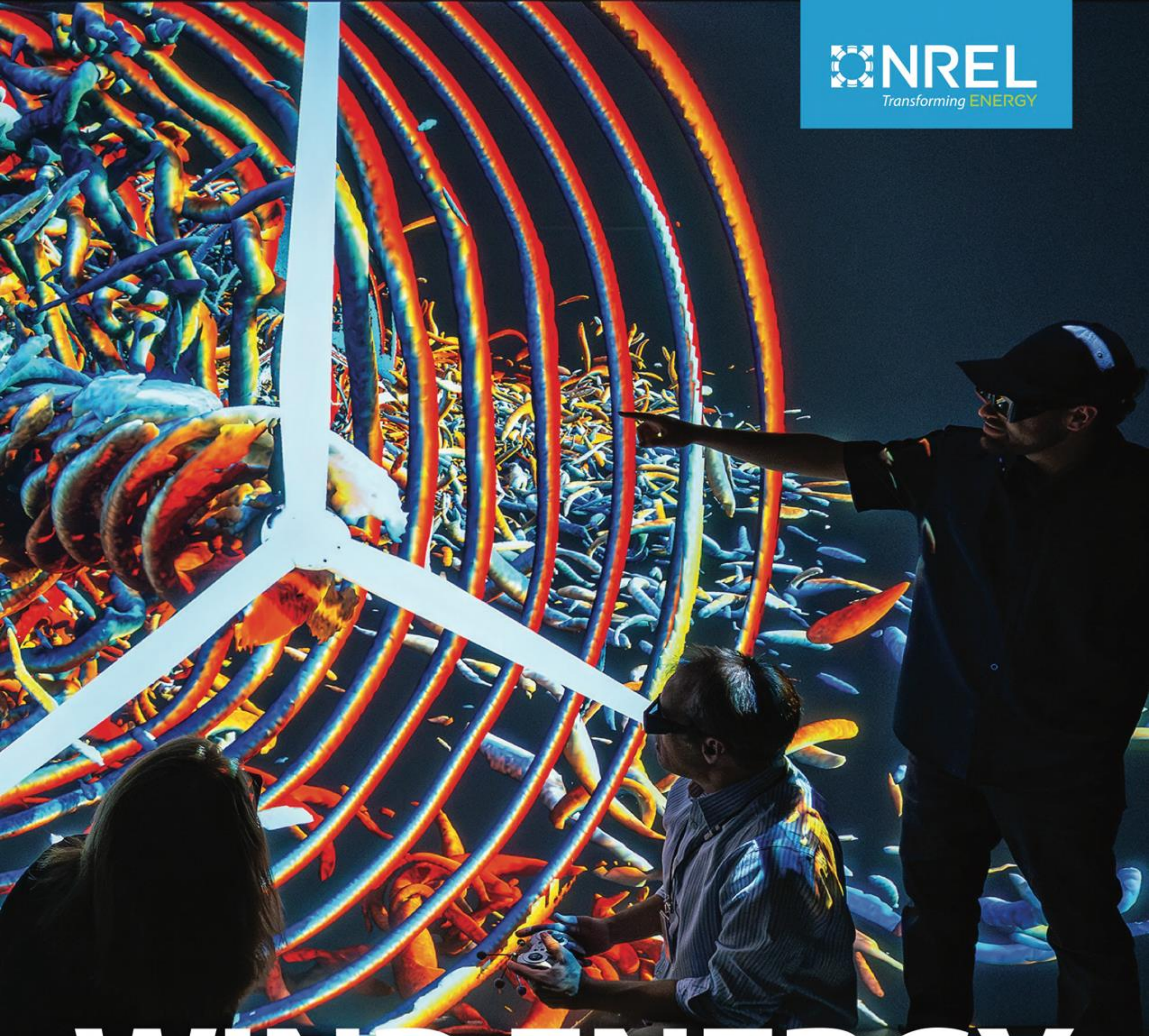

WIND ENERGY

Accomplishments and
Year-End Performance Report
FISCAL YEAR 2023

Notice

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Foreword

As the United States' largest source of renewable energy, wind is already playing a vital role in the nation's shift to electricity generated from sustainable resources. Scientists, engineers, and analysts at the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) are propelling our country closer to this clean energy future with new efficient, reliable, and cost-competitive wind technologies and deployment strategies.

In Fiscal Year 2023 (FY 2023), NREL received national acclaim for recent wind technology breakthroughs, applauded sustained decades of progress in wind energy research, and heralded new initiatives to support the next generation of wind development. This report and NREL's achievements of the last year set the stage for innovative research to come.

Two NREL software innovations used to assess wind technology options were recognized with **R&D 100 Awards**. The Renewable Energy Potential (reV) model helps planners, developers, and researchers calculate wind energy capacity, generation, and cost for specific facilities, fleets and scenarios. NREL's Simulation and Emulation for Advanced Systems validates transmission and distribution solutions to minimize implementation risks. Both of these tools can be applied to a range of renewable solutions to cut costs and improve the reliability of systems in even the most remote locations.

The laboratory commemorated **landmark anniversaries for wind energy research facilities and programs** managed by NREL. The National Wind Technology Center (NWTC) celebrated 30 years as a world-class hub for renewable energy research. An important component of the NWTC on NREL's Flatirons Campus, the one-of-a-kind 7-megawatt (MW) Controllable Grid Interface wind energy research apparatus, turned 10 this year. The Collegiate Wind Competition completed its tenth annual competition in May 2023. Six years after the grand challenges in wind energy science were first compiled, NREL brought together more than 100 wind energy experts from 15 countries to revisit the field's most pressing research needs.

Other **key new research initiatives** examined ways to simultaneously address the needs for skilled wind energy workers and equitable job opportunities. NREL released the first national-level report evaluating offshore wind industry workforce gaps and ways to build a large, diverse pool of job candidates. The lab also co-hosted the International Partnering Forum's Offshore Wind Workforce Summit as part of its ongoing efforts to address the special challenges of that industry sector.

NREL research and development (R&D) for the DOE Wind Energy Technologies Office (WETO) continues to build momentum in its efforts to combat climate change, create clean energy jobs, and promote energy justice. This report provides more detail on these top achievements and other accomplishments made by NREL and its partners during FY 2023 (between Oct. 1, 2022, and Sept. 30, 2023).

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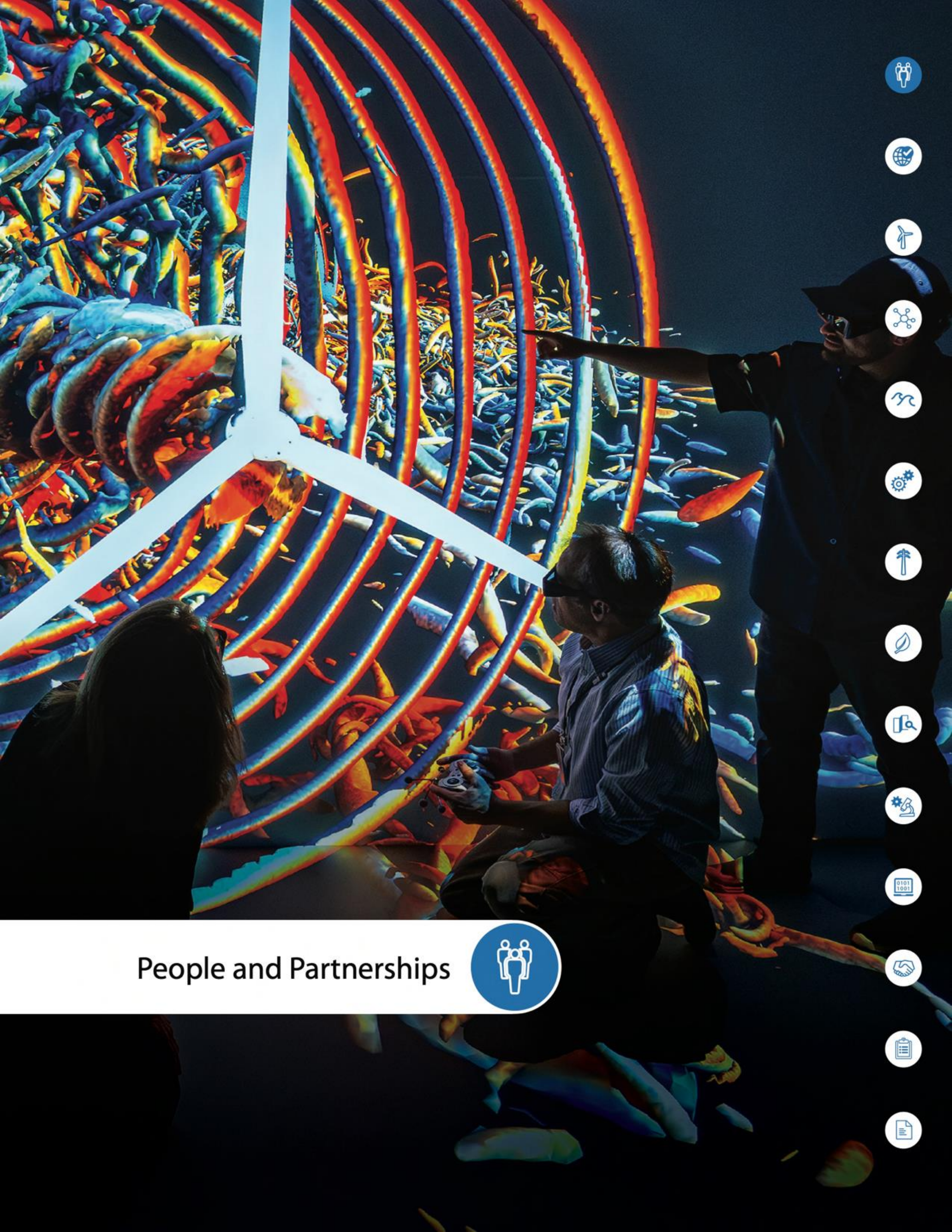


People and Partnerships

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; it also shines a spotlight on the NREL researchers and staff who make this work happen. Offering first-hand insight into NRELians' careers, their work at the lab, and the wind energy industry, Behind the Blades remains one of the most-read series in *The Leading Edge* and is an effective engagement tool on social media. The following are highlights from the three most-clicked Behind the Blades stories of FY 2023.

NREL Remembers Robi Robichaud, the Lab's Optimistic Innovator of 20 Years

Robi Robichaud, who passed away earlier this year, is remembered as a team player who saw the potential in everyone. *Photo from World Resources Institute*

In February 2023, Behind the Blades paid tribute to Robi Robichaud, an NREL researcher of 20 years whose cluttered office reflected his belief in the potential of everything and everyone. Colleagues remembered Robichaud, who passed away earlier this year, sharing how he was a dedicated, down-to-earth team player who excelled at finding solutions and telling meaningful stories.

NREL Tenure Equips Yi Guo for Her Next Career Move

In April 2023, Yi Guo reflected on 11 years as an NREL researcher. Guo, who always aspired to make a positive impact on the environment through renewable energy, monitored NREL's careers site for 2 years before landing her dream job at the lab. During her time at NREL, she collaborated with members of industry and academia to find solutions for enhancing wind turbine component reliability, establishing connections that will continue to serve her in her new adventure at the Technical University of Denmark's Wind and Energy Systems.

Yi Guo, who spent 11 years in her "dream job" at NREL, forged many connections with members of universities and industry to make wind turbines more reliable. Earlier this year, she moved to Denmark to start a new chapter of her career. *Photo from Yi Guo, Technical University of Denmark*

Summer Interns Power NREL Wind Energy Innovation and Research

In August 2023, Behind the Blades profiled 29 interns who participated in NREL's wind energy research through programs like DOE's Science Undergraduate Laboratory Internship Program and the Research Participant Program. Part of the largest intern cohort in the lab's history, the interns supported research on floating offshore wind turbine technology, the impact of turbulent wind conditions on concentrating solar collectors, interactions between wind energy and wildlife, and more. "My favorite part of this internship is being able to find solutions to complex problems that will lead us to a more sustainable future," said intern Ryan Davies, who supported a project to improve software that models the mooring systems for floating offshore wind farms. "It is inspiring to work with so many experts, day in and day out, who are all working toward that common goal."

The summer of 2023, a group of enthusiastic students participated in NREL's internship programs to assist wind energy researchers with a range of projects. Pictured here are (top row, from left) Ahmed Radwan, Elizabeth Eyeson, Samantha Paola White-Murillo, and Katherine Coughlan; and (bottom row, from left) Sita Nyame, Aakash Manapat, and Ryan Davies. *Photos by the interns*

Awards and Recognition

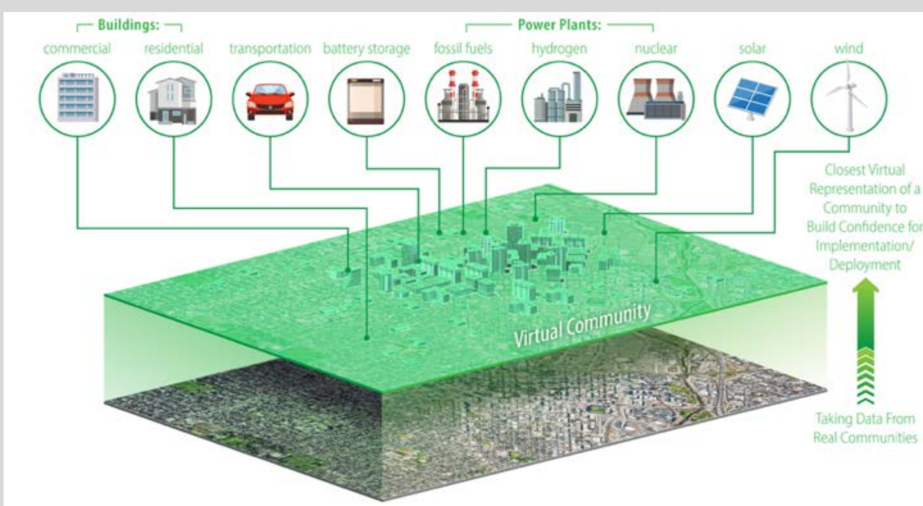
Seeded and Tended by NREL's Wind Energy Team, reV Model Earns R&D 100 Award

The reV model—originally conceived as an effort to consolidate supply curve scripts and codes by NREL's wind energy and analysis researchers with funding from WETO—was honored with a 2023 R&D 100 Award. Since the project began in 2016, the first-of-its-kind model has grown to become an open-source assessment tool that empowers users to calculate wind and solar energy potential, accounting for nuances in technology and regulatory regimes, to inform future clean power systems across the world. Using resources such as NREL's high-performance computing facilities and Wind Integration National Dataset Toolkit, the reV model helps developers understand and characterize specific clean energy scenarios by considering factors such as terrain, ordinances, associated costs, and more.

The reV model is a first-of-its-kind detailed spatio-temporal modeling assessment tool that empowers users to calculate renewable energy capacity, generation, and cost based on geospatial intersection with grid infrastructure and land-use characteristics. *Graphic by NREL*

NREL Wind Energy Researchers Receive R&D 100 Award for Grid Reliability Software

NREL wind energy researchers Jen King, Paul Fleming, and their team earned a 2023 R&D 100 Award for NREL's Simulation and Emulation for Advanced Systems—the only software that simulates and validates energy transmission and distribution solutions across the buildings, transportation, and renewables sectors and the grid. The Simulation and Emulation for Advanced Systems software enables communities and utility companies—such as the Golden Valley Electric Association, the local utility that serves Fairbanks and other Interior Alaska communities—figure out how large-scale wind power can be added to the grid without affecting its performance.



A cross-sectoral virtual layer of the Simulation and Emulation for Advanced Systems software, which lets you test "what if?" scenarios to derisk your options, helping you confidently move from planning to implementation. *Graphic by NREL*

NREL's Brent Summerville (left) received the Windustry Distinguished Service in Community Wind Award in February 2023 for his work on distributed wind energy projects. The winner of a different award, Devon "Rocky" McIntosh (right) of Sonsight Wind, is also a recipient of several Competitiveness Improvement Project awards. *Photo from the Distributed Wind Energy Association*

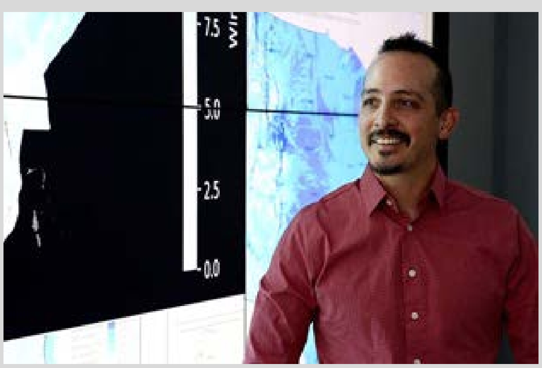
Summerville Receives Award for Contributions to Community, Distributed Wind

Brent Summerville, an NREL systems engineer, received the Windustry 2023 Distinguished Service in Community Wind Award from the Distributed Wind Energy Association. The award is given annually to a person or program that has made significant contributions, over several years, "to the establishment and growth of locally owned and distributed wind as a uniquely valuable form of clean, renewable energy." This award recognizes Summerville's work on numerous distributed wind energy projects—including standards development, the Competitiveness Improvement Project, and deployable wind energy systems—as well as his outstanding dedication, excellence, and achievement in furthering the goals of community wind and distributed renewable energy.

Jonkman Awarded for Advancing Floating Offshore Wind Energy

NREL researcher Jason Jonkman received the 2022 Viterna Award for Engineering Excellence from the Business Network for Offshore Wind, honoring his contributions to the advancement of floating offshore wind energy. The award recognized Jonkman's role in developing NREL's FAST software, an engineering tool for simulating the coupled dynamic response of wind turbines. FAST helped launch the first generation of floating offshore wind turbines and continues to serve the industry today. Jonkman and his NREL research team have worked to expand the functionality of the original software to its latest version, OpenFAST.

The Business Network for Offshore Wind recognized NREL researcher Jason Jonkman (left) for contributions to advancing the development of floating offshore wind energy. *Photo from the Business Network for Offshore Wind*



Anthony Lopez was named the Most Promising Scientist by Great Minds in STEM for his work mentoring young Hispanic generations to pursue careers in STEM and motivating professionals to meaningfully engage with the Hispanic community. *Photo by Deb Lastowka, NREL*

Lopez Named Most Promising Scientist by Great Minds in STEM

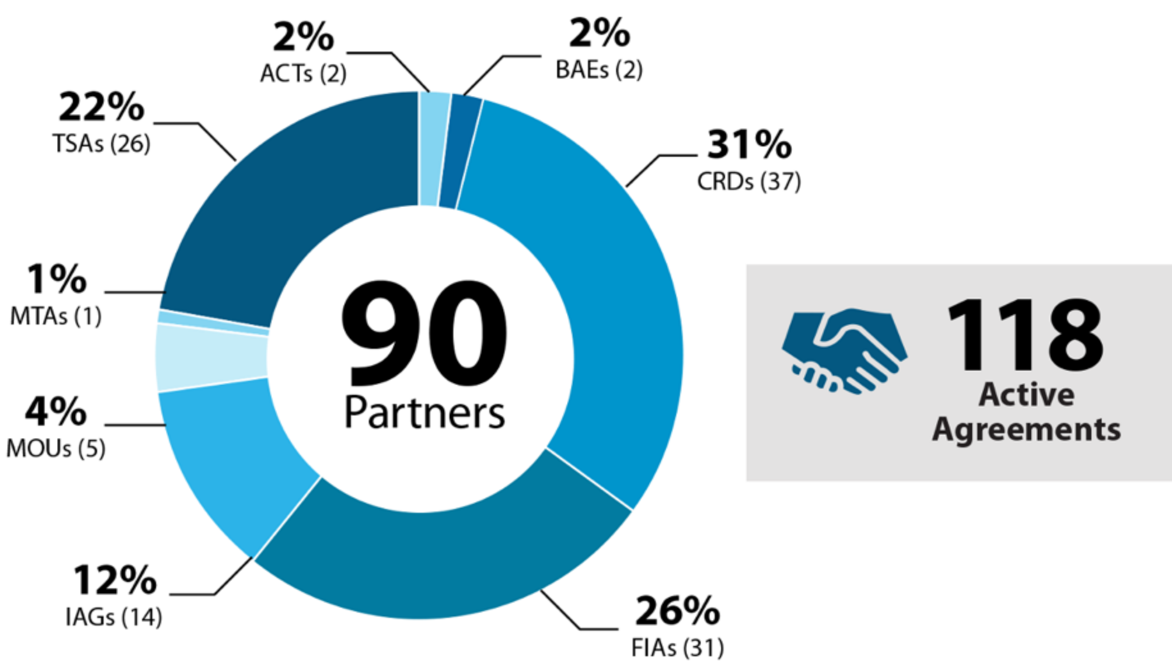
An NREL senior researcher, Anthony Lopez was named the Most Promising Scientist by Great Minds in STEM, an organization dedicated to keeping the United States technologically strong by promoting science, technology, engineering, and mathematics (STEM) careers in underserved communities. The award honors the highest-achieving scientists and engineers from the Hispanic community across the country. With more than a decade of achievements in geospatial data science at NREL, Lopez was recognized for his work mentoring and inspiring younger Hispanic generations to pursue careers in STEM subjects.

NREL Partners Help Accelerate Wind Energy

In FY 2023, NREL and the NWTC worked with 90 partners through 118 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 Comericalizing 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 90 partners, NREL's wind energy program participated in 119 active agreements in FY 2023. *Graphic by Jennifer Breen-Martinez, NREL*

Testing Infrastructure, Standards Development, and International Engagement

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

New Distributed Wind Turbines Procured for Flatirons Campus, Installation and Commissioning Initiated

Based on extensive WETO and private sector investment, the cost of distributed wind energy technology has significantly decreased, making it a competitive player in the distributed energy market. This technology is now self-sustainable or can seamlessly integrate with solar photovoltaic and storage systems for enhanced efficiency. With the development of more cost-competitive distributed wind energy technology, research questions arise related to grid integration, controls, model verification, cybersecurity, and technology hybridization, paired with continued community-focused technology innovation. To support future research and development efforts, NREL staff initiated the installation of three new distributed wind turbines at NREL's Flatirons Campus, including the initial commissioning of two of these turbines. Deployed as the initial investment of the larger Distributed Energy Integration Laboratory, these turbines will play a key role in supporting continued industry wide technology innovation, ensuring that distributed wind energy can support the larger distributed energy and clean energy transition.

Two of three new distributed wind turbines were installed in September 2023 at NREL's Flatirons Campus. *Photo by Ian Baring-Gould, NREL*

Testing Facilities and Capabilities at the National Wind Technology Center

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

NREL Clears the Way for New, State-of-the-Art Wind Turbine at Flatirons Campus

NREL continually evaluates the research needs and facilities at the lab's Flatirons Campus. As facilities age and technology progresses, NREL's research and research operations teams work with DOE program offices to remove or upgrade outdated facilities and make room for new ones that will address upcoming needs. In FY 2023, NREL evaluated the lab's near- and long-term needs and began work to define and procure a new 3-MW wind turbine research platform. This platform will take the place of the outdated 600-kilowatt controls research turbine that NREL removed in FY 2022. Part of the Advanced Research on Integrated Energy Systems (ARIES) platform, these updates ensure NREL facilities remain at the forefront of wind energy research and development.

This throwback to Flatiron's Campus in 2003 shows two Controls Advanced Research Turbines in the forefront, one of which was removed in 2022 as NREL prepares to purchase a new 3-MW wind turbine research platform. This image invokes an appreciation for how technology has progressed and excitement for the future research possibilities and progress on the horizon. *Photo by Warren Gretz, NREL*

Wind Standards Development

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

Alejandro Moreno, DOE's acting assistant secretary for energy efficiency and renewable energy, kicked off the meeting by laying out the direction and goals for the 2-day event. Photo by Werner Slocum, NREL

International Experts Revisit Wind Energy's Grand Challenges

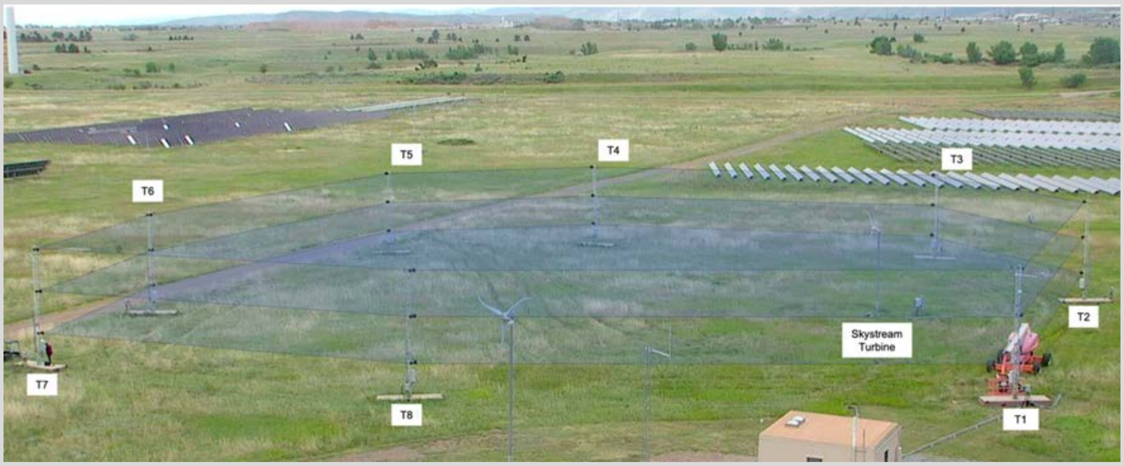
More than 100 wind energy experts from 15 countries attended an International Energy Agency Wind Technology Collaboration Programme (IEA Wind) Topical Experts Meeting in late February 2023 to revisit the grand challenges in wind energy science. Organized by NREL wind energy researchers, the meeting sought 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 research encompasses the social and environmental issues to create integrated systems solutions. The cross-disciplinary challenge highlights the need for better communication, accessible data, and holistic approaches to design and deployment.

Acoustic Tomography

Point of Contact: Emina Maric, Emina.Maric@nrel.gov

Research Underway To Expand NREL Acoustic Tomography Capabilities

Acoustic tomography is a remote-sensing technique that uses acoustic-signal travel times to determine high-resolution measurements of turbulent velocity and temperature fields. In a novel application of acoustic tomography to wind energy, an NREL research team constructed a three-dimensional (3D) acoustic tomography array at NREL's Flatirons Campus that enabled them to accurately study wind turbine wakes and industrial flows. These measurements will help advance wind turbine design and wind power plant control, as well as validate high-fidelity numerical models. Funded by WETO, the work was presented at the Wind Energy Science Conference in May 2023.



