support individuals engaged in wind energy equity work through virtual and in-person gatherings and by documenting and sharing relevant resources
- Developing a guide to help communities better understand how they can benefit from and become involved with wind energy and publishing a database of community benefit information for nearly 300 wind energy projects.

In addition to helping to narrow research gaps related to the Grand Challenges, NREL researchers continue to support a wide array of research, development, and deployment projects for DOE's Wind Energy Technologies Office. In FY 2024, NREL's researchers worked on projects as varied as improved gear oil lubrication, the wind energy workforce, validating infrastructure, future wind turbine recycling, and barriers unique to distributed wind. Research focused on offshore wind included clean hydrogen production from offshore wind turbines, an analysis of using shared anchors to reduce the costs of floating wind plants, and an assessment of loads on wind turbines during hurricanes.

This report provides more detail on these and even more accomplishments of NREL and its partners during FY 2024 (between Oct. 1, 2023, and Sept. 30, 2024).

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People and Partnerships

The People Behind NREL's Wind Energy Research Accomplishments

Brian Smith Witnessed the Wind Industry's Coming of Age

After a 36-year career, the National Renewable Energy Laboratory's (NREL's) Wind Laboratory Program Manager Brian Smith retired, leaving a lasting impact in wind energy research. After working as a chief engineer for a wind energy company in California, Brian applied for a position at the Solar Energy Research Institute in 1988, which became NREL in 1991. In 2002, Smith became NREL's Wind Laboratory Program Manager, where he played a key role in shaping national policies and strategies, always remembering the goal of a clean energy future and the value of wind energy. Reflecting on his time at NREL, Smith said "NREL's culture has changed, growing from a few hundred employees to 4,000. But the people are incredible. They're innovative and intelligent. All of us are working toward a common mission. That's what kept me there over the years. I had a great team to work with and we were doing something that was important for the country and for the world."

Wind Laboratory Program Manager Brian Smith, shown here in 2014, worked at NREL for more than 36 years. He retired Oct. 4, 2024. *Photo by Dennis Schroeder, NREL 28976*

In a Monthly Feature, NREL Staff Step Out From Behind the Blades

Every month, NREL's wind energy newsletter, *The Leading Edge*, includes a staff profile feature called Behind the Blades. Not only does this series showcase NREL's invaluable research and development; it shines a spotlight on the NREL researchers and staff who make this work happen. Offering first-hand insight into the careers of NREL wind researchers, their work at the lab, and the wind energy industry, Behind the Blades remains one of the most engaging series in *The Leading Edge* and is an effective outreach tool on social media. The following are highlights from the three most-clicked Behind the Blades stories of Fiscal Year (FY) 2024.

NREL Summer Interns Spark Wind Energy Advancements

In August 2024, Behind the Blades profiled 6 of 36 interns who participated in NREL's wind energy research through programs like the U.S. Department of Energy's (DOE's) Science Undergraduate Laboratory Internship Program, Research Participant Program, and the Graduate Education Minority Program. The interns supported research on wind energy workforce and development, floating offshore wind turbines, designing and modeling wind farms, and more. "Meeting and brainstorming with others at NREL has been thrilling for me, and publishing on the GitHub repository with my mentor was a rewarding experience," said intern Vishnu Sankar Manivasakan, who worked with NREL researcher Stein Housner on research to improve energy efficiency for floating offshore wind turbines. "Even though it's time to move on from NREL, Housner's vision inspired me, and I plan to complete my master's thesis aligned with that vision."

Six undergraduate- and graduate-level interns shared their NREL wind energy internship experiences. Pictured here are (top row, from left) Bianca Calderon, Kyle Devlin, Storm Mata, (bottom row, from left) Vishnu Sankar Manivasakan, Anjal Paudel, and Leah Sirkis. *Photos from the interns*

Angel McCoy's Background in Meteorology Propels Offshore Wind Forward

In February 2023, Angel McCoy reflected on the professional path that led her to NREL. McCoy began her career in meteorology at the National Weather Service before taking her next leap at the Bureau of Ocean Energy Management (BOEM) where she wrote code for wind and solar models. Now at NREL as part of the offshore wind energy program, McCoy leads engagement with BOEM and the Bureau of Safety and Environmental Enforcement to support the regulatory process for offshore wind energy.

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

Amy Robertson Takes On the Complexities of Floating Offshore Wind

In March 2024, Amy Robertson discussed her time at the forefront of offshore wind energy research. Her career began at Los Alamos National Laboratory, but a life-changing event brought her back to Boulder, Colorado, where she'd attended college. In Boulder, Robertson worked as a consultant for several years and eventually joined NREL to work on fixed-bottom offshore wind turbines. She is currently the group manager of a passionate team and continues to lead research to advance offshore wind energy.

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

Awards and Recognition

Suzanne MacDonald Recognized With Windustry Innovator Award

Suzanne MacDonald, a researcher at NREL's National Wind Technology Center (NWTC), received the Windustry Innovator Award in Community Wind and Distributed Clean Energy at the Distributed Wind Energy Association Conference in February 2024. MacDonald earned the recognition for her leadership and support for community wind energy projects, encouraging rural and island communities to implement energy-efficient practices and projects, as well as her work to help launch the National Distributed Wind Network.

NWTC researcher Suzanne MacDonald (right) was recognized by Windustry for her work in community wind and distributed clean energy. *Photo from Windustry*

Pietro Bortolotti Outstanding Wind Energy Science Reviewer

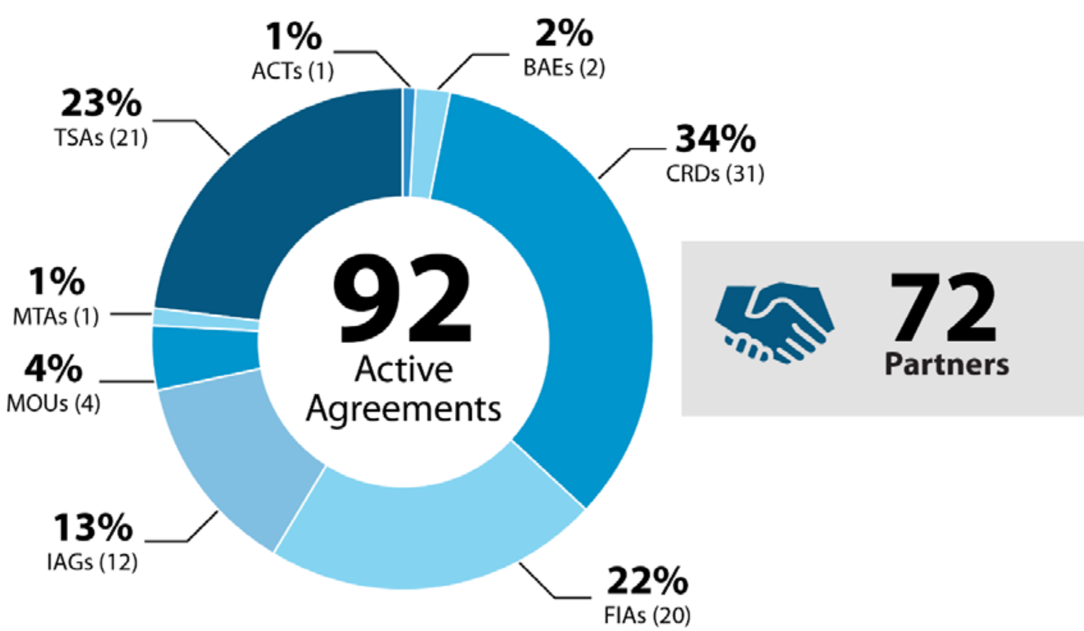
NREL Senior Researcher Pietro Bortolotti was honored with the [2024 *Wind Energy Science* Outstanding Reviewer Award] for his efforts and expertise at the 2024 TORQUE Conference. The *Wind Energy Science* journal editorial board selects reviewers that were helpful and knowledgeable and who gave constructive feedback on manuscripts that were reviewed from 2020 to 2023. Bortolotti is one of seven reviewers to receive the award.

NREL Partners Help Accelerate Wind Energy

In FY 2024, NREL and the NWTC worked with 72 partners through 92 active agreements designed to advance wind energy science, streamline wind energy deployment, and lower the cost of wind-generated electricity.

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

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



ACT: Agreements for Commercializing Technology
BAE: Bailment
CRD: Cooperative Research and Development Agreement
FIA: Funds in Agreement
IAG: Interagency Agreement
MOU: Memorandum of Understanding
MTA: Material Transfer Agreement
TSA: Technical Services Agreement

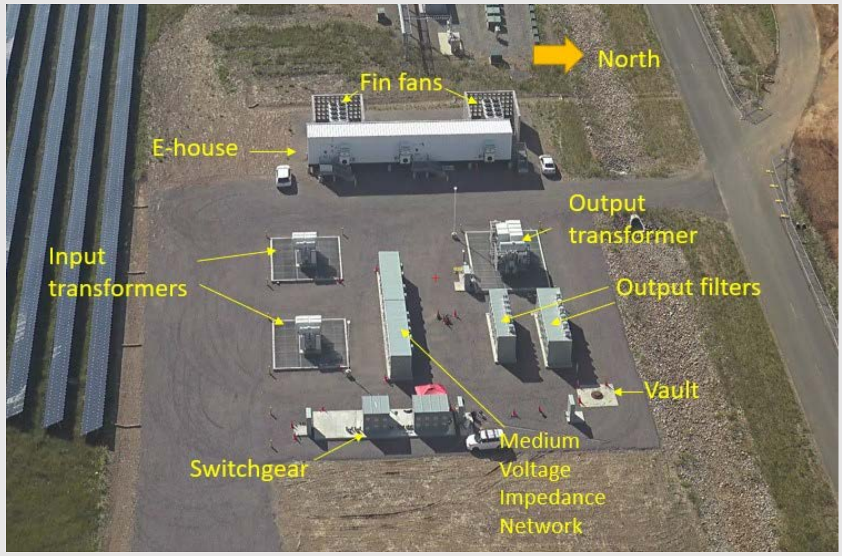
With 72 partners, NREL's wind energy program participated in 92 active agreements in FY 2024. *Graphic by Katie Carney, NREL*

Infrastructure, Standards Development, and International Engagement

Testing Facilities and Capabilities at the National Wind Technology Center

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

New Controllable Grid Interface Ready for Research



NREL's second CGI comprises a variety of components, which are shown here. *Graphic by NREL*

NREL's new, 20-MW Controllable Grid Interface 2 (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 original 7 MW, a 34.5-kilovolt (kV) alternating current (AC) voltage level. 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, making the CGIs core to ARIES capabilities. The CGIs can also emulate devices (storage, generation, and loads) that are not physically on-site.

Testing Facilities and Capabilities at the National Wind Technology Center

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's new wind turbine, capable of generating 3 MW or 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*

NREL is preparing to install a GE 3.4MW turbine with 81m hub height and 140m rotor diameteron the Flatirons Campus that could generate 3 megawatts (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 499 feet 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.

Testing Facilities and Capabilities at the National Wind Technology Center

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

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

NREL is negotiating with Siemens Gamesa Renewable Energy (SGRE) to take ownership of the SGRE Type-4, 2.3-MW wind turbine installed on NREL's Flatirons Campus. A change of turbine ownership would conclude a very successful multiyear, multimillion-dollar R&D partnership with SGRE 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. If the ownership transfer is successful, the SGRE 2.3-MW turbine will supplement the existing GE 1.5-MW turbine on NREL's Flatirons Campus.

Testing Facilities and Capabilities at the National Wind Technology Center

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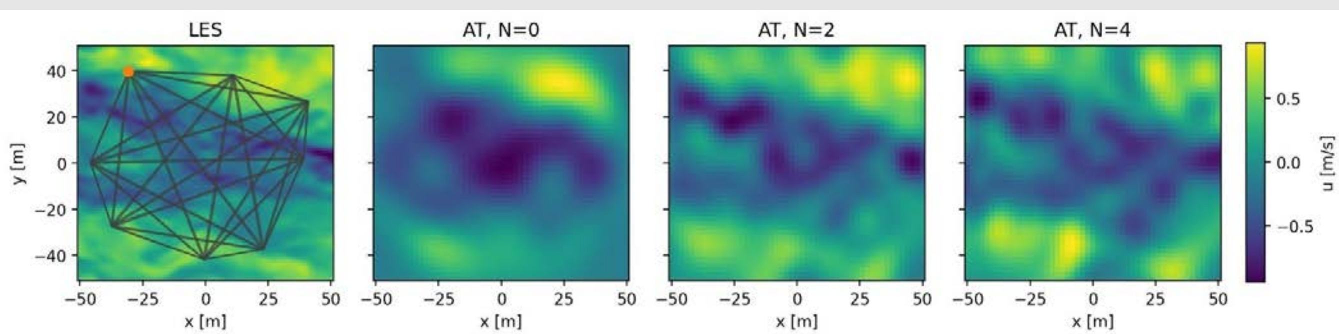
Acoustic Tomography Could Become a New Flatirons Campus Research Capability

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 software tool. Funded by DOE's Wind Energy Technologies Office (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.

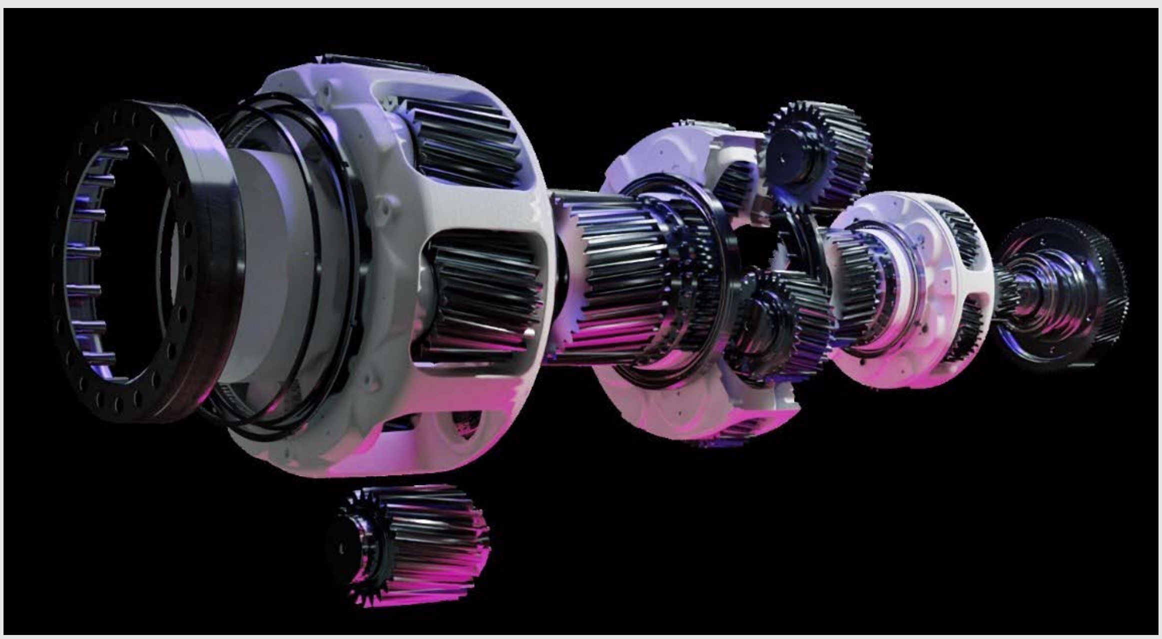


To understand the measurement uncertainty of acoustic tomography, reconstructions using successively larger ensembles of observations are compared to a large-eddy simulation of the turbulent atmospheric boundary layer using AMR-Wind, shown on the left with the travel paths of the virtual acoustic tomography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

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 financiers, 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 to 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 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*

Wind Standards Development

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Wind Turbine Leaves a Research Legacy

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

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

Distributed Wind Research and Development

Distributed Wind Research, Development, and Testing

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Farmers, Rural Businesses To Benefit From Competitiveness Improvement Project Award

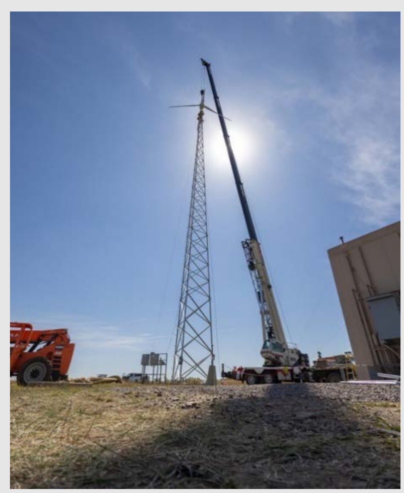
Pecos Wind Power, a recipient of a 2024 CIP award, will begin prototype validation of its new 85-kilowatt distributed wind turbine using CIP funding. *Photo from Pecos Wind Power*

A new crop of Competitiveness Improvement Project (CIP) award selections will benefit farmers and small rural businesses by focusing on how to remove market barriers to distributed wind turbine deployment in agricultural settings. Managed by NREL on behalf of WETO, CIP plans to award $3.2 million to 12 American component suppliers and manufacturers of small- and medium-sized wind turbines for 13 new projects. CIP is designed to make distributed wind energy technologies more cost competitive, reliable, grid compatible, and accessible. In addition, CIP projects advance innovations that enable distributed wind energy technologies to be used in emerging distributed generation markets.

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

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

Videos Communicate Role of Distributed Wind Energy



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

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 Pacific Northwest National Laboratory (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.

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

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

Guidelines Help U.S. Manufacturers Navigate Complex Certification Landscape

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*

NREL managed the publication of the comprehensive Distributed Wind 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 industry to revise U.S. and international standards for small wind turbines. 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: Suzanne MacDonald, Suzanne.MacDonald@nrel.gov

Initiative Empowers Communities To Seize On-Site Wind Energy Opportunities

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.*

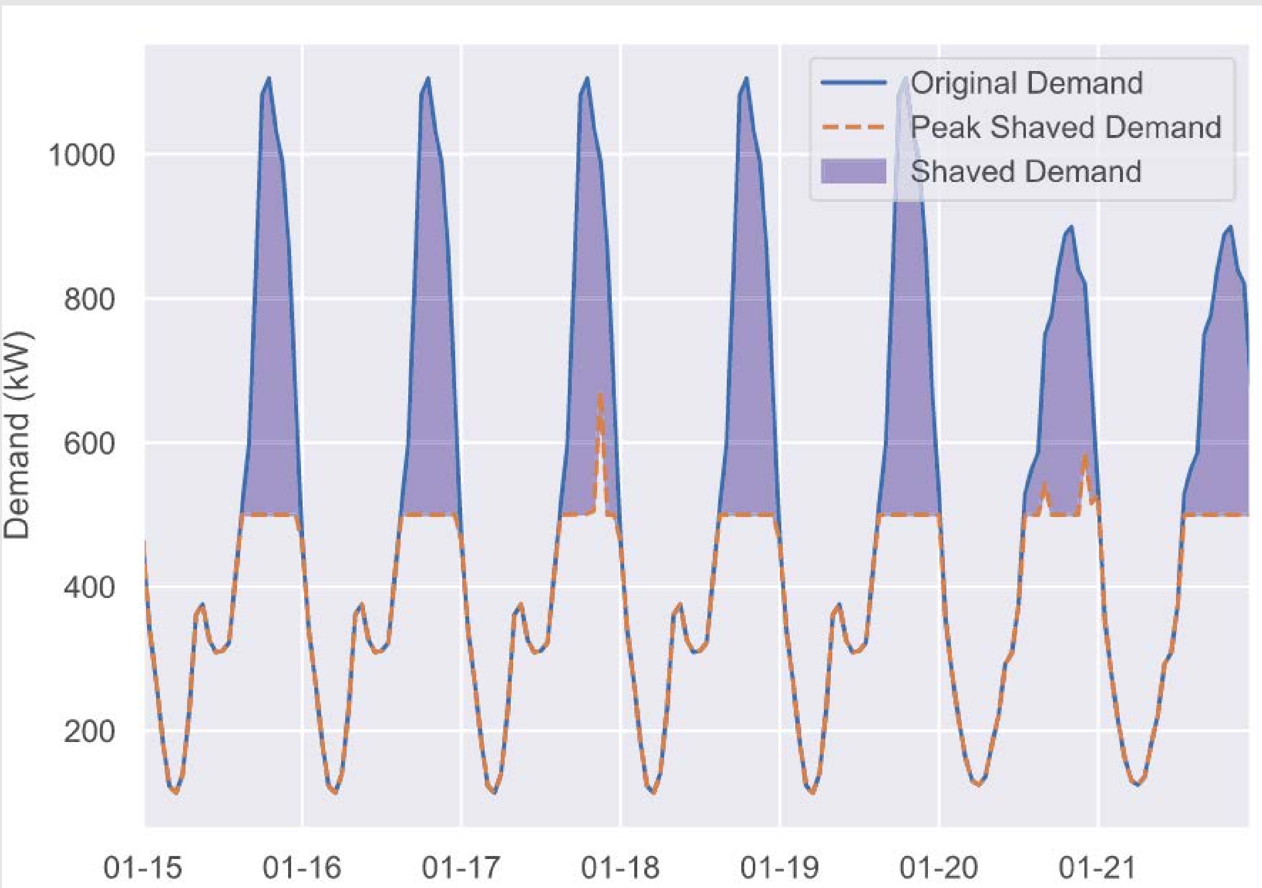
NREL released two new resources that provide comprehensive information, tools, and support to anyone interested in installing distributed wind turbines and taking advantage of the benefits of on-site energy. The National Distributed Wind Network, which was created by NREL in partnership with PNNL and funded by WETO, offers extensive informational resources about distributed wind. The network and its complementary Distributed Wind Energy Resource Hub 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.

On-Site Wind for Rural Load Center

Point of Contact: Brooke Stanislawski, Brooke.Stanislawski@nrel.gov

Wind-Based Hybrid Power Plants Can Alleviate Electric Vehicles' Impact on the Grid

NREL researchers designed a configurable tool to size and simulate hybrid power plants with a peak shaving battery dispatch strategy that prioritizes electric vehicle charging outside of peak load times. By applying this tool to a case study in Boulder, Colorado, researchers found hybrid systems that incorporate wind power with another type of energy source can reduce system size and energy production costs while meeting performance demands—even when electric vehicles are added to the mix. The software tool—the Hybrid Optimization and Performance Platform, or HOPP—gives commercial and industrial users the ability to design and optimize hybrid distributed behind-the-meter energy systems that generate renewable energy locally and minimize costs.

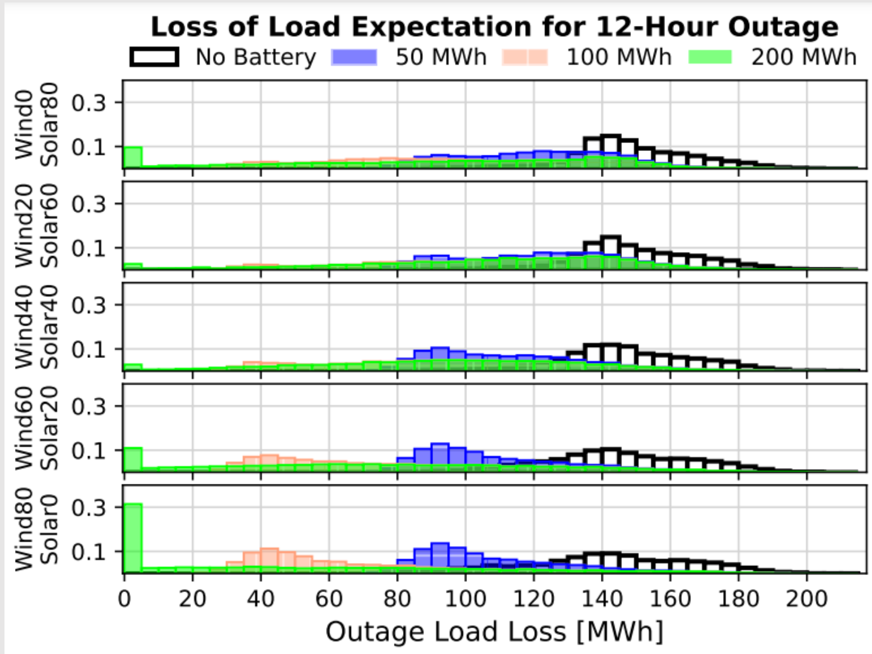


Time series of power demand showcases the software tool's new peak-shaving capability. *Graphic by Cameron Irmas, NREL*

On-Site Wind for Rural Load Center

Point of Contact: Brooke Stanislawski, Brooke.Stanislawski@nrel.gov

Study Quantifies Incremental Value of Installing Additional Wind or Solar Capacity



Results illustrate how in a "worst-case" outage event of 12 hours, the loss-of-load expectation shifts with respect to increasing battery capacity (shown by the different colors and shading) and with respect to wind and solar capacities (rows).

A study published by NREL researchers in the journal *Energy*, "Hybrid Power Plants: An Effective Way of Decreasing Loss-of-Load Expectation," introduces a new approach to reducing the loss-of-load expectation for varying outage scenarios. The proposed analysis methodology, which describes the incremental benefit of various renewable assets operated as part of a hybrid power plant, fills a gap in existing research by quantifying the impact of component capacity investments on resilience. This approach will help advance the field by highlighting the trade-offs related to added component capacities when a developer considers expanding current generation instead of building a new plant.

On-Site Wind for Rural Load Center

Point of Contact: Brooke Stanislawski, Brooke.Stanislawski@nrel.gov

Outreach Encourages Rural Communities To Evaluate Wind-Based Hybrid Energy Potential

Distributed wind-based hybrid energy systems that combine different generation resources (e.g. wind, solar, and battery storage) are growing because of their ability to contribute to local energy and resilience needs. But rural communities are not always aware of how these systems could benefit them. That's why NREL researchers developed a fact sheet that gives an overview of hybrid distributed wind energy systems to help rural communities evaluate the potential of these technologies to meet their needs. A multi-laboratory team from NREL, Idaho National Laboratory (INL), and PNNL developed this resource, which will serve as a first step for the deployment of hybrid distributed wind energy systems in rural communities.

On-Site Wind for Rural Load Center

Point of Contact: Brooke Stanislawski, Brooke.Stanislawski@nrel.gov

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

To support stakeholders interested in installing distributed wind 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 of behind-the-meter-wind deployment. This value will be enhanced when EV charging capabilities are coupled with the advanced vehicle-to-grid services that are expected shortly from several 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 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 and presented on it again at the TORQUE Conference in Italy in May.

On-Site Wind for Rural Load Center

Point of Contact: Brooke Stanislawski, Brooke.Stanislawski@nrel.gov

NREL Provides Technical Assistance for Lake Region Electric Cooperative

Project team members from NREL, INL, and 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 co-op's investments in renewable energy, which the co-op 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 using 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.

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 designers to maintain alignment with the wind. OpenFAST now includes code for the resistance encountered when the turbine turns to face the wind—called yaw friction—and code for upwind, tail-vane-controlled turbines, both of which have been validated using experimental wind tunnel data with further validation 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*

Distributed Wind Aeroelastic Modeling (dWAM)

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

New Application Automates, Simplifies Wind Turbine Analysis

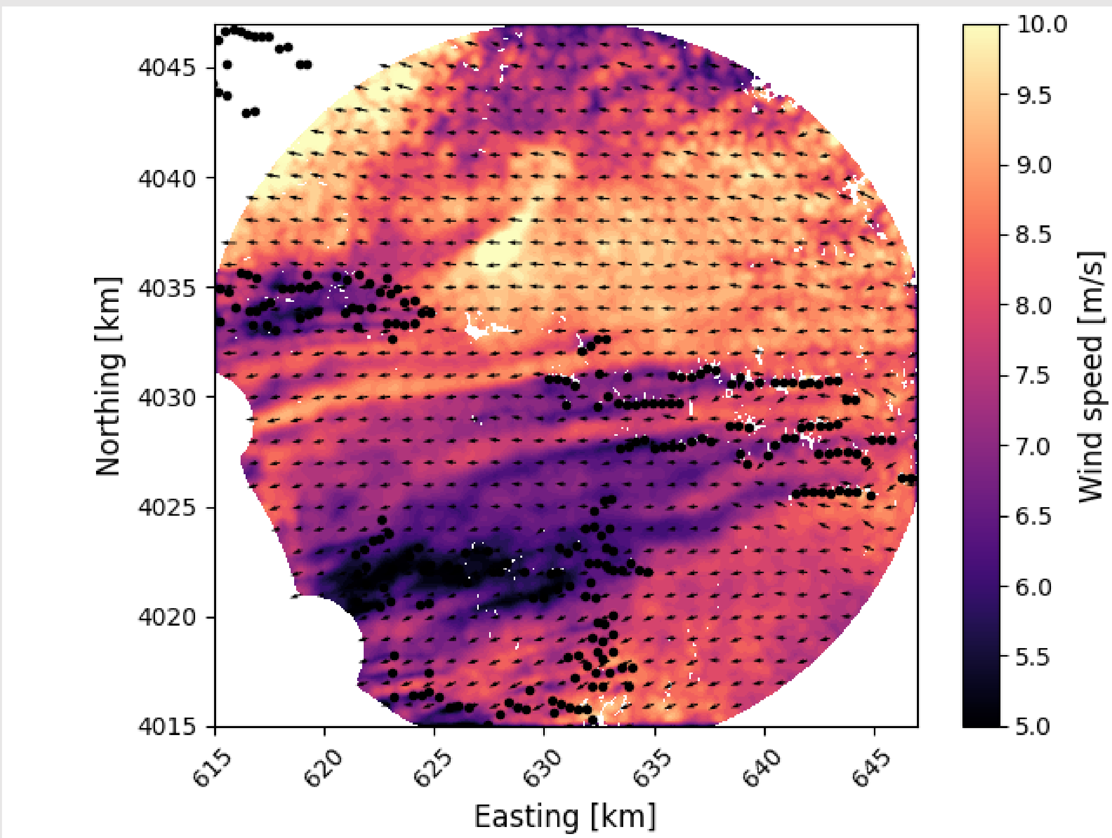
NREL introduced the Automated Campbell Diagram Code (ACDC), a new application that automates the preparation of OpenFAST wind turbine models, runs simulations, and postprocesses results. ACDC simplifies the generation of Campbell diagrams, which describe a wind turbine's dynamic properties, and the visualization of structural vibration across various wind and rotor speeds. ACDC was developed to characterize distributed wind turbines under the Distributed Wind Aeroelastic Modeling project and has been used to analyze a variety of designs, including offshore floating turbines.

Atmosphere to Electrons

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

AWAKEN Field Campaign Identifies Wind Plant Wakes

The American WAKE experimeNt (AWAKEN) research team, which is led by NREL, collected atmospheric and wind turbine operational data from five wind plants in northern Oklahoma over the past year. Collected from over 50 instruments, such as radars and lidars, and nearly 600 wind turbines, this dataset is unique in its size and scope in the wind energy industry. The research team has begun processing the vast amount of data and have observed wind plant wake behavior that can cause downwind wind plants to lose energy. Using the AWAKEN data, researchers have created an international benchmark that will be used to validate and improve models for wind plant wake interactions, which are currently not well understood. The benchmarking exercise is taking place under the auspices of IEA Task 57 – Joint Assessment of Models (JAM) and currently has 30 participants representing a wide cross section of the wind industry.

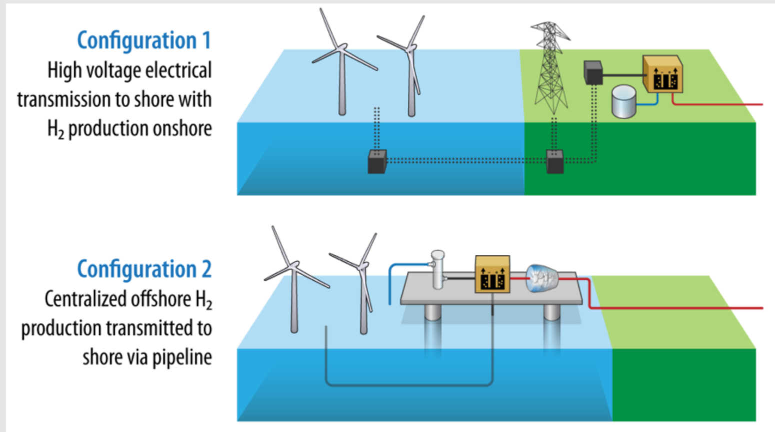


Visualization of Texas Tech radar observations of wind speeds around three wind plants in the AWAKEN domain. The black dots represent individual wind turbines and darker colors indicate lower wind speeds, highlighting wind plant wakes. Winds are easterly, causing wakes from the eastern wind plant to propagate and lower the energy production of the wind plant to the southwest. *Image by Patrick Moriarty, NREL*

NREL Wind to Hydrogen Activities (Green Steel) Green Steel

Point of Contact: Kaitlin Brunik, Kaitlin.Brunik@nrel.gov

Study Shows Offshore Wind Turbines Could Produce Cost-Effective Clean Hydrogen



Researchers studied the economics of two different configurations for generating clean hydrogen using offshore wind energy. The research suggests a pathway to produce clean hydrogen for less than $2 per kilogram, which could make it cost-competitive in some applications with conventional carbon-intensive methods of producing hydrogen. *Illustration by Alfred Hicks, NREL*

NREL research suggests that by 2030, with policy incentives, fixed-bottom offshore wind turbines and land-based electrolysis could produce clean hydrogen for less than $2 per kilogram. Researchers presented their results at TORQUE 2024, a leading scientific wind energy conference. The analysis, published in the Journal of Physics: Conference Series, has received more than 362 downloads, nine news outlet mentions, and three blogs since publication in June 2024. This engagement has led to additional interest from industry in collaborating with NREL on solutions to use offshore wind to generate clean hydrogen. This research supports DOE's Hydrogen Shot goal of reducing the cost of clean hydrogen to $1 per kilogram within a decade and U.S. goals to transition to a net-zero emissions economy by 2050.

NREL Wind to Hydrogen Activities (Green Steel) Green Steel

Point of Contact: Jared Thomas, Jared.Thomas@nrel.gov

Reference Hybrid Energy to End Product Plant Designs Pave the Way to Decarbonizing Heavy Industry

Combining wind, solar, battery, and other generation and storage technologies can help to lower the cost of decarbonizing industrial products. The reference plants demonstrate what such "hybrid renewables to end product" plants might look like and how they could perform both in terms of cost and production. *Photo by Werner Slocum, NREL*

In the reference design task of the Green Steel/Ammonia project NREL researchers created a set of five open-source wind-based "hybrid energy to end product" reference designs. The reference designs demonstrate potential design elements and pathways for decarbonizing heavy industry using wind-based hybrid energy plants. This work sets the stage for industry partnerships for continued research and paves the way for industry to successfully develop their own renewably powered industrial plants. It also demonstrates pathways for increased wind energy deployment and decarbonization with minimal grid or interconnection requirements.

Floating Turbine High-Fidelity Modeling and Simulation

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

ExaWind Model Ready for Prime Time

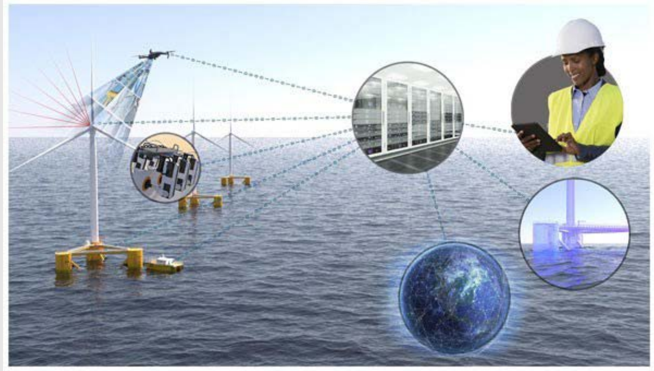
The open-source ExaWind tool will enable high-fidelity simulations of wind turbine designs on modern supercomputers that help developers simulate turbine geometry and rotor blades, down to millimeters of resolution, to optimize their designs for performance and efficiency. This novel approach, which leverages two solvers to model the flow around the blades and the background flow, was recently 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 turbines using a high-fidelity fluid-structure interaction capability. Now that these demonstrations are complete, ExaWind is another step towards creating the highest-fidelity wind 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 advances in technology.

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

Wind Energy Digitalization

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

The Roadmap To Achieving Wind Industry 4.0



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*

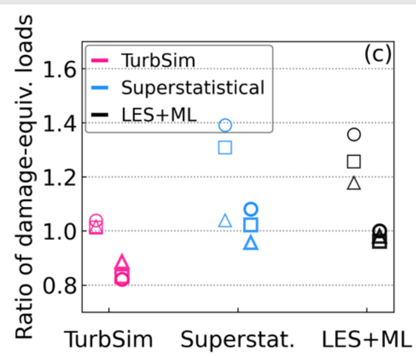
Achieving aggressive wind energy deployment goals will require new digital tools that enable deployment and operations at an unprecedented scale. Funded by WETO and conducted by researchers from NREL, PNNL, and INL, a wind energy digitalization roadmap identifies top R&D topic areas and activities needed 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 in early 2025. It can be used to direct future wind energy digitalization research.

Rotor Aerodynamics, Aeroelastics and Wake (`) Project

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

Wind Simulation Realism Leads to Greater Accuracy

NREL wind researchers developed a methodology to increase the realism of simulation tools used in wind energy research and operations. The researchers began by considering three ways to increase the realism in computer simulations of wind turbines: (1) forcing the wind simulation to match wind measurements, (2) making the simulated blades match the position of the real blades, and (3) using high-fidelity models for the wind flow. They found that adding realism provided by the enhanced modeling significantly improves the prediction of structural loads on wind turbine components. In addition to improving structural load predictions, adding realism also completely eradicated errors of predicted structural fatigue for a case study.



Damage-equivalent loads of simulated fore-aft moments relative to measurements (vertical axis). Colors represent three different wind simulation methods (horizontal axis), with the leftmost (rightmost) having less (more) realism. Thin (thick) markers represent less (more) realism in the wind turbine simulation. Different shapes refer to different quantities: tower base (square) and mid (circle) and blade root (triangle). Simulations with most realism (black, thick markers) showed the best prediction of damage equivalent loads. *Image by Paula Doubrawa, NREL*

Rotor Wake Measurements & Predictions for Validation

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

Unique Measurements To Improve Wind Plant Wakes

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.

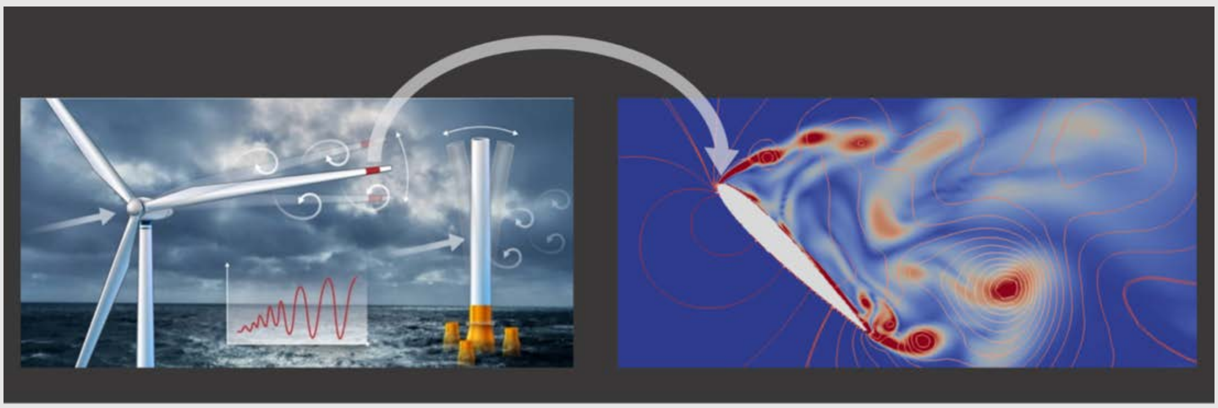
NREL researchers triggered faults on this wind turbine to cause structural loads, resulting in the tower deflection shown here. The markers on the tower and blades were used to measure these motions. *Photo by Nicholas Hamilton, NREL*

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 cause vibration—sometimes enough to cause permanent structural damage. As a result, researchers used the NREL-developed ExaWind software to demonstrate that the 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 damage to wind turbines. *Graphics by Shreyas Bidadi, NREL*

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

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

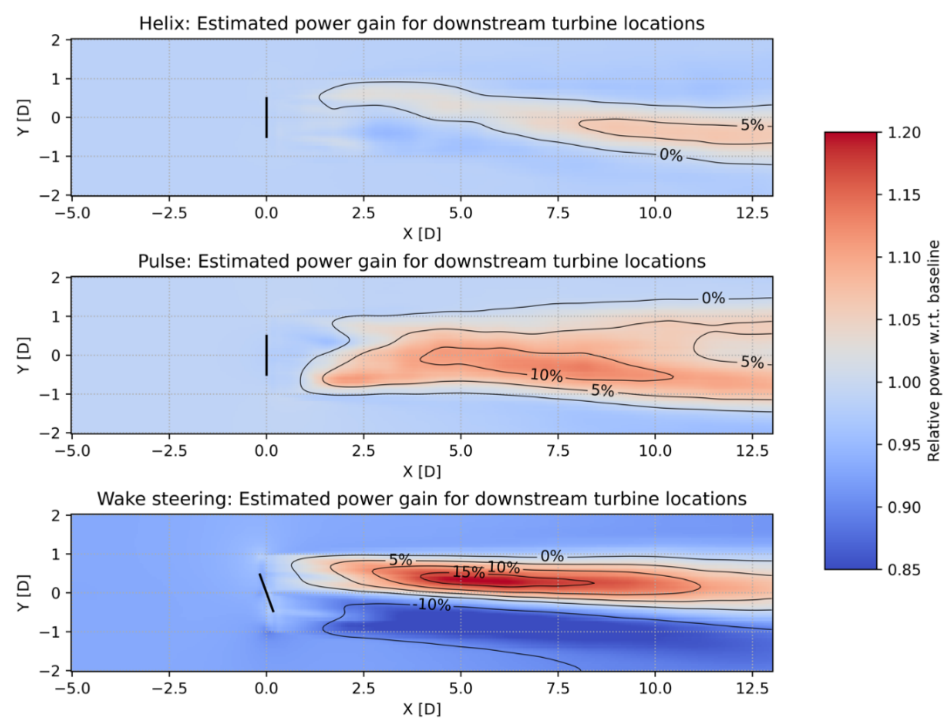
NREL Enhances Wind Turbine Control With Latest Release of ROSCO Software

NREL recently released a new version of the Reference OpenSource 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 plant developers without these proprietary methods, easing collaboration among these stakeholders. The new version of ROSCO offers additional support for wind 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: Paul Fleming, Paul.Fleming@nrel.gov

Wake Steering or Wake Mixing? Determining the Best Strategy for Boosting Wind Power Production

NREL, in collaboration with Sandia National Laboratories (Sandia), investigated different wind farm control strategies to assess their effect on power production and turbine lifetime. With wind farm flow control, each turbine can be adjusted to manage the way air moves in the wake behind the turbine, with the aim of boosting power production or reducing turbine wear and tear. Two main control strategies are wake steering, where turbines are angled slightly to direct the disrupted air away from turbines behind them, and wake mixing, which adjusts the blades to mix the slow-moving air with faster wind moving around the turbine for quicker wake recovery. Using a high-fidelity computer simulation called the AMR-Wind flow solver and the IEA Wind 15-MW turbine model, the team found that wake-mixing control strategies increased total power by between 4.1% and 8.4%. Wake steering increased power by 7.6%, with only a minor increase in turbine stresses as compared to wake mixing, making wake steering the best overall control strategy for the specific scenario investigated. The team will continue to identify effective strategies for various wind conditions and turbine layouts, refining these techniques to improve wind plant performance and expand wind energy deployment.