Correlations between direct measurements and assumed models for travel paths obtained at the acoustic tomography array at NREL, for wind energy research and development applications, offers a promising path forward for high-resolution measurements. *Graphic by Nicholas Hamilton, NREL*

High-Performance Computing

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

Researchers Get Priority Access to Dedicated Computing on Supercomputer

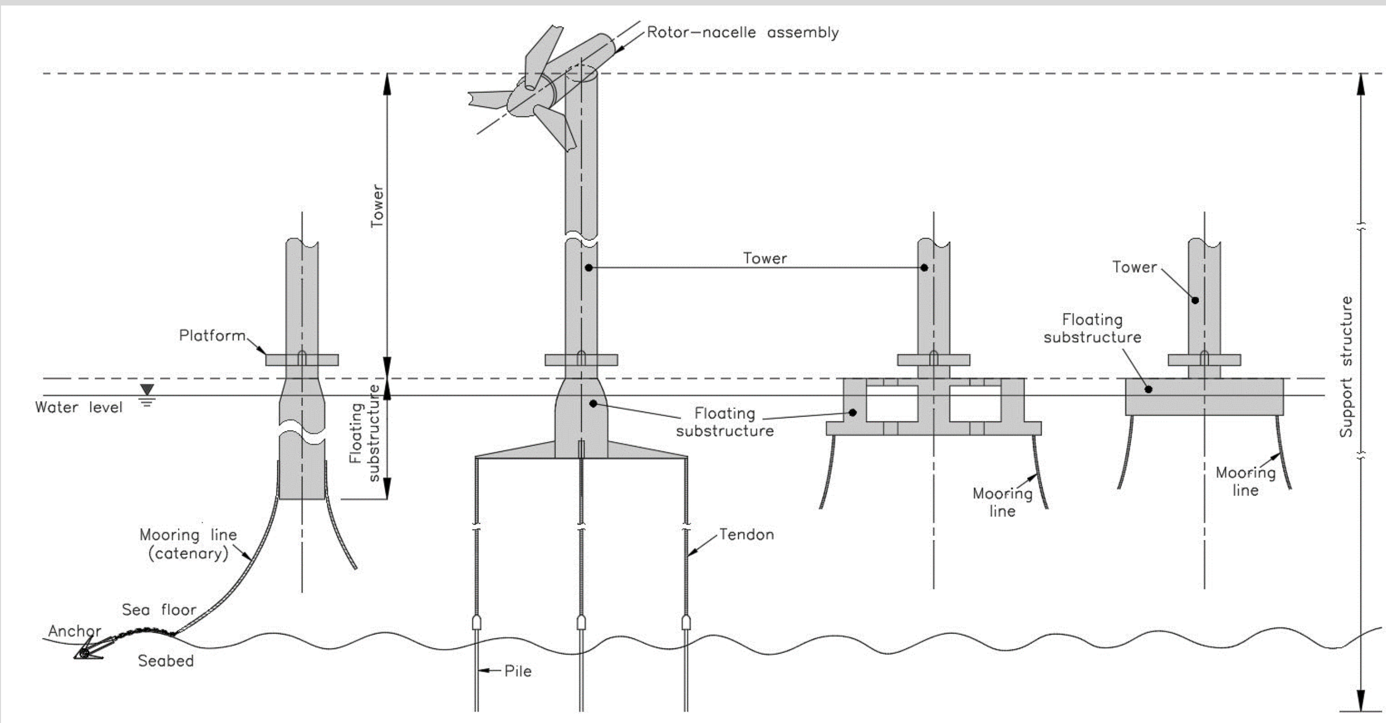
The demand for high-performance computing cycles has increased in recent years from various DOE program offices. To ensure success and continuity of the projects, WETO projects get priority access to 288 nodes, which is equivalent to 7.2 million allocation units per allocation cycle on the Eagle supercomputer at NREL. In FY 2023, researchers accomplished approximately 45% of WETO's computing workload using this dedicated partition of Eagle, enabling the acceleration of work across 34 WETO projects.

The Eagle high-performance supercomputer at NREL. *Photo by Kristin Munch, NREL*

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

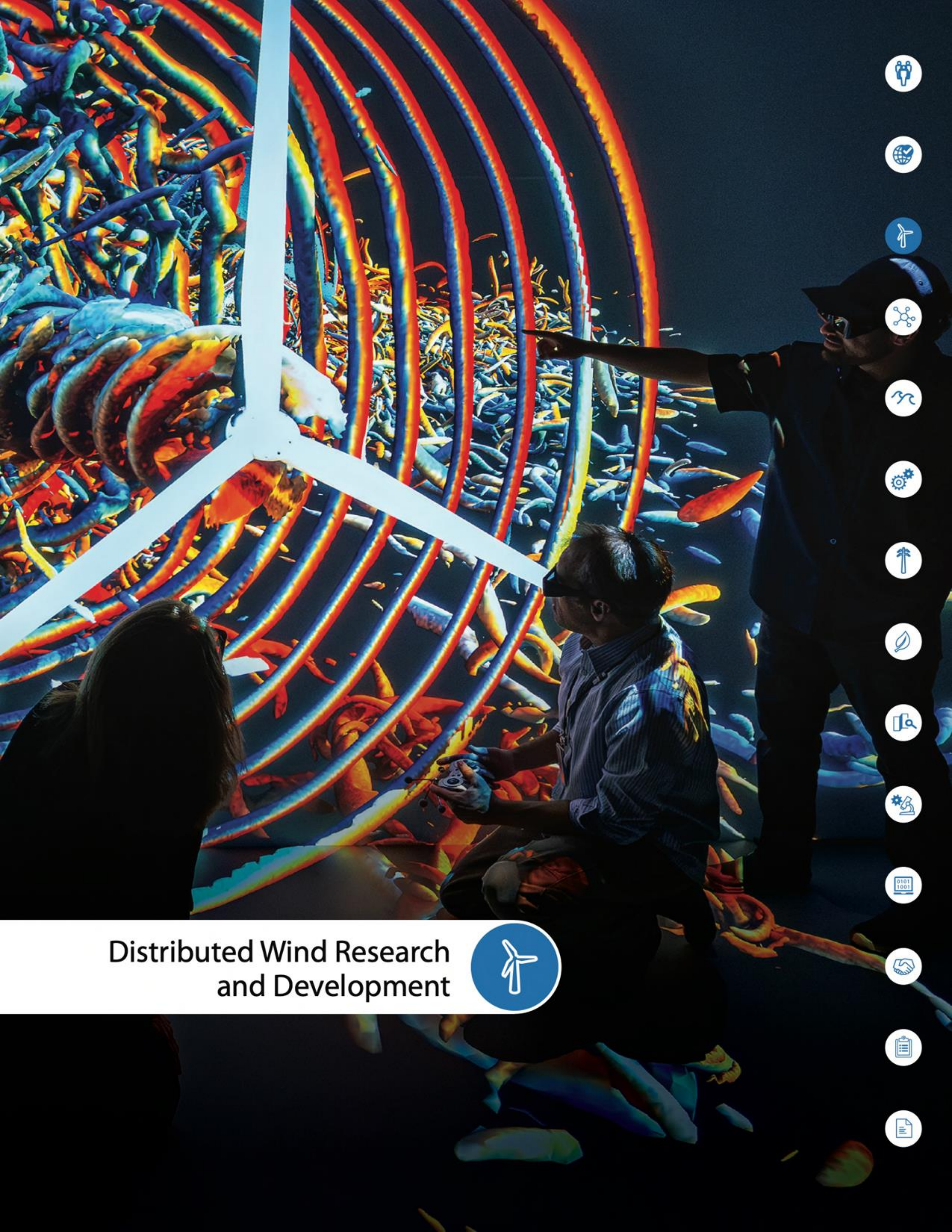
Floating Offshore Wind Turbine Design Standard on Track for International Release

The International Electrotechnical Commission (IEC) 61400-3-2 technical specification was first published to provide guidance for the emerging floating offshore wind turbine industry to ensure the engineering integrity of prototypes. Given the growth in floating offshore wind turbine maturity in recent years, an international maintenance team within IEC was formed in 2020 to address known limitations of the technical specification and to upgrade it into a full-fledged standard, establishing international design requirements. The committee draft for voting of the newest version of IEC 61400-3-2 was recently approved by international committees and the maintenance team has recently been busy addressing the final comments before final approval and publication. NREL co-led the initiative with experts from the United States, South Korea, and Germany, as well as other participants across Europe, Asia, and the Americas—and solicited feedback from the U.S. national committee. Approval and publication of IEC 61400-3-2 as an international standard should further advance the commercial maturity of the floating offshore wind turbine industry.



NREL co-led an initiative to upgrade the IEC standard that establishes international design requirements for floating offshore wind turbines, like the design illustrated here. *Graphic by Hyun Kyoung Shin, University of Ulsan*

Distributed Wind Research and Development



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

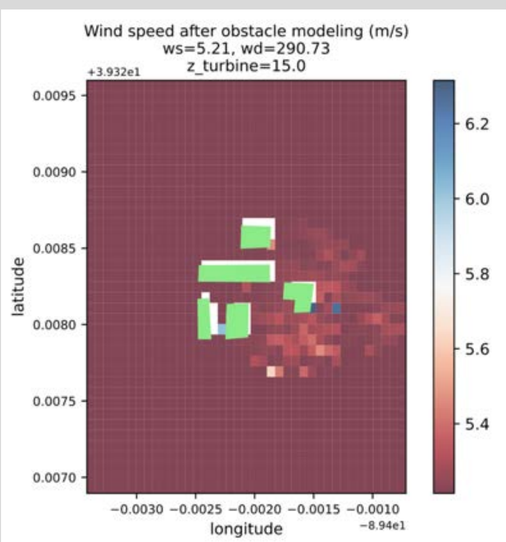
Competitiveness Improvement Project Remodeling Workshop To Evolve Successful Program

Distributed wind energy stakeholders, such as Sonsight Wind (the distributed wind turbine of which is pictured here at the Beech Mountain test site in North Carolina), brought helpful ideas on how to remodel the successful Competitiveness Improvement Project. *Photo from Rocky McIntosh, Sonsight Wind*

The Competitiveness Improvement Project, managed on behalf of WETO, has been credited with helping the distributed wind energy industry to develop certified and cost competitive small and mid-scale wind turbines, awarding a record total of 12 awards in the support of this industry this year. In an effort to continuously improve distributed wind energy technologies, in June 2023, NREL held a virtual workshop for distributed wind energy industry stakeholders to solicit ideas on ways to provide additional support to the growing industry. Workshop topics included expansion of diversity and inclusivity; review of topic areas with increased emphasis on market development and commercialization; updated scoring criteria beyond levelized cost of energy; and lab-based technical assistance needs. There were 48 participants representing a broad spectrum of the industry, including wind turbine and component manufacturers, certification experts, and consultants. Many contributed ideas, suggestions, and comments on barriers, challenges, and solutions that they had experienced working to develop the distributed wind energy industry.

Tools Assessing Performance

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



A new software feature enables users to determine precisely how close to obstacles (such as buildings and trees, which are represented by green shapes) a wind turbine can be installed. *Graph by Dmitry Duplyakin, NREL*

New Feature Allows Users To Visualize Wind Speed Deficit Behind Trees and Buildings

Being able to accurately predict the potential power production of a small- or mid-scale wind turbine without on-site wind speed measurements has long been a barrier to the development of distributed wind energy projects. The Tools Assessing Performance software allows users to estimate the average wind speed and direction at prospective distributed wind energy project sites. One of the newest features added to the software is a heat map—a high-resolution image of the wind speed at several hundred points within the project domain. This new feature allows stakeholders in the wind industry to understand the extent of the disturbed flow in the lee or wake of building and vegetation obstacles. Users can then determine precisely how close to the obstacles the distributed wind turbine can be installed. The software heat maps leverage two obstacle modeling approaches, one from Los Alamos National Laboratory and the other from Argonne National Laboratory.

On-Site Wind for Rural Load Centers

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

National Lab Partnership Shapes Resilient Hybrid Power Plant Design for Iowa Grid Enhancement

In partnership with Algona Municipal Utilities, researchers from NREL, Iowa State University, Idaho National Laboratory, and Pacific Northwest National Laboratory conducted a case study to design a resilient-optimal hybrid power plant in Algona, Iowa. The team integrated NREL's Hybrid Optimization and Performance Platform, Resilience Framework for Distributed Energy Systems from Idaho National Laboratory, and Pacific Northwest National Laboratory's Valuation Tool to simulate how well a hybrid power plant could perform during power outage scenarios. Algona Municipal Utilities will use the results of this research to justify grid investments. Results were used to support federal funding applications and cooperative investments in hybrid power plant technologies.

NREL's Method Reveals Hybrid Power Plants Can Help Keep the Lights On

Hybrid power plants, or energy systems that combine wind energy, solar power, and battery assets, can reduce the impact of power outages on surrounding customers and communities. However, quantifying the incremental value of capacity investments so that grid owners and operators know what technologies to invest in and how much to invest can be difficult. In FY 2023, NREL developed a method to show how each addition of wind energy, solar power, and battery technologies to power systems can reduce the chance of power shortages during both shorter and longer power outages. NREL applied this method to a community case study in the U.S. Midwest and found that by adding more wind energy and battery storage to a hybrid wind and solar energy system, they could greatly reduce the chance of power shortages.

MIRACL Team Publishes Results Compendium

Making their project's outcomes more accessible to a broader audience, researchers working on the Microgrids, Infrastructure Resilience, & advanced Controls Launchpad (MIRACL) project recently published a compendium of results in a publicly accessible web page. This compendium assembles all project outputs, including models, code, reports, data, presentations, and articles. The project, which brought together researchers from Pacific Northwest National Laboratory, Idaho National Laboratory, Sandia National Laboratories and was led by NREL, officially ended in FY 2022.

A 900-kilowatt Emergya Wind Technologies turbine began operating in 2019 in St. Mary's, Alaska. The MIRACL project analyzed its resilience benefits and value streams, along with the potential benefits of more advanced control. *Photo from DOE*

National Distributed Wind Network

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

Extensive Engagement With Distributed Wind Stakeholders Lays Groundwork for Future Deployment Support

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

The U.S. market is ripe for distributed wind energy, yet a knowledge and capacity gap persist with many entities that could support its deployment. Throughout FY 2023, the NREL team behind the Strategize, Engage, Network, Deploy Distributed Wind project engaged with more than 100 members from the distributed wind energy community—including manufacturers, operators, owners, state and federal agencies, utilities, representatives of tribal nations, energy transition communities, nonprofit organizations, and consultants from across the country. The goal was to better understand deployment challenges and opportunities for distributed wind energy's expansion, as well as the resources and support that could help them to move forward with their decision making around the deployment of distributed wind energy. The feedback from this engagement is helping the team shape the development of a deployment-focused distributed wind energy resource hub that will launch in FY 2024.

Distributed Wind Aeroelastic Modeling

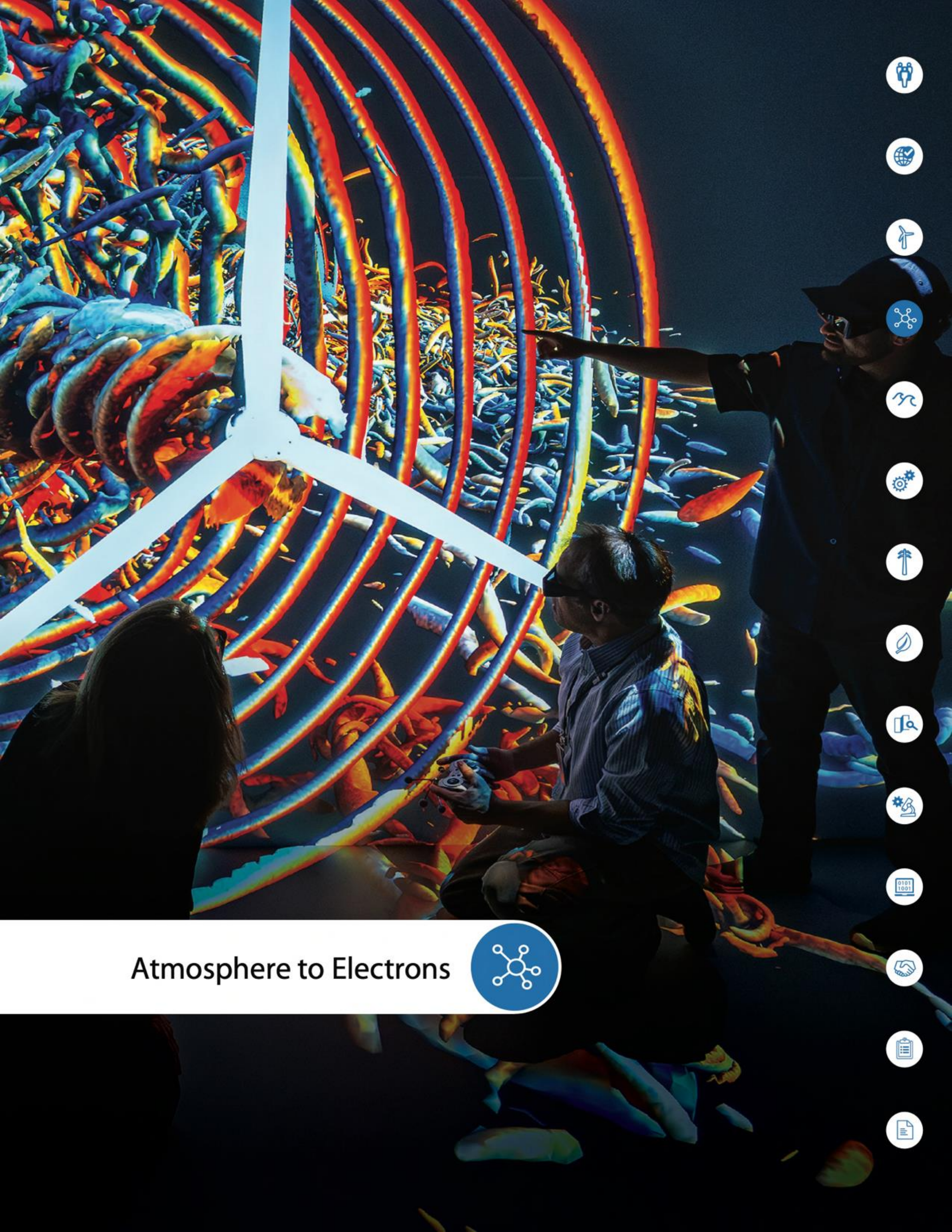
Point of Contact: Brent Summerville, Brent.Summerville@nrel.gov

Industry Insiders Share Lessons for Distributed Wind Energy Success at NREL Workshop

NREL hosted a 4-hour workshop that brought current and former distributed wind energy insiders together to discuss lessons learned from this sector of wind energy. NREL reached out to people from across the distributed wind energy industry with the intention that attendees and, by extension, the greater distributed wind energy industry, would benefit from the knowledge shared. NREL specifically invited:

- Turbine manufacturers to share their experiences with field failures, warranty claims, and challenging market conditions, as well as the many lessons the wind industry has taught them
- Testing and certification experts to discuss their experiences evaluating technology in extreme conditions and partnering with manufacturers to test and certify their designs
- Turbine service providers and installers to share stories of site visits, troubleshooting, logistics, and repair.

Key takeaways from the workshop will be included in the NREL's Distributed Wind Aeroelastic Modeling project guidance document, which is being designed to help wind turbine designers select critical versus non-design-driving load cases and create a design load basis for distributed wind turbine modeling based on real-world failure modes observed in the field.



Atmosphere to Electrons

American WAKE experimeNt

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

AWAKEN Deploys Final Tools for Unparalleled Wind Plant Atmosphere Interaction Observations

The American WAKE experimeNt (AWAKEN) aims to answer the most pressing science questions about how individual wind turbines interact with one another and the atmosphere in a wind power plant. In FY 2023, AWAKEN researchers from NREL collaborated with industry, and international partners completed the deployment of over 50 unique instruments—including scanning lidars, specialized radars, and numerous meteorological stations—at 13 field sites and on four operating wind turbines. These instruments are gathering the highest-fidelity observations to date of the atmospheric flow in and around multiple wind power plants in the Southern Great Plains region of the United States. The observations from these instruments will allow researchers to gather unique insights into how wind power plants interact with the atmosphere and, subsequently, how they impact the local environment. The insights can then be translated into more accurate predictive tools that will help the wind energy industry better design and operate their wind farms for lower cost of energy.

Lidars and a disdrometer were installed on the top of a nacelle of a wind turbine in the King Plains wind farm as part of the AWAKEN project. Nacelle-mounted instruments provide valuable observations of the local flow and atmosphere at hub height that have a powerful influence on wind turbine energy production and response. *Photo by Andy Scholbrock, NREL*

Foundational Artificial Intelligence for Wind Energy

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

NREL Hosts a Successful Workshop on Artificial Intelligence for Wind Energy Science

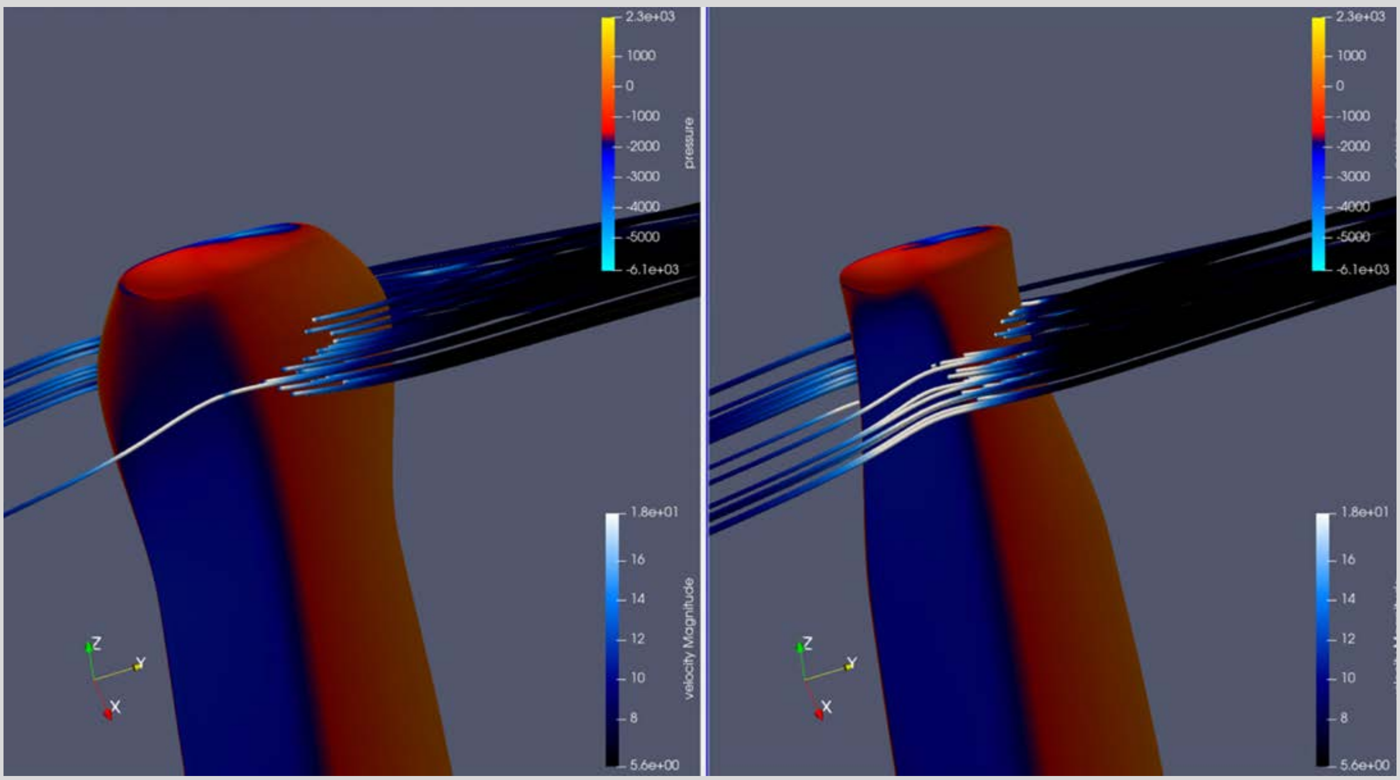
Through the execution of an Artificial Intelligence for Wind Energy Workshop held in June 2023 in Boulder, Colorado, a team of NREL researchers identified opportunities for artificial intelligence and machine learning to advance wind energy science and develop a strategy to inform DOE investments. The workshop was facilitated by the Renewable and Sustainable Energy Institute, a joint institute between NREL and the University of Colorado Boulder. This workshop brought together stakeholders from industry, academia, labs, and DOE to discuss wind energy challenges, identify promising artificial intelligence and machine learning solutions, and understand elements of a successful artificial intelligence and machine learning ecosystem. Outcomes from the event were recorded in a workshop report to share the findings with the broader wind energy community at the end of FY 2023.

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

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

No-Vortex Rotor Reveals Opportunity for High-Fidelity Models To Capture Performance Improvements

NREL is working to employ high-fidelity modeling capabilities for wind turbine design. Low-fidelity modeling tools—the current industry standard—are inexpensive and can generate projections quickly, yet they do not capture as much detail as high-fidelity tools. And while high-fidelity modeling tools include more detail, they can be too costly and time-consuming to be used in design where frequent iteration is necessary. In FY 2023, NREL researchers gained a provisional patent on the No-Vortex Rotor, which proposes a wind turbine blade shape that expands at the tip. The team found that this design offers performance improvements that are only revealed via high-fidelity modeling tools—a discovery that indicates untapped potential and future opportunities to apply high-fidelity modeling to wind turbine design.



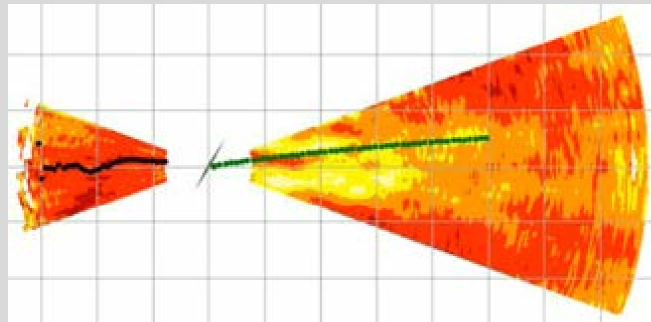
This simulation shows wind flow paths over a No-Vortex Rotor blade tip (left) versus a more conventional blade tip (right). Colors on the blade indicate pressure whereas tube colors indicate velocity magnitude. *Graphic by Louis (Tony) Martinez, NREL*

Rotor Wake Measurements and Predictions for Validation

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

Field Measurements Capture Turbulence-to-Loads Relationships in Unprecedented Detail

Researchers at NREL and Sandia National Laboratories partnered with General Electric to perform detailed measurements of a 2.8-MW wind turbine in Texas. The atmospheric sensors deployed by the team intricately measure the wind turbulence in front of and behind the wind turbine. Other sensors measure the structural response of the turbine's blades, such as how much it might bend when hit by a gust. With these sensors in place, researchers can see how specific air flows affect individual components of large wind turbines with tall towers and flexible blades. This knowledge is being used to improve the way computer models represent these wind turbines, which will help designers create new wind turbine technology that can leverage any wind conditions it may encounter.