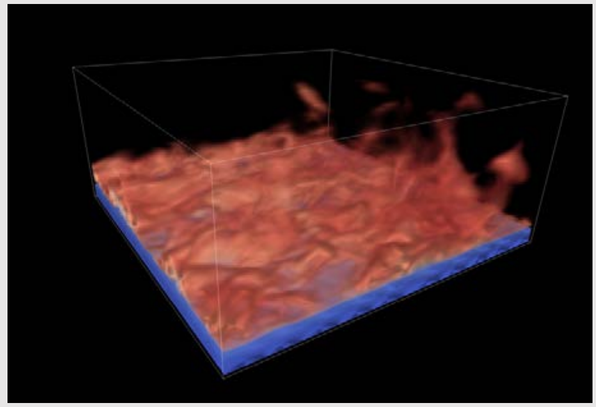
By analyzing the wind speed in the wake of a turbine for different control strategies, the effectiveness of different wake control strategies can be analyzed to determine which is most effective depending on the location of a downstream turbine. This figure shows how much power uplift can be achieved by a two-turbine wind farm with respect to a baseline case of no cooperative wind farm control strategy. *Graphic by Joeri Frederik, NREL*

Observationally driven Resource Assessment with CoupLEd models (ORACLE)

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

ORACLE Project Enhances Offshore Wind Energy Forecasting

NREL's Observationally driven 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's NWTC 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 wind turbines offshore. By studying these interactions, they hope to make offshore wind energy more reliable and efficient, particularly along the Pacific Coast.



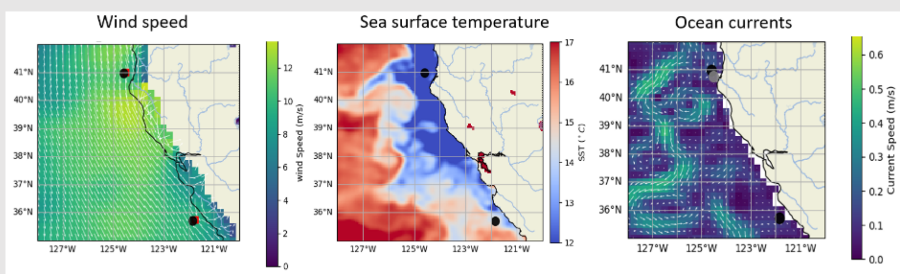
NREL's ORACLE project works to improve offshore wind energy by reducing forecast uncertainty, achieved through comparisons between novel observational data and detailed ocean wave–atmosphere modeling. *Image by Tony Martinez, NREL*

ORACLE

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

Wind-Driven Ocean Circulation Over the U.S. West Coast Observed From Satellite Data

Coastal upwelling occurs when wind blowing over the ocean surface drags surface waters away from shore and deeper water cycles upward to replace it. This phenomenon is responsible for nurturing U.S. West Coast ecosystems and fisheries, which are deeply intertwined with the region's cultural identity. The team used the satellite-derived upwelling index to study the spatial and temporal occurrence and variability of coastal upwelling along the U.S. West Coast and found that the most dominant upwelling time scales are annual and take place over days to weeks. Spatial patterns were studied and revealed four typical upwelling patterns that are driven by the large-sale atmospheric forces. This research aimed to provide observational insights from satellites to deepen the scientific understanding of coastal upwelling processes and eventually inform sustainable energy policies with broader implications for coastal ecosystems.

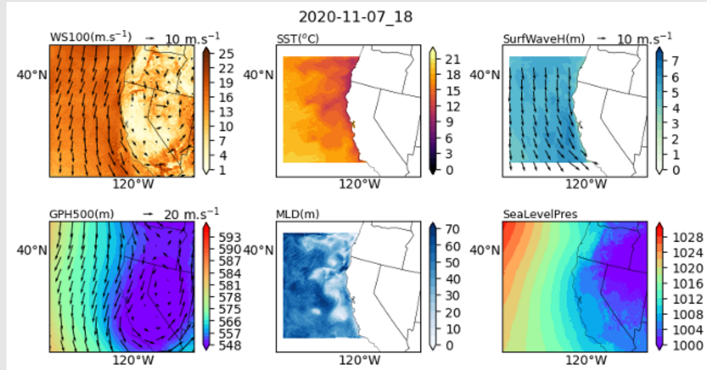


Satellite datasets of wind speed, sea surface temperature, and ocean currents, characterizing a day with strong upwelling on July 23, 2021. Coastal upwelling transport indices from the ocean model were 1.9 m^2/s near Humboldt Bay (41°N, upper black dot) and 2.2 m^2/s near Morro Bay (36°N, lower black dot). *Graphic by Ulrike Egerer, NREL*

ORACLE

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

Model Helps Simulate Extreme Wind Events for Wind Energy



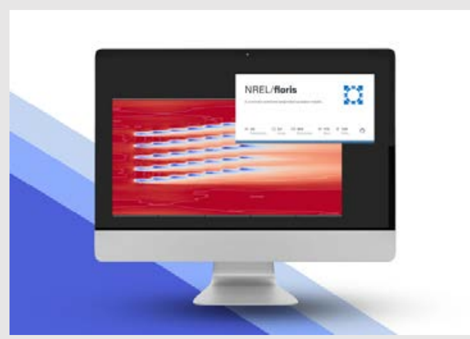
A snapshot of spatial pattern for hub-height wind speed (WS100), sea surface temperature (SST), surface wave height (SurWaveH), 500mb geopotential height (GPH500, mix layer depth (MLD) and sea surface pressure (SeaLevelPres) from the fully three-way coupled simulation. *Graphic by Geng Xia, NREL*

Using a coupled ocean wave–atmosphere mesoscale model, the NREL team simulated extreme wind events along the California coast and calculated potential uncertainties in the results. The coupled model combines the Regional Ocean Modeling System (ROMS) for ocean processes, the WaveWatch III (WW3) model for wave dynamics, and the Weather Research and Forecasting (WRF) model for atmospheric conditions. The integrated model gives a complete picture of how the ocean and atmosphere work together, which is essential for offshore energy applications. The results from this study can be used to quantify model errors to identify conditions where the model is more accurate and the conditions where improvements are needed.

Advanced Control and Systems Design for Offshore Wind Turbines and Plants

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

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



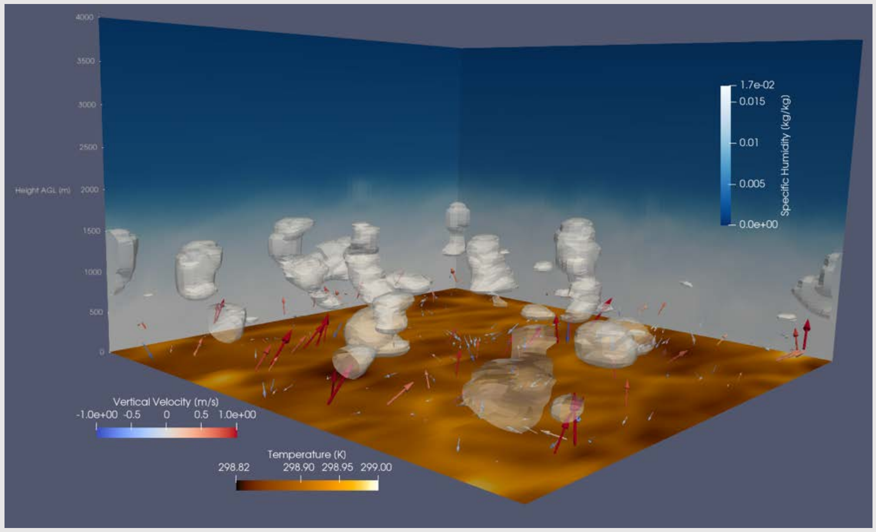
The latest release of NREL's FLORIS, which can be accessed publicly on GitHub, expands the software's capabilities and makes it more user-friendly. *Graphic by Christiann Vaughn and Misha Sinner, NREL*

NREL's [FLOw Redirection and Induction in Steady State]() (FLORIS) open-source software models the interaction between wind turbines in a wind 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 plant performance; and individual turbine shut-off. The FLORIS team also added the ability to evaluate the impact of different wind 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 plants. The updates expand FLORIS's capabilities, making it more user-friendly and facilitating easier integration with new features and modules.

Energy Research and Forecast Modeling

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

Industry Partner To Adopt Energy Research and Forecasting for Regional Wind Energy Modeling



Simulation of the atmosphere over a tropical ocean using ERF. Here, humid air over a relatively warm ocean surface leads to the formation of low-level cumulus clouds. This snapshot demonstrates the ability of ERF to predict interactions between momentum, heat, and moisture in the atmosphere. *Graphic by Eliot Quon, NREL*

As part of a new 3-year project, the renewable energy developer TotalEnergies is adopting the Energy Research and Forecasting (ERF) model, a tool that can measure the impact of large-scale weather on local wind plants. The tool is being developed by Lawrence Berkeley National Laboratory, NREL, Argonne National Laboratory, and Lawrence Livermore National Laboratory. During this project, the research team will model six sites for wind energy from around the world. The project team chose the ERF model over more established numerical weather prediction models because it can be run on a variety of supercomputers and can provide efficient, accurate simulations of real-world operating conditions and power production from wind plants.

Joint Industry Program (NOWRDC) - Interarray Wakes

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

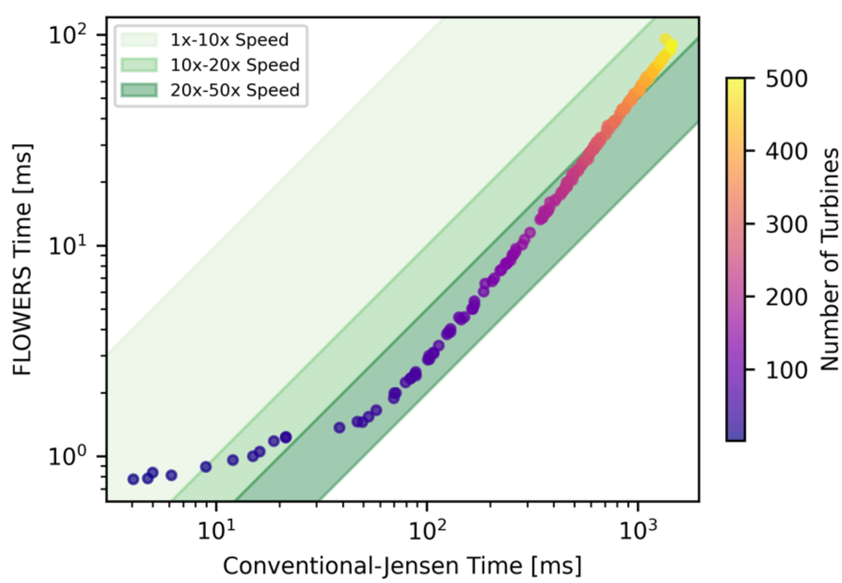
NREL Partners With Academia, Industry, and Government Agencies To Analyze Wind Plant-to-Plant Wake Effects off the U.S. East Coast

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 BOEM, DOE, and the state of Maryland to kick off a joint-industry project on interarray wake effects at wind 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 plants along the entire U.S. East Coast and assess suitable locations of future wind plant lease areas. This is NREL's first-ever joint-industry project and will open the door for similar projects in the future.

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 Technical University of Denmark 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 meters (m), and a hub height of 170 m. The generator adopts the popular direct-drive configuration, which couples the rotor to a large generator without using a gearbox. The turbine can model operations with either fixed-bottom or floating support structures. The turbine will support practitioners in both academia and industry for 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, prototype, and deploy ever-larger wind turbines.



The computational time for annual energy production predictions of the FLOWERS model plotted versus the time required by the conventional Jensen model implemented in NREL's wind farm solver Floris. The comparison is setup for 200 randomized cases (i.e., randomized number of turbines, layout of turbines, and wind rose) and shows how most of the cases achieve a 20/50x speed up with comparable accuracy. *Image by Michael LoCascio, Stanford University and NREL*

Offshore Wind Energy Research and Development

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

Largest Field Campaign To Collect Offshore Wind Energy Data Kicks Off

NREL researchers launched the Third Wind Forecast Improvement Project, the large field campaign focused on offshore wind energy in the United States. As of late 2024, the team deployed a barge and weather instruments in the North Atlantic off the U.S. Outer Continental Shelf, which extends from North Carolina to Maine. Researchers will use the platform, which will remain anchored near newly built offshore wind turbines, to collect unprecedented measurements of both wind and weather. These data will help researchers and developers dramatically increase their understanding of offshore wind resources and develop more accurate models to inform future development.

A photo of the offshore barge as it was deployed off the coast of Rhode Island. More than 10 weather instruments are hosted on the platform, including four by NREL. *Photo from Anthony Kirincich, Woods Hole Oceanographic Institution*

Offshore Wind System Design & Tool Validation

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

Wake Effects on Fixed and Floating 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 interaction 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 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 us 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 wind plant relative to an equivalent fixed system. Next steps include further model improvements to FAST.Farm for floating offshore wind 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*

Offshore Wind System Design & Tool Validation

Point of Contact: Jason Jonkman, Jason.Jonkman@nrel.gov, Amy Robertson, Amy.Robertson@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 Rotor Aerodynamics, Aeroelastics, and Wake (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.

Offshore Wind System Design & Tool Validation

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

International Collaboration Will Support Floating Offshore Wind Design Innovation

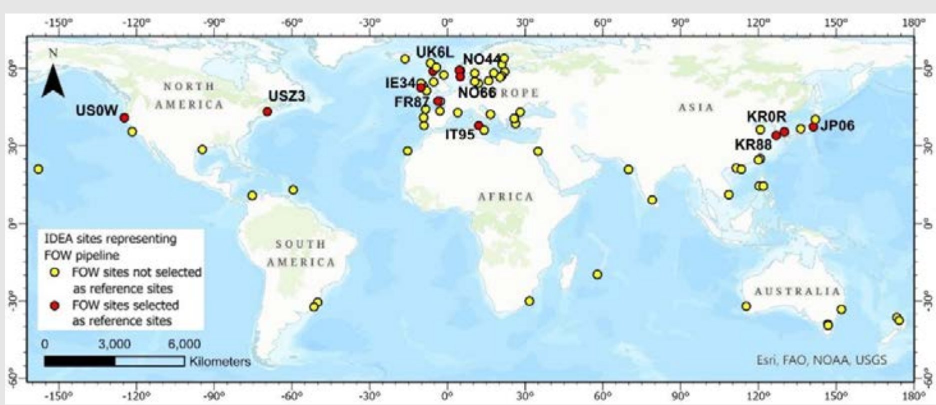
IEA Wind has approved the Offshore Code Comparison Collaboration 7 (OC7) project as a new wind energy research task (Task 56), slated to operate from FY 2024 to FY 2027. Building on the successes of the OC3–OC6 endeavors, OC7 aims to refine modeling tools and methods for offshore wind energy design, 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 within floating wind plants to optimize floating wind plant design. As an IEA Wind initiative, OC7 brings together more than 100 industry leaders worldwide, fostering collaborative innovation to overcome these challenges.

IEA Annex Task 49: Integrated DEsign of floating wind Arrays (IDEA)

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

NREL Advances Floating Wind Plant Reference Site Conditions and Design Considerations in IEA Wind Task 49

IEA Wind Task 49 aims to advance the global development of floating wind technology by addressing challenges and opportunities that arise when designing multiple-turbine 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 that can be used for floating wind turbine research projects, including data contributed from NREL researchers for Humboldt Bay and the Gulf of Maine. NREL researchers also led the creation of a design basis for floating wind arrays, coordinating inputs from a broad international group of technical experts. The design basis report outlines key engineering considerations when designing floating wind plants. This document provides the foundation for ongoing efforts to develop three reference floating wind plant designs for use by offshore wind energy researchers and technology developers.



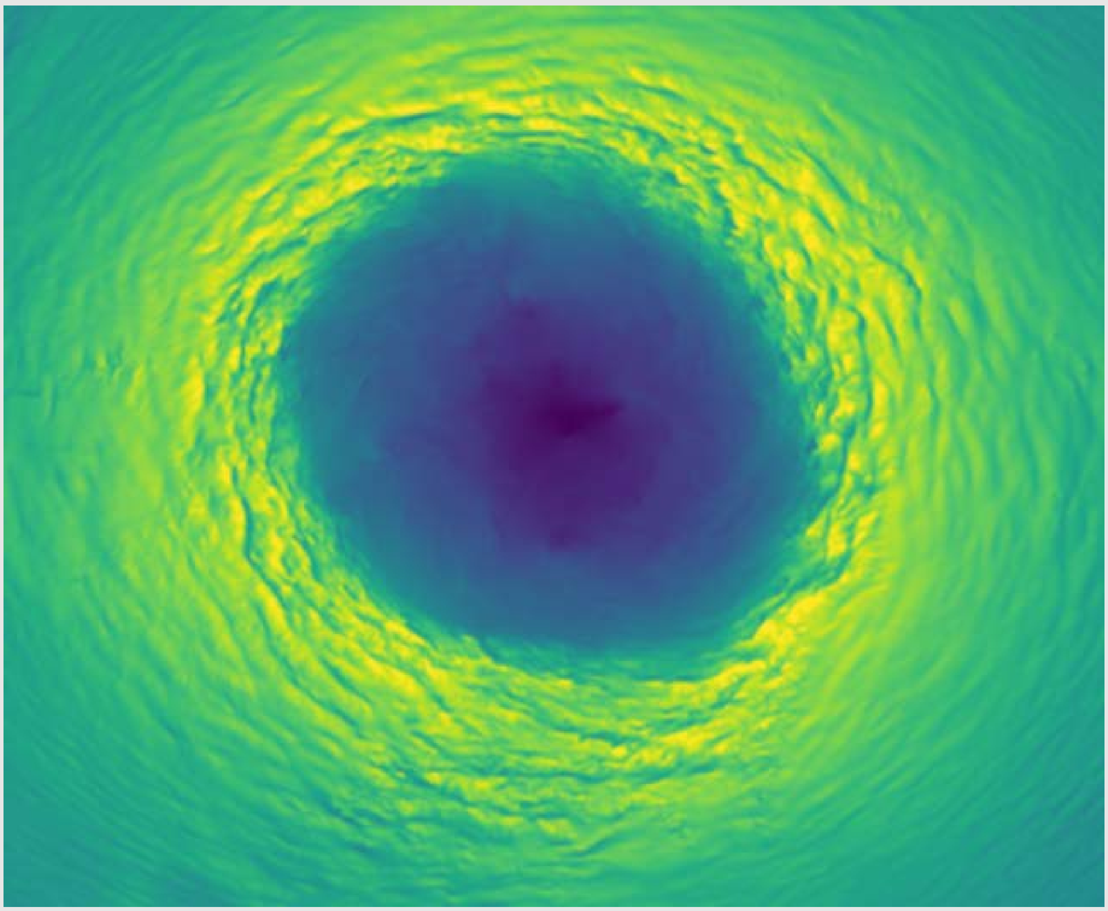
An NREL team gathered wind, wave, and water depth data for the two North American sites identified here, which will be part of IEA Wind Task 49's floating wind plant site condition dataset. *Graphic from Shauna Creane, Gavin & Doherty Geosolutions*

Simulation-based Turbine design fOr hurricane Resilience and loads Mitigation (STORM)

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

Hurricane Simulations Highlight Need for Enhanced Offshore Wind Design Standards

To assess whether existing wind turbine design guidelines adequately address the intense conditions of major tropical cyclones, or 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.



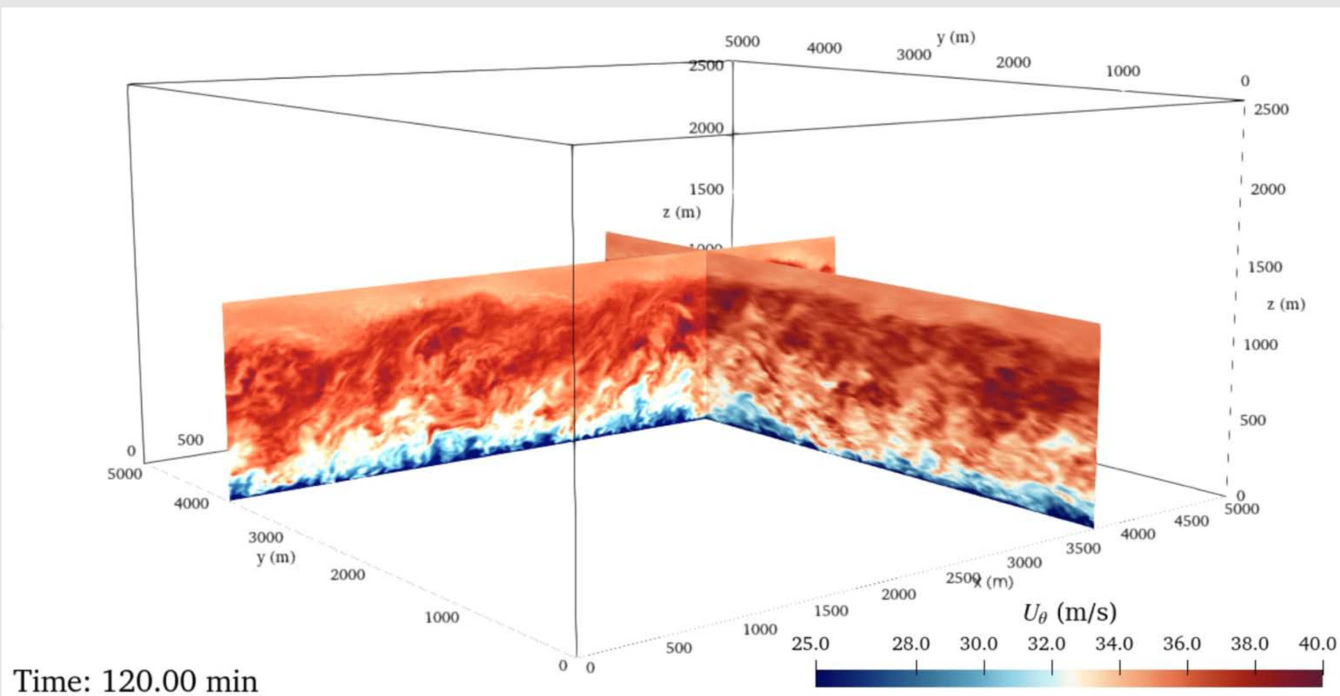
NREL's STORM team simulated Category 1–5 hurricanes to see how well the current wind turbine guidelines work in those storms. This image shows a simulation of the instantaneous horizontal wind speed at 100 m above the surface of a Category 3 hurricane, which is representative of the design limit state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

Influences of Future Tropical and Extratropical Storms on Wind Energy over the Eastern United States and Offshore (TREXO) and Simulation-based Turbine design fOr hurricane Resilience and loads Mitigation (STORM)

Point of Contact: Matthew Churchfield (TREXO), Matthew.Churchfield@nrel.gov, Georgios Deskos (STORM), Georgios.Deskos@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 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 approach and develop a method to simulate the wind fields in the particularly challenging region near the hurricane eyewall. This work will enable industry development of more hurricane-resistant offshore wind turbines.



A snapshot of a simulation of a hurricane wind field using the high-fidelity ExaWind code. The color contours show the rotating wind speed in a hurricane, approximately 40 kilometers (km) 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*

Floating Offshore Wind Platform Industrialization Support

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

NREL Support Drives Floating Wind Commercialization

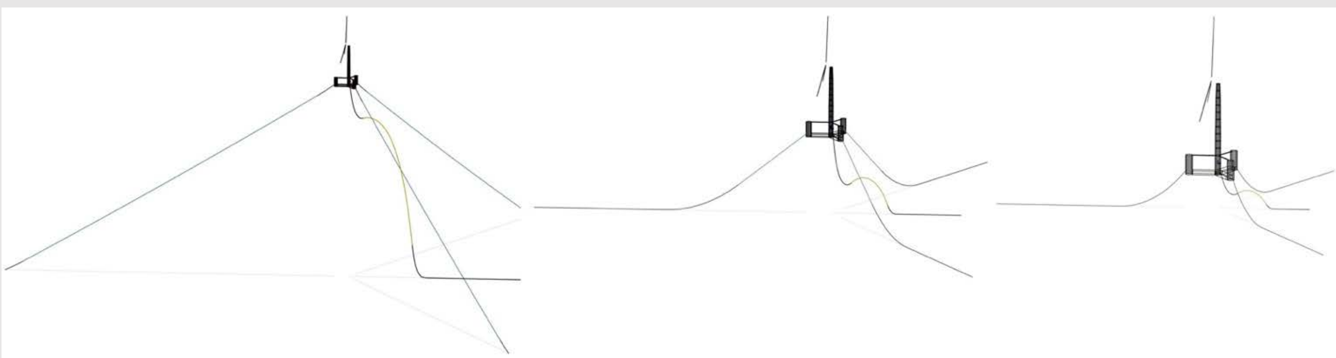
In FY 2024, NREL provided support to winning teams in the Floating Offshore Wind ReadINess (FLOWIN) Prize in the form of technical vouchers that were used for technical modeling, supply chain analysis, and techno-economic modeling. This support has enabled the winning teams to make significant strides in addressing key challenges related to floating wind commercialization, contributing to the overall advancement of innovative wind technologies. The goal of the prize is to accelerate the commercialization of U.S. floating offshore wind turbines by advancing designs, improving supply chain readiness, and reducing costs and risks.

This image depicts floating wind turbines in action, representing the future of sustainable energy in deeper waters, which NREL is supporting through their voucher work in the FLOWIN Prize. *Graphic by Besiki Kazaishvili, NREL*

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 plants will be key contributors to meeting offshore wind energy targets. 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, including a lack of power cables integrated 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—Northern California, the Gulf of Maine, and the Gulf of Mexico—and created mooring system and dynamic power cable designs for each region. These new component designs will extend the capabilities of the VolturnUS-S reference design to allow for floating wind plant analysis in a range of site conditions.

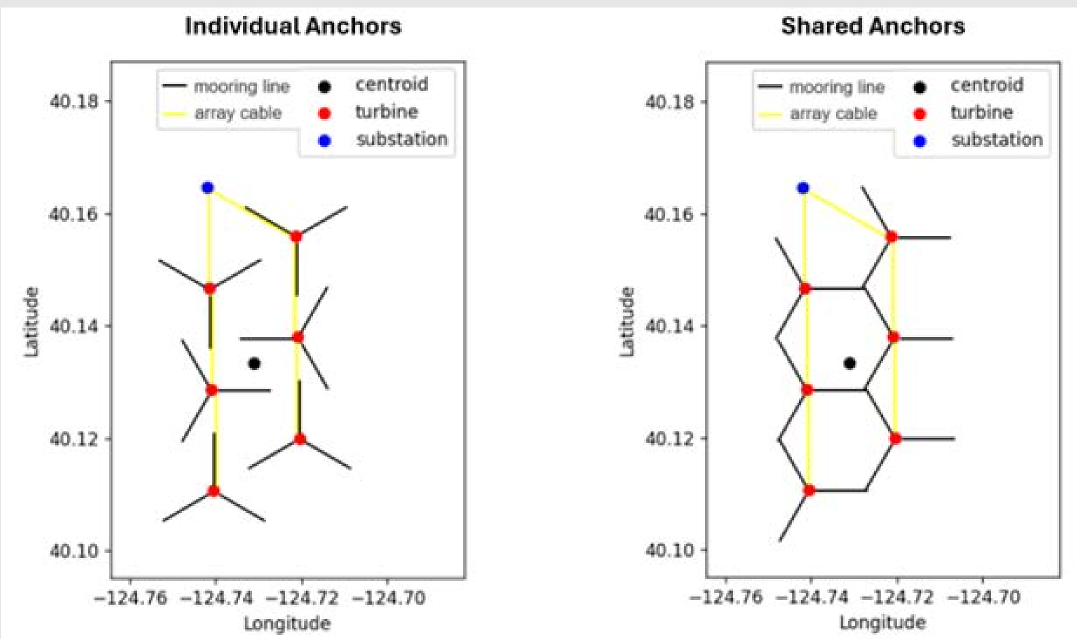


An NREL team created designs for mooring lines and dynamic power cables connected to a reference floating wind turbine at three different sites, which are visualized here from deepest (on the left) to shallowest depths. *Graphic by Matthew Hall, NREL*

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

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

In mooring systems for floating offshore wind 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 plant with individually moored anchors and a floating offshore wind plant with shared anchors for two different sizes of wind plants: a pilot-scale project comprising six floating wind turbines, and a gigawatt-scale project of 100 floating wind turbines. The team used consistent water depths, distances from shore, turbine spacings, and mooring line types between the individual and shared anchor wind plants, and consistent adjustments to the shared anchor design and installation procedure in their analysis. They found that using shared anchors in the pilot-scale wind plant contributed to a 3.8% reduction in LCOE to $155.6 per megawatt-hour (MWh), and in the gigawatt-scale wind plant, a 0.9% reduction in LCOE to $79.1/MWh. Using these assumptions, the team found that shared anchors in a floating offshore wind plant decrease project costs, which is more noticeable in smaller wind plants, but absolute LCOE is still significantly lower in utility-scale wind plants.

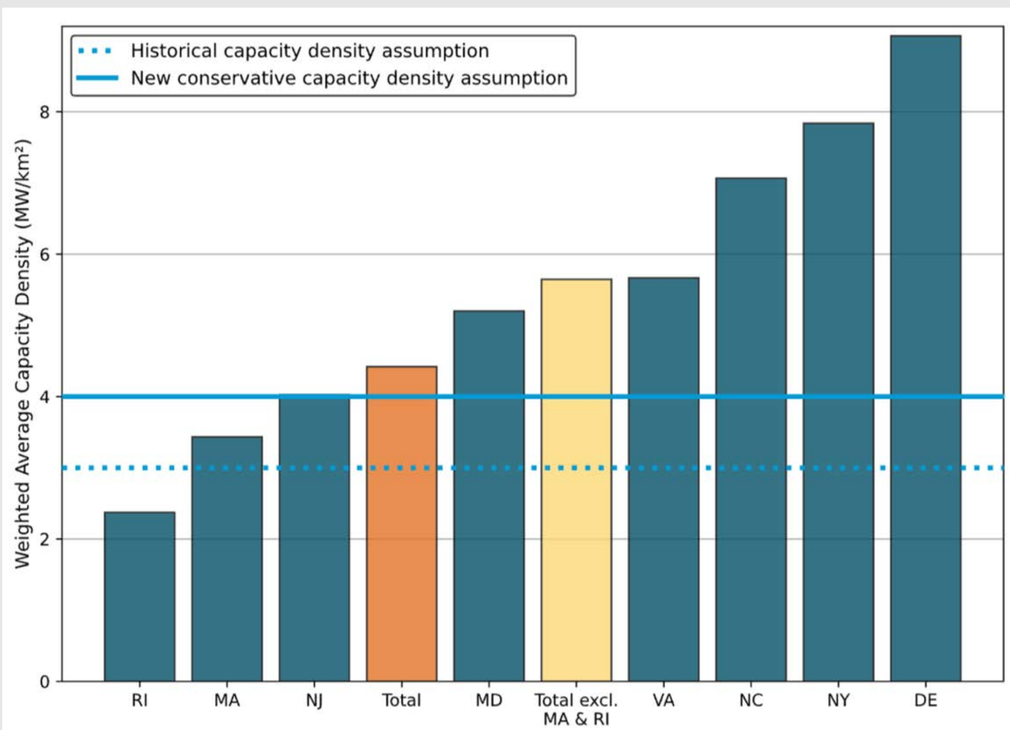


The NREL team studied the economic impact of shared anchors on a pilot-scale floating offshore wind plant of six turbines: one with individually moored anchors (left) and one with shared anchors (right) with the same turbine layout, array cable layout, and distance from shore. *Graphic by Stein Housner,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

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

Report Establishes a More Realistic Offshore Wind Capacity Density Metric

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 megawatts per square kilometer (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 to increase the report's capacity density assumption by 33% in the 2023 edition of the report. The increase has important implications for the estimated pipeline capacity and the amount of ocean space needed to achieve national renewable energy targets. The finding also influences the estimates from supply chain and workforce assessments.



This plot shows the variability of capacity density by state, from smallest capacity density to largest. The dotted blue line indicates the historical capacity density assumption of 3 MW/km^2, whereas the solid blue line indicates the new capacity density assumption of 4 MW/km^2. The states with the lowest densities—Massachusetts and Rhode Island—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 in orange, and the U.S. weighted average, excluding Massachusetts and Rhode Island projects, of 5.6 MW/km^2 in yellow. *Graphic by Daniel Mulas Hernando, NREL*

BOEM HQ Interagency Agreement: Techno-Economic Project Modeling and Analysis

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

WAVES Software Illuminates the Life Cycle Costs of Offshore Wind 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, like the Offshore Renewables Balance-of-system and Installation Tool (ORBIT), for capital expenditures estimation; the Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT), for operational expenditures estimation; and FLORIS, for annual energy production estimation. 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.

Materials, Manufacturing, and Design Innovation

Big Adaptive Rotor

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

Land-Based Wind Turbines Likely To Continue Facing the Wind

A cross-institution research team quantified the increased loading (or extra strain and stress on the structure) and noise that wind turbines that face downwind are likely subjected to compared to equivalent ones that face upwind. Recently, wind turbine designers and researchers considered downwind turbines as a way to build lighter and cheaper rotors, which could help reduce costs. But the new validation study—which was conducted by a team from NREL, Sandia, the Technical University of Denmark, and Resono Pressure Systems—shows that downwind turbines may come with more downsides than benefits. For their study, the researchers flipped the rotor of NREL's General Electric 1.5-MW wind turbine to operate it as a downwind rotor and deployed experimental devices to measure pressure distributions along one of the blades. Data from the new pressure devices will help improve modern simulation tools, such as OpenFAST and HAWC2, used to model airflow and turbine behavior.

Evening work on the GE 1.5-MW wind turbine located at NREL Flatirons Campus. In this photo the team of technicians is removing the DTU pressure belts from one of the three blades after the experiment was successfully completed. *Photo by Pietro Bortolotti*

Big Adaptive Rotor

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

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

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

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.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.

Manufacturing and Additive Design of Electric Machines by 3D Printing

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

Advanced Wind Turbine Generator Design and Printing Could Reduce Demand for Critical Materials

A multi-institution team developed new design and 3D-printing capabilities that could lighten the weight of every component of a wind turbine generator. This work was part of the Manufacturing and Additive Design of Electric Machines by 3D Printing (MADE3D™) project, which aims to advance the next generation of lightweight wind turbine generators to reduce demand for critical materials by more than 25%. NREL researchers led the project and partnered with Oak Ridge National Laboratory, NASA's Glenn Research Center, and a small wind turbine manufacturer, Bergey Windpower Company. The team developed novel approaches to optimize magnets and conductors that resulted in substantial mass savings for a prototype 15-kilowatt generator. A new shape profiling method was developed for the conductors that leveraged the printing technique developed by NASA Glenn. The method helped identify conductor designs with differing thicknesses and cross sections for each turn, which resulted in substantial reductions in conductor mass for similar performance. The details of the approach and results will be available in an upcoming technical report.

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

Program To Yield Pitch Bearing Reliability Insights

There is increasing interest from industry in the reliability of wind turbine pitch bearings, both for existing land-based wind power plants and for new offshore installations. Pitch bearings have a 10% replacement rate in only 7.5 years for turbines installed after 2016. There is a 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 (1) installing instrumentation on a pitch bearing of the DOE 1.5-MW wind turbine and collecting operating data during the current wind season and (2) 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 (right)*

Wind Recycling Prize Support

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

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

In January, 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 awarded 20 winners of its first phase, aims to advance the development of a cost-effective and sustainable U.S. recycling industry for wind turbine materials. *Graphic by Joelynn Schroeder, NREL*

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 Roadmap 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 in early 2025. 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. *Illustration by Alfred Hicks, NREL*

Materials, Manufacturing and Design Innovation 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 released *An Operations and Maintenance Roadmap for U.S. Offshore Wind*, 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*

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

Fiber-Optic Strain Sensors Provide Accurate Alternative To Monitor Gearbox Usage

NREL researchers demonstrated a robust and accurate solution to monitor gearbox use for a fleet of wind turbines by installing fiber-optic strain sensors on a 2-MW wind turbine at NREL's Flatirons Campus. Accurate knowledge of wind turbine gearbox stressors is essential in modern gearbox designs because increasing torque density demands make it difficult to maintain gearbox reliability and estimate a gearbox's remaining useful life. The traditional method of measuring gearbox loads using strain gauges and transmitting the resulting signals is unsuitable for fleet deployment because of technical and economic constraints. NREL's research validated an alternative method using fiber-optic strain sensors to verify gearbox loads.

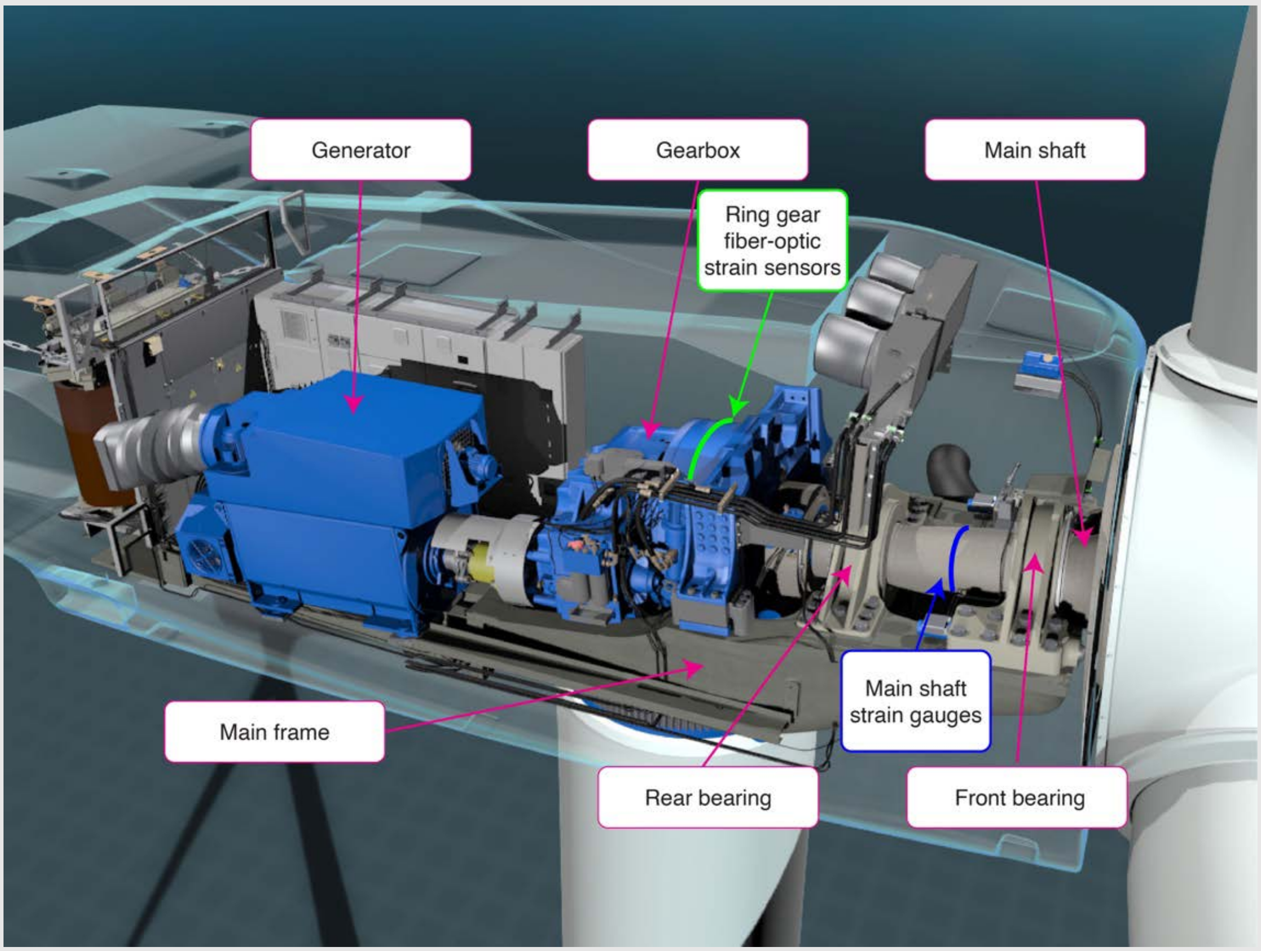
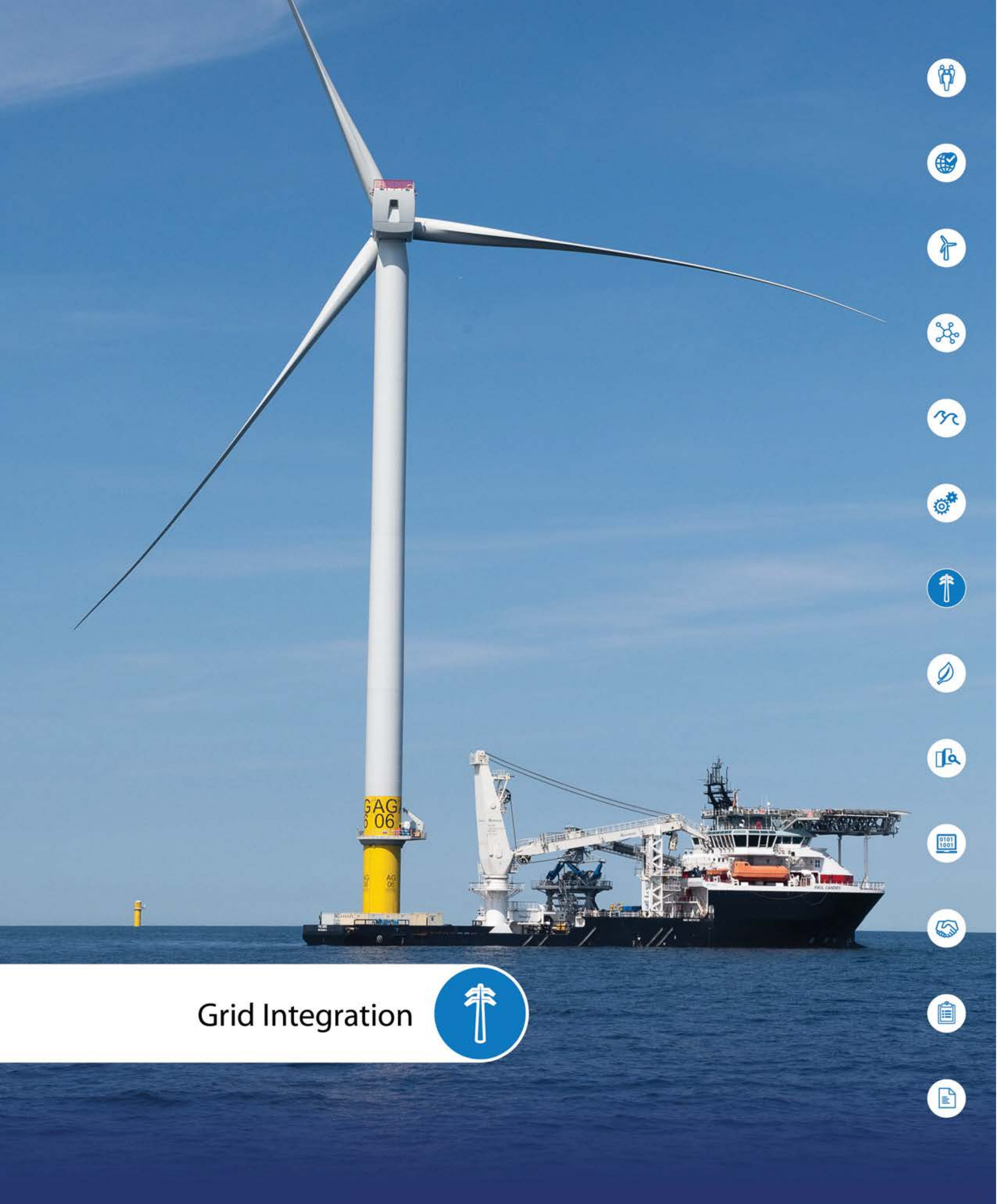


Illustration of Gamesa G97 nacelle with the location of fiber-optic strain sensors on the input stage ring gear and main-shaft strain gauges. *Graphic from Nextwave Media*

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 gigawatts (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 projects to the electric grid and how the country can increase transmission over the next several decades. The team has presented the findings of the work to system operators, state regulators, public webinars, industry groups, and at several conferences.