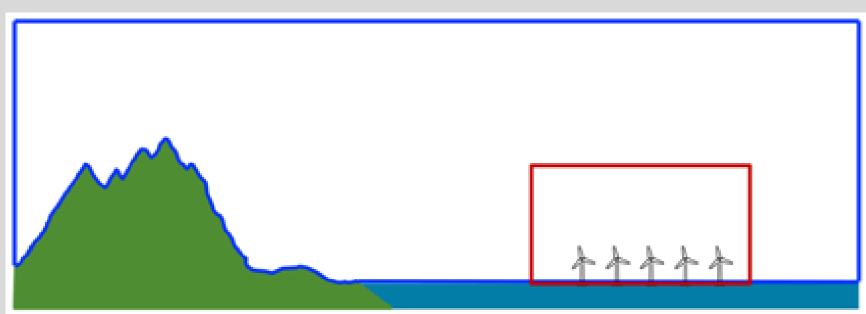
A horizontal view of wind measurements ahead (left) and behind (right) of the heavily instrumented 2.8-MW General Electric wind turbine in Lubbock, Texas, in a 1-mile gridded area shows the strength of the winds. The graph indicates that wind speed is lower and the turbulence is higher in the wake of the wind turbine. *Graph by Stefano Letizia, NREL*

Energy Research and Forecast Modeling

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

Robustness, Performance, and Capabilities Enhanced in Energy Research and Forecast Model

NREL's Energy Research and Forecasting (ERF) team has worked alongside Lawrence Berkeley National Laboratory (the project lead), Lawrence Livermore National Laboratory, and Argonne National Laboratory to implement, test, and optimize additional capabilities within the ERF software. These newly implemented capabilities include boundary conditions, microphysics models to represent cloud and precipitation processes, and an atmospheric radiation model. In addition, the team has developed an interface that allows users to drive the model with real global or regional atmospheric data. They tested and optimized both computer processing unit and graphics processing unit performance while developing those capabilities. They also verified the accuracy of the ERF solver. With these advancements, ERF has become a flexible computational framework for exploring atmospheric physics modeling and characterizing large-scale air flow, which impacts the ability of wind turbines to generate wind energy. ERF's current capabilities have been summarized in the *Journal of Open Source Software.*



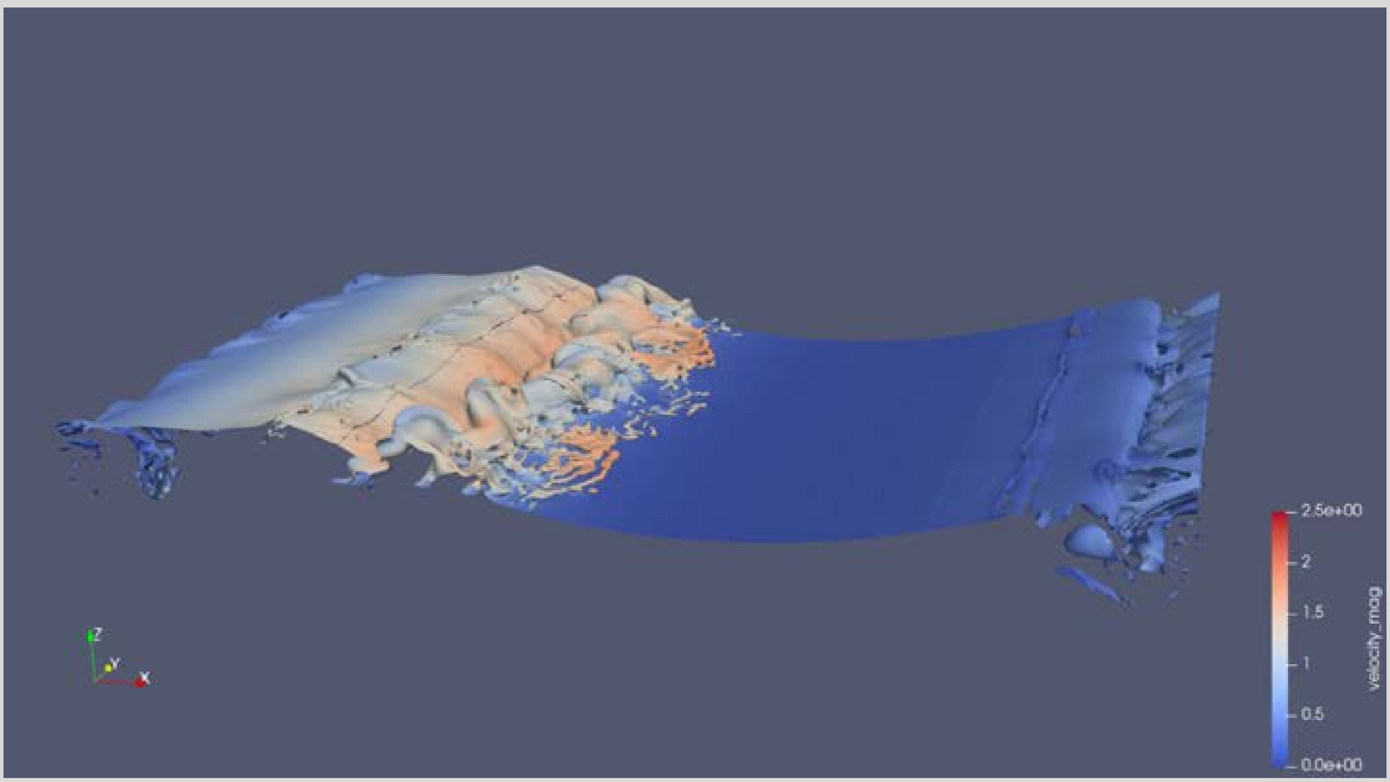
This illustration shows how the ERF model will work with the AMR-Wind model to simulate an offshore wind farm adjacent to non-flat terrain. *Graphic by Bruce Perry, NREL*

Floating Turbine High-Fidelity Modeling and Simulation

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

Enhanced ExaWind Code Enables High-Fidelity Simulations of Breaking Waves for Offshore Wind Energy

Led by NREL, a multilaboratory team of researchers developed ExaWind, a high-fidelity suite of codes designed for high-performance computing, including the first exascale-class supercomputer, Frontier. Originally designed for land-based wind turbines and plants, ExaWind, thanks to the team's recent efforts, can now produce high-fidelity simulations of the wind-wave environment, which is a key step toward simulating floating offshore wind turbines. This capability is key to achieving U.S. offshore wind energy deployment goals. In FY 2023, the AMR-Wind solver in ExaWind was enhanced to simulate breaking waves, a highly nonlinear phenomenon, that is important for modeling and understanding the dynamics and loads of offshore wind turbines. In addition to increasing our understanding of an incredibly complex system, simulations from high-fidelity models, like ExaWind, serve as the foundation for next-generation engineering models.



ExaWind's AMR-Wind flow solver simulated breaking waves, a key phenomenon that must be resolved to predict the loads and dynamics of floating offshore wind turbines. This simulation was performed on DOE's Summit supercomputer at the Oak Ridge Leadership Computing Facility under a computer-time grant from the Advanced Scientific Computing Research Leadership Computing Challenge. *Graphic by Michael Kuhn, NREL*

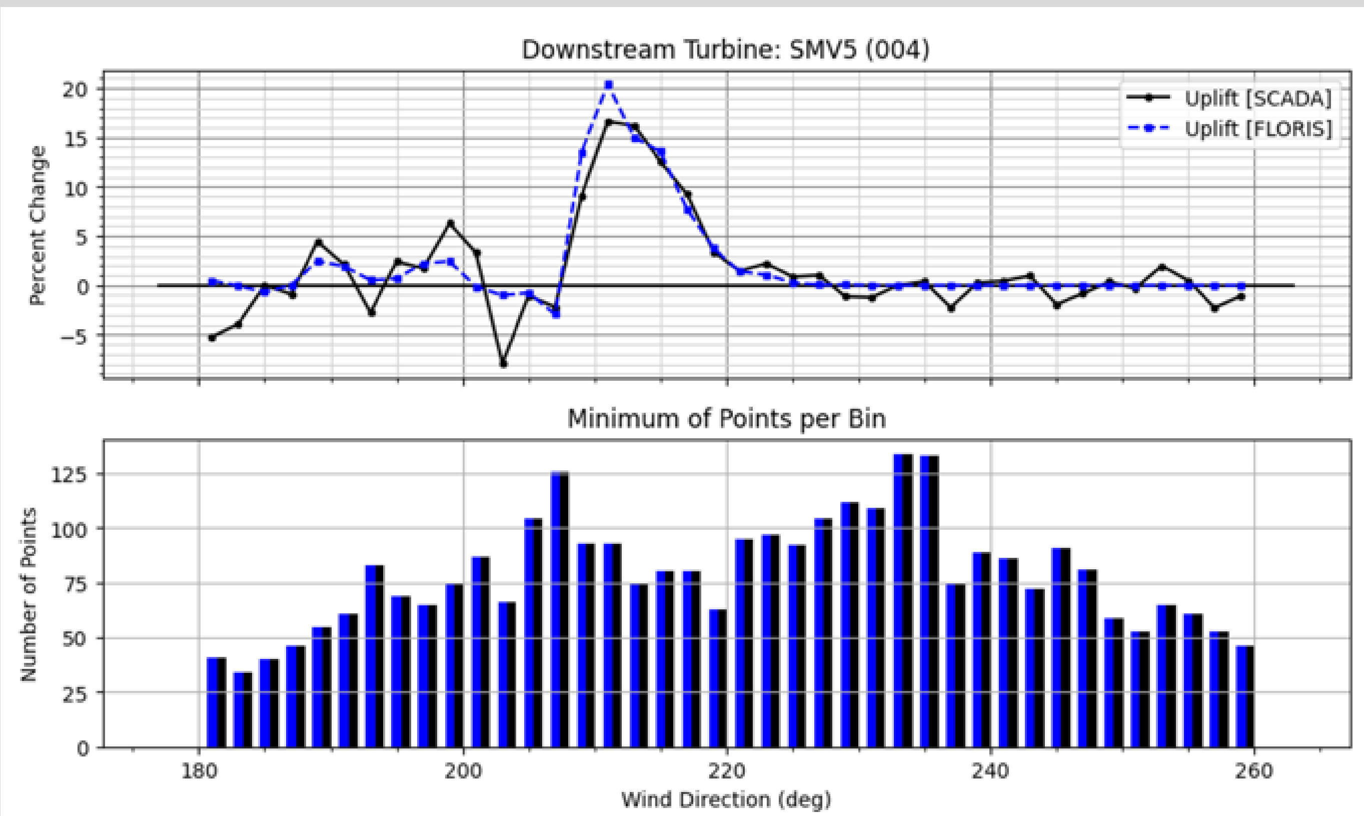
Point of Contact: Paul Fleming, Paul.Fleming@nrel.gov

Upgraded Tool Boosts Accuracy and Insights for Wind Power Plant Performance Analysis

NREL's open-source, FLOw Redirection and Induction in Steady State (FLORIS)-based Analysis for Supervisory Control and data acquisition (FLASC) tool, which supports FLORIS software, enables researchers and industrial experts to analyze complex wind plant field validation campaign data. In FY 2023, NREL made several improvements to FLASC, including:

- Automatic detection of impacting turbines
- Routines for detecting yaw calibration errors
- An organized suite of data filtering methods.

NREL researchers also added a data set from a seven-turbine wake-steering test at a commercial wind plant in Sole du Moulin Vieux, France. By using real data to demonstrate FLASC's capabilities, the researchers substantially improved the tool by providing better usage illustrations of the functionality. The FLASC examples demonstrated by the NREL team provide useful context for future users by recreating the analysis from the original paper through real-data examples.



This graph shows a comparison of FLORIS model with supervisory control and data acquisition data for the SMARTEOLE Wind Farm Control open data set included with FLASC. The upper plot compares the change in the energy ratio of the turbine in the wake of the controlled turbine caused by wake steering. The blue line represents the results expected from FLORIS whereas black is based on SCADA analysis. The lower figure gives number of data points per binned bar. *Graphs by Eric Simley, NREL*

FLORIS Now Ready for Advanced Control of Floating Wind Turbines

NREL researchers included new capabilities to capture the performance impacts and characteristics of floating offshore wind turbines in Version 3.4 of [FLORIS](https://www.nrel.gov/wind/floris.html), which was released in FY 2023. These capabilities include changes to the wind turbine's power and thrust as well as vertical wake deflection due to the wind-speed-dependent tilt of the floating wind turbine's platform. These new capabilities will support NREL researchers, industry partners, and academic colleagues in the design and development of floating offshore wind power plants, helping advance offshore wind energy development in previously inaccessible areas.

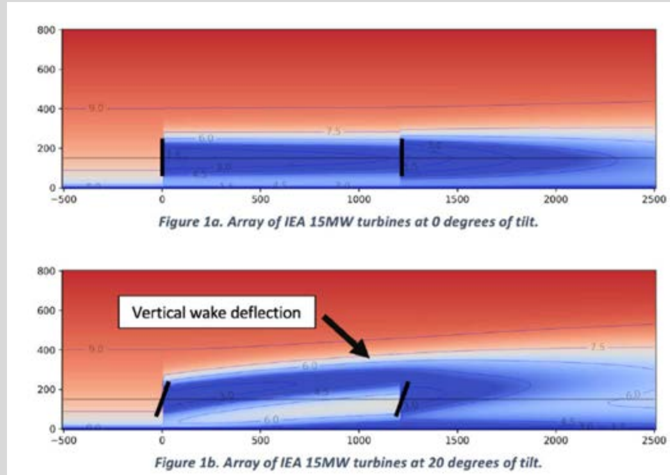


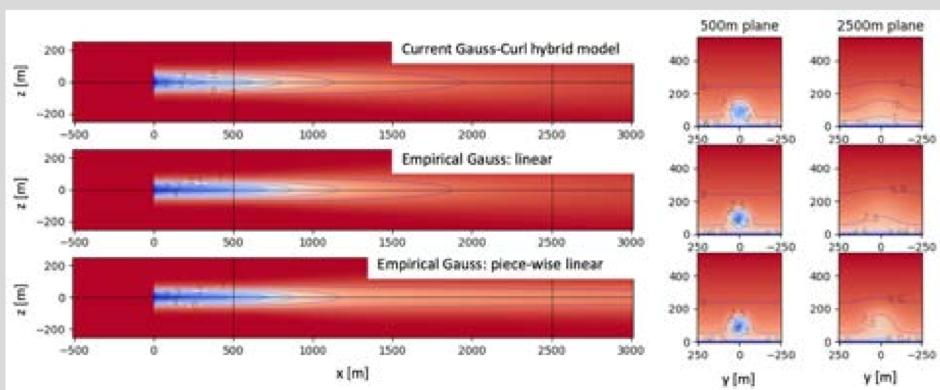
Figure 1a. Array of IEA 15MW turbines at 0 degrees of tilt.

Figure 1b. Array of IEA 15MW turbines at 20 degrees of tilt.

The lower graph captures the vertical wake deflection due to the tilt of the floating offshore wind turbine versus no tilt in the upper graph, an upward displacement of the wake is shown. This effect is driven by the amount of tilt of the floating turbine, which is determined by the current wind condition and operating state of the wind turbine. *Graphs by Christopher Bay and Michael Sinner, NREL*

New, Agile Wind Turbine Wake Model To Boost Solutions for Wind Plant Efficiency

Physics-derived wind turbine wake models work well in situations for which they have been designed and tested but are difficult to adapt to circumstances outside of the original design set, such as larger wind power plants, offshore wind conditions, or different data formats. To bridge this gap, NREL researchers developed Empirical Gaussian (EmG), a new wind turbine wake model designed to easily adapt to observed data. The EmG model, which is included in Version 3.4 of the [FLORIS](https://www.nrel.gov/wind/floris.html) wind power plant control modeling tool, draws inspiration from earlier physics-derived models but simplifies the model structure by limiting the number of parameters and avoiding any parameter impacting multiple aspects of the model simultaneously. This design enables more rapid and accurate data fitting, allowing researchers to expand their analysis of experimental data and produce new specialized controls solutions for wind power plants. The EmG model has been successfully deployed by NREL researchers fitting data from a large-scale wake steering campaign as part of a technical service agreement with Regional Energy Systems, a commercial wind power plant operator.



The new EmG wake model can be adapted to closely match (middle row) existing physics-derived wake models (such as the Gauss-Curl-hybrid model, top row) but can be quickly modified to better match observed features of operational wind plant data, such as more persistent wakes (bottom row). Left-hand plots show a top-down view of the wake deficits, whereas the right-hand plots show a cross-section of the wake near the turbine (500-m plane) and further downstream (2,500-m plane). *Figure by Misha Sinner, NREL*

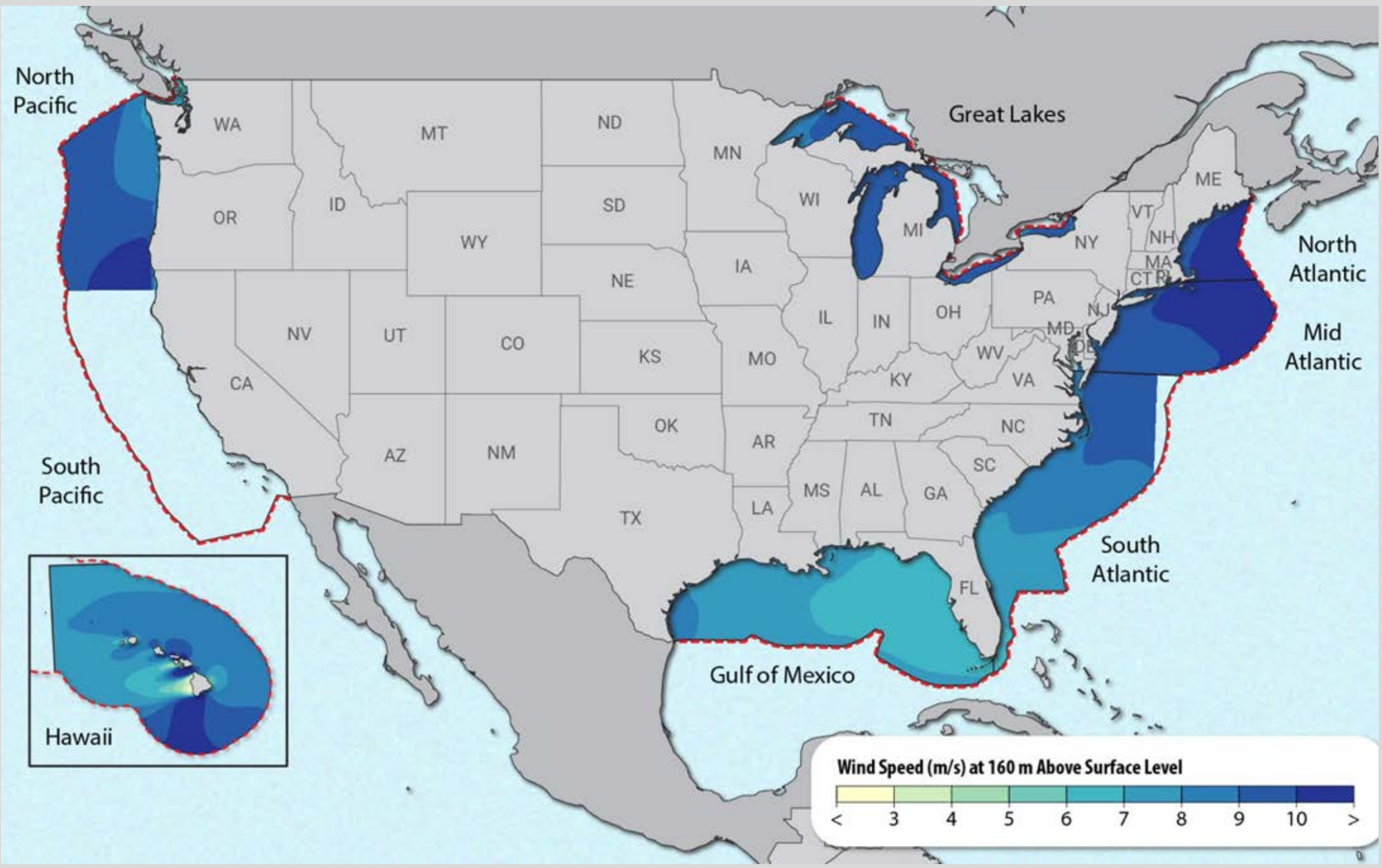
Offshore Wind Energy Research and Development

National Offshore Wind Resource Dataset

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

NREL Releases National Offshore Wind Resource Data for Estimating Energy Production

NREL released the 2023 National Offshore Wind (NOW-23), which characterizes offshore wind speed and critical atmospheric variables over a span of more than 20 years. NOW-23 will provide wind energy stakeholders with accurate, geographically specific descriptions of U.S. offshore wind resources over the entire Outer Continental Shelf and the Great Lakes. The data are publicly available at no cost.



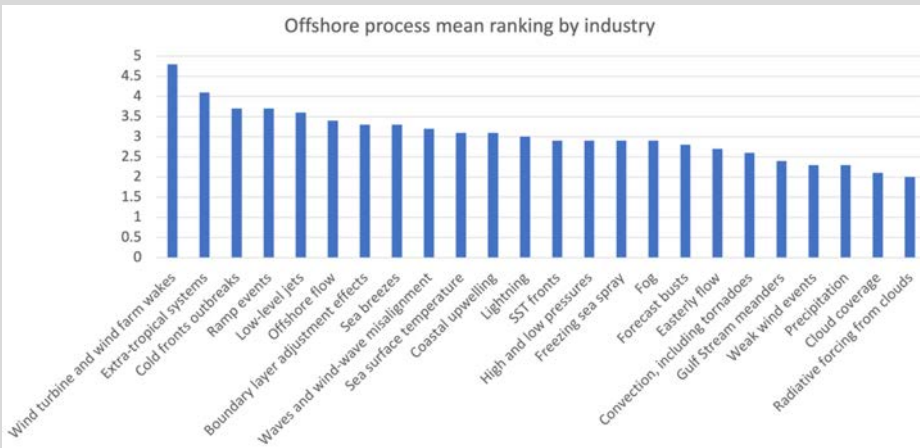
Mean long-term wind speed at 160 m from the NOW-23 data set, for all U.S. offshore regions (except for Alaska). The red dashed lines represent the limit of the U.S. Exclusive Economic Zone. Updated data for the California region will be released in early FY 2024. *Graphic by Billy Roberts, NREL*

Offshore Wind Resource Science

Point of Contact: Nicola Bodini, Nicola.Bodini@nrelgov

Industry Priorities To Inform Offshore Wind Energy Field Campaign

NREL researchers worked with offshore wind energy stakeholders to develop guidelines summarizing industry priorities for offshore wind energy resource assessments. These guidelines will help ensure broad impact of the third Wind Forecast Improvement Project offshore wind energy field campaign within the industry and inform the campaign's design. This work was conducted as part of planning the project that is scheduled to start in early 2024.



Histogram summarizing the mean ranking given by the industry stakeholders who were part of the NREL survey to a variety of offshore wind metocean processes. *Graph by Nicola Bodini, NREL*

Great Lakes Offshore Wind

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

Huge Potential of Offshore Wind Energy in the Great Lakes Is Just the Tip of the Iceberg

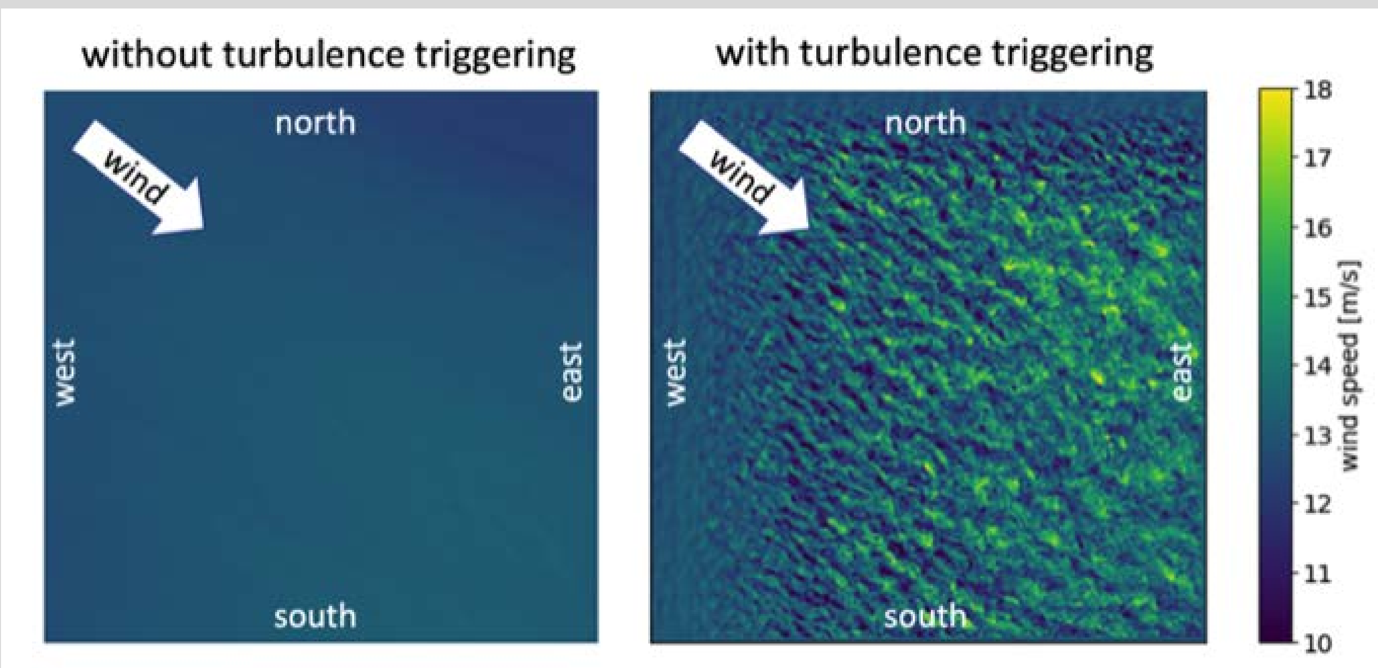
The potential amount of offshore wind energy in the Great Lakes region of the United States could be substantial. More than enough, in fact, to accommodate the electricity consumption of most nearby states. But the lakes' freshwater environment poses different challenges than those faced by ocean-based offshore wind energy development. Freshwater ice, for example, is stronger than sea ice and more prevalent in the Great Lakes than in Atlantic offshore wind energy project sites, meaning that more robust offshore wind energy structures will be required for operation in the Great Lakes. Summarizing research conducted on behalf of WETO, NREL's *Great Lakes Wind Energy Challenges and Opportunities Assessment* identifies a commercial pathway for Great Lakes wind energy that begins before 2035. In addition to outlining the region's wind energy potential, the report identifies the key issues that need to be tackled for this potential to be realized and defines a comprehensive research program to address these challenges.


NREL assessed the opportunities and challenges around the development of offshore wind energy in the Great Lakes of North America. *Photo from The Great Lakes page in the National Aeronautics and Space Administration's Ocean Color Image Gallery*

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

Offshore Atmospheric Modeling Projects Come to Successful Conclusions

Coming to a successful close in the first quarter of FY 2023, the Offshore Wind Atmospheric Coupling (OWAC) and Mesoscale–Microscale Coupling (MMC) projects resulted in robust strategies for connecting regional-scale weather information with wind-power-plant-scale turbulent flow simulations. The figure shows a bird's-eye view of the wind 100 meters (m) above the ocean from two turbulence-resolving simulations. Wind data from a regional-scale weather model, which does not resolve turbulence, are fed into this high-resolution turbulent simulation from the northwest. One critical aspect of coupling such models is how to trigger turbulence in the simulation. The simulation (shown in the figure on the right) uses a turbulence-triggering method to effectively spin up realistic turbulence, whereas the one in the left figure does not, showing just how important these triggering methods are. These coupling strategies vastly increase the realism and range of conditions under which industry and researchers can simulate plantwide flows. The projects culminated with a symposium hosted by the OWAC/MMC team and a *Wind Energy Science* journal article, "Lessons Learned in Coupling Atmospheric Models Across Scales for Onshore and Offshore Wind Energy." Findings are now informing new DOE-funded projects that would not be possible without the OWAC/MMC research, including research to simulate and better understand U.S. Pacific Coast weather and winds and U.S. Atlantic Coast hurricane weather and winds. Understanding operational and extreme conditions is important in both locations, which are planned for many offshore wind farms.

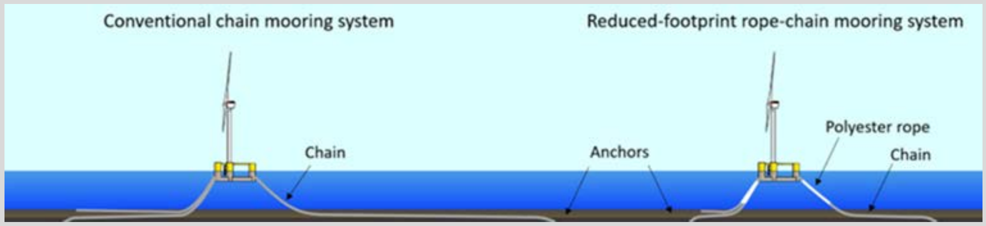


A bird's-eye view of the computed wind speed in a 5-kilometer-by-5-kilometer plane 100 m above the surface (at typical offshore wind turbine heights) at an offshore location using simulations without (left) and with (right) turbulence triggering. *Graphic by Regis Thedin, NREL*

Floating Wind Array Design

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

Newly Integrated Tools Will Enable Design of Floating Offshore Wind Energy Arrays



A new mooring system (right) uses hybrid tethers made of both polyester rope and chains, which reduce the footprint of floating offshore wind turbines as compared to conventional chain (left) mooring systems, which increase marine accessibility and acceptance by the fishing industry, an NREL study found. *Graphic by Stein Housner and Matt Hall, NREL*

Arrays of floating wind turbines are interconnected by complex configurations of mooring lines, power cables, and anchors. These components are constrained by a wide range of interrelated design challenges and subject to varied meteorological ocean and seabed conditions. In 2023, NREL's Floating Wind Array Design project has been working to address these challenges by developing an open-source design tool set. The team enhanced existing simulation and optimization tools for floating wind turbines and created new connections between the tools to evaluate aspects of floating wind turbine arrays that were not already considered. The impacts on turbine system loads and responses due to variable seabed bathymetry and water currents were added to the NREL-developed quasistatic mooring model MoorPy, which allows these mooring-specific factors to be considered in the early-stage design of a floating offshore wind energy project. The team also extended NREL's frequency-domain wind turbine model called Response Amplitudes of Floating Turbines to support multiturbine arrays and coupled the model with FLORIS to account for wind plant wake effects. Additionally, the team is curating a set of meteorological ocean (wind, wave, and current) data representative of different U.S. offshore wind regions to enable site-specific research and development of future floating wind arrays. The 3-year project will ultimately produce an integrated tool set for design optimization of floating wind arrays along with reference array designs for different U.S. regions that can be used by researchers and industry alike to improve the design of U.S. floating wind power plants.