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 565783087*

Wind as a Real Synchronous Generator (WindSG)

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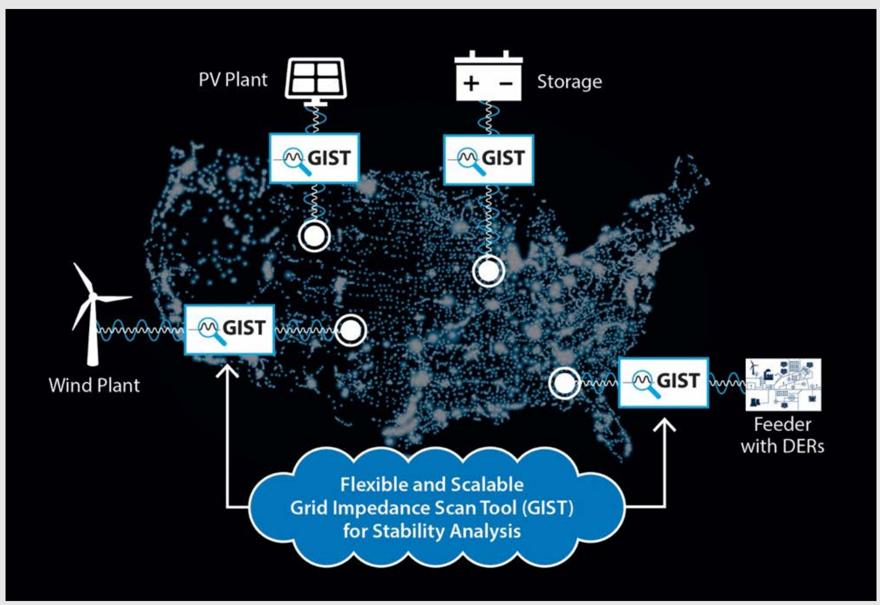
Power-Hardware-in-the-Loop Validation Explores Type 5 Turbine Technology

A team of researchers from NREL and the 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 validation 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.

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

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

Validation Tool Ensures Renewables and the Grid Are in Tune



The Grid Impedance Scan Tool (GIST) can evaluate the stability impact of wind plants, PV plants, storage, and feeder with DERs. *Illustration by Taylor Henry, NREL*

NREL's Grid Impedance Scan Tool (GIST) helped the Australian Energy Market Operator (AEMO) identify the devices and controls causing grid instability problems under certain operating conditions and explore targeted solutions with generators. AEMO is now using GIST to conduct follow-up analyses of its system with the goal of integrating more renewable energy devices to meet a national goal of net-zero emissions by 2050. Using digital models of devices and the surrounding electrical system, GIST software measures the impedance, or electrical resistance, of devices at their point of grid interconnection to evaluate system stability. In addition to software-only scans, GIST can also evaluate hardware such as battery storage on-site at the lab. NREL created GIST with support from WETO.

Wind Consortium Cyber Threat Model

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

Drivetrain Validation Highlights Potential for More Wind on Electric Grids

NREL and a team from GE conducted validation 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 validation 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 validations 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.

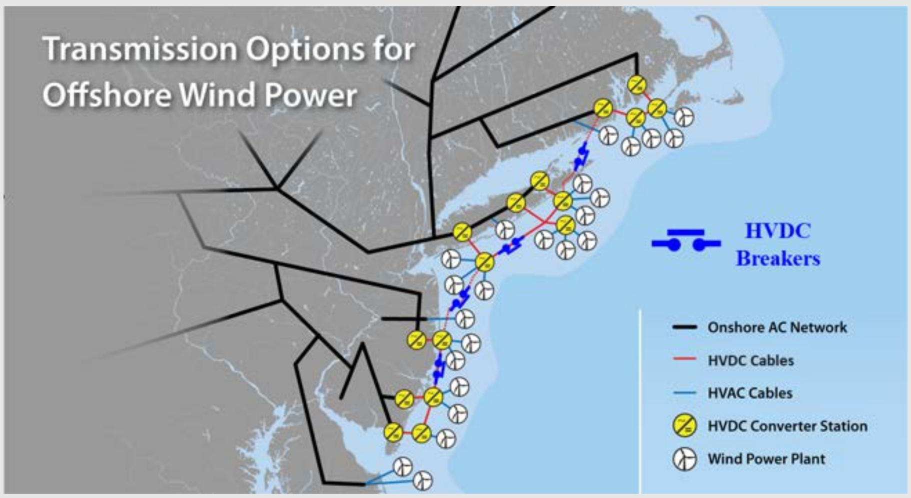
Researchers subjected GE's 2.5-MW wind turbine drivetrain, shown here attached to NREL's 5-MW dynamometer, to grid faults to validate its stability in grid-forming mode. *Composite photo by Pat Corkery, Mark McDade, and Dennis Schroeder, NREL*

Understanding the Protection and HVDC Breaker Needs for Offshore Grid Developments in the Atlantic Region

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

Models Evaluate Performance and Stability of Offshore Wind Integration With the Onshore Grid

NREL researchers have developed detailed simulation models based on the multi-terminal high-voltage direct current (HVDC) transmission systems used to integrate large amounts of offshore wind energy with onshore grids. The simulation models are being used to evaluate the fault performance of offshore HVDC transmission systems for different topologies and control schemes.



Notional diagram showing offshore transmission for integrating energy from offshore wind to onshore electric grids. *Graphic by Shalil Shah, NREL*

WindWeasel: PLC Monitoring, Analysis, and Alerting System

Point of Contact: Charles MaGill, Charles.MaGill@nrel.gov

Breakthrough Could Revolutionize Wind Energy System Security

Using a combination of cyber and physical data, NREL researchers, along with Sandia, are developing a machine-learning-based system to detect cyber intrusions at wind power installations and alert owners/operators of malicious operations. This year, the NREL team created a mechanism to capture data from the DOE 1.5-MW wind turbine at Flatirons Campus and developed a data pipeline to parse and analyze the data. The data include both controller and network traffic information (on the cyber side of the wind turbine's operations), and supervisory control and data acquisition measurements from the turbine (on the physical side of the turbine's operations). Combining the cyber and physical data in an intrusion detection system will lead wind power plant owners/operators to better understand anomalies and lead systems to better detect and issue alerts for intrusions for wind energy systems so wind plant owners/operators can react quickly to a security threat. In the next phase, the team will create various rules for the intrusion detection system by analyzing the cyber and physical data they captured.

Wind Security through Hardware Installation, Education, and Layered Defense (WindSHIELD Valuation)

Point of Contact: Charles Magill, Charles.MaGill@nrel.gov

Tools Enhance Wind Energy Cybersecurity

The WindShield project recently compared two tools, the Cyber Security Evaluation Tool (CSET) and Distributed Energy Resource Cybersecurity Framework (DER-CF), to determine their effectiveness in enhancing the security of energy sector assets, particularly in the wind energy sector. This research is crucial as it helps identify the best applications for each tool, highlights gaps in current cybersecurity practices, and suggests areas for future research, ultimately advancing the field of wind energy by improving its cybersecurity posture. The next steps involve developing enhanced cost/benefit analyses for cybersecurity measures and exploring interoperability between the tools for more comprehensive evaluations.

NREL researchers are improving wind energy industry cybersecurity through the WindSHIELD program. *Illustration from GE Vernova*

Point of Contact: Charles MaGill, Charles.MaGill@nrel.gov

A Cybersecurity Blueprint for Offshore Wind Farms

NREL researchers developed a comprehensive cyber-physical reference architecture and simulation for offshore wind plant cybersecurity. Establishing a standardized framework helps protect essential offshore wind infrastructure from cyber threats, ensuring the security of rapidly expanding offshore renewable energy sources. With 4,097 MW under construction in the United States, 3,378 MW approved for deployment, and more in development, securing these renewable energy sources is paramount. NREL's next step is to validate the reference architecture against various cyber threats and develop more detailed cybersecurity guidelines specific to offshore wind farms.

Vineyard Wind is the first utility-scale offshore wind energy project in the United States and sits over 15 miles off the coast of Massachusetts. Cybersecurity is an important consideration for new facilities to generate reliable, clean renewable energy. *Photo by Joe DelNero, NREL*

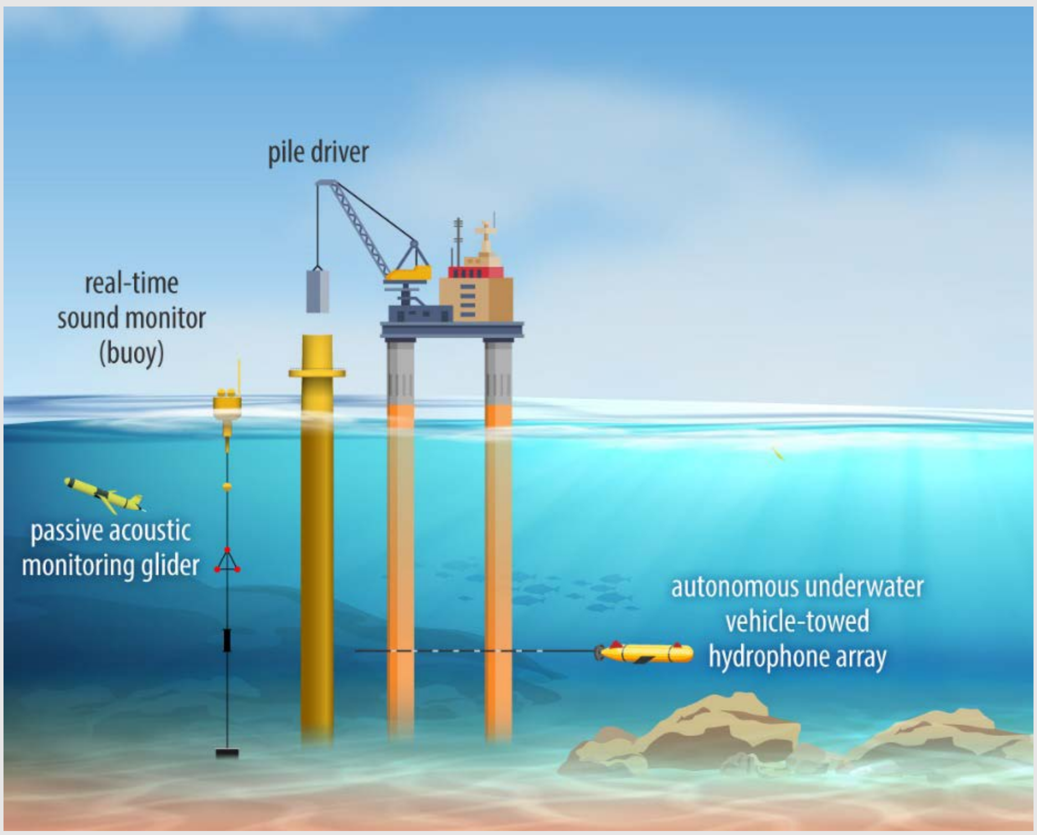
Environmental Research

Evaluation of Tools and Technologies for Detecting Marine Mammals Around Offshore Wind Construction Activities

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

NREL Partners To Protect Whales Near Offshore Wind Energy Construction Sites

NREL and PNNL are developing a framework to validate technologies that can detect the presence and track the movement of whales around offshore wind energy construction activities, which can create underwater noise harmful to marine wildlife, including whales. Mitigating impacts from pile driving and other noise sources during construction is imperative, given whales are protected under federal law. The project, which is overseen by several federal agencies, the Regional Wildlife Science Collaboration, and the Marine Technologies Society, has held two workshops. With more than 175 attendees at each, the workshops provided stakeholder input in preparation for a final technical report (expected in early 2025).



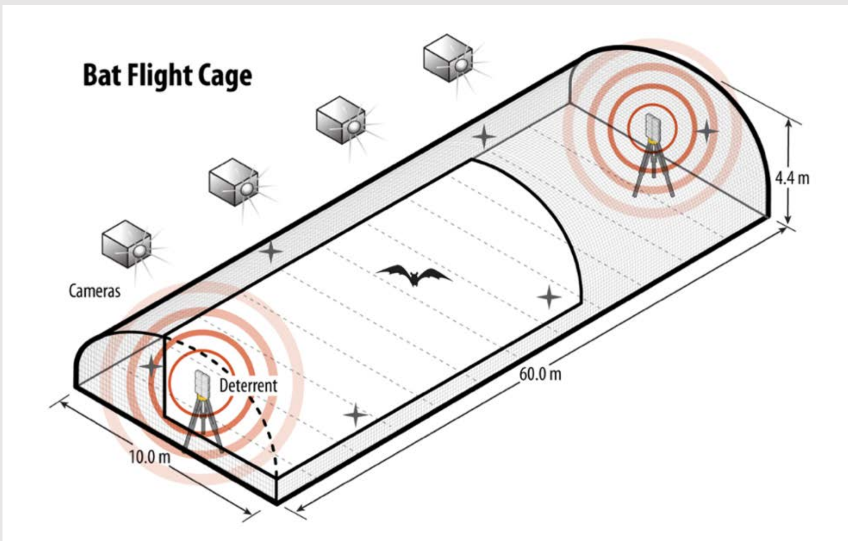
Pile driving activities during offshore wind energy construction generate underwater noise that can be detrimental to whales. Acoustic sensors are one means of detecting the presence of whales near construction sites and can help inform when it is safe to proceed with pile driving. *Graphic by Alfred Hicks, NREL*

Wind Operational Issue Mitigation

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 ultrasonic 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*

Wind Operational Issue Mitigation

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

Regional Training Focuses on Reducing Wind Energy and Wildlife Interaction

NREL, in partnership with the Renewable Energy Wildlife Institute, organized a virtual training to educate state agencies from Colorado, New Mexico, Texas, Utah, and Wyoming and other stakeholder groups on current practices for monitoring and mitigating wind energy and wildlife interactions. The four-day training included speakers from government agencies, research labs, nongovernmental organizations, and private industry. They discussed existing government regulations, the state of the science, and lessons learned from validating emerging technologies used in research. Attendance ranged from 116 to 211 people across the four days.

IEA Task 34: WREN

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

Tool Summarizes 100 Environmental Research Technologies Used in Wind Energy Projects

IEA Wind Task 34 – Working Together to Resolve Environmental Effects of Wind Energy (WREN), reached a 100-summary milestone on its online Wind Energy Monitoring and Mitigation Technologies Tool. NREL, which leads WREN, partnered with PNNL to develop and maintain the tool, which provides summaries of 100 individual technologies used in environmental research at land-based and offshore wind energy projects. The tool, which has received nearly 4,000 page views, also includes links to literature related to the validation and use of each technology.

Identiflight, a camera-based mitigation technology used to reduce eagle collisions with wind turbines, is one of over 100 technologies included in the Technologies Tool. *Photo by Dennis Schroeder, 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 along 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-93636326*

Stakeholder Engagement and Wind Energy Workforce

Community Benefit

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

NREL Launches First-of-Its-Kind Community of Practice

In June 2024, NREL officially launched "LIFT: A Community of Practice to UpLIFT Equity and Justice in Wind Energy Deployment." As the amount of both offshore and land-based wind energy deployment grows, DOE and NREL are seeking to support the growing number of individuals engaged in wind energy equity-related work. LIFT will support participants through virtual and in-person gatherings and by documenting and sharing relevant resources. Over the next three years, LIFT will help participants share knowledge and best practices, collaborate with others in the field, innovate to address key challenges, and bridge gaps in understanding and practice.

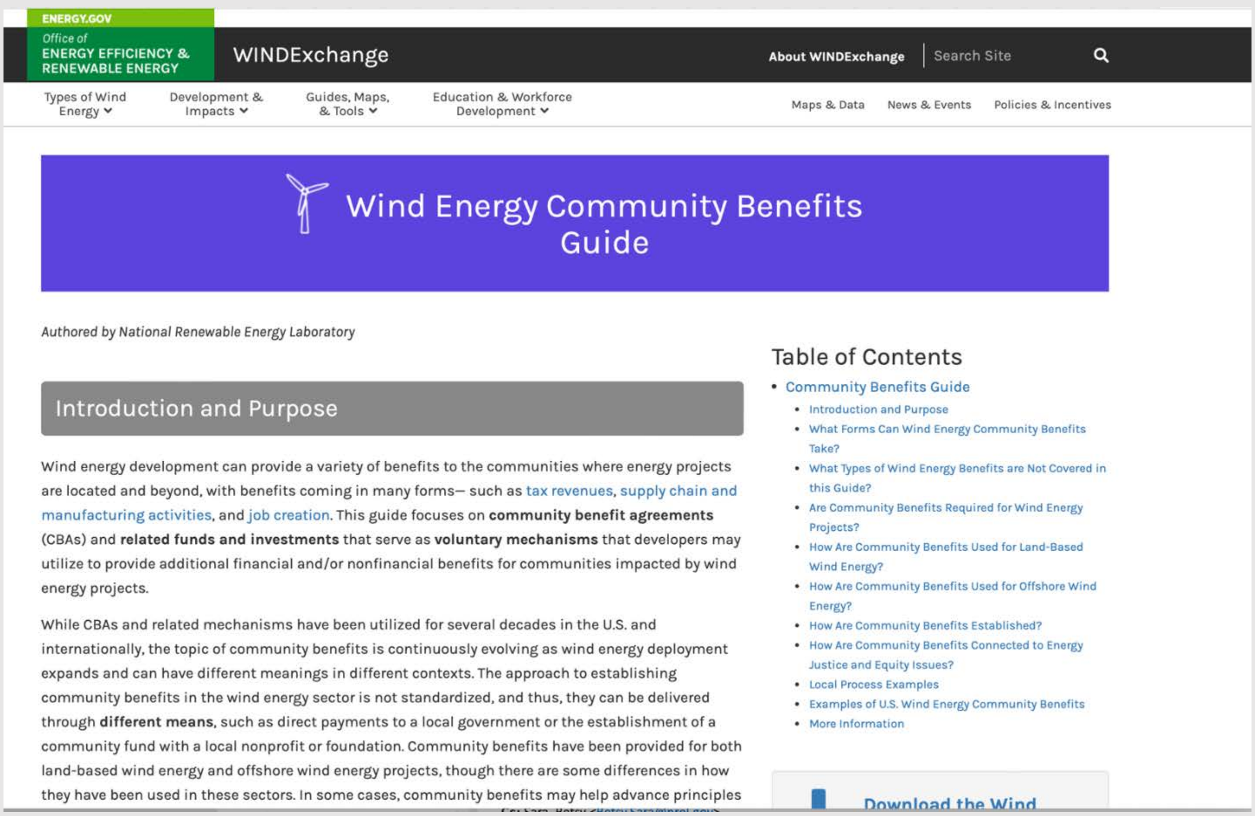
The Block Island Wind Farm, pictured here from Block Island, is the first U.S. offshore wind farm. The five Halide 6-MW turbines were installed by Deepwater Wind and came online in December 2016. *Photo by Dennis Schroeder, NREL*

WINDExchange and Regional Resource Centers

Point of Contact: Matilda Kreider, Matilda.Kreider@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 benefit mechanisms, including community benefit agreements and funds. NREL developed the guide by conducting stakeholder interviews, collecting examples of community benefit agreements across the United States, reviewing literature, and hosting a peer exchange workshop with community and Tribal leaders and other parties working on community benefits for offshore wind energy. After publishing the guide, NREL hosted a community benefits webinar in February and launched a 2024 study exploring national community benefit use trends, the results of which will be published in FY 2025. On DOE's WINDExchange platform, NREL published a database of community benefit information for nearly 300 land-based and offshore wind energy projects.



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 Prepares the Next-Generation Workforce

The Collegiate Wind Competition, which is managed by NREL on behalf of DOE, demonstrates that participating students seek employment in the clean energy and sustainability sectors. Their real-world technology, project development, and outreach experience benefits their employers and the nation in the effort to build energy resiliency and meet decarbonization goals. Since 2014, the competition has convened more than 50 U.S. colleges and universities and ~1,500 students to participate in the annual competition, which prepares college students for jobs in the wind and renewable energy sectors through real-world experience. Thousands of companies have provided mentorship, software, technical, and financial support. A Collegiate Wind Competition alumnus is 1.5 times more likely to get a job in the wind industry because of their participation in the competition. In Fiscal Year 2024 alone, 32 schools competed for a finalist slot in the annual competition's wind energy education program. The 2024 Collegiate Wind Competition culminated at American Clean Power's CLEANPOWER conference in May 2024 in Minneapolis, Minnesota, where California State University Maritime Academy took home first place. The 2025 Collegiate Wind Competition launched in March 2024 and is expected to be completed in May 2025.

California State University Maritime Academy claimed first place at the 2024 Collegiate Wind Competition. *Photo by Mark McDade, NREL*

Wind for Schools and Wind Workforce

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

New Resources Help Explain Inflation Reduction Act Prevailing Wage and Apprenticeship (PWA) Resources Tax Incentives

NREL experts created resources to clarify how the Inflation Reduction Act's Prevailing Wage and Apprenticeship requirements could affect a wind energy company's ability to qualify for increased credit or deduction amounts through certain clean energy tax incentives. The Prevailing Wage and Apprenticeship provision offers enhanced tax credit benefits for eligible clean energy projects that pay applicable workers the prevailing wage and meet the stated apprenticeship requirements. The new NREL resources include a webinar that introduces viewers to the provision's requirements, flowcharts to help taxpayers understand the law, and a series of fact sheets with workforce specific explainers on how to implement the policy. These resources are meant to support subcontractors, midsize developers, education and training institutions, and local workforce development boards.

Wind for Schools and Wind Workforce

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

New Wind Energy Workforce Initiative Can Help Workers, Industry Collaborate

Stakeholders gather for the 2024 Offshore Wind Workforce Summit, where panelists shared information and participants addressed workforce needs. *Photos from Dwayne Wilkins*

NREL researchers developed the new Wind Energy Workforce Network Initiative to foster opportunities for members of the wind energy workforce and industry to connect and collaborate. This initiative is also designed to amplify and unite wind energy workforce development efforts at the regional and national levels. To achieve this goal, NREL experts convened several meetings for the existing Offshore Wind Energy Workforce Network and developed a new Land-Based Wind Energy Workforce Network. These networks provide a forum for members of the wind energy workforce and industry to share knowledge and resources, discuss wind energy workforce challenges and opportunities, and identify solutions. The team also partnered with the Oceantic Network to host the 2024 Offshore Wind Workforce Summit where approximately 150 participants discussed how to address offshore wind energy industry workforce needs, raise awareness of wind energy careers, and ensure the industry can prioritize equitable hiring and offer good jobs.

Wind for Schools and Wind Workforce

Point of Contact: Bailey Pons, Bailey.Pons@nrel.gov

Wind Works Forum Bridges Career Gaps in Wind Industry

Building on past research identifying gaps between career seekers and wind energy employers, NREL developed the Wind Works Forum—a gathering dedicated to helping students, recent graduates, and career changers explore and build exciting, impactful careers in the wind energy industry. For the inaugural year, the forum took place virtually Sept. 23–26, 2024. Career seekers, industry members, and education and training programs across the United States participated and contributed to the forum, helping career seekers generate knowledge, develop meaningful connections and lasting relationships, and explore opportunities alongside industry members and education and training programs.

Wind for Schools and Wind Workforce

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

Updated Database Can Help Connect Industry and Workers to Wind Energy Education and Training Programs

NREL researchers developed a new mapping tool for the Wind Energy Education and Training Database, a national catalog of wind education and training programs that can prepare workers for any wind energy occupation. The mapping tool is designed to help increase awareness of existing education and training programs and connect potential students to those programs. The database includes an inventory of universities, community colleges, vocational schools, and training providers that offer degrees and courses in wind energy as well as apprenticeship programs that train students in wind energy-related skilled trades.

WINDExchange and Regional Resource Centers

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

Webinars Connect the Public With NREL Experts on Key Topics in Wind Energy

NREL and DOE's platform hosted three webinars in FY 2024 exploring different aspects of wind energy: community benefits, end of service and recycling, and incentives and the Inflation Reduction Act. In February, Matilda Kreider presented alongside external speakers about community benefit mechanisms in wind energy deployment, drawing on NREL's multiple years of research and engagement on this topic. **In May**, Chloe Constant and Derek Berry spoke about end-of-service and recycling processes, highlighting NREL's Bipartisan Infrastructure Law-funded research and engagement projects. **In September**, Brinn McDowell spoke about the Inflation Reduction Act's impact on wind energy incentives and workforce, alongside an external speaker presenting on the history of incentives and tax credits. The webinars received hundreds of live attendees and hundreds of additional views of the recorded versions online.

WINDExchange and Regional Resource Centers

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 living near wind energy projects, sharing their perspectives as rural farmers, marine industry occupational trainers, local government workers, parents, environmental protectors, and Indigenous elders and community members. NREL presented findings from the sessions at two conferences and in a technical report published in FY 2023 on the project. Researchers will also present findings of the study to the Gallup community in a learning session co-hosted with the Gallup partner organization.

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*

WINDExchange and Regional Resource Centers

Point of Contact: Lucas Eshuis, Lucas.Eshuis@nrel.gov

New WINDExchange Resources Boost Visibility and Availability of High-Priority Datasets

By publishing new information, NREL closed a data accessibility gap on WINDExchange. Past analysis determined that wind energy ordinances, community benefits, and equity data help wind energy stakeholders make informed decisions, yet this information was not accessible to WINDExchange users. To close this gap, NREL updated the existing Wind Energy Ordinances Database to include ease-of-use features and explainer text for added functionality and information clarity. NREL researchers published a comprehensive database of land-based and offshore wind community benefits in the United States and created a new mapping tool that overlays equity data with U.S. wind turbine locations.

Community and Stakeholder Engagement

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

Listening Sessions Offer Community Perspectives About Wind Energy End of Service

NREL completed its Community and Stakeholder Engagement project in February 2024 and has been focusing its effort on writing a report to summarize the various activities and takeaways from the project to inform ongoing, community-focused end-of-service resource development and engagement efforts. As part of the summary effort, NREL attended the DOE/WETO Bipartisan Infrastructure Law Project Meeting that was held in Washington, D.C., on June 6, 2024. Ongoing efforts in this space include the update of the End of Service Guide.

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

Modeling and Analysis

Wind Plant Technology Optimization

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

New Study Identifies Key Trade-Offs of Wind Turbine Upsizing

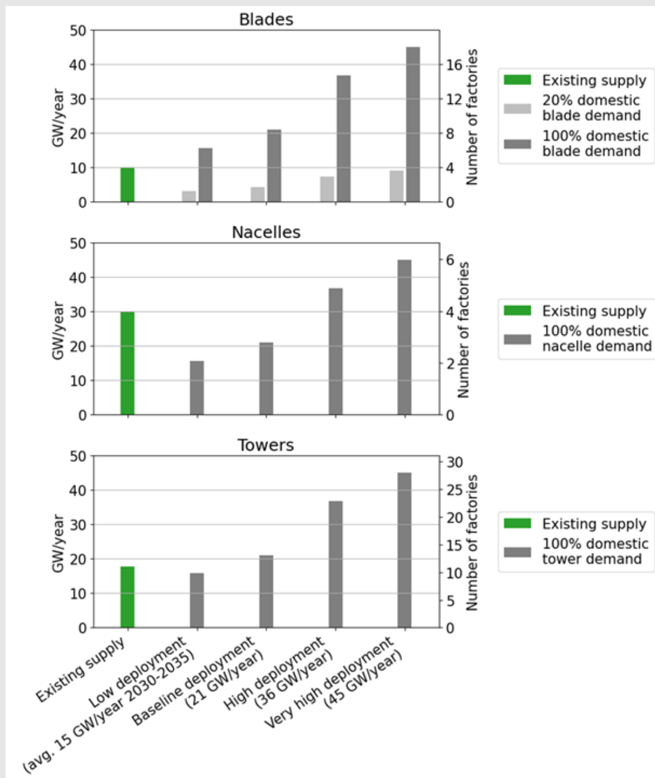
NREL's Wind Energy Community Benefits Guide on DOE's WINDExchange platform is designed to help communities better understand how they can benefit from and become involved with wind energy. The guide provides information about land-based and offshore wind energy community benefit mechanisms, including community benefit agreements and funds. NREL developed the guide by conducting stakeholder interviews, collecting examples of community benefit agreements across the United States, reviewing literature, and hosting a peer exchange workshop with community and Tribal leaders and other parties working on community benefits for offshore wind energy. After publishing the guide, NREL hosted a community benefits webinar in February and launched a 2024 study exploring national community benefit use trends, the results of which will be published in FY 2025. On DOE's WINDExchange platform, NREL published a database of community benefit information for nearly 300 land-based and offshore wind energy projects.

Wind Plant Technology Characterization

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

NREL Analyzes the Impact of the Inflation Reduction Act on Land-Based Wind 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 1–2 nacelle manufacturing facilities, 12–17 tower facilities, and 10–14 blade facilities.



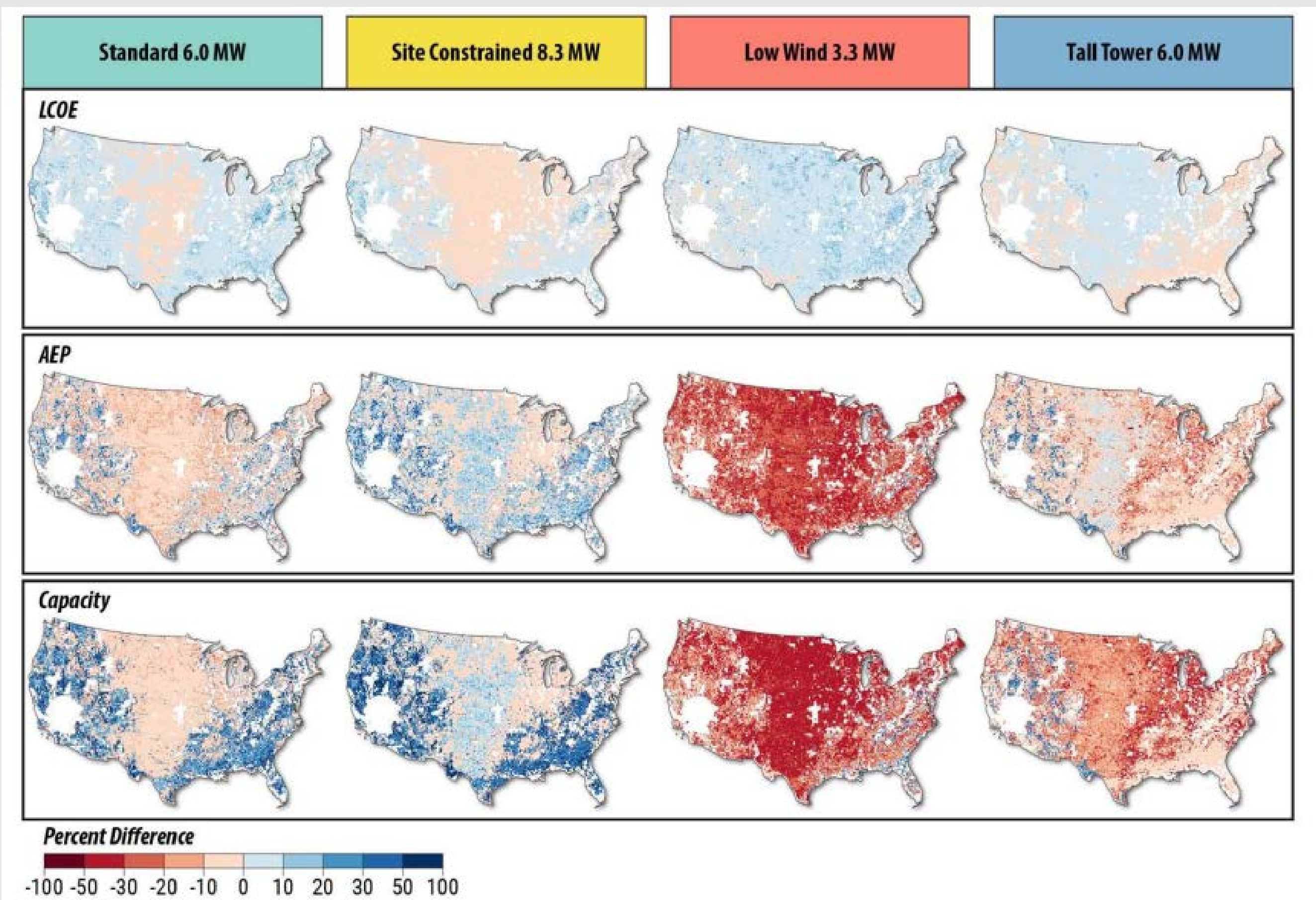
An NREL study mapped out average 2030–2035 component supply and demand for deployment scenarios ranging from 15–45 GW/year. New manufacturing facilities would be required for most projects to obtain the domestic content bonus from the Inflation Reduction Act for high or very high deployment rates. *Graphic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

Wind Plant Technology Characterization

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 sited 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 km2 of land, which could grow to 11.9 terawatts on just 2.6 million km2 of land with modest continued technology improvements. But uncertainty in siting could reduce developable land down to 0.76 million km2—potentially reducing wind energy's 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*

IEA Task 57 – Joint Assessment of Models

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

International Collaboration Works To Validate Wind Energy Models

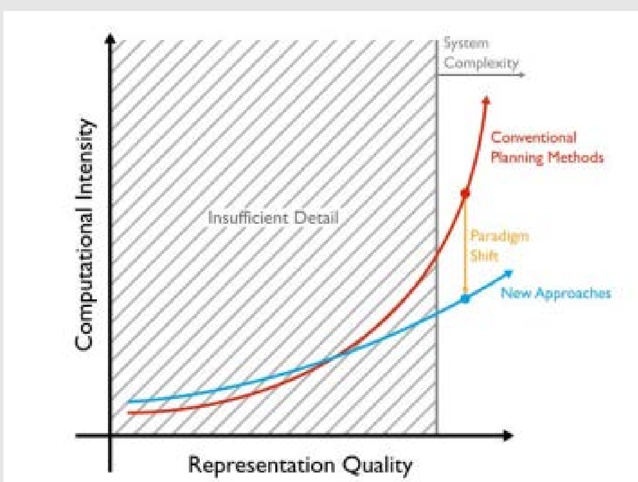
NREL experts led the development of the new IEA Wind Task 57 – Joint Assessment of Models to coordinate international research in the field of wind flow, wind turbine, and wind farm simulation. This task will bring together a group of international experimental scientists and computer modelers to assess the performance of wind energy models and ensure that wind energy technology development, deployment, and operation are based on comprehensive experimental datasets and reliable simulation results. This international coordination is critical for researchers and the industry to amplify research outcomes, learn from one another, and accelerate advances in the wind energy industry.

Energy Sector Modeling

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

New Modeling Approach Could Help Analyze Stress Periods for the Electricity Grid

NREL researchers proposed a new framework, called Adaptive Stress Period Planning, to generate more accurate spatially and temporally resolved estimates for future decarbonization scenarios. Such scenarios are typically evaluated using capacity expansion models that optimize for the lowest-cost planning objectives. These models often estimate capacity credit—how much generation capacity is available in periods of high stress on the grid—to evaluate the system's ability to respond to varying peaks in demand. The team's new methodology would capture energy limitations and considers interactions between generation resources and load to identify which resources respond to stress periods. The framework could be used to develop more accurate models of grid events to appropriately evaluate decarbonized grid scenarios.



The goal of the new Adaptive Stress Period Planning method is to achieve better computational performance at the levels of representation quality required to model modern power systems. *Graphic by Jess Kuna, NREL*

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

New Capabilities Added to Wind Power Plant Operational Assessment

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 for 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.

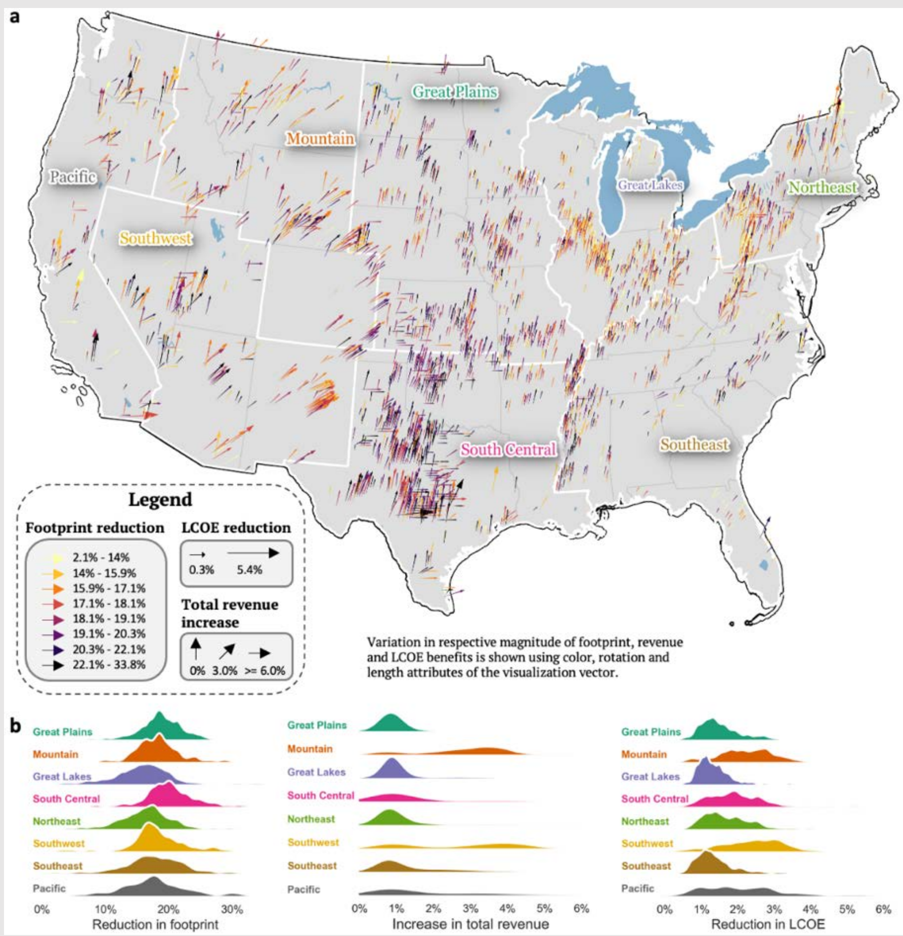
The OpenOA software features a variety of operational wind power plant data, utilities toolkits, and core operational assessment methods, which now include wake loss and static yaw misalignment. *Graphic by Eric Simley, NREL*

Note: SCADA = supervisory data and acquisition; met = meteorological; AEP = annual energy production; EYA = Energy Yield Assessment

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

Study Employs Artificial Intelligence To Identify Substantial Benefits of Wake Steering

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).

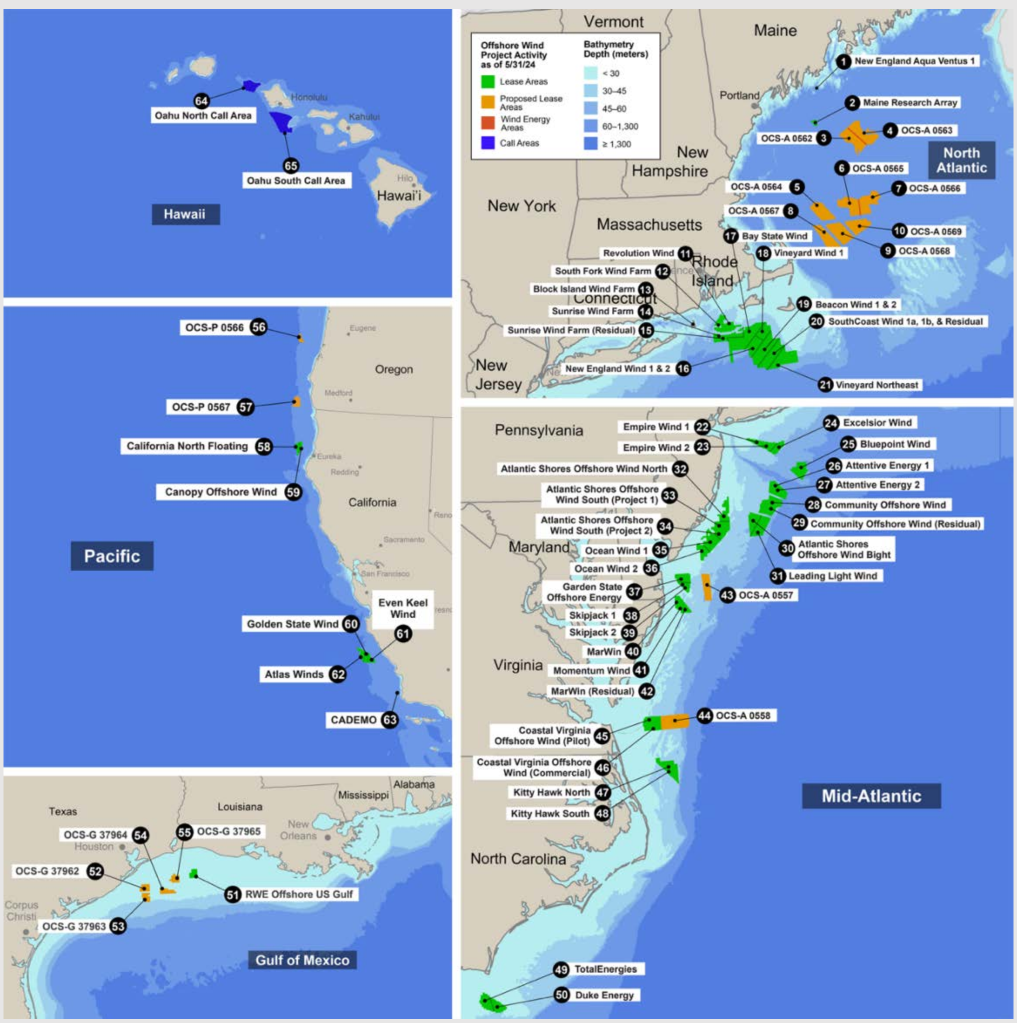


Researchers used artificial intelligence to identify how use of wake-steering technologies could reduce a wind power plant's footprint, decrease the LCOE, or increase the plant's revenue. *Graphic by Dylan Harrison-Atlas, NREL*

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

Report Details Historic Year in Offshore Wind

NREL experts published the annual Offshore Wind Market Report, which summarizes critical permitting, policy, technology, cost, and supply chain events in the growing offshore wind energy market. This year's report recounts events that occurred between January 2023 and May 2024, a period that includes some momentous events in U.S. offshore wind energy development. For example, the first commercial-scale projects delivered power to the grid, and the pipeline of upcoming wind energy projects grew to a new high of 80 GW of potential generating capacity. The report also highlights critical advances in state offshore wind targets and federal leasing activities and examines states' ability to respond to economic challenges and project cancellations through restructured procurement mechanisms.

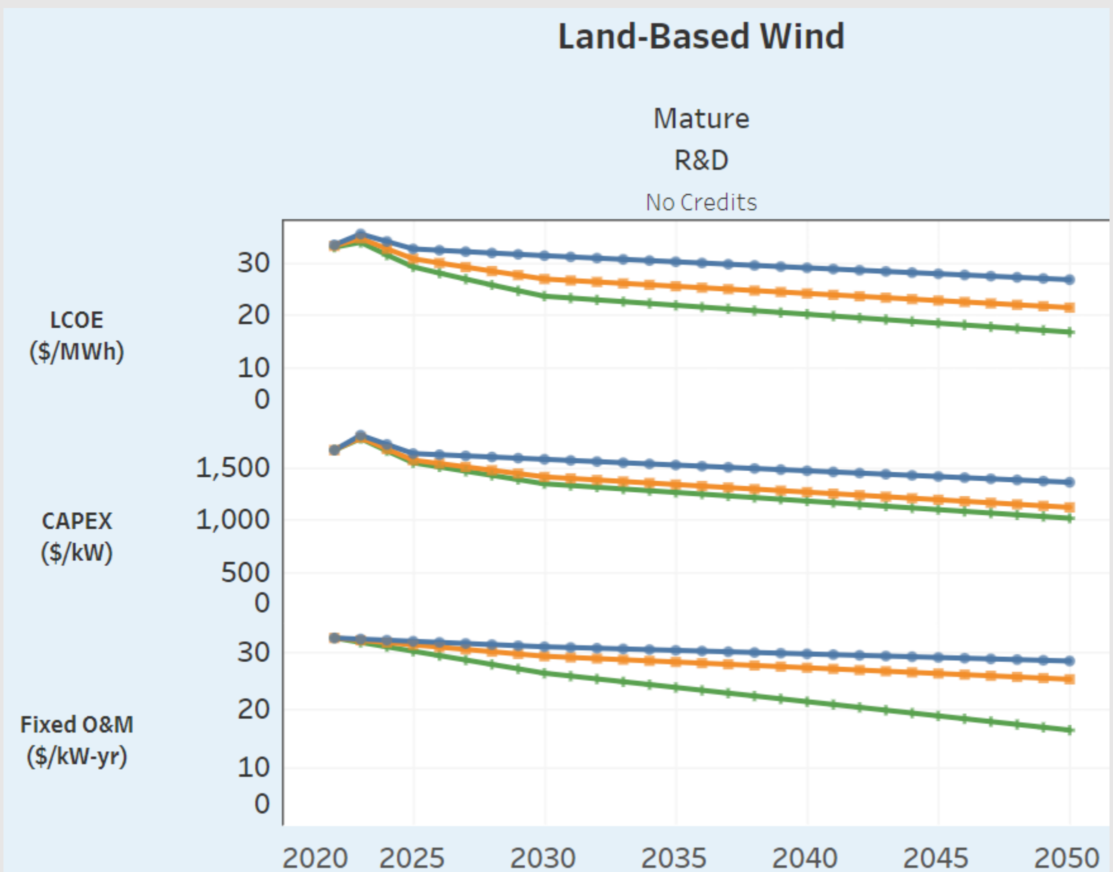


Locations of U.S. offshore wind energy pipeline activity and Call Areas as of May 31, 2024. *Graphic by John Frenzl, NREL*

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

New Benchmark Cost Data for Current and Future Wind Energy Costs

In FY 2024, NREL researchers updated a dataset that was originally developed as part of the Distributed Wind Futures Study, a cornerstone dataset of the techno-economic potential of distributed wind energy. The improved modeling results now include data on the cost thresholds at which distributed wind could be economically competitive, distributed wind technical potential, and annual energy production for front-of-the-meter and behind-the-meter distributed wind energy. The new dataset also provides high-resolution results for more than 150 million land parcels in the contiguous United States, offers increased modeling accuracy, and could be easily integrated into other tools to produce accessible and informative data for end users and policymakers.