Reduced-Footprint Synthetic Rope Mooring System

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

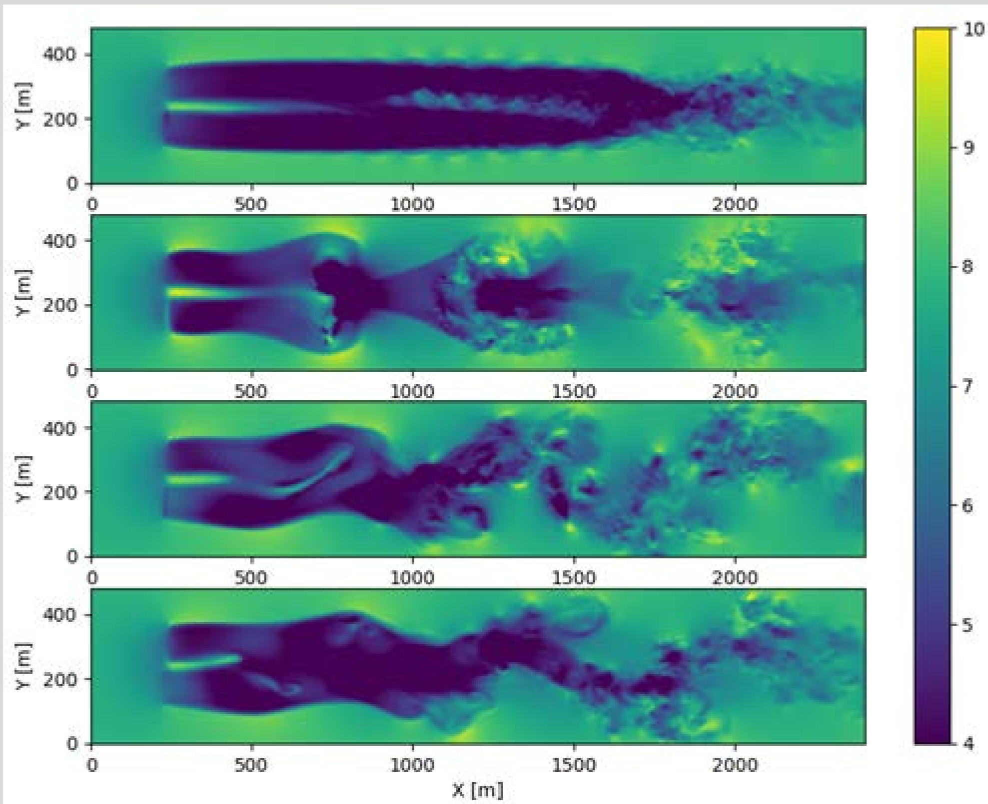
IEA Wind OC6 Project Ends With Successful Validation of the Novel Stiesdal Tetraspar

In Phase IV, the culminating stage, of the IEA Wind's International Offshore Code Comparison Collaboration, Continued with Correlation and unCertainty (OC6) project, led by NREL, global participants confirmed the loading and motion of an innovative floating offshore wind energy system design. Using 16 distinct software tools, international collaborators developed numerical models of a 3.6-MW horizontal-axis wind turbine atop the Stiesdal TetraSpar floating platform, assessing their accuracy against data from a 1:43 Froude-scale test conducted by researchers at the University of Maine wave basin. While participants saw notable successes in estimating aerodynamic loading and tower base bending, challenges persist in accurately predicting the dynamic loading for the upwind mooring, which could be related to influences from the instrumentation cable bundle. Encouragingly, they also saw good alignment between the numerical models and experimental results for keel line tensions, connecting the main support structure to a hanging ballast. This suggests that floating wind turbine designers' ability to accurately predict the loads experienced by individual structural subcomponents within floating offshore wind turbine support structures is improving because of the OC6 collaborations, which will lead to more streamlined, cost-effective floating wind designs.

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

Wake Mixing Can Maximize Wind Farm Power

Wake mixing is a wind farm control strategy wherein wind turbines pitch their blades in a way that promotes mixing of their wakes with higher-velocity free-stream flow, thus improving wake recovery. By enhancing this mixing, wind farms can gain more power from downstream waked wind turbines. In collaboration with Sandia, NREL researchers developed a controller that can implement different wake-mixing strategies in NREL's OpenFAST wind turbine simulation tool and assess the effectiveness of the control strategies using AMR-Wind, the high-fidelity flow solver for wind power plant simulations. The team found that wake-mixing strategies can increase the wind velocity in a turbine's wake by up to 45% in an ideal case and up to 25% for typical offshore wind conditions.

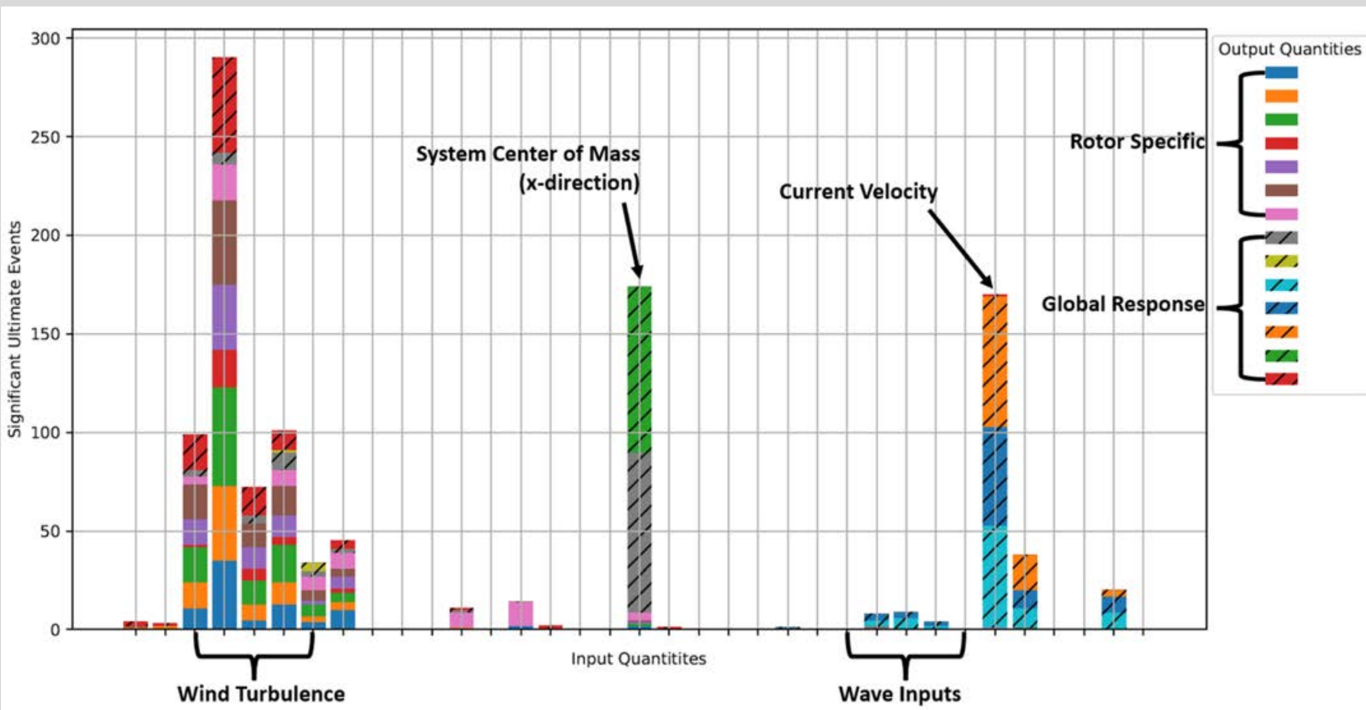


Wake development behind a turbine with different wake-mixing strategies in ideal, nonturbulent wind conditions were simulated, from top to bottom, as a baseline case (no wake mixing strategy implemented), collective pitch control (typically called "dynamic induction control"), and individual pitch wake mixing control. The latter method uses the individual blade pitch angles to rotate the wake, giving it a helical shape. This method is therefore referred to as the helix method. The third figure shows the helix method in counterclockwise rotational direction, the bottom figure in clockwise direction. *Graphic by Joeri Frederik, NREL*

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

Sensitivity Assessment Identifies Most Influential Parameters Effecting Floating Wind Turbine Loading

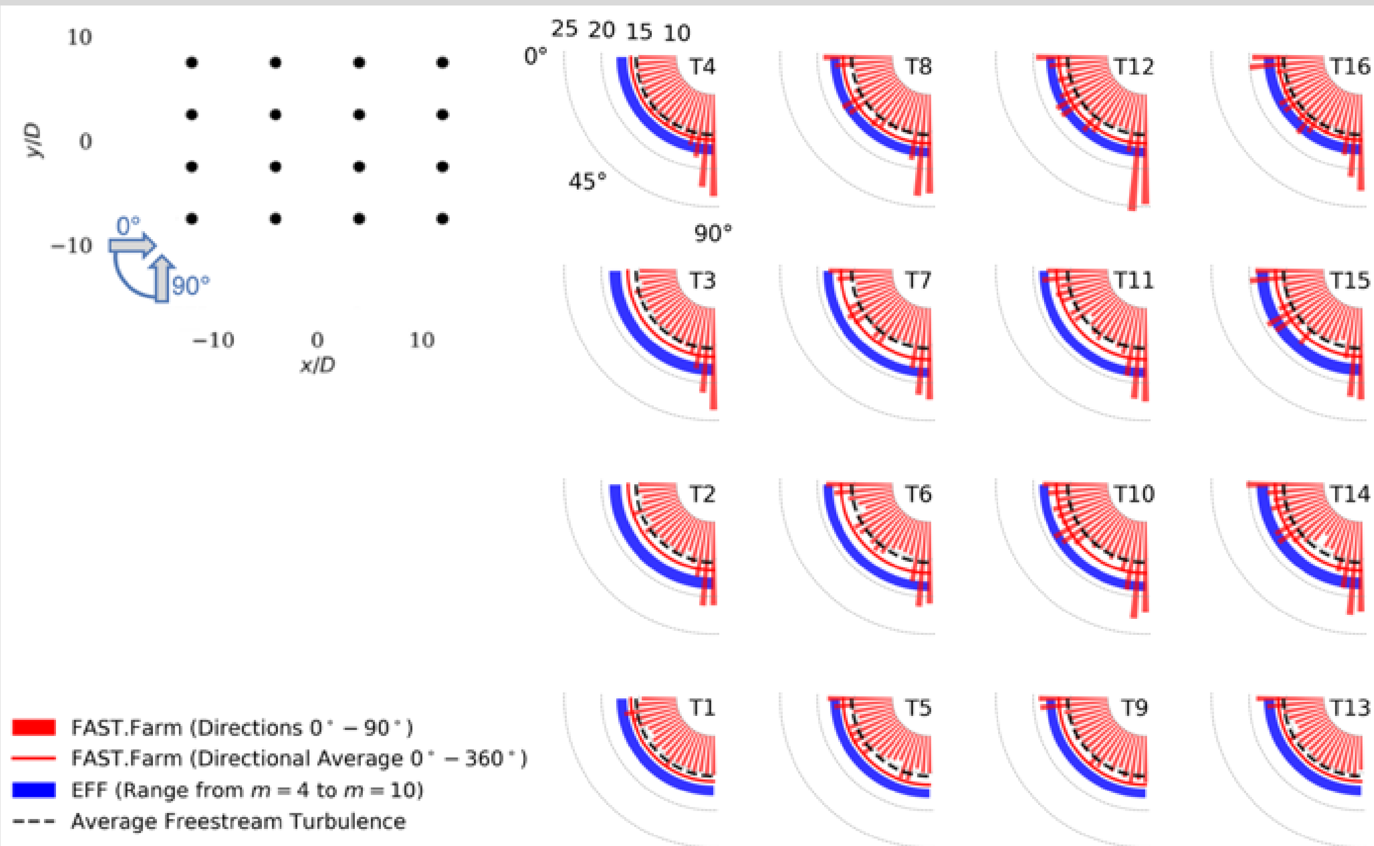
As designers move to advance and optimize floating offshore wind turbine technology, it is important to better understand how uncertainties impact modeling predictions. As a result, NREL researchers performed a sensitivity assessment to identify the information put into engineering models that likely has significant uncertainty/variability—such as inflow turbulence, sea state, and system properties—that are most influential to the resulting floating offshore wind turbine design loads. As a case study, researchers used the NREL 5-MW wind turbine atop the Offshore Code Comparison Collaboration Continuation (OC4) DeepCwind semisubmersible under normal operating conditions. A draft paper summarizing the methodology and results was submitted for review and publication in *Wind Energy Science*. The results of this work will better inform the wind turbine design process and site-suitability analyses and help when planning wind turbine measurement projects.



Results of a sensitivity assessment for ultimate loads showing the relative importance of various input parameters influencing floating offshore wind turbine loads and motions. *Graph by Will Wiley, NREL*

Assessment of IEC Effective Turbulence Model Encourages Use of FAST.Farm to Improve Wind Power Plant Design

Now that physics-based, high-fidelity, and engineering models capturing the power and loading of wind turbines in a full wind farm are becoming more accurate and available, it is likely that turbines can be better designed and optimized based on more realistic inflow conditions, wakes, and array effects. Two models are recommended in IEC wind turbine design standards for accounting for wake effects in design and site-suitability analyses. NREL researchers compared the IEC effective turbulence model and the dynamic wake meandering model as implemented in FAST.Farm, an engineering tool for predicting the power performance and structural loads of wind turbines within a wind farm. An idealized four-by-four array of 5-MW wind turbines with a spacing of 5-by-8 rotor diameters and three wind speed scenarios was simulated with both models. The results were compared in terms of ambient turbulence, wind power plant turbulence, and structural response. A draft paper summarizing the methodology and results was submitted for review and publication in *Wind Energy Science*. This work should encourage the wind energy community to apply physics-based models, such as FAST.Farm or similar models, to improve the wind turbine and farm design process.



The left-hand graph shows a wind farm layout, and the rose diagrams on the right show turbulence intensity results dependent on wind direction for each wind turbine in that wind power plant. *Graphic by Paula Doubrawa, NREL*

Recent Enhancements Enable Improved Aerodynamic Design Accuracy in OpenFAST

Wind turbines usually operate within uneven and turbulent wind fields because of many factors, including skew caused by misalignment of the rotor and wind direction, shear and veer that naturally occur in the wind, and inflow turbulence. OpenFAST is one of the primary wind turbine engineering design tools used by the industry today but recent work to validate it against experimental measurements—for example, under the IEA Wind Task 47 collaborative and within the Rotor Aerodynamics, Aeroelastics, and Wake experiment—has demonstrated an unacceptable level of uncertainty in its main aerodynamics module when predicting aerodynamic loading and turbine responses under highly skewed and highly sheared flow. An NREL team recently developed significant enhancements of the main aerodynamics model to enable better estimations of skew and shear through a more rigorous and accurate representation of the underlying physics. They validated the improved aerodynamics model in OpenFAST against reference solutions from a higher-fidelity vortex-based method. The upgraded OpenFAST model is a much better representation of real-world turbulent wind conditions that will enable the wind energy community to improve wind turbine performance and structural loads calculations for more reliable designs.

West Coasts Ports Study
Point of Contact: Matt Shields, Matt.Shields@nrel.gov

West Coasts Ports Study Reveals What It Will Take To Unlock U.S. Floating Offshore Wind Energy

A massive 2.8 terawatts of energy potential—enough to power 350 million homes—could be captured off the U.S. coasts with floating wind turbines. To deploy commercial-scale floating offshore wind energy development, the United States will have to develop ports. An NREL study, recently published in a report titled *The Impacts of Developing a Port Network for Floating Offshore Wind on the West Coast of the United States*, focused on what it will take for the country to develop a system of ports. That includes the $5 billion–$10 billion to develop the installation and maintenance ports needed to build and operate 25–55 GW of floating offshore wind energy on the West Coast and at least another $10 billion to build manufacturing ports to support a local domestic supply chain that will need to be coordinated by California, Oregon, and Washington.

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Developing a network of ports and supply chain along the U.S. West Coast is a first step toward making commercial-scale floating offshore wind energy development a reality in the United States. The foundation for a floating offshore wind turbine, like this one for an 8.4-megawatt turbine in Portugal, can be towed out to sea from one of these ports, where it can generate clean, renewable energy far offshore. *Photo from Principle Power*

Extreme Weather

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

Symposium Unites Industry and Experts To Tackle Challenges of Offshore Wind Energy and Extreme Weather

NREL, in collaboration with Argonne National Laboratory, the National Center for Atmospheric Research, and Pacific Northwest National Laboratory, organized the Tropical and Extra-tropical Cyclone Impacts on Future Offshore Wind Energy symposium. The symposium, which took place June 1–2, 2023, brought together representatives from industry, national labs, and academia to discuss scientific and engineering challenges around extreme weather and offshore wind energy, present on state-of-the-art extreme weather approaches of offshore wind energy technologies, pose research questions on the subject matter, and create a road map to solve the major challenges. NREL researchers Jason Jonkman, Walter Musial, Paul Veers, and Georgios Deskos gave overviews of research efforts at NREL while pointing out key technical challenges that need to be addressed, particularly to make wind offshore wind turbines more resilient to hurricanes. An upcoming, follow-up technical report prepared by NREL will inform future research pathways at DOE and set the stage for a full-scale extreme weather research program that the industry needs to deploy wind turbines safely in the south Atlantic and Gulf of Mexico.

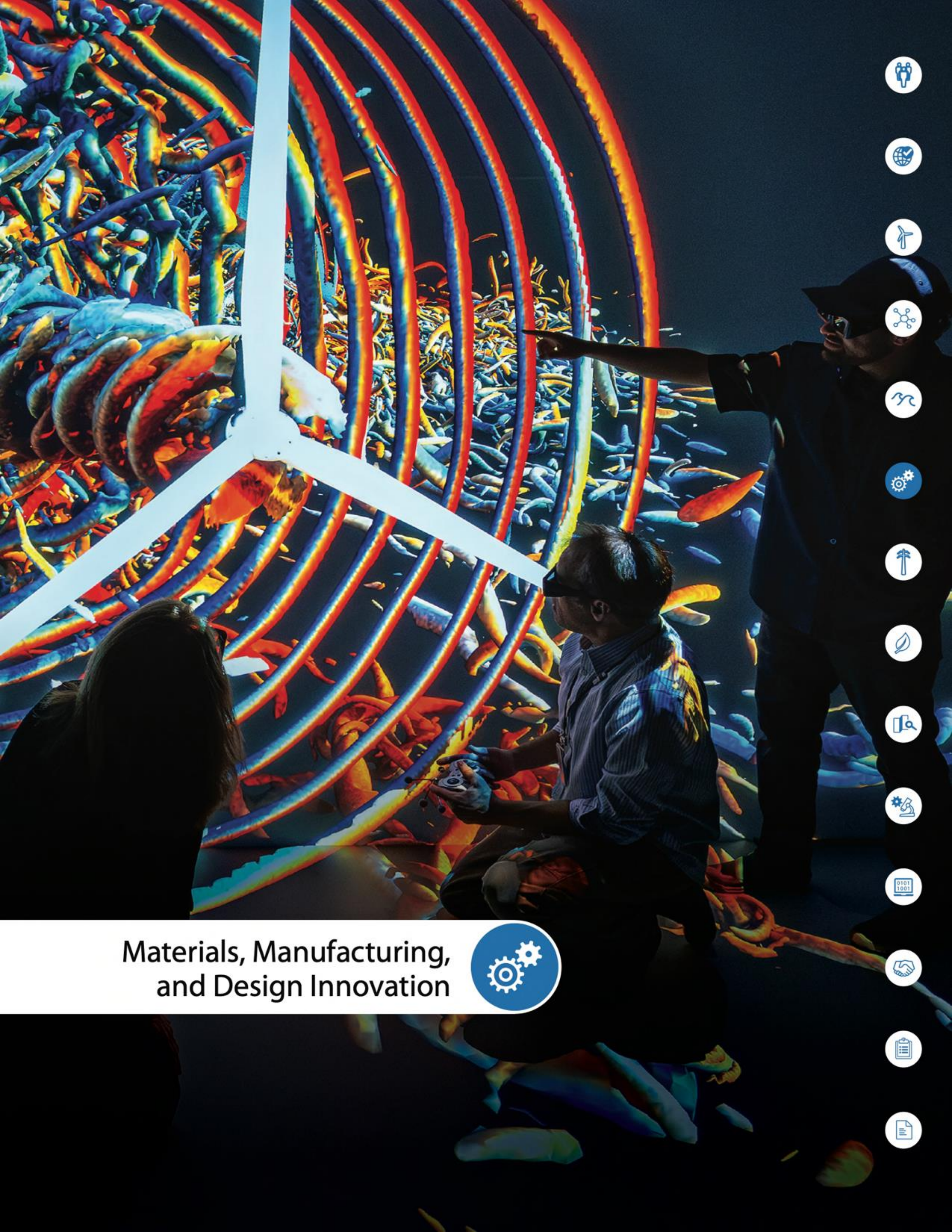
Floating Offshore Wind Platform Industrialization Support

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

Floating Offshore Wind Energy Supply Chain Prize Moves to Phase Two

In March 2023, DOE announced nine winners of the first phase of the NREL-administered American-Made FLoating Offshore Wind ReadINess (FLOWIN) Prize, kicking off Phase Two. Launched as WETO's first-ever wind energy prize in September 2022, the three-phase competition aims to bridge manufacturing and logistics gaps to help meet the nation's goals to deploy 15 gigawatts (GW) and reduce the cost (by 70%) of floating offshore wind energy by 2035. In Phase One, teams submitted floating offshore wind turbine platform designs that can help tackle the offshore wind energy industry's biggest manufacturing and supply chain challenges. Each Phase One winning team received $100,000 in cash and $75,000 in vouchers for technical support provided by DOE national laboratories, including NREL. Winners from Phase One were eligible to move into the second phase of the competition, in which each team develops a pathway for mass manufacturing and deployment of its floating offshore wind energy substructure design.

The FLOWIN Prize is an American-Made competition designed to accelerate the market readiness of U.S. floating offshore wind energy technologies. *Graphic by Besiki Kazaishvili, NREL*



Materials, Manufacturing, and Design Innovation

OpenOA

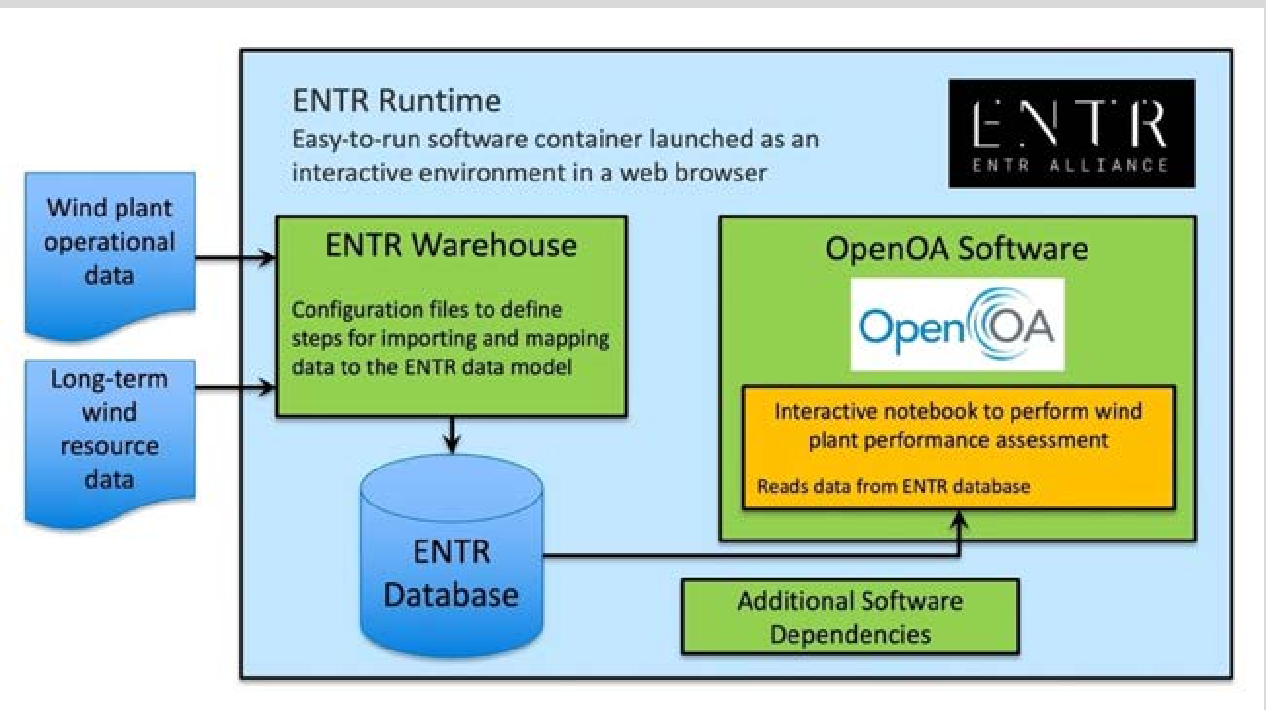
Point of Contact: Eric Simley, Eric.Simley@nrel.gov

New Software Improves Efficiency of Wind Power Plant Data Analysis

The wind energy industry faces several challenges related to analyzing wind power plant data, including the significant amount of time required to import and prepare operational data. Many of these challenges are caused by the lack of standards and reference methods needed to assess wind power plant performance, which results in uncertainty in analytical results. To address these challenges, NREL teamed up with the ENergy TRansition (ENTR) Alliance—a wind energy data standardization industry consortium—as part of a DOE Technology Commercialization Fund project to create a standard data analysis environment. At the 2023 ENTR Developer's Conference in Boulder, Colorado, the team released the ENTR Runtime package, publicly available on GitHub, which comprises the following components compiled in an easy-to-run software tool:

- The ENTR Warehouse, a set of configuration files and software scripts for importing and transforming raw operational data into the standard ENTR data model
- A database for storing the imported data
- NREL's Open Operational Assessment (OpenOA) library of reference operational wind plant performance assessment methods
- Example wind power plant performance data, which can be analyzed.

This ready-to-use software package can improve efficiency in the wind energy industry by allowing analysts to assess the performance of their wind power plants across their fleets while avoiding time-consuming data standardization processes. The project team demonstrated the ENTR Runtime software by using OpenOA to estimate long-term expected annual energy production and wind turbine yaw misalignment using data from wind power plants operated by project partner Apex Clean Energy.



Overview of the ENTR Runtime operational wind power plant data analysis environment. *Graphic by Eric Simley, NREL*

Offshore Wind Roadmap Development

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

Road Map To Enable Cost-Effective and Sustainable U.S. Offshore Wind Energy Industry

Recommendations identified in the offshore wind energy O&M road map will help lower costs and improve sustainability of U.S. offshore wind power plants. *Photo from Siemens AG, NREL*

Researchers from NREL and Sandia National Laboratories drafted an operations and maintenance (O&M) road map (forthcoming) for the U.S. offshore wind energy industry. Members from industry and academia informed the national lab team's development of the road map through one-on-one interviews and stakeholder engagement events in both the United States and Europe, which leverages land-based wind power plant O&M experiences and other offshore wind energy road maps and projects to focus on O&M challenges that apply to the U.S. offshore wind energy market (including floating technologies). The road map highlights public-sector research and development investment opportunities that are high risk and high reward, at lower technology readiness levels with longer development times, and not typically addressed by the private sector alone. The publication discusses major offshore wind turbine and plant components, each including failure modes and mitigation, monitoring, sensing and inspection, maintenance execution, and cross-cutting topic areas. It also provides recommended O&M research and development activities for members of the U.S. offshore wind energy industry, according to short-, medium-, and long-term time horizons between 2023 and 2035. The road map is a strategic resource on new O&M technologies and processes that can enhance the cost-effectiveness, efficiency, performance, and reliability at U.S. offshore wind energy sites, enabling a cost-effective and sustainable U.S. offshore wind energy industry and contributing to the success of offshore wind energy in the United States.