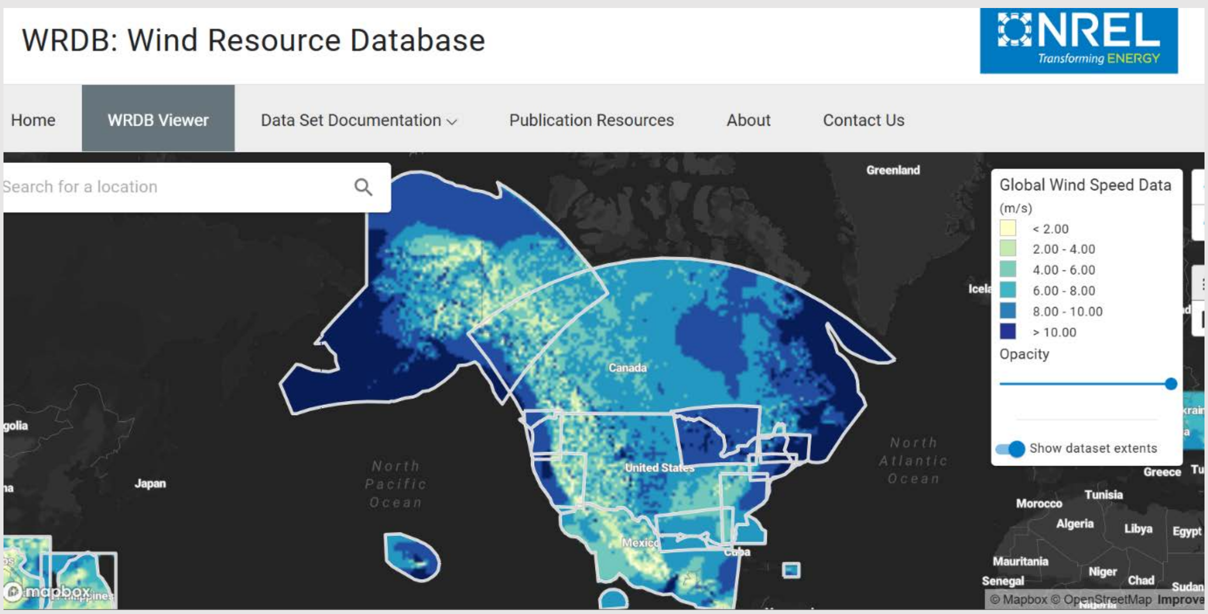


Land-based wind projections for levelized cost of energy, capital expenditures, and operational expenditures based on site-optimized wind turbine selection. *Graphic by NREL's Annual Technology Baseline Team*

Point of Contact: Nicola Bodini, Nicola.Bodini@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 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. Researchers convened a workshop with industry, academia, and national labs to explore how the dataset can fill gaps in the existing resources and continue to grow as a tool for wind analysts. NREL has published a slide deck summarizing the findings of the workshop, a report describing the WIND Toolkit Large Ensemble Dataset resource, and a final phase of data release from the Wind Resource 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*

Programmatic Support

NREL Technical Management and Support

Point of Contact: Kendra Ryan, Kendra.Ryan@nrel.gov

Empowering Wind Energy: NREL's Project Management Team Drives Innovation and Strategic Partnerships for a Sustainable Future

NREL Wind's project managers help keep all the research on track and are crucial to the success of the program.

In the past year, the NREL Wind Program has made significant strides in achieving our operational goals, thanks in large part to our dedicated project management team. This group has been pivotal in redefining how we deliver on our commitments as the wind program continues to expand. Their focus on client-oriented systems and enhanced coordination has streamlined our core functions, allowing us to effectively respond to the growing demand for our expertise in wind energy. By fostering a culture that emphasizes diversity, inclusivity, and efficiency, our team has laid a solid foundation for NREL's success and the advancement of our critical objectives.

Additionally, our strategic partnerships have played a crucial role in amplifying our impact across the renewable energy landscape. By collaborating with academia, industry, and government institutions, we are ensuring that our work remains relevant and aligned with the nation's pressing challenges. This year, we actively engaged with various stakeholders to enhance our partnership portfolio, allowing us to leverage our world-class facilities and capabilities in innovative ways. Moving forward, we remain committed to refining NREL's People Strategy by incorporating staff feedback to create an engaging work environment that supports our long-term vision and enhances our overall research goals. In FY 2024, notable achievements included:

- Managed portfolio of 162 projects (DOE- and non-DOE-funded projects), streamlining project timelines, processes and procedures, and enhancing team collaboration to achieve key milestones efficiently
- Supported the International Energy Agency's Wind Technology Collaboration Programme, enhancing international collaboration on wind energy advancements
- Contributed to multiple high-impact publications—including the offshore wind market report, a suite of transmission studies, and a recycling assessment—which help to shape national wind energy policy, inform legislative decisions, advance U.S. leadership in wind energy development, and drive the adoption of innovative wind technologies
- Provided WETO with direct programmatic support through management and operations contracts—Alexsandra Lemke, Michael Robinson, and Richard Tusing were instrumental in helping to define, develop, shape, and support the implementation of WETO's research and development portfolio.

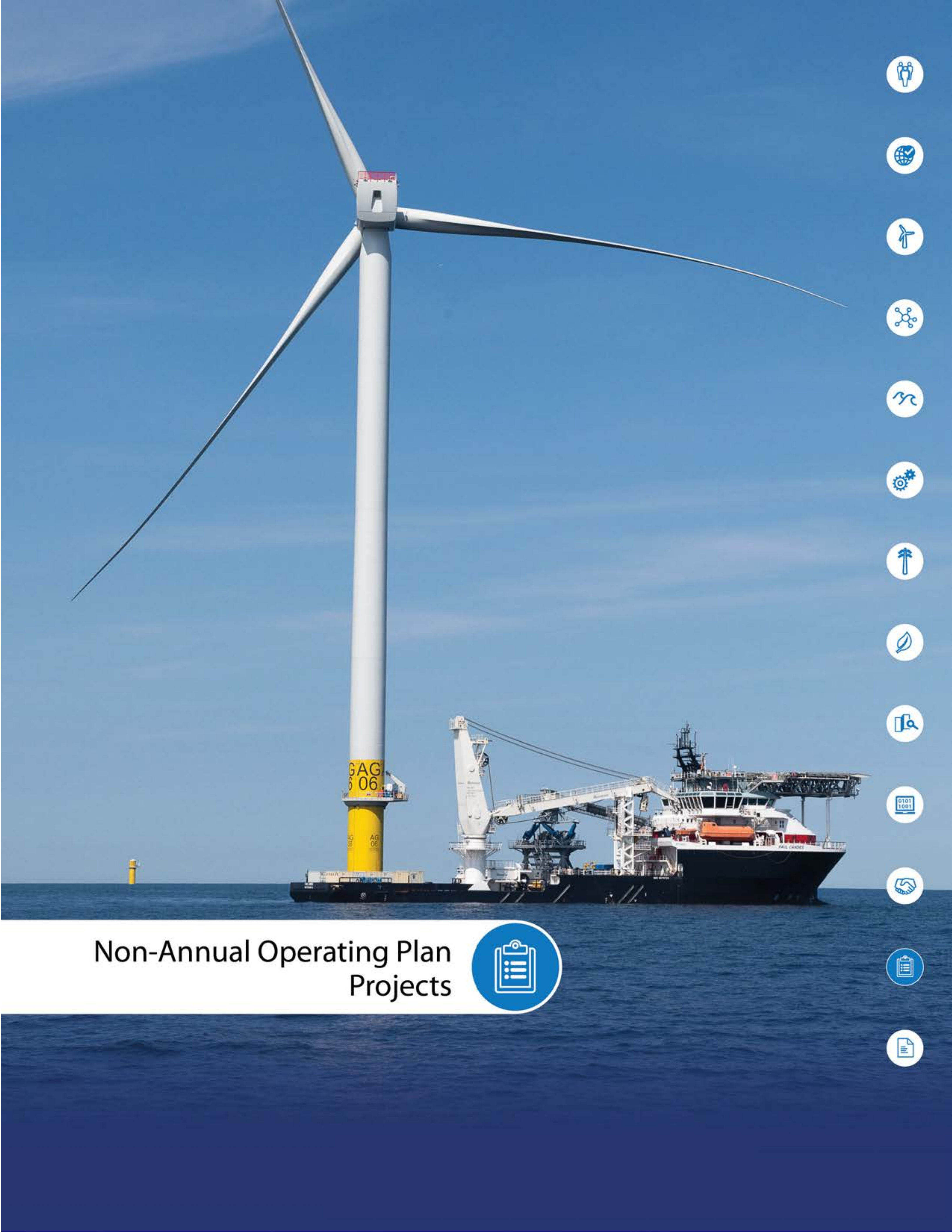
Communications Support

Point of Contact: Laura Carter, Laura.Carter@nrel.gov

Communications Collaboration To Share Wind Energy Updates

In FY 2024, the NREL Wind Energy Program's communications team collaborated with the WETO communications team to release the spring and fall R&D newsletters and the articles therein, in which groundbreaking work was profiled. These topics included understanding the interactions between wildlife and offshore wind, noise from land-based wind turbines, interconnection between wind and other renewable energy sources, and protecting wind energy systems from cyberattacks.

The communications team also published 11 issues of the NREL Wind Energy Program newsletter, the Leading Edge, which includes staff profiles in the Behind the Blades series, as well as news about recently published reports, research updates, news and events.



Non-Annual Operating Plan Projects

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 3–4 wind turbine installation vessels, 3–4 service operation vessels, and 7–11 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 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.

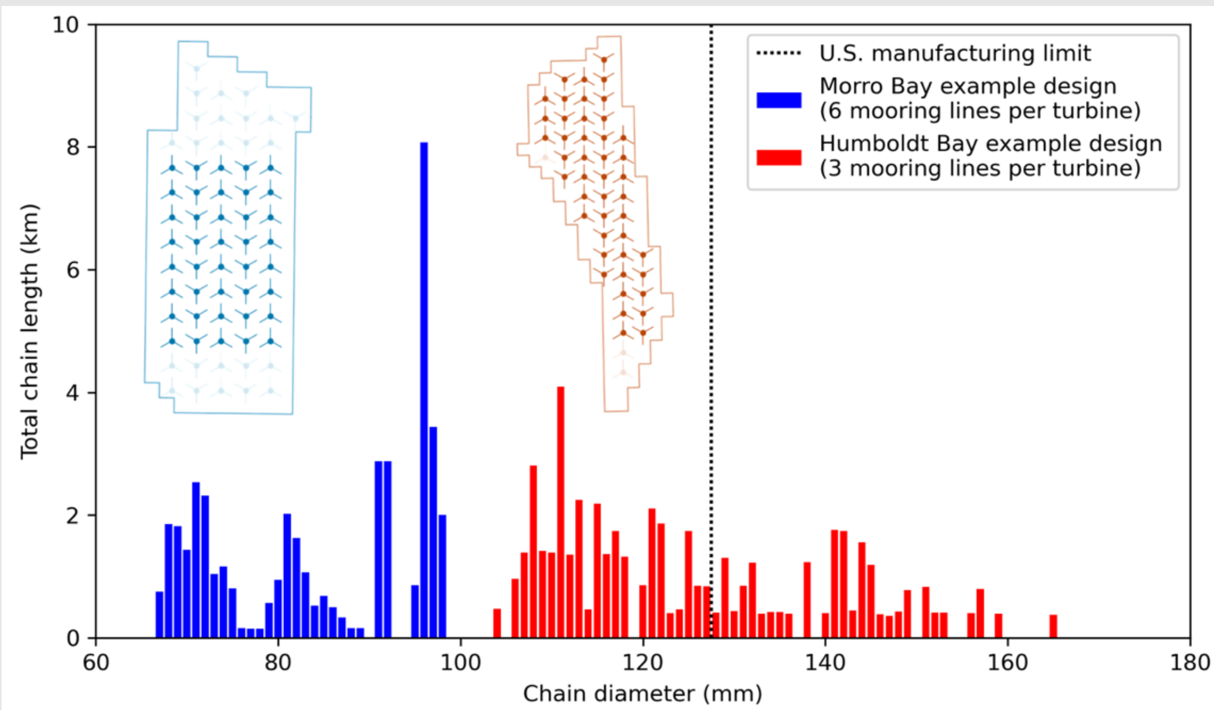
At the American Clean Power's 2023 Offshore WINDPOWER Conference, (from left to right) NREL researchers George Hagerman and Daniel Mulas Hernando, along with Brigitte Hagen-Peter of New Wave Offshore Energy and Jonathan Lints of Clarksons Offshore & Renewables, presented supply and demand forecasts,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

Standardized Scalable Mooring Solutions Optimized for the U.S. Supply Chain

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

Floating Wind Farm Mooring Designs for California Illustrate Supply Chain Challenges

The supply chain—including raw material sources, factories, shipping vessels, and port infrastructure—can limit the deployment rate of floating offshore wind energy projects. With funding from the National Offshore Wind Research and Development Consortium, NREL and project partner Delmar Systems are exploring the potential for mooring line and anchor design alternatives to reduce supply chain bottlenecks. Initial results show that delivery of materials and components used in example mooring systems for two 1-GW floating wind plants in California could take 2-4 years with the existing domestic supply chain. In addition, some mooring chain diameters specified in these examples are larger than what can currently be produced in the United States.

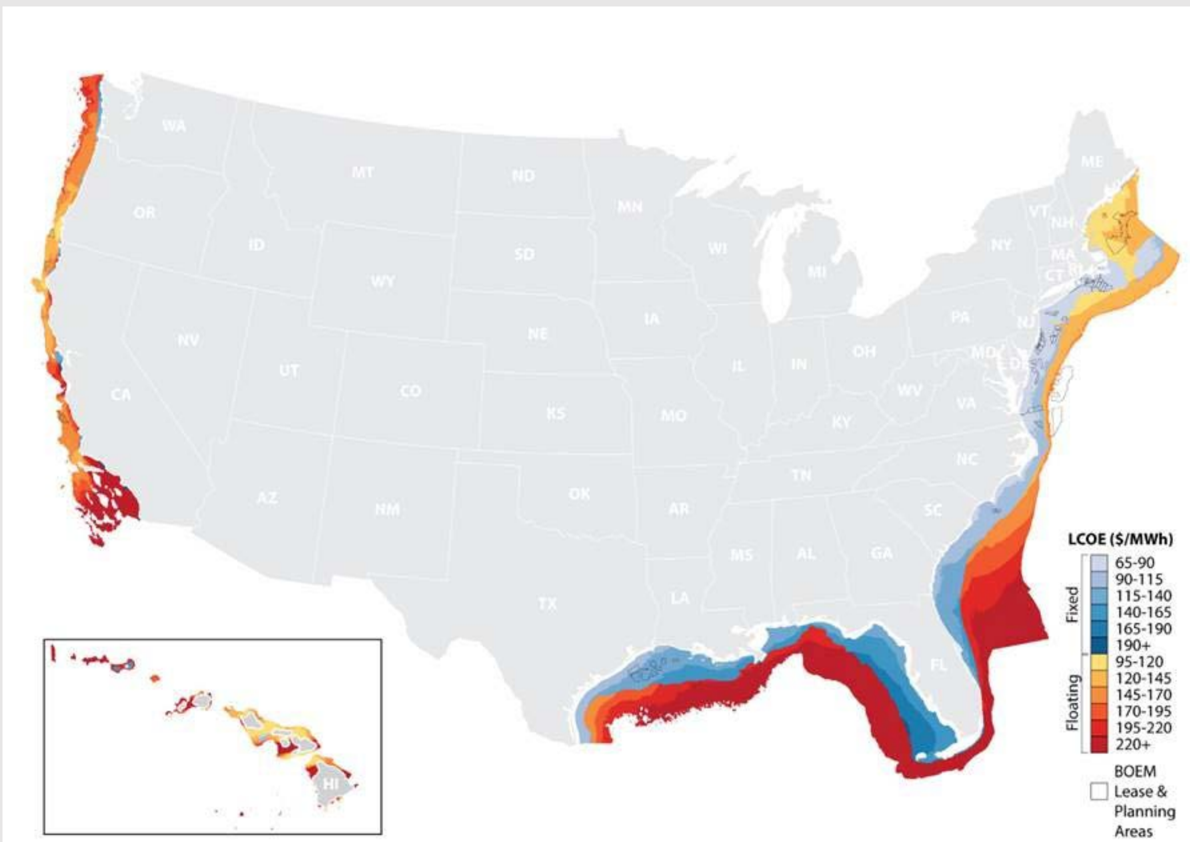


Plot of the total lengths required for different chain sizes in example mooring systems for floating wind farms in two California lease areas. The layout of the two wind farms in their lease area boundaries is also shown. The distribution shows the massive amount of chain required and that some designs use chain diameters that are larger than can currently be produced domestically. *Graphic by Matthew Hall, NREL*

Point of Contact: Walter Musial, Walter.Musial@nrel.gov

NREL Published Updated Estimates of Offshore Wind Costs

The BOEM-funded report presents estimates of the LCOE of offshore wind energy throughout major U.S. coastal regions between 2025 and 2050, accounting for factors such as revised deployment figures, supply chain shocks, inflation, and rising interest rates. The analysis estimates the LCOE of a reference fixed-bottom project on the East Coast to be around $129/MWh for commercial operation starting in 2025 with a range of +28%/−20%. These costs could decrease by around 39% by 2035 and 45% by 2050 as the industry matures and gains experience through expanded deployment. It also estimates the LCOE of floating projects at a reference West Coast site to be around $198/MWh for commercial operation dates in 2030 in the “mid” scenario with a −32%/+58% range. Floating wind can achieve significant cost reductions as key infrastructure (such as ports and transmission) are developed, technology evolves, and financing costs decrease as confidence rises in a growing industry.



National LCOE (dollars per megawatt-hour) for 2035 in 2022 U.S. dollars. *Figure by Gabriel R. Zuckerman, NREL*

Energy Support Services to USDA's Rural Energy for America Program

Point of Contact: Sophie Farr, Sophie.Farr@nrel.gov

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 Charlie Neibergal*

NREL researchers completed 56 technical assistance requests submitted by grant reviewers for the U.S. Department of Agriculture's (USDA'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 and storage, and distributed wind on rural farms and businesses. This interagency project leverages NREL's scientific expertise and USDA's connection with rural communities, farmers, and other rural businesses to accelerate the clean energy transition and expand opportunities for economic development and energy equity. Starting with a focus on distributed wind in June 2024, NREL began hosting technology-focused webinars to better prepare REAP applicants and REAP application reviewers for success. NREL is also working with the National Association of Farm Broadcasters to produce a series of audio interviews with NREL subject matter experts discussing renewable energy technologies, including distributed wind, in the context of drafting a successful REAP application. Providing a direct line of communication between NREL's subject matter experts and REAP grant reviewers, as well as providing helpful resources to applicants, maximizes the quality of applications and helps ensure that allocated funds are well-placed.

Grand Challenges in Wind Energy

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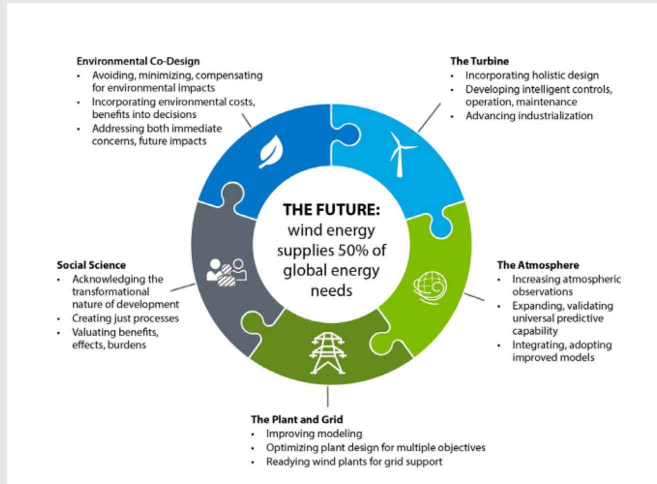
International Experts Revisit Wind Energy's Grand Challenges

More than 100 wind energy experts from 15 countries attended an IEA Wind Technology Collaboration Programme Topical Experts Meeting in late February to revisit the grand challenges in wind energy science. Organized by NREL wind energy researchers, the meeting sought to create better understanding of how the social and environmental impacts of wind energy should be integrated into future research on the grand challenges of wind research: the atmosphere, wind turbine, and plant and grid. Meeting outcomes will provide guidance for researchers at NREL—and around the world—to ensure future wind energy projects consider the social and environmental impacts of increased wind energy deployment.



Addressing critical issues within each of the five Grand Challenge areas will help to ensure that wind energy is poised to play a greater role in global energy needs. *Illustration by Taylor Henry, NREL*

Scientific and Technical Services for the Pacific Outer Continental Shelf Region

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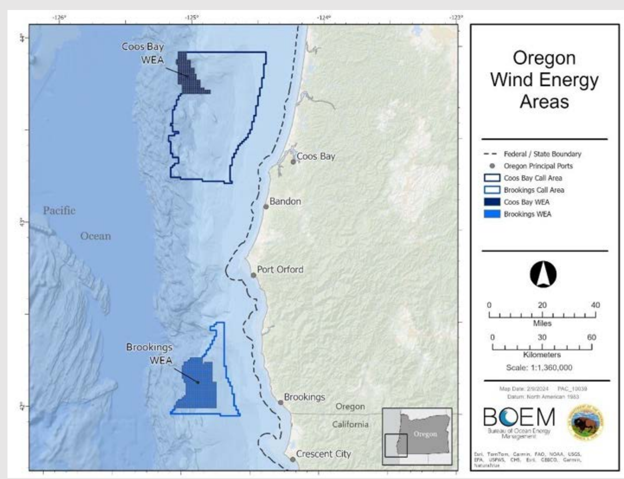
Research Could Unlock Oregon Floating Offshore Wind Opportunities

By providing scientific and technical assistance to BOEM, NREL is enabling deployment of floating offshore wind energy projects from California to Washington. NREL produced a Representative Project Design Envelope for the California lease areas, laying out a range of component sizes, generation capacities, and other important parameters. For Oregon, NREL published an analysis of wind speed, water depth, and distance to land-based infrastructure within the Brookings wind energy areas. A fourth report examined the challenges of deploying floating offshore wind in ultradeep water between 1,300 and 3,000 m deep.



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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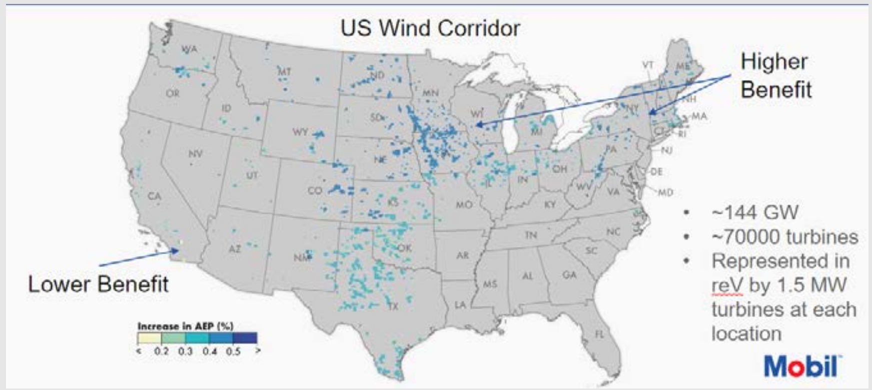
Advances in Gear Oil Technology May Save Billions of Dollars for the U.S. Wind Turbine Fleet



Benefits to Annual Energy Production from Gear Oil Technology Improvements (stretch vs. baseline scenarios) for current U.S. wind fleet. *Graphic by Gabe Zuckerman, NREL*

NREL researchers, with sponsorship from ExxonMobil Research and Engineering Company, estimated the impact of improved gear lubrication on the overall cost of energy of the U.S. wind turbine fleet. Lubrication plays a key role in wind turbine performance and can improve efficiency, component reliability, and the frequency of needed maintenance. With inputs provided by ExxonMobil and industry stakeholders, a cross-disciplinary team of NREL researchers led by the NWTC carried out the modeling and analysis work based on WOMBAT, System Advisor Model (SAM), and Renewable Energy Potential Model (reV) simulations. After investigating multiple market and gear oil technology scenarios, the team concluded that gear oil technology improvement can help reduce the median levelized cost of energy by between 0.8% and 2.0%, with potential savings of up to $6 billion over 30 years.

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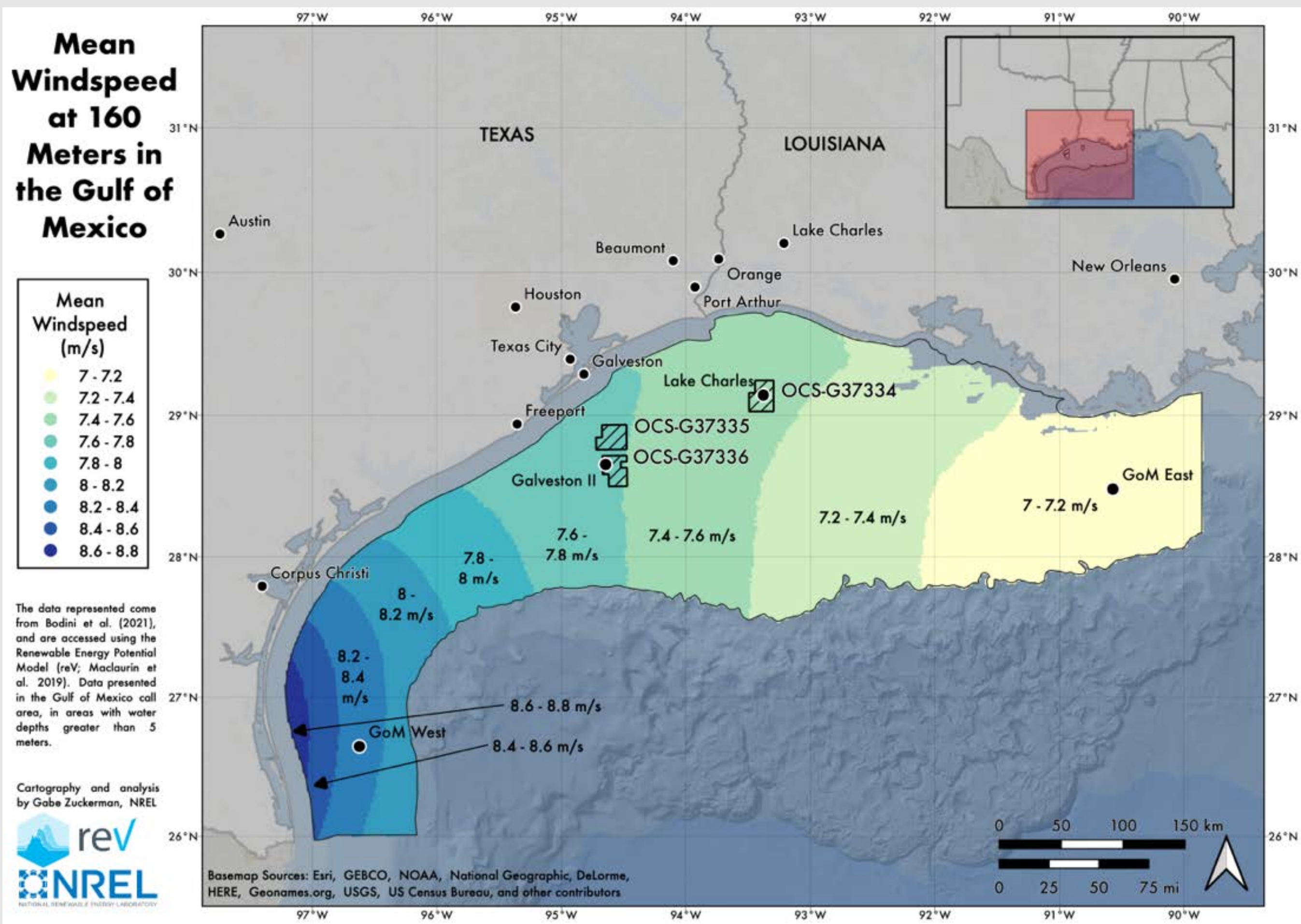
Challenges of Offshore Wind Energy Illuminated in Gulf of Mexico Study

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 can withstand extremely high winds, but low-specific-power rotors may be needed to optimize energy capture of the area's more common low wind speeds. Battery backup systems are another recommended option for all wind turbines during grid failure caused by hurricanes. The Gulf of Mexico's experience with offshore industrial activities means that 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*

ATLANTIS – Wind Energy with Integrated Servo-Control (WEIS): A Toolset to Enable Controls Co-Design of Floating Offshore Wind Energy Systems

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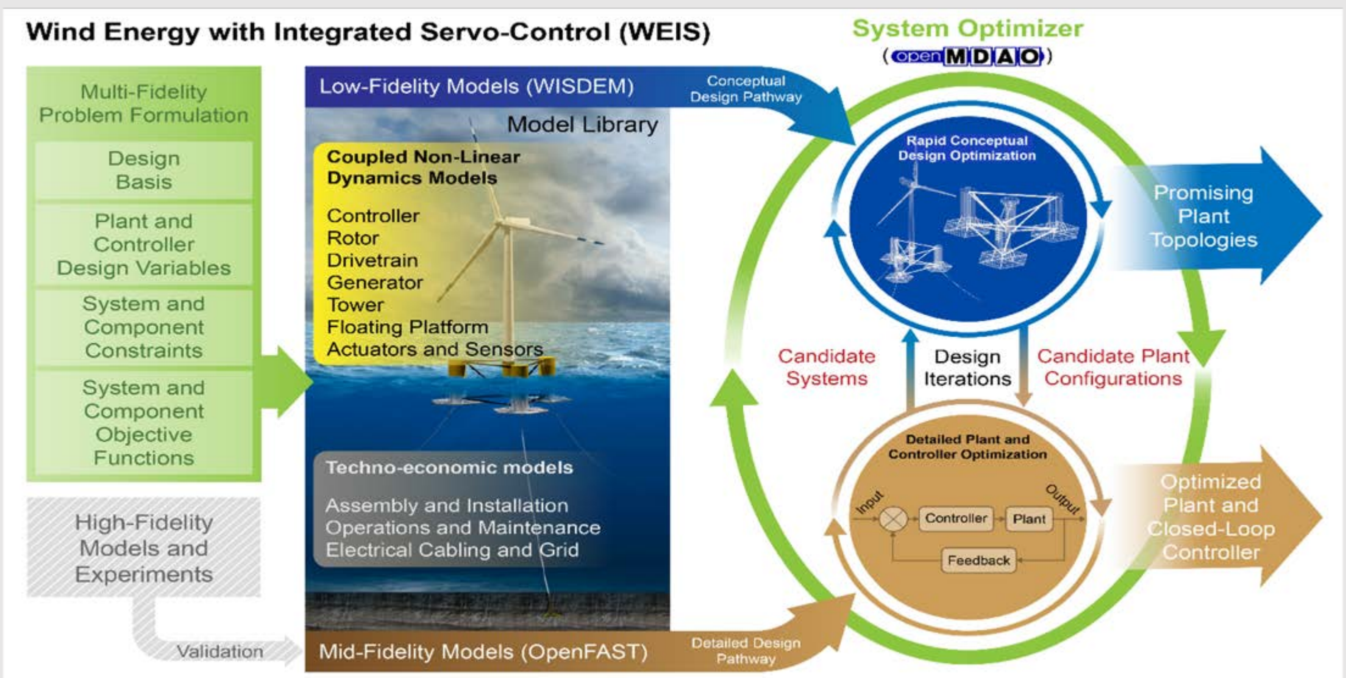
Updates to Wind Energy With Integrated Servo-Controls Program Expand Tool's Capabilities

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, wind 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 into an integrated design environment, where floating offshore wind turbines and their controllers can be fine-tuned and optimized. *Illustration by WEIS team, NREL*

Note: WISDEM® = Wind-Plant Integrated System Design & Engineering Model

Shell Offshore Wind

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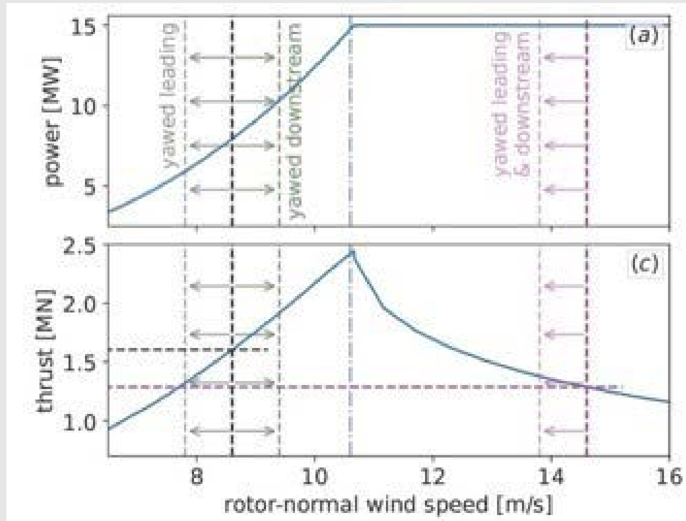
Study Investigates Use of Wake Steering for Wind Turbine Load Reduction



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*

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 can increase power production of a wind plant, is typically implemented when wind speeds are below the rated speed of the turbine, at the cost of increased load cycles, or oscillations on the structure that shorten the total lifetime of the turbine and plant. This study by NREL researchers investigated whether 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 reductions of up to 5% (depending on the component) can be achieved 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 unlikely operational strategy. This result differed from the original hypothesis, which anticipated load oscillation reductions for all angles, and was therefore a helpful guide to inform wind plant operation. The results of the study were presented at the TORQUE Conference in May 2024.

The Laboratory Directed Research and Development Program at NREL

Each year, NREL is a proud contributor of innovations built through DOE's Laboratory Directed Research and Development (LDRD) program. Read about two of the innovative LDRD projects at NREL that aim to shape the future of wind energy and wind energy deployment.

Tunable Material Systems
Point of Contact: Robynne Murray, Robynne.Murray@nrel.gov

Novel Plant-Based Material Could Help Reduce Wind Turbine Waste

NREL researchers presented a novel resin created from biomass—or plant-based materials—that could be used to build recyclable wind turbine blades that perform just as well as those made with traditional thermoset resins. The team used the new resin to construct a 9-m turbine blade prototype, which could be manufactured using processes similar to traditional turbine blades. If adopted, the novel material could make it easier to recycle and reuse wind turbine blades when they reach the end of their life cycle.

An NREL scientist holds small cubes of a new, plant-based resin for building recyclable wind turbine blades. *Photo by Werner Slocum, NREL*

Optimal Design of Energy Cluster Offshore
Point of Contact: Chloe Constant, Chloe.Constant@nrel.gov

Research Team Assesses How To Integrate and Optimize Offshore Energy Production

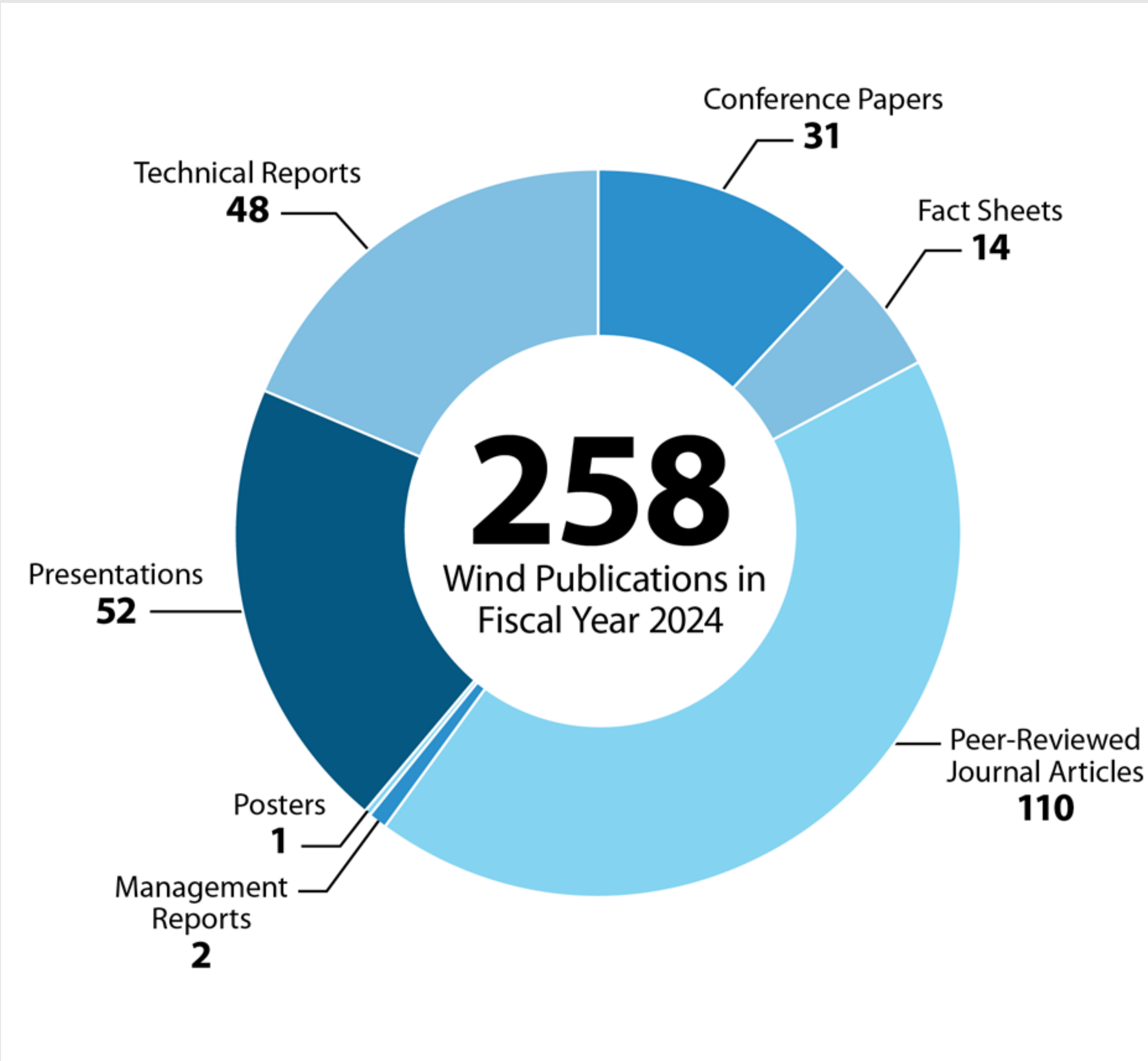
NREL researchers recently presented an update on an ongoing project on offshore energy systems that integrate multiple types of renewable energy technologies to optimize energy output. Called energy clusters offshore, these integrated systems could generate and store energy more efficiently than systems that rely on just one technology type. The NREL team is working to identify and model specific technologies and configurations to understand which have the greatest potential. The team optimized a Hawaii-based offshore energy cluster that produced hydrogen using energy from offshore wind turbines and solar panels, wave energy converters, and batteries.

Publications Overview

Publications produced by NREL Wind Energy Program staff provide information about the many areas of wind energy research conducted at the lab. In FY 2024, NREL researchers published their latest scientific findings and breakthroughs in 258 technical reports, peer-reviewed journal articles, conference papers, fact sheets, and more.

Fiscal Year 2024 NREL Wind Energy Publications

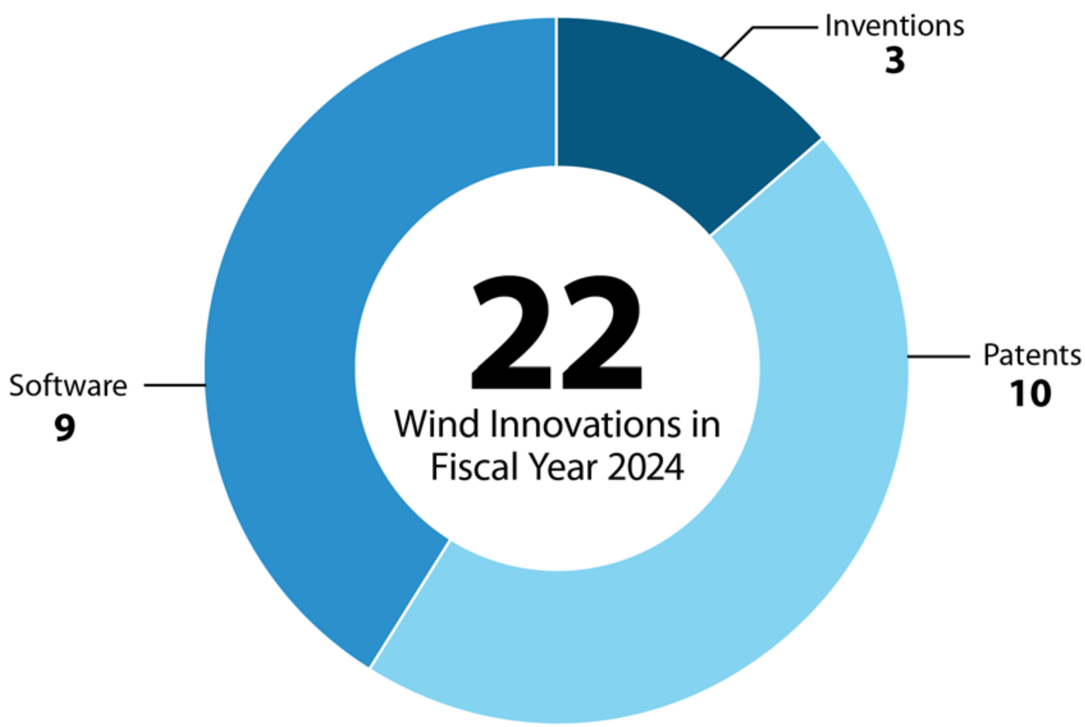
These publications provide reliable, unbiased information that researchers from academia, other national laboratories, government agencies, and private industry organizations can use to advance wind energy science.



In FY 2024, NREL published 258 wind energy technical documents. *Graphic by Katie Carney, NREL*

Fiscal Year 2024 NREL Wind Innovations

Wind energy researchers at NREL continuously produce world-class technology to advance the commercialization of wind energy. Below is a summary of NREL's wind energy innovations submitted or approved for patenting or licensing in FY 2024.



In FY 2024, 22 wind energy innovations were submitted or approved for patenting and licensing. *Graphic by Katie Carney, NREL*

Notable Publications

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Visit the NREL Wind Research Publications page to find a list of all wind energy-related journal articles and technical reports published in FY 2024.

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