Big Adaptive Rotor

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

Conversion of Turbine to Downwind Operations Will Answer Decades-Old Questions

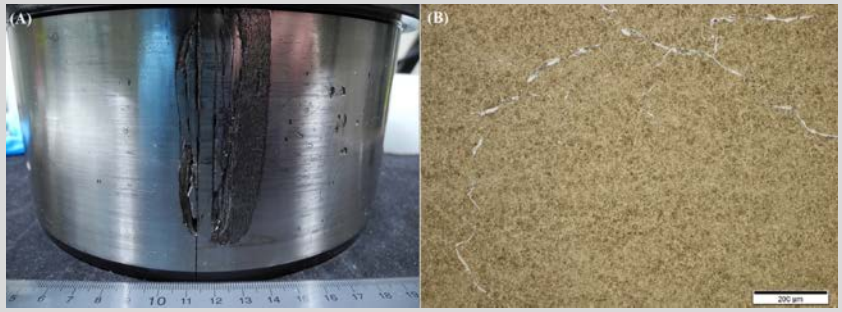
A 1.5-MW wind turbine located at NREL's Flatirons Campus is being prepared for downwind operation. *Photo by Jeroen van Dam, NREL*

Recent studies have shown the potential of downwind wind turbines to reduce turbine capital costs and increase wind farm power production. To help answer decades-old questions about the feasibility, reliability, performance, and economic viability of downwind wind turbines, the NREL Big Adaptive Rotor project team is preparing the DOE 1.5-MW wind turbine located at NREL's Flatirons Campus for downwind operations. The turbine will be equipped with sensors to measure loads, performance, and noise emissions. The sensor readings will be compared to those obtained during standard upwind operation.

Wind Turbine Drivetrain Reliability

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

Solutions for Reducing Gearbox Failures and Maintenance Costs Assessed



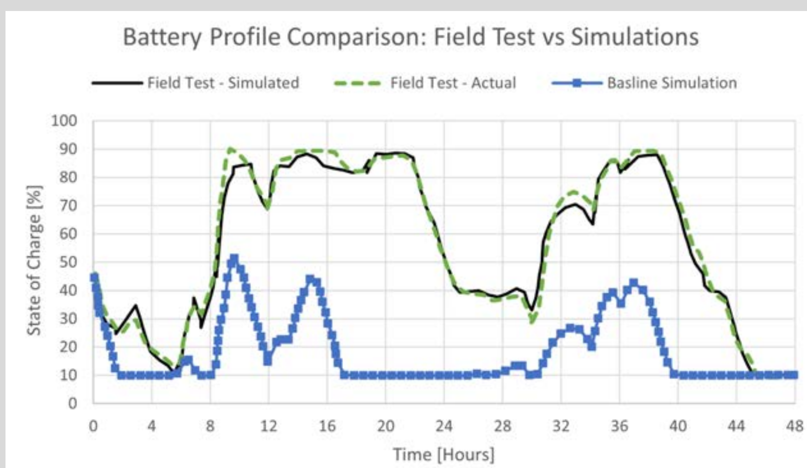
This photo shows an example of a bearing that failed due to white-etch cracking, ultimately requiring replacement, unscheduled maintenance, and wind turbine downtime. *Photo from Aaron Greco, Argonne National Laboratory*

Through the multiyear Drivetrain Reliability Collaborative research and validation program, NREL researchers evaluated the efficiency of cost-effective bearing, lubricant, and controller design changes on the probability of failure for roller bearings in wind turbine gearboxes resulting from white-etch cracking. Research results indicated that increasing average gearbox lubricant temperatures can reduce the probability of failure by up to 4%. It is likely less preferable to more tightly control the lubricant temperature to avoid cold temperature operations of less than 45°C than to increase temperatures to as high as 80°C because this could increase the risk of other failure modes. Additionally, the research determined that minor increases in bearing clearance had only a slight benefit while changing the lubricant absolute viscosity had little to no benefit. The Drivetrain Reliability Collaborative is funded by WETO and led by NREL researchers.

Hybrid Optimization and Performance Platform

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

Field Test Brings Hybrid Power Plant Model Closer to Commercialization



This figure compares the simulated state of charge of the battery (in percent) from HOPP (Field Test - Simulated) to the actual state of charge from the field test (Field Test - Actual) while also comparing the results from the simulation that does not use a model-based forecasting control strategy (Baseline Simulation). *Graph by Jonathan Martin, NREL*

NREL researchers have completed a field test validating the Hybrid Optimization and Performance Platform (HOPP), a tool that can model the behavior of a multitechnology hybrid power plant and provide a financial estimate on the value of the plant configuration. The field test used historical weather and power data from NREL's Flatirons Campus wind and solar ARIES assets to validate the control strategies in HOPP and show that they can be applied to physical equipment. Part of the platform's validation process, the field test was an important step in preparing the tool for industry use.

3D-Printed Blade Core Material

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

Using Large-Scale Additive Manufacturing for Wind Turbine Blade Core Structures

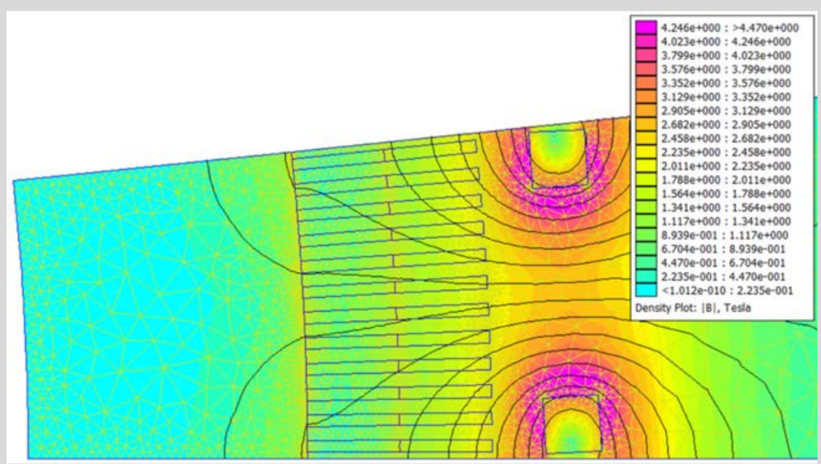
In FY 2023, NREL, in partnership with Oak Ridge National Laboratory, investigated several promising thermoplastic and thermoset-based 3D-printed materials as an alternative to industry-standard balsa wood and foam core materials, with a goal of domestically producing a 3D-printed wind turbine blade core at a lower cost. The team's research revealed new and unforeseen challenges regarding the potential of using additive manufacturing technologies to create mass-critical, high-performance, and cost-constrained large wind turbine blade structures. The team summarized these challenges and presented future research pathways in a report. This research supports DOE and White House goals to lower the cost of energy, increase U.S. domestic manufacturing production, and enhance the supply chain resiliency of U.S. wind energy systems, thereby enabling broader deployment of next-generation wind energy systems.

An NREL study evaluated the benefits and limitations to 3D-printed wind turbine blades, which are traditionally hand built, like this blade at NREL's Flatirons Campus. *Photo by Dennis Schroeder, NREL*

High-Efficiency Ultra-Light Superconducting Generator for Offshore Wind

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

NREL Partners With General Electric Researchers To Compare Offshore Wind Turbine Drivetrain Technologies



Visualization of the magnetic field of a 15-MW superconducting generator, a promising technology for the next generation of offshore wind turbines documented by an NREL-GE research team that compared three drivetrain technologies. *Image by Pietro Bortolotti, NREL*

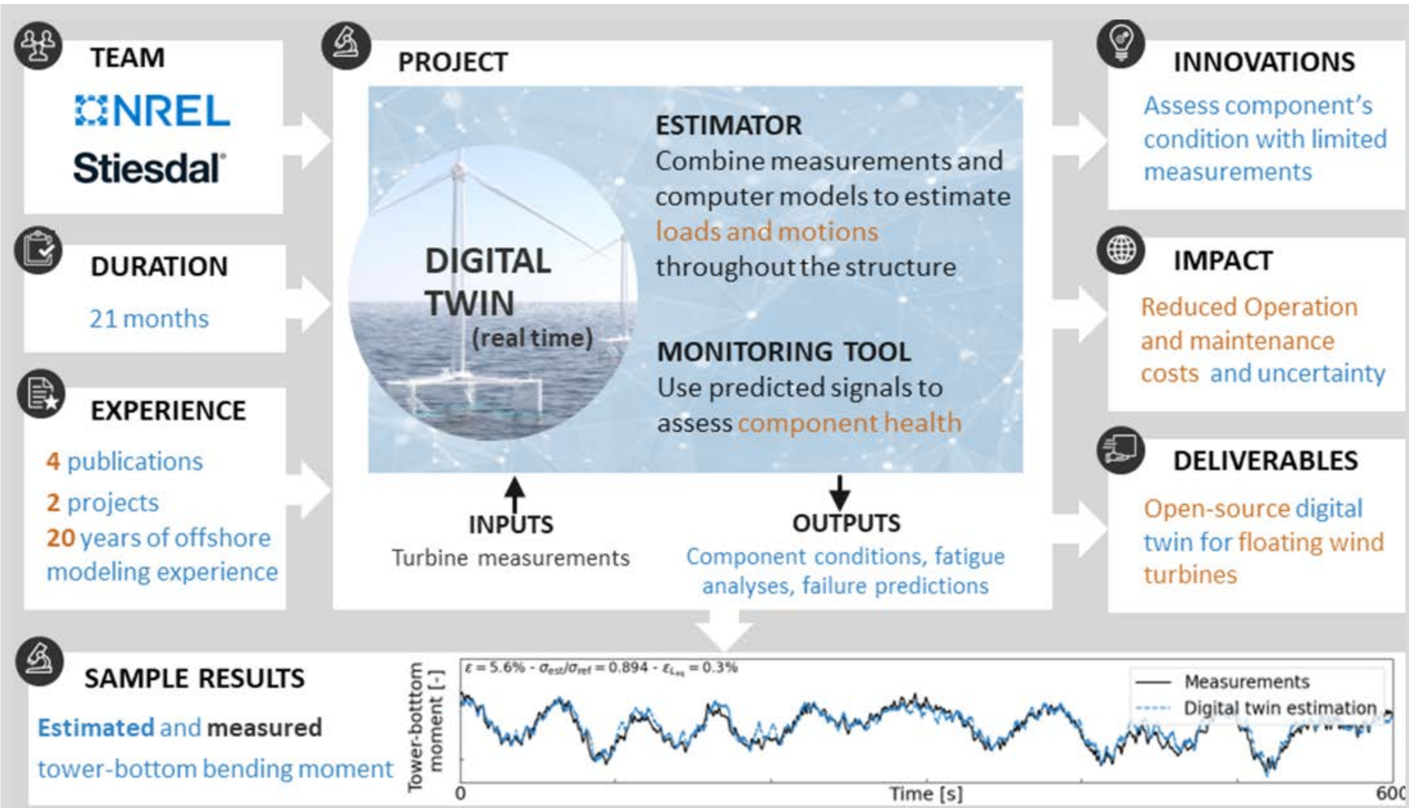
To help ensure that drivetrains keep pace with the growth in size and capacity of offshore wind turbines, an NREL and General Electric research team documented design studies comparing three drivetrain technologies for fixed-bottom and floating turbine designs. These technologies were direct-drive and medium-speed permanent-magnet synchronous generators and a low-temperature direct-drive superconducting generator at five power ratings (15, 17, 20, 22, and 25 MW). A resulting publication discusses the challenges and opportunities of each technology. Low-temperature superconducting generators and medium-speed permanent-magnet synchronous generators offer a pathway to reduce costs if their reliability can reach the levels of the more popular direct-drive interior permanent-magnet synchronous generators.

Offshore Wind Turbine Digital Twin for the Prediction of Component Failures

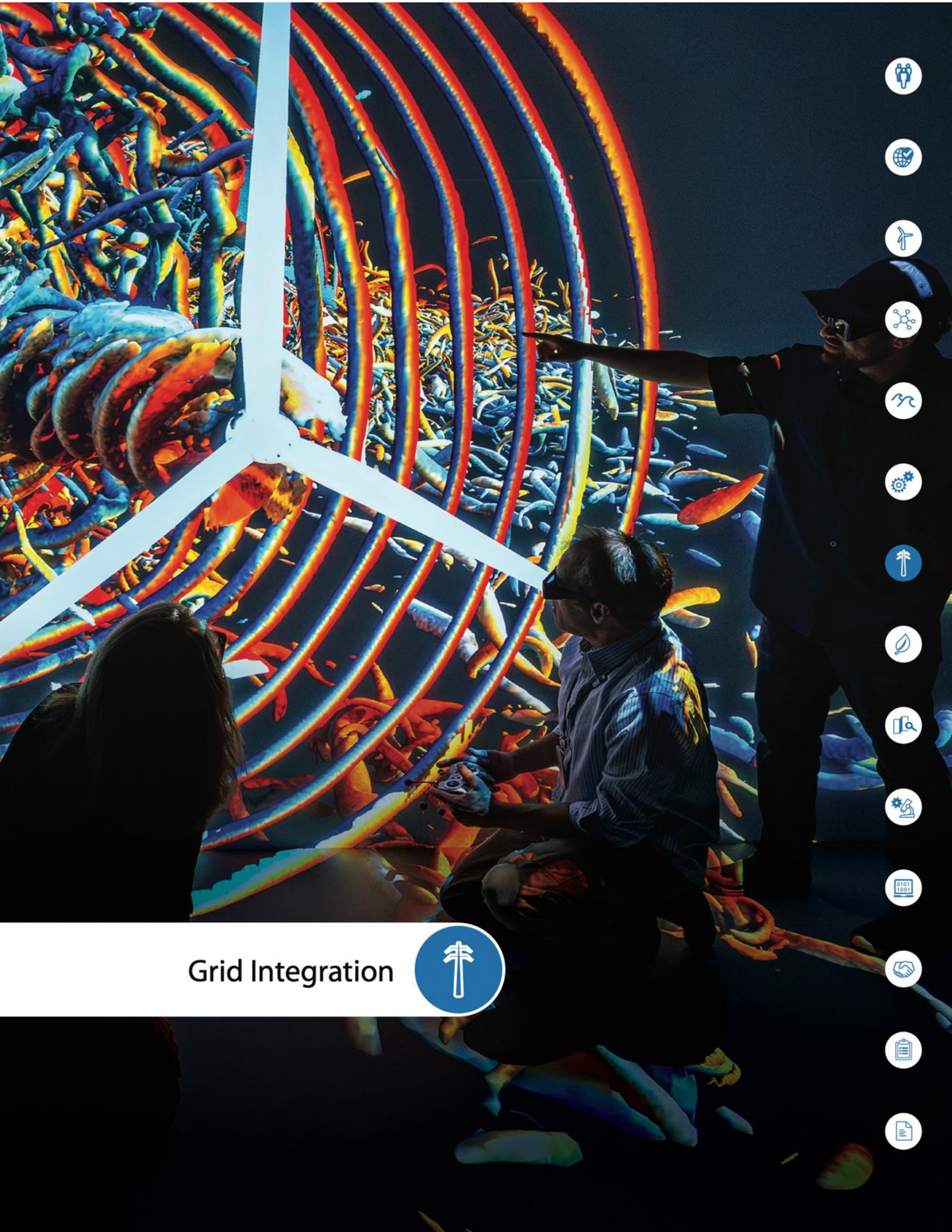
Point of Contact: Emmanuel Branlard, Emmanuel.Branlard@nrel.gov

Digital Twin Solution Opens Door To Reduce Offshore Wind Operation and Maintenance Costs

O&M costs can account for approximately one-third of life cycle expenditures for a fixed-bottom offshore wind energy project and are expected to be higher for floating projects. Condition-based operation and maintenance can achieve cost savings, but the current approach, which involves adding sensors to a wind turbine, has prohibitive costs. As an alternative, NREL researchers have developed a digital-twin framework, which uses numerical tools to follow the life cycle of a physical asset and perform virtual estimations of what sensors would measure without the need to install them on an actual wind turbine.



Overview of the offshore wind turbine digital twin project, *Graphic by Emmanuel Branlard and John Frenzl, NREL*



Grid Integration

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

Results From Atlantic Offshore Wind Transmission Study To Enable up to 110 GW of Offshore Wind Energy Deployment by 2050

NREL researchers, along with Pacific Northwest National Laboratory research partners, completed the 2-year, WETO-funded Atlantic Offshore Wind Transmission Study. The project's final report will be published later in 2023. In this study, the team:

- Named scenarios of offshore wind energy deployment with transmission topologies (such as radial lines, shared backbones, or a meshed network), sequencing, and build-out in the Atlantic for 2030 through 2050 that meet or exceed reliability and resilience criteria while considering ocean co-use
- Evaluated environmental considerations in the development of offshore transmission topologies from 2030 through 2050
- Quantified the resource adequacy and other reliability impacts of offshore wind energy transmission
- Estimated the economic benefits and cost of transmission topologies.

The results from this study will enable power systems planners to evaluate the benefits of interregional cooperation for offshore wind energy transmission and leverage the offshore wind energy investment to improve the power systems landscape and enable the United States to take the next steps to transition to a low-carbon grid.

The locations of the current U.S. Atlantic Coast offshore wind projects being considered or developed as of April 30, 2021. *Graphic by NREL*

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

Grid Stability Software Now Easier To Use

Renewable energy can have an unwelcome impact on power grids including electrical oscillations, which can destabilize systems and result in lower revenue and loss of power for millions of people. NREL's Grid Impedance Scan Tool, which was named a 2023 R&D 100 Award finalist, scans the electrical behavior of any network and grid devices to discover problematic electrical interactions that could cause damaging oscillations. The tool has become a trusted and unique solution that has already saved grid operators and manufacturers worldwide from multi-million-dollar curtailments of renewable energy. The Grid Impedance Scan Tool is now easier to use, thanks to a new graphical user interface and advanced features developed by NREL researchers.

Wind Consortium Cyber Threat Model

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

NREL Researchers Develop Combined Wind Power Plant and Turbine Reference Architecture Model and Simulation

Reference architectures provide advantages to analyzing a complex system, especially for cybersecurity, such as accelerating the design process for new technology integration and identifying potential gaps in standards and security best practices. As a result, a combined reference architecture of a wind power plant and wind turbine was developed by NREL researchers and simulated to perform research that can identify and mitigate cybersecurity risks to wind energy systems. The simulation is modularly designed to be integrated into additional work, such as NREL's cyber range and future wind cybersecurity projects. This combined reference architecture model and simulation will help the wind energy industry by providing the ability to analyze and evaluate wind energy systems, incorporate security by design, integrate new technology, and improve system best practices and standards.

A new combined reference architecture model and simulation will help the wind energy industry by providing the ability to analyze and evaluate wind energy systems, incorporate security by design, integrate new technology, and improve system best practices and standards. *Photo by Dennis Schroeder, NREL*

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

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

Models Enable Study of Promising Offshore Wind Energy Transmission Technology

The current estimated capacity of the points of interconnection for integrating offshore wind energy generation in the Atlantic region of the U.S. Eastern Interconnection of the electrical grid is 28 GW. This is substantially lower than the federal goal of integrating 110 GW of offshore wind energy generation in the United States by 2050, most of which will be connected in the Atlantic region. Multiterminal high-voltage direct-current (HVDC) offshore transmission corridors could reduce the need for points of interconnection by 50%. To study the fault behavior and performance requirements of this promising technology, NREL researchers developed high-fidelity electromagnetic transient models of point-to-point and multiterminal HVDC transmission networks. These models will enhance understanding of how the networks will behave during dynamic events and will determine feasibility of various multiterminal HVDC offshore transmission topologies for the Atlantic region that could reduce the points of interconnection, minimize the environmental impacts, and lessen developmental timelines of offshore wind energy projects.

Wind Power as Virtual Synchronous Generation

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

Type-5 Wind Turbine Generator Topology Offers Many Advantages for Grid Integration

A Type-5 wind turbine uses a hydraulic torque converter between the gearbox's low-speed shaft and the generator's high-speed shaft to match the generator speed with the electrical synchronous speed. This type of machine then uses a synchronous generator directly connected to the medium-voltage grid. The Type-5 configuration has many advantages over other wind turbines, including the ability to provide high levels of fault currents, maintain grid strength, and provide inertia to the grid. In FY 2023, an NREL and Idaho National Laboratory team developed a model to simulate a single Type-5 wind turbine generator as well as multiple Type-5 wind turbines, offering developers insight into how they might perform in a wind power plant. They also developed real-time models of torque converters used by Type-5 wind turbine generators. To validate their models, they conducted experiments using a 2.5-MW dynamometer and a real, synchronous machine at NREL's Flatirons Campus at multimegawatt scales. Using the model, the team demonstrated the benefits of Type-5 wind turbines contributing wind energy to the power grid, which included improving reliability.

WindWeasel: PLC Monitoring, Analysis, and Alerting System

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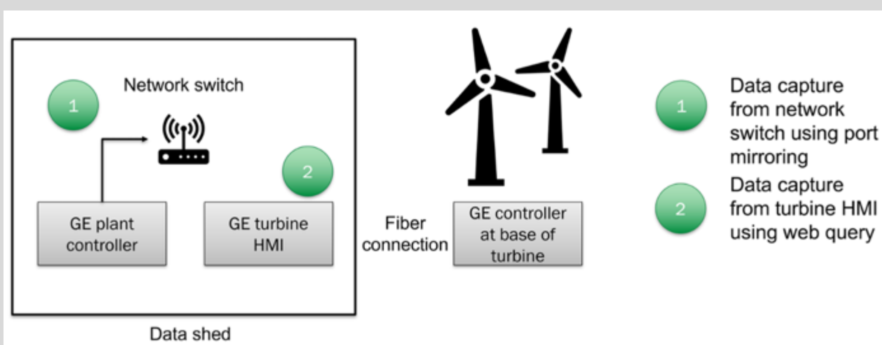
Introducing Physics to Intrusion Detection Systems To Safeguard Wind Energy Installations

Using a combination of cyber and physical data, NREL researchers, along with those from Sandia National Laboratories, 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 NREL's 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.



This setup allowed data capture from the DOE 1.5 MW turbine at NREL's Flatirons Campus through two different mechanisms, using (1) port mirroring (cyber data), and (2) web query through the human–machine interface, or HMI (physical data). *Graphic by Venkatesh Venkataramanan, NREL*

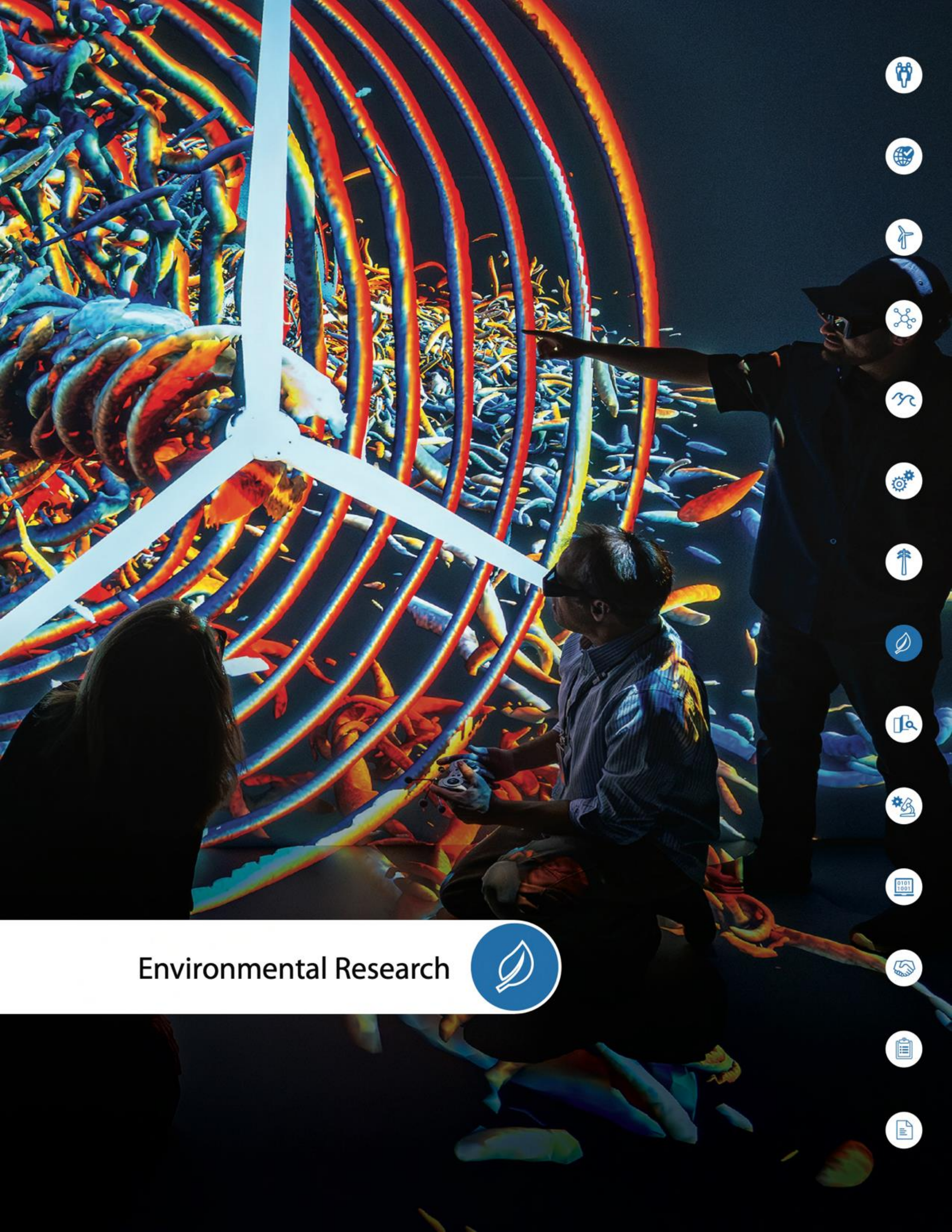
Wind Grid Integration Stakeholder Engagement

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

Industry Engagement Promotes Grid Integration Best Practices and State-of-the-Art Research

The Wind Grid Integration Stakeholder Engagement project supports NREL expert engagement in a range of industry activities to help disseminate leading research and guide best practices. In FY 2023, NREL researchers represented WETO-funded work at multiple activities for IEA Wind Task 25. NREL's participation in these activities included presenting the lab's research and highlighting it in Task 25 joint reports and providing guidance for the Task 25 recommended practices draft report. NREL researchers also provided leadership in the Energy Systems Integration Group by helping organize and contribute content to numerous industry-leading workshops on grid integration, market design, and forecasting. This work helps limit integration barriers and encourage adoption of cost-effective solutions by informing industry and stakeholders and leveraging NREL's research. Furthermore, NREL stakeholder engagement activities educate decision makers on operational and market impacts of wind energy.

Engaging industry experts, NREL helps coordinate discussions around grid integration of wind energy. *Photo by Werner Slocum, NREL*



Environmental Research

Wind Operational Issue Mitigation

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

Joining Forces To Minimize Wind Energy Impacts on Birds and Bats

NREL, as the coordinating organization for the Bats and Wind Energy Cooperative, released a set of priorities to inform future research on bats and wind energy. These priorities, which were developed at the cooperative's sixth Science and All Committees Meeting and captured in the workshop proceedings, include research to improve understanding of bat populations, bat behavior, and minimization strategies. These priorities are intended to help wind industry stakeholders identify key research activities for minimizing wind energy's impact on bats.

Migratory bat species, such as this red bat, are vulnerable to collisions with wind turbine blades. *Photo by Cris Hein, NREL*

Offshore Wind Synthesis of Environmental Effects Research

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

Recommendations for Environmental Research on U.S. Pacific Coast Offshore Wind Energy Development

Northern gannets are one of several seabird species that may be impacted by offshore wind energy development. New databases compiled by NREL and Pacific Northwest National Laboratory are designed to provide information that could help minimize potential impacts caused by offshore wind energy development. *Photo from iStock*

Researchers from NREL and Pacific Northwest National Laboratory published a report on recommendations for offshore wind energy and environmental preconstruction research on the U.S. Pacific Coast. Hundreds of participants from industry, state and federal agencies, and conservation organizations provided feedback during a 3-day workshop that focused on marine mammals and sea turtles, birds and bats, and fish and invertebrates. The team created an online web tool to display these recommendations to the public and increase their accessibility. They can also be accessed through additional published resources.

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

Joining Forces To Minimize Wind Energy Impacts on Birds and Bats

NREL, in partnership with the Renewable Energy Wildlife Institute and the Consensus Building Institute, hosted a workshop with technology innovators, wind industry operators, researchers, and government agencies to discuss strategies to protect birds and bats from wind energy technologies. Proceedings from the workshop highlight the need for greater engagement between technology innovators and wind turbine manufacturers to integrate mitigation technologies with wind turbines. Additional needs include streamlining funding mechanisms to increase accessibility and reduce the administrative burden of proposal development and project management and reviewing the regulatory framework to incentivize research and development of solutions for wind energy and wildlife interactions.

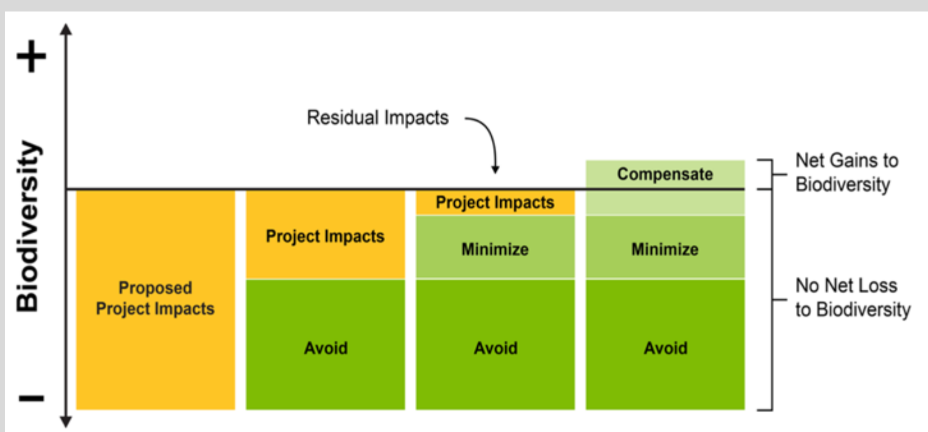
Identiflight reduces interactions between raptors and wind turbines by using cameras to curtail selective wind turbines when raptors approach. *Photo by Dennis Shroeder, NREL*

Working Together To Resolve Environmental Effects of Wind Energy

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

Understanding the Mitigation Hierarchy in the Context of Wind Energy

As the lead for IEA Wind Task 34 (Working Together To Resolve Environmental Effects of Wind Energy), NREL published an educational research brief on the mitigation hierarchy. The hierarchy is a framework to inform conservation decisions and includes three stages: 1) avoidance, 2) minimization, and 3) compensation. However, the lack of consensus regarding definitions across jurisdictions and organizations may cause confusion for project developers. Thus, it is important for stakeholders to agree on terminology and expectations throughout the project life cycle. This brief was also translated into Spanish to increase accessibility.

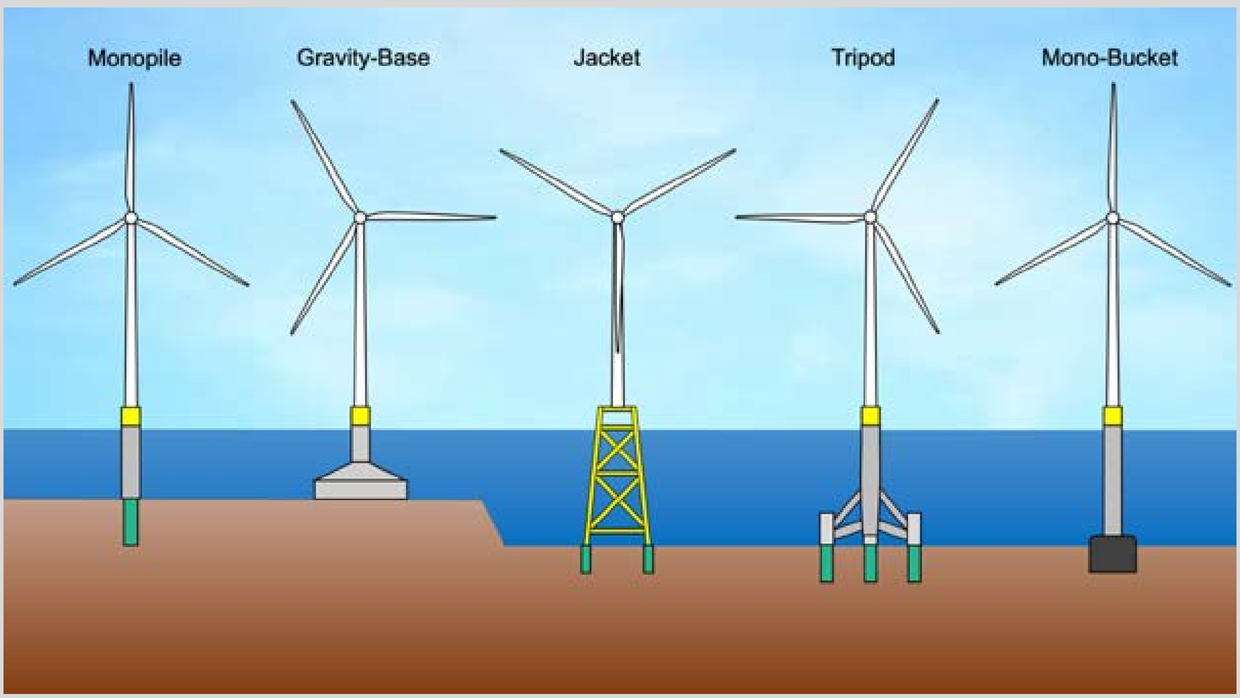


Visual representation of applying the mitigation hierarchy to reduce impacts of a project. *Graphic by Nicole Leon, NREL, adapted from Rio Tinto. 2008.* Rio Tinto and Biodiversity. *London, England: Rio Tinto. https://bobbloomfield.files.wordpress.com/2013/03/2008riotintobidoversitystrategy.pdf.*

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

Workshop Addresses Offshore Wind Energy Noise Reduction

In spring 2023, researchers from NREL and Pacific Northwest National Laboratory distributed an online questionnaire to gather feedback on research and development priorities regarding underwater noise associated with fixed-bottom offshore wind turbine installations in U.S. waters. The questionnaire was used to refine and enhance the results of the U.S. Offshore Wind Energy Noise Reduction Workshop, hosted by NREL and Pacific Northwest National Laboratory in December 2022. The research and development themes resulting from the initial workshop informed the six topics presented in the questionnaire: data access, standardization, and model consistency; research, development, and deployment of alternative foundation types, new monitoring strategies and technologies, and noise abatement and mitigation technologies (including alternative installation techniques); research to assess disturbance on marine species and habitats; and supply chain and infrastructure Improvements. A final report summarizes the 46 responses to the 12 questions and provides recommendations to WETO on research and development priorities regarding reducing the impact and increasing efficiencies of fixed-bottom offshore wind energy installations.



The initial workshop focused on comparing these various fixed-bottom foundation types, their installation methods, noise abatement strategies to their installation, monitoring, and the barriers to reducing noise. *Graphic by Stein Housner, NREL*

Siting Research and Development

WINDExchange Stakeholder Engagement and Outreach

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

Community Engagement Series Will Help Improve Wind Energy Equity

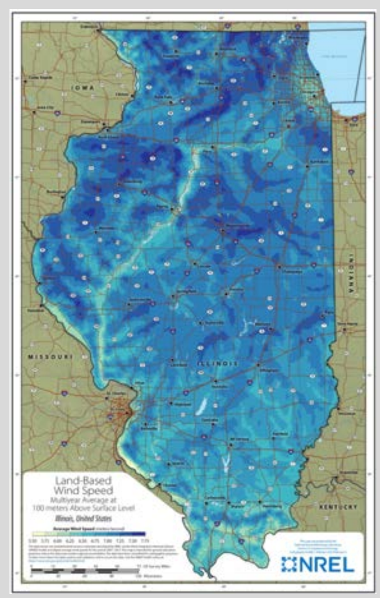
As wind energy development increases, community considerations and impacts are of growing importance so the country can ensure deployment is both equitable and meets community values. Through the Wind Energy Equity Engagement project, NREL researchers are gathering information from stakeholders and communities that host wind energy facilities to define and study the equity implications of large-scale, land-based, and offshore wind energy facilities. In 2022, the team designed and distributed a questionnaire to stakeholders who participated in DOE's WINDExchange initiative in addition to interviewing 13 subject-matter experts from academia, government agencies, and nonprofit organizations. NREL also hosted a workshop to bring together diverse stakeholders to discuss wind energy equity. The workshop lasted 2 days and included expert speakers and interactive discussions. Following the workshop, the team wrote a report, titled *Setting the Baseline: The Current Understanding of Equity in Land-Based Wind Energy Development and Operation*, highlighting what was learned up to this point in the project.

WINDExchange Webinar Series Addresses Stakeholder Needs

The NREL Stakeholder Engagement and Outreach team hosted three new webinars in the WETO WINDExchange initiative's Offshore Wind Basics webinar series focused on stakeholder concerns and impacts. The first webinar, "Navigating the Offshore Wind Energy Decision-Making Process," featured speakers from the Bureau of Ocean Energy Management, Rhode Island Sea Grant, and the Special Initiative for Offshore Wind. The second webinar, "Gearing Up for 2030: Building the Offshore Wind Supply Chain and Workforce Needed to Deploy 30 Gigawatts and Beyond," featured NREL's offshore wind energy supply chain expert, Matt Shields, and wind energy workforce expert, Jeremy Stefek. In the third webinar, "Offshore Wind Energy and Communities: Perspectives on Local Impacts," an expert panel discussed the various ways offshore wind energy projects can impact the coastal communities near where they are sited. With thousands of viewers watching the recordings, this webinar series increases awareness of offshore wind energy basics as the industry grows in the United States. All webinars were recorded and made accessible to the public.

All 50 States and Puerto Rico Included in WINDExchange 100-M Wind Resource Map Collection

NREL produced maps showing land-based and offshore wind resources at 100 m above the ground for all 50 states and Puerto Rico. These maps provide wind energy developers and community leaders with tools to help assess and characterize a region's available wind resources, which will support the development, siting, and operation of wind energy projects in the United States. Wind resource maps and other information are publicly available through the WINDExchange platform along with a guide to help navigate the more than 300 wind resource maps available.



Updated wind maps, such as this one for the state of Illinois, provide state and local leaders understanding of their local wind energy development potential. *Image by NREL*

End of Service Community and Stakeholder Engagement

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

Discussions Shed Light on Community Intersections With End-of-Service Activities

Following the publication of the Wind Energy End-of-Service Guide on WETO's public-facing WINDExchange initiative website to help communities and local decision makers better understand repowering or decommissioning processes for wind turbines, NREL hosted a series of 10 roundtable discussions with diverse stakeholders to discuss community intersections with end-of-service activities. These roundtable discussions sought to understand the community impacts of wind energy end-of-service activities, like decommissioning bonds, component removal and future land use, and blade processing. These findings will be reflected in updates to the online and downloadable guide and inform the next phase of community listening sessions.

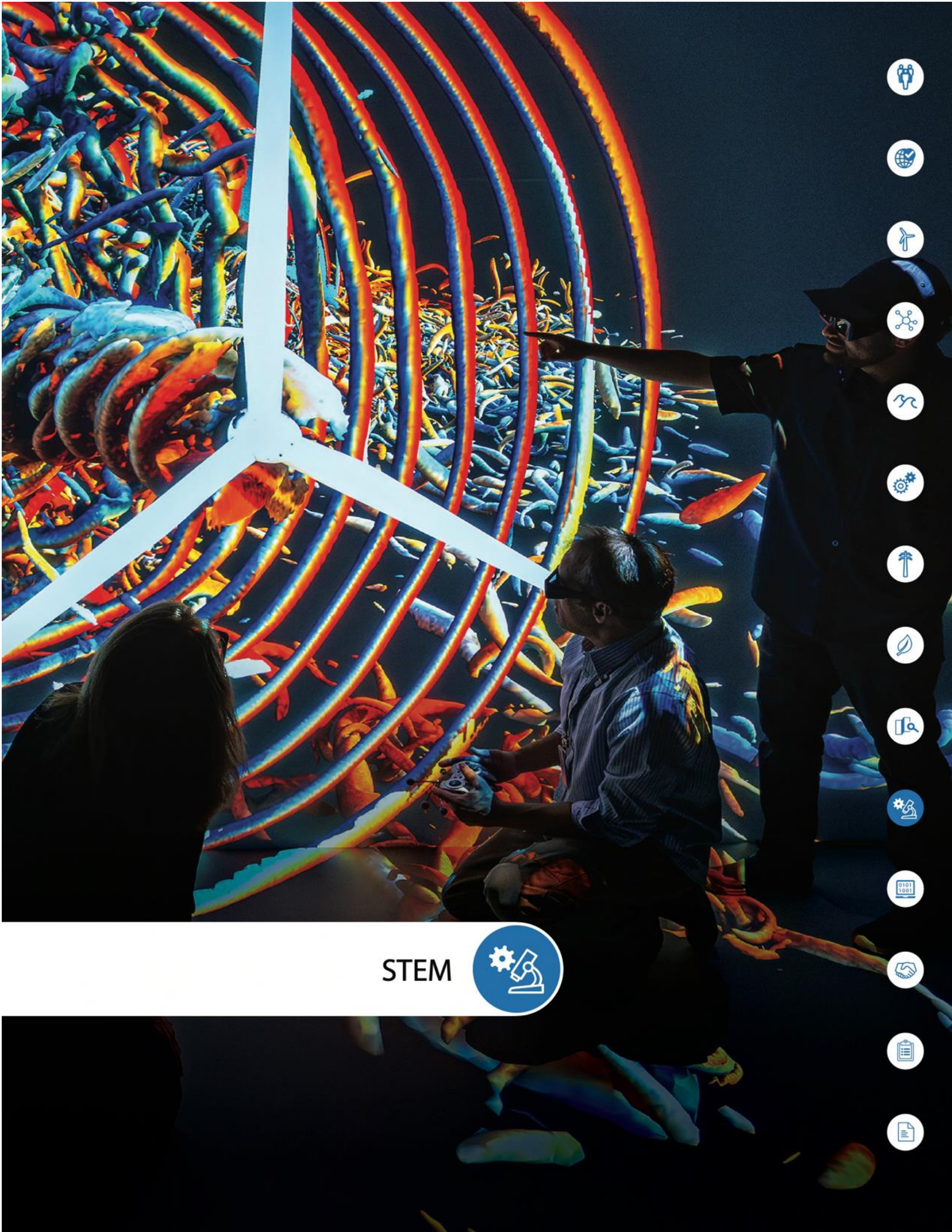
Economic Development/Community Benefits

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

Research Informs Stakeholder Resources on Wind Energy Community Benefit Agreements

As the U.S. wind energy industry rapidly expands, so does the number of communities weighing the pros and cons of this development. Community benefit agreements are one way in which communities and developers, in some cases with input from state or federal government entities, can expand opportunities for local investment and address negative impacts. Yet, NREL's research has found that the process of discussing the community benefits of wind energy can be unclear, time-consuming, and resource-intensive. In FY 2023, NREL researchers from the Stakeholder Engagement and Outreach team conducted foundational research about this topic, which will be published in FY 2024. This information will cover considerations for community benefits in land-based and offshore wind energy development, including a sample of agreements.

New research by NREL informed the development of stakeholder resources on the use of community benefits agreements in land-based and offshore wind energy development. *Photo by Dennis Schroeder, NREL*



STEM

Collegiate Wind Competition

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

Annual Collegiate Wind Competition Continues To Inspire Future Workforce

DOE's 2023 Collegiate Wind Competition final event took place at the Balch Fieldhouse on the University of Colorado Boulder campus in Boulder, Colorado, in May 2023. *Photo by Taylor Mankle, NREL*

The DOE Collegiate Wind Competition, which is managed by NREL on behalf of DOE and held its 10th annual final event in FY 2023, aims to inspire and prepare the next generation of engineers, scientists, and business leaders to contribute to the growing field of wind energy. Over 150 students participate in the competition each year, collaborating across disciplines and gaining valuable hands-on experience with wind energy technology, project development, and outreach. Since the competition's 2014 launch, over 40 U.S. colleges and universities have participated in the event, hundreds of companies have partnered with the competition to provide mentorship and support, and over a hundred competition alumni have landed jobs in the renewable energy sector.

Wind Energy Workforce

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

National Wind Workforce Assessment To Help United States Meet Wind Energy Targets

Researchers at NREL have been working to survey wind energy industry stakeholders to better understand what is needed to grow the U.S. wind energy workforce and bridge the wind energy workforce gap. In FY 2023, NREL conducted a new round of surveys across employees, job seekers, students, and educators to gain additional insight into the key factors influencing the development of the expanding wind energy workforce. The research team developed a new systems dynamics approach to model industry workforce needs and showed how different elements can affect workforce projections. The expanded survey effort and model, whose methodology and key findings will be published early FY 2024, will:

- Empower an updated national assessment of the wind energy workforce by supplying new wind energy workforce forecasts based on new deployment targets
- More realistically display the effects of actions taken to mitigate the wind energy industry's workforce gap
- Provide industry and educators with information to develop the workforce to meet U.S. wind energy deployment goals.

Seed Grant Program To Improve Wind Energy Education

NREL created a pilot Academic Seed Grant program to help universities and community colleges across the nation provide more wind- and renewable-energy-specific academic programming. The program was designed to support the need for a greatly expanded U.S. land-based and offshore wind energy industry workforce. Minority-serving educational institutions and institutions that had not previously worked with NREL were especially encouraged to apply for up to $6,000 in seed funding. The Academic Seed Grant program was conducted by NREL in partnership with REpowering Schools. By the end of the pilot, all available grants were awarded to universities across 11 different states and including four minority-serving institutions and/or historically Black colleges and universities.

NREL's pilot Academic Seed Grant Program helped U.S. universities and community colleges provide more wind- and renewable-energy-specific academic programming to meet the need for a future wind energy workforce. *Photo by Werner Slocum, NREL*

Events Support Wind Energy Workforce Development

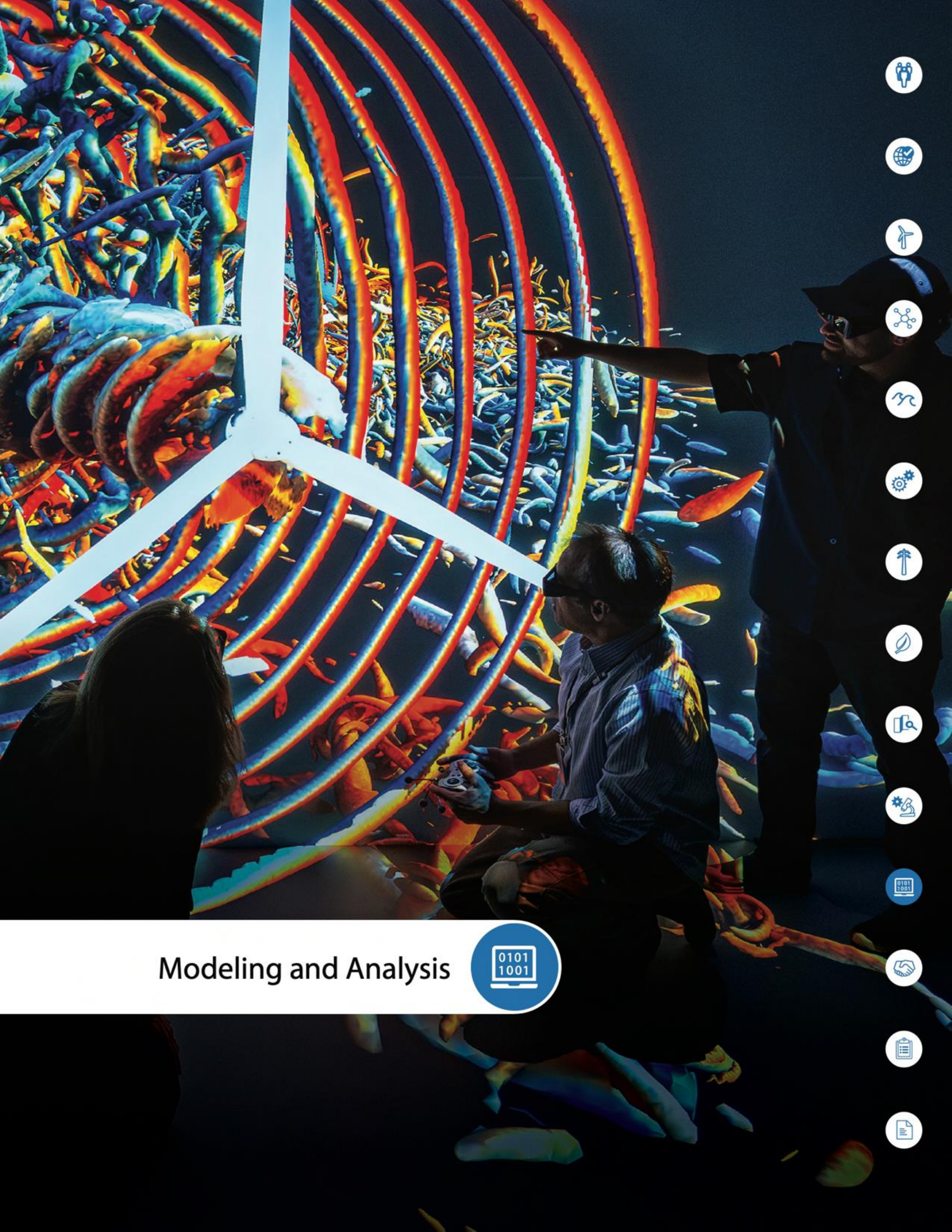
In the first half of FY 2023, NREL supported several events designed to encourage wind energy industry workforce development. For the third year, NREL organized the U.S. Offshore Wind Workforce Summit, in conjunction with the Business Network for Offshore Wind's 2023 International Partnering Forum in March 2023, to foster partnership, collaboration, and the formation of new programs to address offshore wind energy industry workforce needs. More than 250 participants representing stakeholder groups across workforce development discussed ways to connect stakeholders that do not currently interact. In addition, NREL hosted International Partnering Forum roundtable discussions about K–12 education on wind energy and state collaboration on workforce development. NREL also helped REpowering Schools host a student symposium at the Distributed Wind Energy Association's Distributed Wind 2023 conference, providing an opportunity for students researching small wind turbines to connect directly with members of the industry.

NREL's National Offshore Wind Workforce Network Dives Deep To Tackle Priority Challenges

In FY 2023, NREL's National Offshore Wind Workforce Network produced resources tackling some of the priority topics considered by the network's stakeholders. These topics included:

- Workplace safety standards
- Best practices for workforce development as discussed at the annual International Partnering Forum's Offshore Wind Workforce Summit hosted by NREL and the Business Network for Offshore Wind
- Offshore wind energy manufacturing needs.

Established in 2022, the network comprises more than 150 diverse stakeholders who collaborate and coordinate closely on workforce issues in the U.S. offshore wind energy industry. These collaborations, and the resulting resources they yield, offer insights to drive safety, workforce development, and manufacturing excellence in the industry.



Modeling and Analysis

Wind Analysis for Priority Needs

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

NREL Provides Analysis Support for Clean Energy Policy Decisions

The nation's current focus on offshore wind energy, coupled with the passage of the Inflation Reduction Act into law in 2022, generated an array of critical questions from decision makers. These questions are heavily focused on policy implementation and understanding the structure and make-up of the industry. An NREL analysis team provided quick-turnaround responses on an array of fronts to support these impactful decisions. The team:

- Reviewed and compiled component and electrical equipment cost data to help inform estimates and analysis of the value of equipment coming from U.S. sources
- Examined and synthesized the literature on local and regional content policies to inform strategy around offshore wind content and economic development questions
- Evaluated vessel demand and inventories to help inform potential investments in the offshore wind vessel fleet analysis
- Evaluated the potential impacts of inflation on contracted project viabilities.

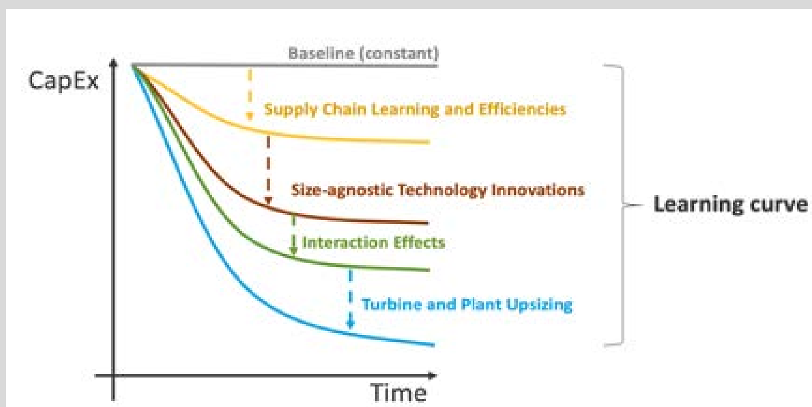
Overall, this work provided timely expert insight and perspective to inform clean energy policy decision making at local, state, and federal levels.

Wind Power Plant Technology Characterization

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

New NREL Model Estimates Future Offshore Wind Energy Costs

Understanding the future costs of offshore wind energy projects can help developers make informed decisions. However, predicting the future is notoriously challenging and full of uncertainty. NREL researchers have developed the Forecasting Offshore Wind Reductions in Cost of Energy model to forecast the cost of offshore wind energy for a given year with ranges based on historical trends, technology assumptions, site conditions, and future deployment levels. The model estimates the average levelized cost of offshore wind energy could decrease from $75/megawatt-hour (MWh) in 2021 to $53/MWh in 2035 for fixed-bottom offshore wind energy and from $207/MWh to $64/MWh in 2035 for floating offshore wind energy. The team's NREL report provides further details.

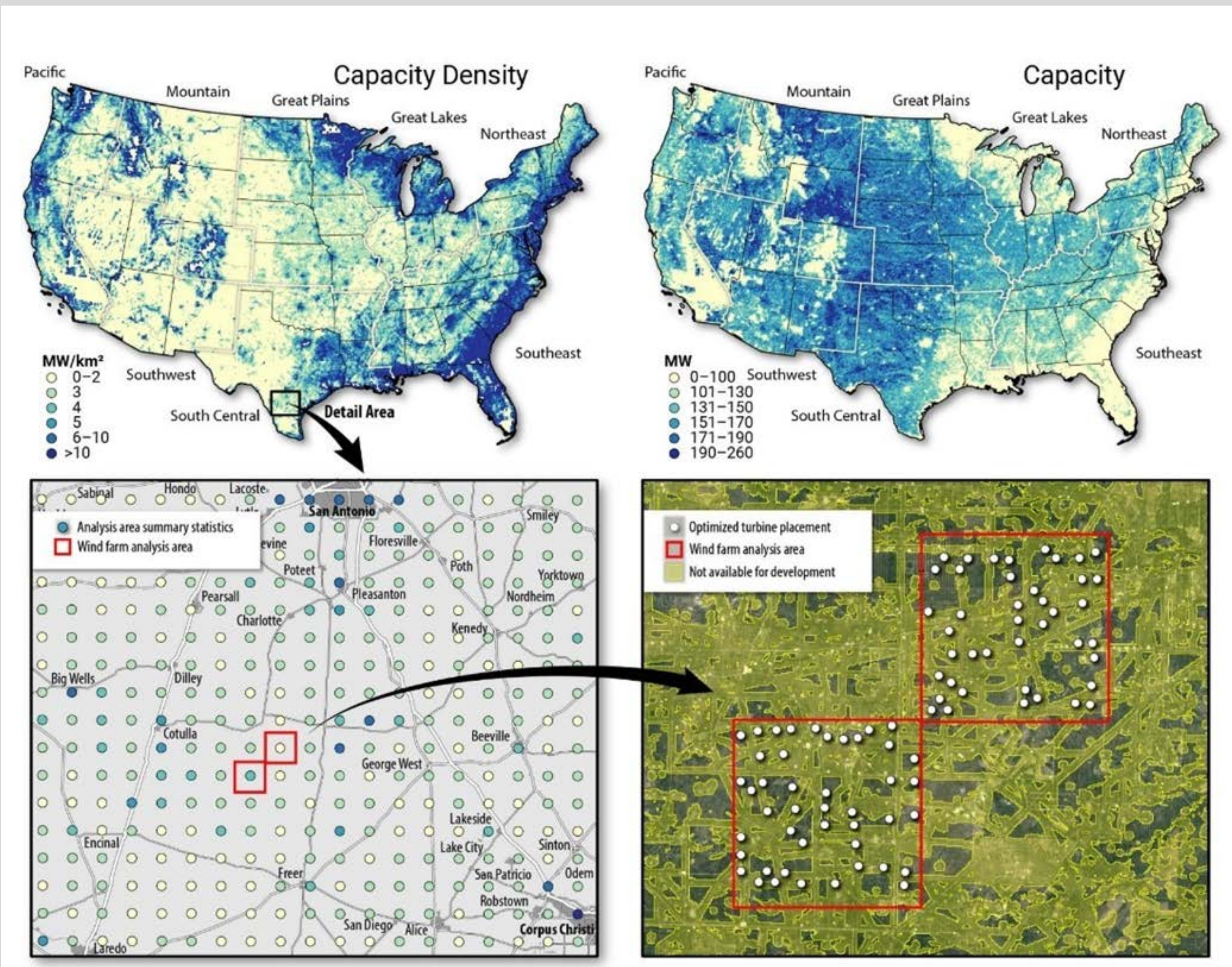


The Forecasting Offshore Wind Reductions in Cost of Energy model calculates a learning curve based on historical wind energy cost data on global installed offshore wind energy projects and future anticipated deployment. The monetary investment required for wind energy project development, or the capital expenditure (CapEx), decreases at faster and faster rates from a flat baseline because of effects such as supply chain and learning efficiencies. These effects are captured by the FORCE model, ultimately determining the shape of the learning curve and the forecasted cost of offshore wind energy. *Graphic by NREL*

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

U.S. Wind Potential Assessment Optimizes Turbine Placement Using Details at Scale

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

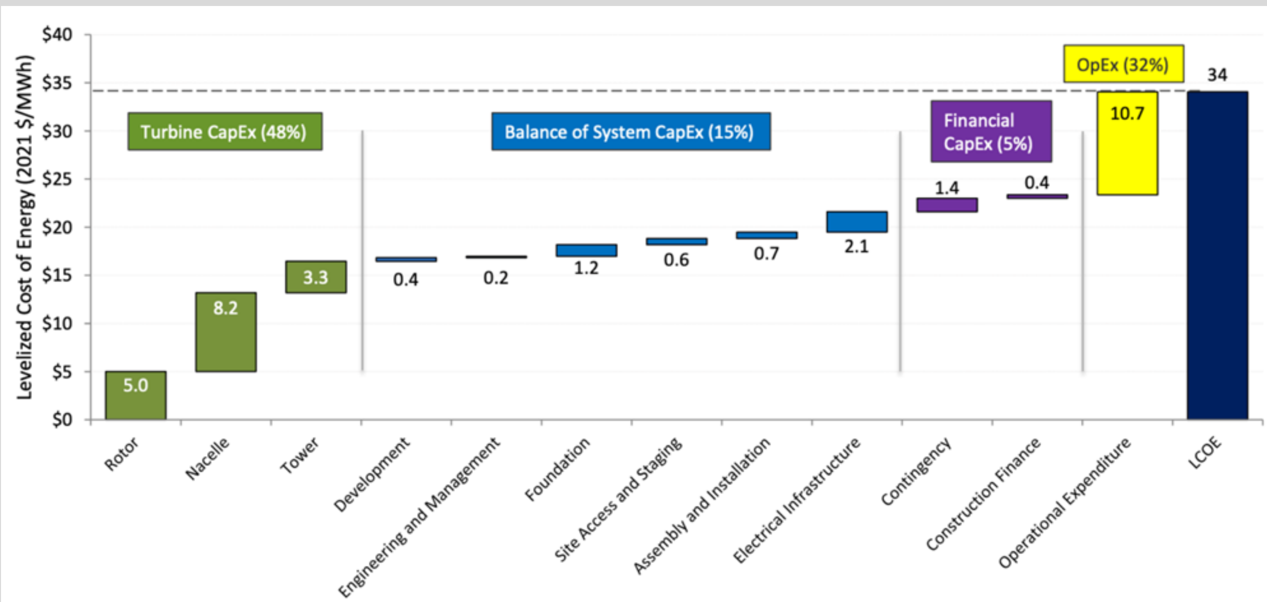


National wind capacity and capacity density results demonstrating the detail at scale. Each dot on the map represents a wind energy site and its resulting capacity density (upper-left map) and capacity (upper-right map) for one siting scenario and a 2018 market average turbine. The bottom-left map shows the density of wind sites for a detailed area, whereas the bottom-right map shows yet more detail and the optimized wind turbine locations. *Graphics by Billy J. Roberts, NREL*

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

Researchers Publish Estimates on the Cost of Wind Energy

NREL researchers published the *2021 Cost of Wind Energy Review*. The 11th edition of this annual report estimates levelized cost of energy for representative land-based and offshore wind power plants as well as residential- and commercial-scale distributed wind energy projects in the United States. Levelized cost of energy estimates are based on U.S. commissioned power plant and wind resource data from 2021 and calculated with the aid of state-of-the-art modeling capabilities and data accumulated from throughout the global wind energy industry. The results of this report provide cost data to DOE to meet the annual reporting requirements set by the Government Performance and Results Act and offer component-level costs that aid researchers, developers, investors, and utilities.



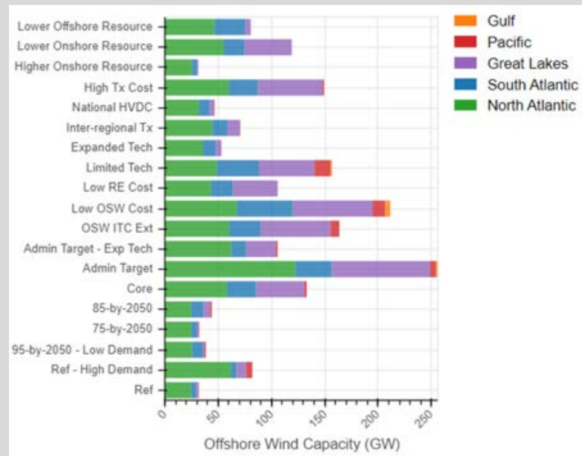
A snapshot of the component-level cost breakdown for the land-based wind energy reference project using U.S. commissioned power plant and wind resource information in 2021 with the support of state-of-the-art cost models. *Graphic by NREL*

Energy Sector Modeling and Impacts Analysis

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

Expanded Modeling Scenarios Show Importance of Offshore Wind Energy in U.S. Decarbonization

The declining costs of offshore wind energy technologies, growing ambition of state offshore policies, and expectations for the first large-scale commercial projects to be installed off the Atlantic Coast suggest that offshore wind energy can emerge as a major source of electricity for the United States. In FY 2023, an NREL team of researchers examined the potential role of offshore wind energy in the U.S. electric system through 2050 by considering a broad array of scenarios that cover uncertainties in future policies, electricity demand growth, technology costs, transmission expansion constraints, and land use and other siting considerations. They found that offshore wind energy deployment is sensitive to many of these drivers, some of which are rarely examined. But in the most optimistic cases, offshore wind energy can contribute up to 8% of total U.S. electricity supply and more than 20% in New York and New England to support decarbonization of the U.S. electricity and energy sectors. This work demonstrates the need for the United States to examine an expanded set of future scenarios than traditionally evaluated, especially for newer technologies that might influence deployment.



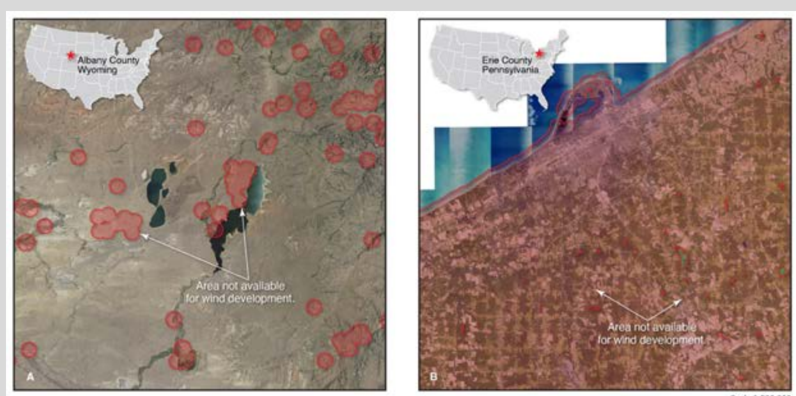
These results show 2050 offshore wind deployment by region projected using NREL's Regional Energy Deployment System model, demonstrating the sensitivity of future U.S. offshore wind to a wide range of drivers. *Graphic by Matt Mowers, NREL*

Advancing the Supply Curve

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

The Impact and Increase of Renewable Energy Deployment Ordinances

Local ordinances governing renewable energy deployment are on the rise as the wind and solar energy industries mature. In addition to helping ensure sustainable and responsible development of renewable energy, these ordinances can also help determine how much land is available for renewable energy deployment. In a FY 2023 *Nature Energy* article, NREL examined and studied the types of ordinances in effect and how they could change the amount of available land over time.



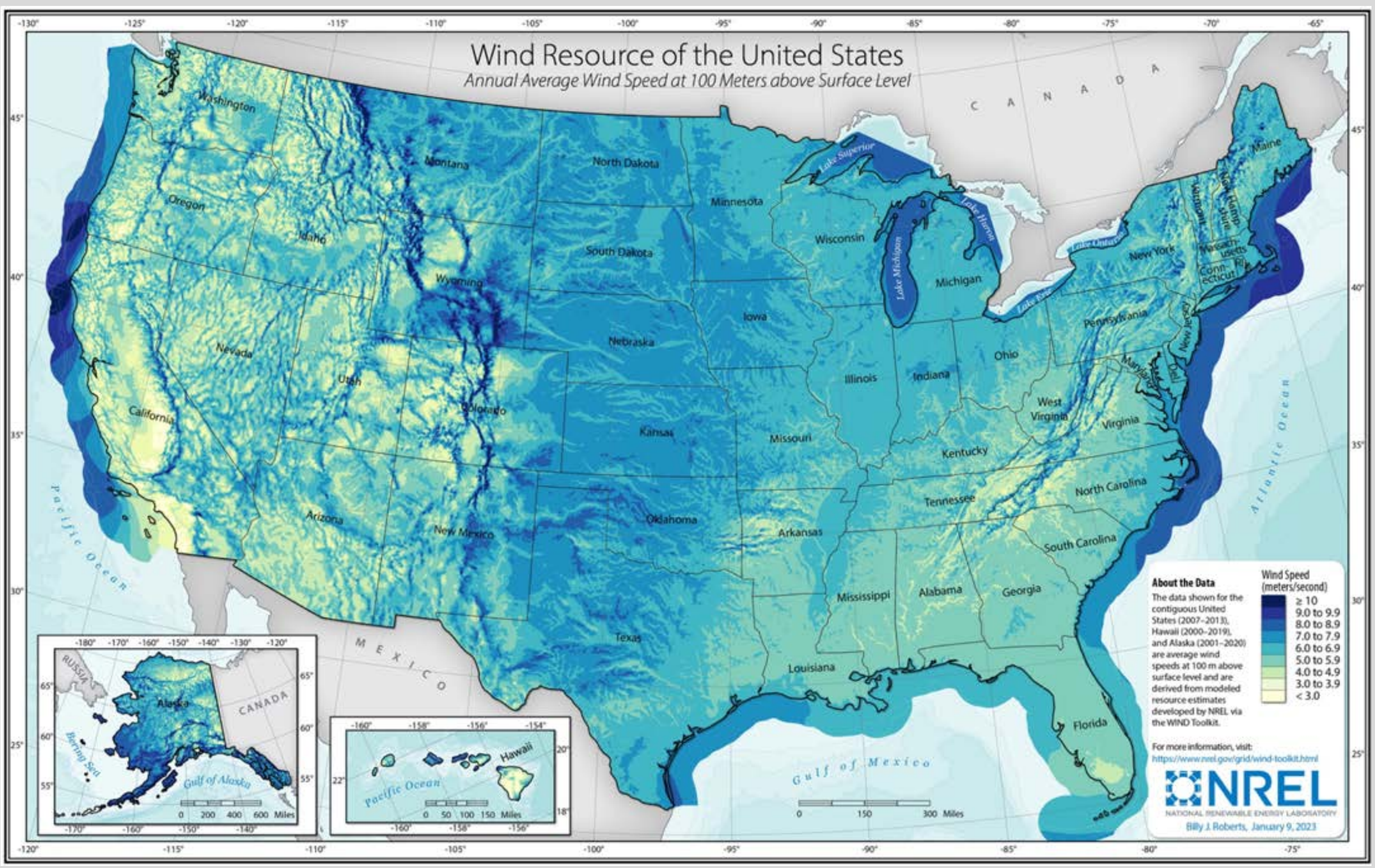
Example structure setbacks for Albany County, Wyoming (left), and Erie County, Pennsylvania (right), using a 5.5-times-tip-height setback for Albany County and a 5-times setback for Erie County. Counties with high structure densities and large setbacks can become nearly fully excluded from development, while those that are sparse in structures could have ample space available even with large setback distances. *Imagery from U.S. Department of Agriculture's National Agricultural Imagery Program; modified by Billy J. Roberts, NREL*

National Wind Resource Data

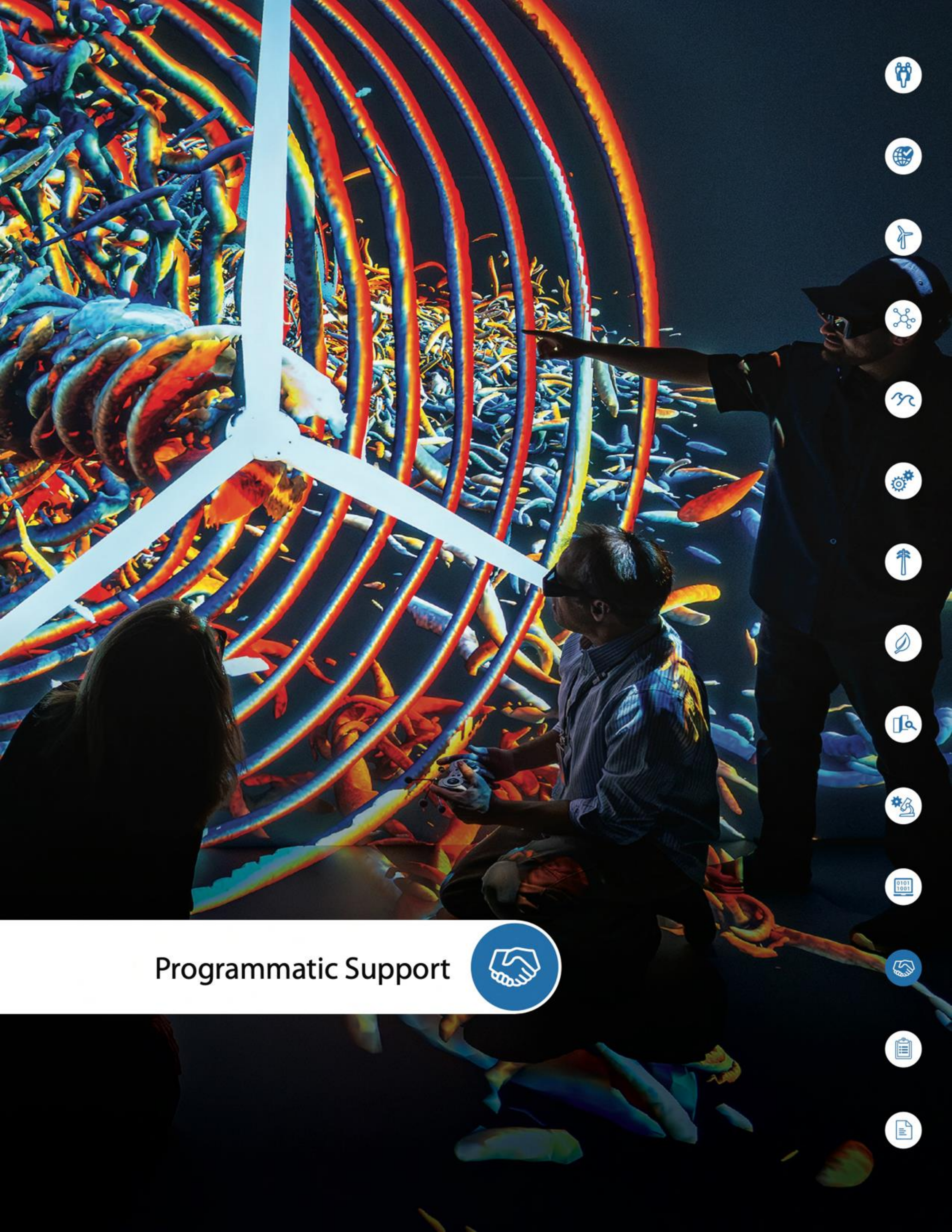
Point of Contact: Caroline Draxl, Caroline.Draxl@nrel.gov

Public-Facing Web Platform To Provide Wind Resource Insights

Knowing where wind resources can be found is key to identifying a good wind energy site. As a result, NREL is developing a public-facing web platform that will allow researchers, community decision makers, and members of the wind energy industry to explore, visualize, and download NREL's wind resource data sets. During the second half of FY 2023, the team improved automation around new data integrations, which will reduce costs associated with adding new data. A primary component to building and making the new web-based platform available to the public is the integration with preexisting backend services, notably the large-scale download service, which is the mechanism in which the large volumes of data are provided to all audiences. Once complete, this platform will enable multiple teams in different locations and with diverse areas of expertise to collaboratively continue wind data development activities while efficiently delivering that data to multiple audiences.



Wind resource estimates have historically been portrayed in maps, like this one. The new platform will enable large scale download capabilities of time series data over large areas. *Graphic by NREL*



Programmatic Support

NREL Technology Management and Support

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

Effective Programmatic Support Enhances Wind Energy Research Impact

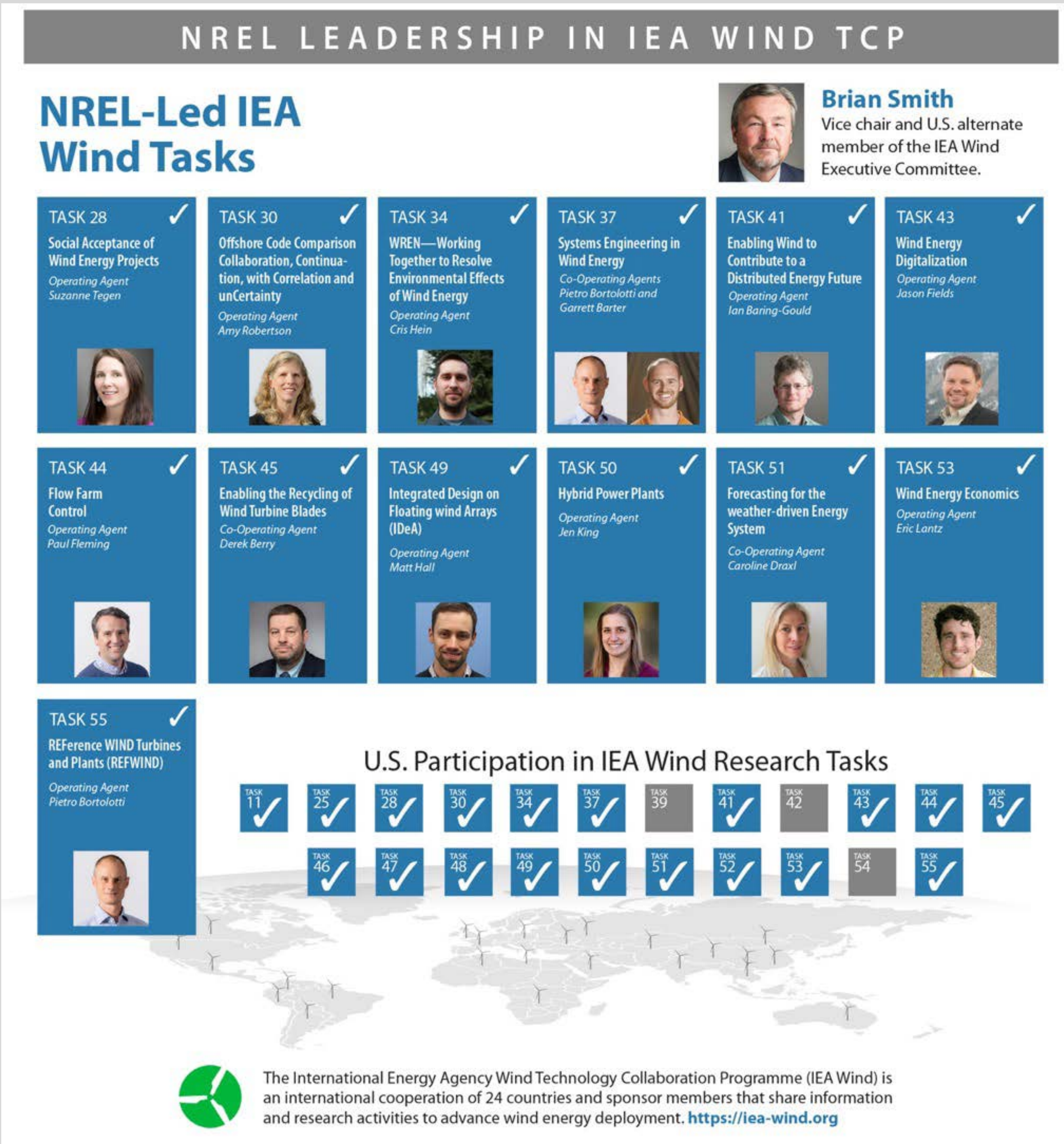
NREL's wind energy program actively manages a diverse project portfolio that advances technologies for offshore, land-based, and distributed wind energy, as well as wind energy's integration with the electric grid. NREL supports WETO's main objectives of achieving aggressive cost reductions, addressing environmental and siting challenges, providing grid services, ensuring cybersecurity, and advancing hybrid systems. To meet the significant acceleration and scale-up of wind energy deployment needed to achieve carbon-emissions-free electricity by 2035 and net-zero greenhouse gas emissions by 2050, NREL wind energy research includes workforce development and education, social science and acceptance, analysis and modeling, and energy equity and environmental justice. Achievements include:

Attendees of the IEA Wind Topical Expert Meeting, Grand Challenges in the Science and of Wind Energy, at the University of Colorado Boulder. *Photo by Werner Slocum, NREL*

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

NREL's International Wind Collaborations Leadership Grows

With the addition of IEA Wind Task 55, NREL experts led or co-led 13 international, collaborative IEA Wind research tasks in FY 2023. NREL Wind Energy Laboratory Program Manager Brian Smith served as vice chair and U.S. alternate member of the IEA Wind Executive Committee, 13 NREL researchers led these individual tasks as operating agents, and NREL communications staff wrote the U.S. chapter of the 2022 IEA Wind annual report. By participating in 19 of the 22 IEA Wind research tasks, DOE and NREL strengthened the nation's presence and influence among member countries, the European Commission, the Chinese Wind Energy Association, and WindEurope.



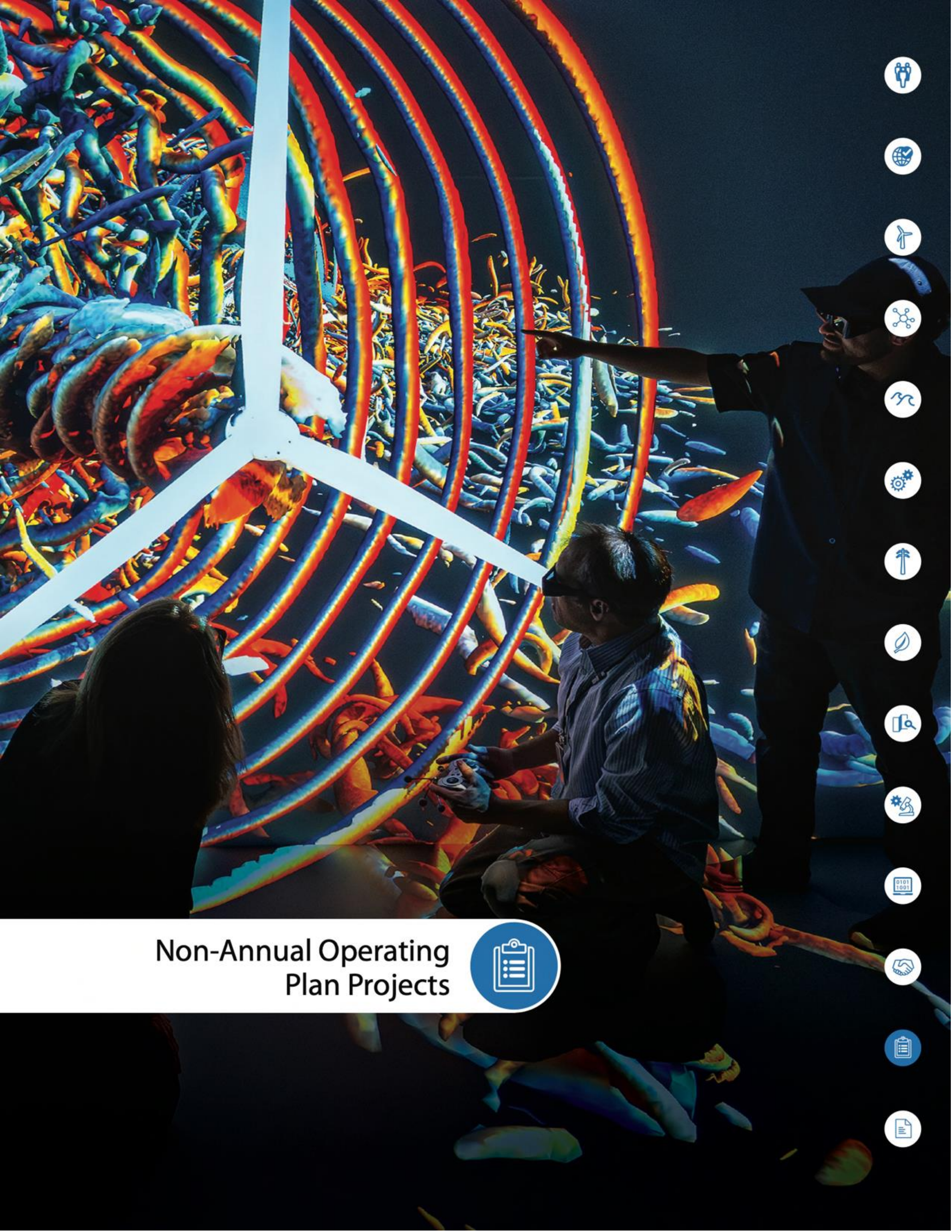
This graphic details NREL's FY 2023 participation in IEA Wind tasks. *Graphic by John Frenzl, NREL*

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

Wind Turbine-Radar Interference, Sustainability, and Distributed Wind Animation

In FY 2023, the NREL wind energy program's communications team collaborated with the WETO communications team to launch two new research pages: Mitigating Wind Turbine Radar Interference and Wind Turbine Sustainability to highlight research areas in wind energy. Additionally, a new animation allows communities and businesses to imagine how distributed wind can be incorporated into their renewable energy portfolios.

A new distributed wind energy animation developed by NREL's wind energy communications team provides users with an interactive way to learn about disturbed wind energy. *Screenshot from WETO's Distributed Wind webpage*



Non-Annual Operating Plan Projects

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

ATLANTIS Projects Improve Floating Offshore Wind Energy Technology Designs

NREL researchers have successfully completed three projects aimed at advancing innovative floating offshore wind turbine technology designs by embedding control systems as an integral aspect of the design methodology. These projects were funded under the DOE Advanced Research Projects Agency-Energy (ARPA-E) awards as part of the Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control (ATLANTIS) program. Notably, two of these projects are set to transition into Phase II, during which their designs and methodologies will undergo rigorous testing through open-ocean demonstration initiatives.

Led by Daniel Zalkind, the Wind Energy with Integrated Servo-control (WEIS) project team produced an open-source toolkit capable of seamlessly integrating control features within a system-level design framework. This breakthrough empowers engineers specializing in floating offshore wind energy systems to craft entirely novel systems at significantly reduced costs. Collaborating with the University of Illinois Urbana-Champaign, NREL is primed to expand the tool set's capabilities during Phase II, introducing new capabilities and a better user experience to yield substantial cost savings for offshore wind energy technology design.

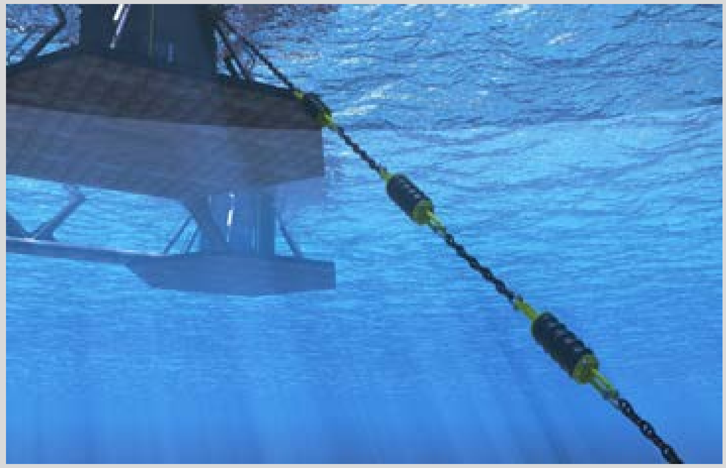
The Floating Offshore-wind and Controls Advanced Laboratory (FOCAL) project team led by Amy Robertson created a groundbreaking data set for scale-model floating offshore wind turbines that is publicly accessible on the Atmosphere to electrons website. Distinguished by its incorporation of advanced wind turbine and hull controls, coupled with hull flexibility, this data set enables the comprehensive evaluation of design trade-offs to identify optimal strategies for achieving maximum cost-effectiveness in floating offshore wind energy technology design. NREL collaborated closely with the University of Maine and DNV GL on this project.

Senu Sirnivas led the Ultraflexible Smart FLoating Offshore Wind Turbine (USFLOWT) project team to advance a floating offshore wind energy platform design, SpiderFLOAT, by simplifying the construction and maintenance logistics for deep-water deployment. USFLOWT Phase I involved a partnership between NREL, the Colorado School of Mines, University of Colorado Boulder, University of Virginia, and American Bureau of Shipping. In Phase II, a scaled version of the USFLOWT design will be tested in a wave basin under a controlled environment with control algorithms serving as a tangible proof of concept. This concept will be followed with a subscale design in open waters to further de-risk the technology.

Demonstration of Shallow-Water Mooring Components

Point of Contact: Ericka Lozon, Ericka.Lozon@nrel.gov

Polymer Springs Improve Shallow-Water Mooring System Performance



Shallow-water mooring system with polymer springs attached near the platform. *Graphic from TFI Marine*

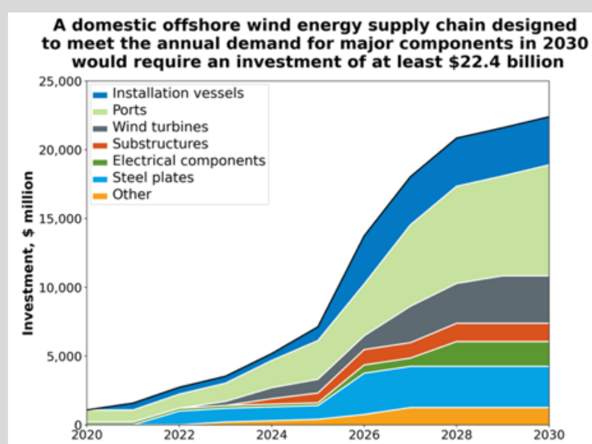
Shallow-water mooring systems for floating offshore wind turbines are subject to large tension fluctuations and snap loads, which increase the required size of mooring components and their cost. The ShallowFloat project is evaluating polymer springs with nonlinear tension-strain response curves as a potential method to mitigate against peak loads on shallow-water mooring systems. To accomplish this, an NREL team has improved MoorDyn, the mooring dynamics module, to allow accurate modeling of these polymer spring components. Using MoorDyn and working with partners Principle Power and TFI Marine, NREL researchers designed and analyzed mooring systems with polymer springs to evaluate the benefits and drawbacks of these components. Through this work, researchers found that mooring systems with polymer springs can reduce extreme tensions up to 60% and improve fatigue life, thus lowering the required chain diameter by 20% compared to a traditional catenary-chain system. These results show clear benefits in reducing line diameter, anchor radius, and anchor loads when using polymer springs in shallow-water mooring systems, which will lower cost and allow more flexibility in siting floating wind turbines.

Offshore Wind Supply Chain

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

U.S. Offshore Wind Supply Chain Road Map Identifies Challenges and Solutions to Meeting National Goals

The United States has an ambitious goal of installing 30 GW of offshore wind energy by 2030 and developing a domestic supply chain to support this target. Achieving this goal will require a significant increase in domestic manufacturing, ports, vessels, and workforce. Supported by the National Offshore Wind Research and Development Consortium, NREL led a study to develop a road map that identifies challenges and solutions to developing a nationally focused offshore wind energy supply chain. *A Supply Chain Road Map for Offshore Wind Energy in the United States* estimates the potential impacts of a domestic supply chain on deployment, cost, workforce, and energy justice. The report suggests short-, medium-, and long-term actions to overcome barriers to development and create a resilient, equitable, and comprehensive offshore wind energy supply chain.



Cumulative investment over time in the major components of a domestic offshore wind energy supply chain. *Graph by Matt Shields, NREL*

Northern California and Southern Oregon Mission Compatibility and Transmission Infrastructure Assessment

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

Unlocking Transmission Pathways for Offshore Wind on the West Coast

NREL assessed the costs and benefits of 10 alternative configurations of subsea and overland transmission lines for delivering electricity from West Coast offshore wind power plants to the California and Oregon electric grid. The California–Oregon border region has outstanding offshore wind resources but relatively little capacity to export power to major population centers. Developing new transmission will bring competing objectives of minimizing cost, maximizing power delivery, maintaining system reliability, and providing equitable access to clean energy for local communities. As part of a partnership led by the Schatz Energy Research Center at California Polytechnic State University Humboldt, NREL's analysis provides information that will help transmission planners identify the best options for delivering offshore wind energy to the U.S. Pacific Coast.

Cost, efficiency, reliability, and equity are important considerations for future transmission infrastructure to deliver power from offshore wind plants along the coasts of California and Oregon, like these transmission lines in southern California. *Photo by Dennis Schroeder, NREL*

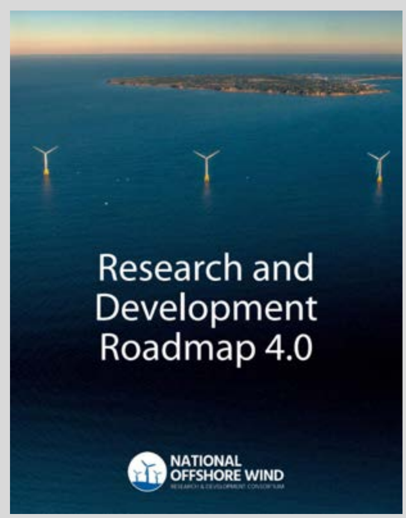
Technical Advisor of the National Offshore Wind Research and Development Consortium

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

Five Years in, NREL Advisors Continue To Help Set Offshore Wind Energy Research Agenda

In FY 2023, NREL assisted the New York State Energy Research and Development Authority in its winning bid to run the National Offshore Wind Research and Development Consortium (NOWRDC). Led by Walter Musial, a technical team of offshore wind experts from NREL have supported NOWRDC since the nonprofit's establishment in 2018. In the past 5 years, NREL has helped NOWRDC award 52 research contracts with the goal of advancing offshore wind technology in the United States through high-impact research projects that enable cost-effective, responsible development and maximize economic benefits. In April 2023, NREL led the effort to update and publish NOWRDC's Research and Development Roadmap 4.0, which provides overarching guidance for U.S. offshore wind energy technology advancement thorough the following key pillars:

- Offshore Wind Farm Technology Advancement
- Offshore Wind Power Resource and Physical Site Characterization
- Installation, Operations and Maintenance, and Supply Chain.



In April 2023, NOWRDC published their Research and Development Roadmap 4.0. NREL experts helped develop the document, which outlines U.S. offshore wind energy technology advancement needs. *Cover image from NOWRDC*

The Laboratory Directed Research and Development Program at NREL

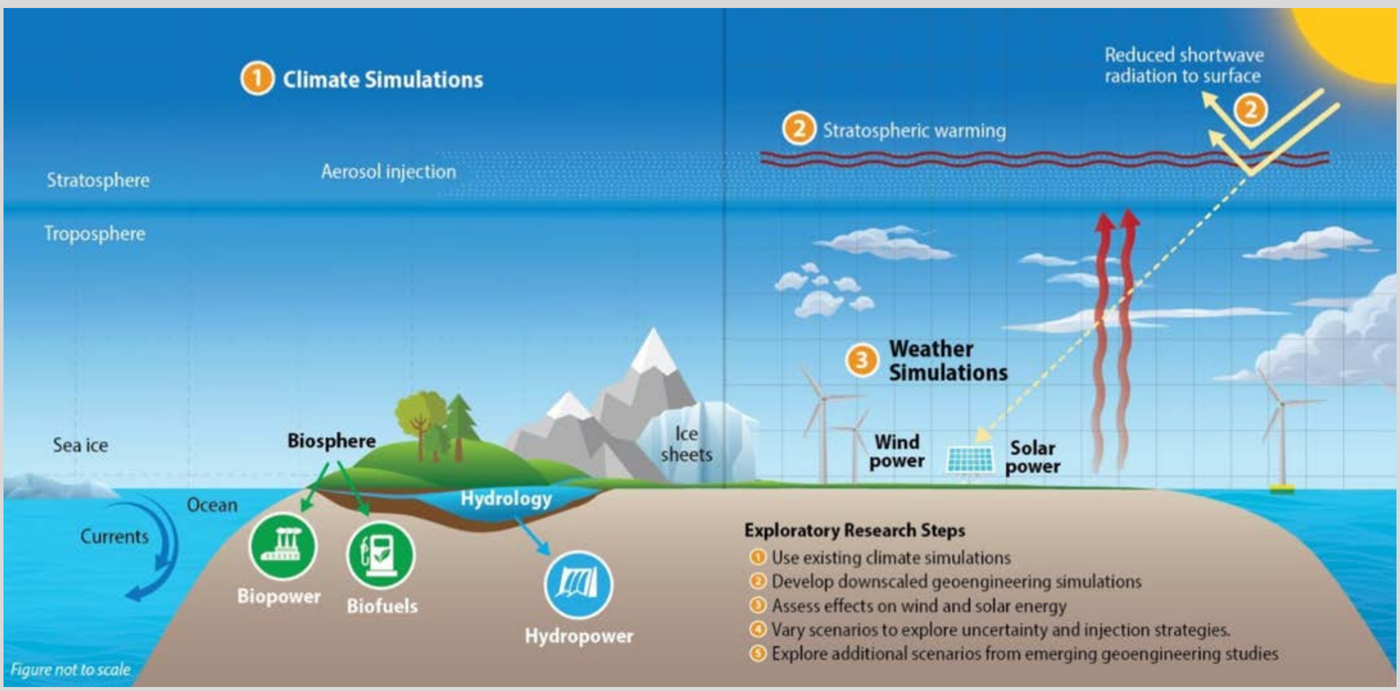
Each year, NREL is a proud contributor of innovations built through DOE's Laboratory Directed Research and Development (LDRD) program. Read about three of the innovative LDRD projects at NREL that aim to shape the future of wind energy and wind energy deployment.

Wind and Solar Geoengineering

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

Geoengineering Project Leverages Cutting-Edge Climate Science

Geoengineering refers to a set of emerging technologies that could change the environment to partially offset some of the impacts of climate change. NREL's Effects of Solar Geoengineering on Renewable Energy LDRD project aims to develop analytic techniques that simulate geoengineering effects on the climate system to estimate the associated impacts on wind and solar energy resources. Project results will help wind energy investors and planners better understand climate and geoengineering risks. To support the project's goals, the NREL research team formed a technical review committee comprising leading climate scientists who are analyzing geoengineering.



Using existing climate and weather simulations, the Effects of Solar Geoengineering on Renewable Energy research team will assess the impacts of solar geoengineering on wind and solar energy and connect with the community to discuss whether to use geoengineering approaches. *Graphic by Joelynn Schroeder, NREL*

Autonomous Urbanization for Mobility and Communities

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

Demonstration Shows Renewable Energy Technologies Could Replace Building Energy Storage

NREL researchers working on this LDRD project demonstrated that scalable, coordinated control of different renewable energy technologies could replace batteries and other energy storage technologies in buildings. Using a distributed approach to manage the power consumption and generation of each asset on the electricity grid, researchers simulated integrated electric-vehicle-charging infrastructure and distributed renewables at the community scale—including more than 100 buildings, ranging from multifamily homes to commercial buildings. Results indicated that coordinated control across multiple technologies not only yields significant flexibility by shifting when electricity is used but can also be used instead of relying solely on investments in large batteries or other storage technologies. The project is designed to develop large-scale control strategies that can operate across multiple technologies to accelerate the integration of renewables.

Optimal Design of Energy Cluster Offshore

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

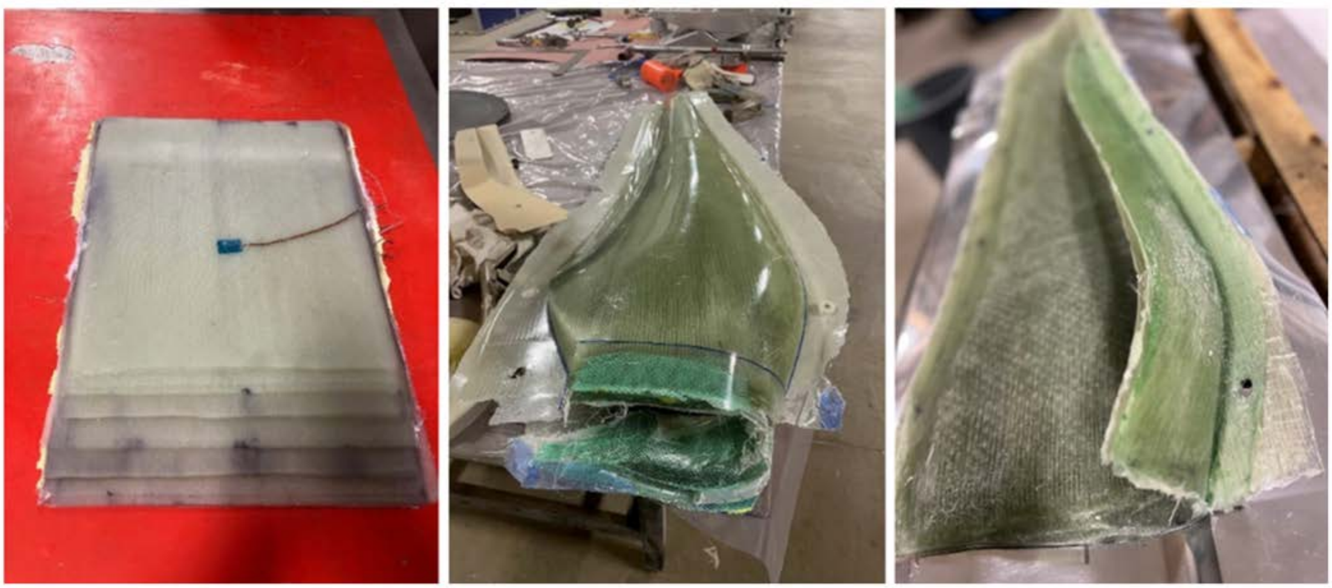
NREL Shows the Potential for Hybrid Offshore Energy Plants Using Advanced Modeling and Simulation Capabilities

Currently in its second year, the Optimal Design of Energy Cluster Offshore project aims to explore the potential for integrating and optimizing complementary technologies for generating, storing, and using energy at large scales offshore. In FY 2023, NREL researchers added new modeling and simulation capabilities for the Optimal Design of Energy Cluster Offshore concept technologies to the HOPP software tool and started building emulation capabilities that map to wave, offshore wind, battery, and electrolyzer capabilities to be validated using NREL's ARIES platform.

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

Plant-Based Resin Offers Recyclability and Better Performance Than Traditional Wind Turbine Blade Materials

With LDRD funding, NREL researchers developed a recyclable, plant-based resin—the polyester covalently adaptable network (or PECAN) formulation—that has similar, if not better, performance over thermoset and thermoplastic composite materials currently used in manufacturing wind turbine blades. The team manufactured 24-ply-thick fiberglass composites similar to a turbine blade root section using several PECAN formulations. Because PECAN can be used with the same manufacturing infrastructure as existing materials, it is an excellent drop-in replacement for nonrecyclable, petroleum-based materials currently used for large wind turbine blades. The team has developed an initial design validation setup to measure and validate the PECAN blade's performance for practical geometries used for large composite structures.



NREL's recyclable, plant-based polyester covalently adaptable network composite demonstrates better performance than thermoset and thermoplastic composite wind turbine blade materials. *Photos by Robynne Murray, NREL*

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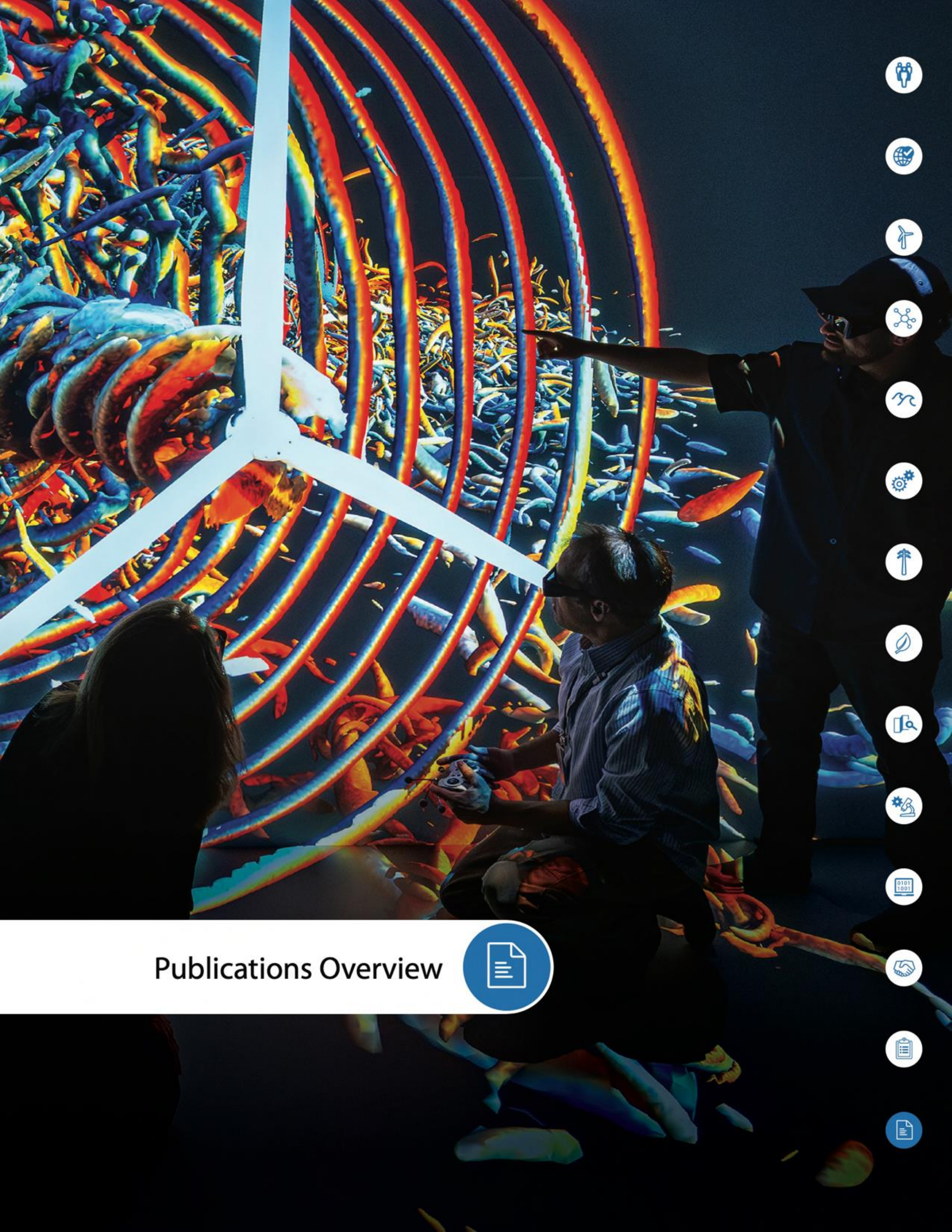


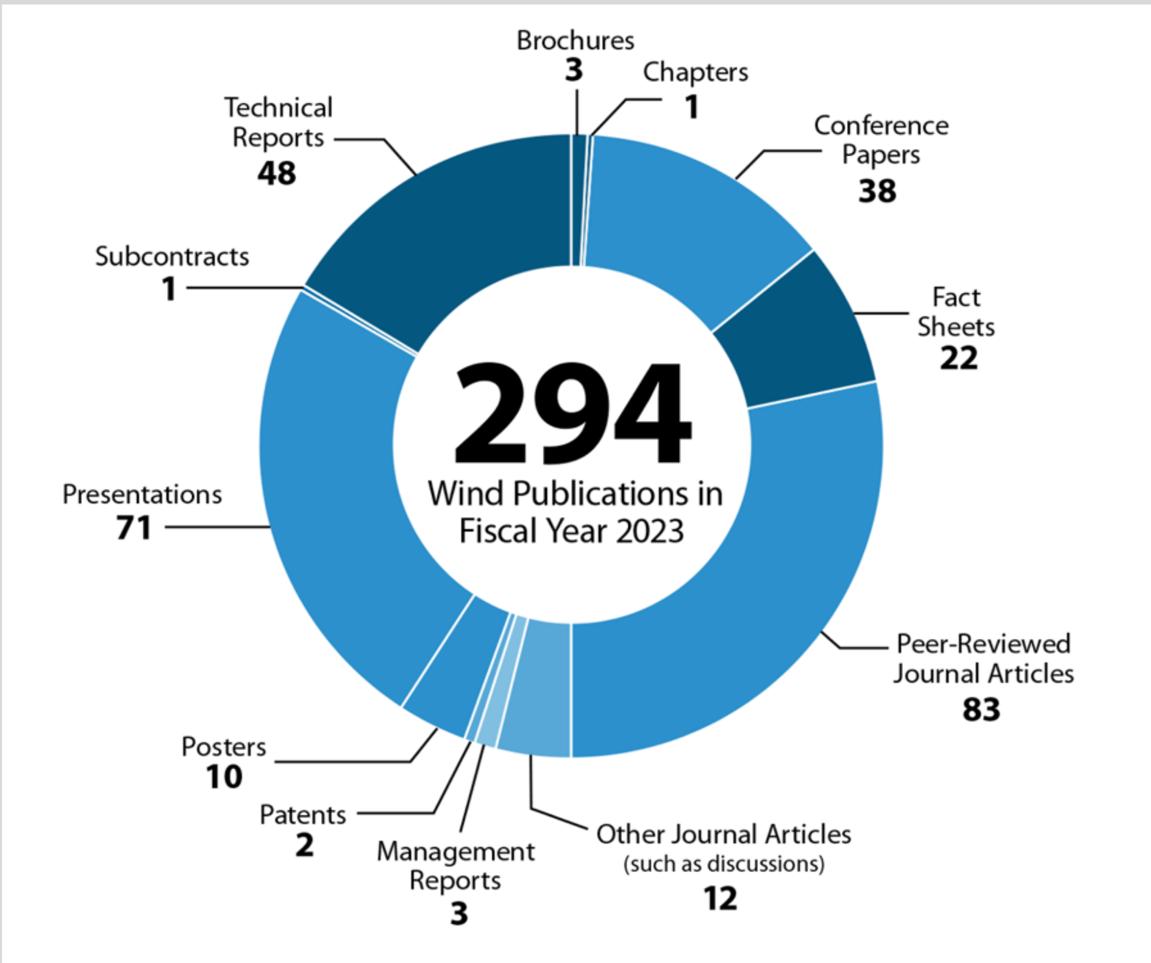
Publications Overview

Publications Overview

Publications produced by NREL wind energy program staff provide information about the many areas of wind energy research conducted at the lab. In FY 2023, NREL researchers published their latest scientific findings and breakthroughs in 294 technical reports, peer-reviewed journal articles, conference papers, fact sheets, and more.

Fiscal Year 2023 NREL Wind Energy Publications

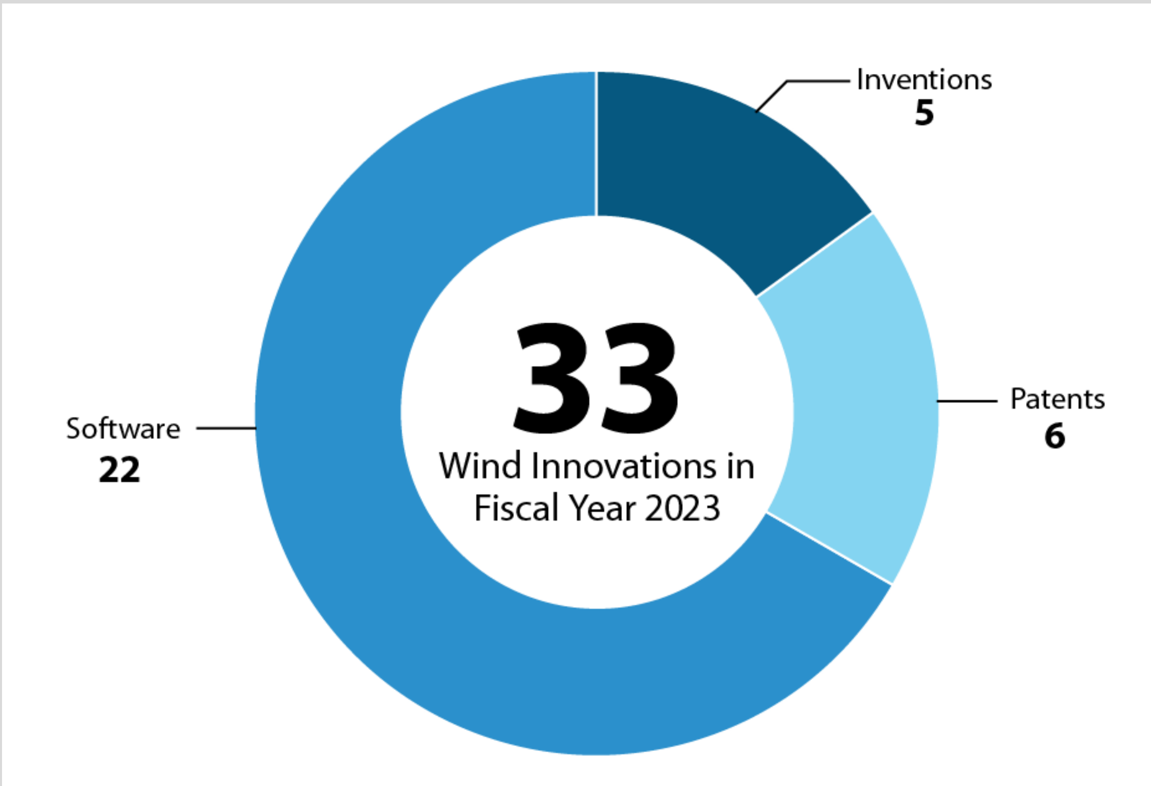
These publications provide reliable, unbiased information that researchers from academia, other national laboratories, government agencies, and private industry organizations can use to advance wind energy science.



In FY 2023, NREL published 294 wind energy documents. *Graphic by Jennifer Breen-Martinez, NREL*

Fiscal Year 2023 NREL Wind Energy 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 2023.



In FY 2023, 33 wind energy innovations were submitted or approved for patenting and licensing. *Graphic by Jennifer Breen-Martinez, NREL*

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Veers, Paul, Katherine Dykes, Sukanta Basu, Alessandro Bianchini, Andrew Clifton, Peter Green, et al. 2022. "Grand Challenges: Wind Energy Research Needs for a Global Energy Transition." ***Wind Energy Science*** 7: 2491–2496. https://www.nrel.gov/docs/fy23osti/85183.pdf

Visit the NREL Wind Research Publications page to find a list of all wind energy-related journal articles and technical reports published in FY 2023.

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The front and back cover images show NREL researchers reviewing a 3D ExaWind model visualization in the Insight Center powered by NREL's high-powered computer in the Energy Systems Integration Facility. Insight Center enhancements added in 2023 improved the fidelity and clarity of data visualizations. *Front and back cover photos by Werner Slocum, NREL*

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