Accomplishments & Year-End Performance REPORT

WIND ENERGY PROGRAM: FISCAL YEAR 2020

NREL
Transforming ENERGY

For nearly five decades, researchers from the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) have helped guide the development of a wide range of wind energy technologies by advancing scientific and engineering knowledge.

The world-renowned expertise of NREL's wind energy research program has been integral in identifying clear pathways toward realizing a future in which wind becomes one of the predominant sources of low-cost electricity generation by uncoupling the scientific, engineering, ecological, and social barriers to wind energy.

The National Wind Technology Center (NWTC) at NREL's Flatirons Campus provides an ideal environment for the research and development (R&D) of advanced energy technologies to help bring about this wind-powered future. During fiscal year (FY) 2020, NREL unveiled the Advanced Research on Integrated Energy Systems (ARIES) research platform, which will provide researchers an investigative environment to match the complexity of modern energy systems and determine how integrated energy systems can play out in a real-world setting. Other top accomplishments include the creation of the International Energy Agency (IEA) Wind 15-megawatt (MW) reference wind turbine alongside the Technical University of Denmark and the University of Maine, the completion of NREL's Power Generation Upgrade Project that doubles the power accessible to Flatirons Campus from 10 to 19.9 MW, and publication of the "Grand Challenges in the Science of Wind Energy" in Science that will serve as the basis of NREL's wind technology roadmap moving forward.

This report takes stock of the research NREL conducted on behalf of DOE's Wind Energy Technologies Office (WETO), other funding and research partners, and the people of the United States during FY20 (between Oct. 1, 2019 and Sept. 30, 2020). While diverse, all of these efforts shared a common goal to accelerate the deployment of wind energy technologies by helping to improve wind power performance, lower costs, and reduce market barriers to create a more sustainable, secure, and resilient power grid and a cleaner energy future.

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Active Partners,
Projects, and Publications

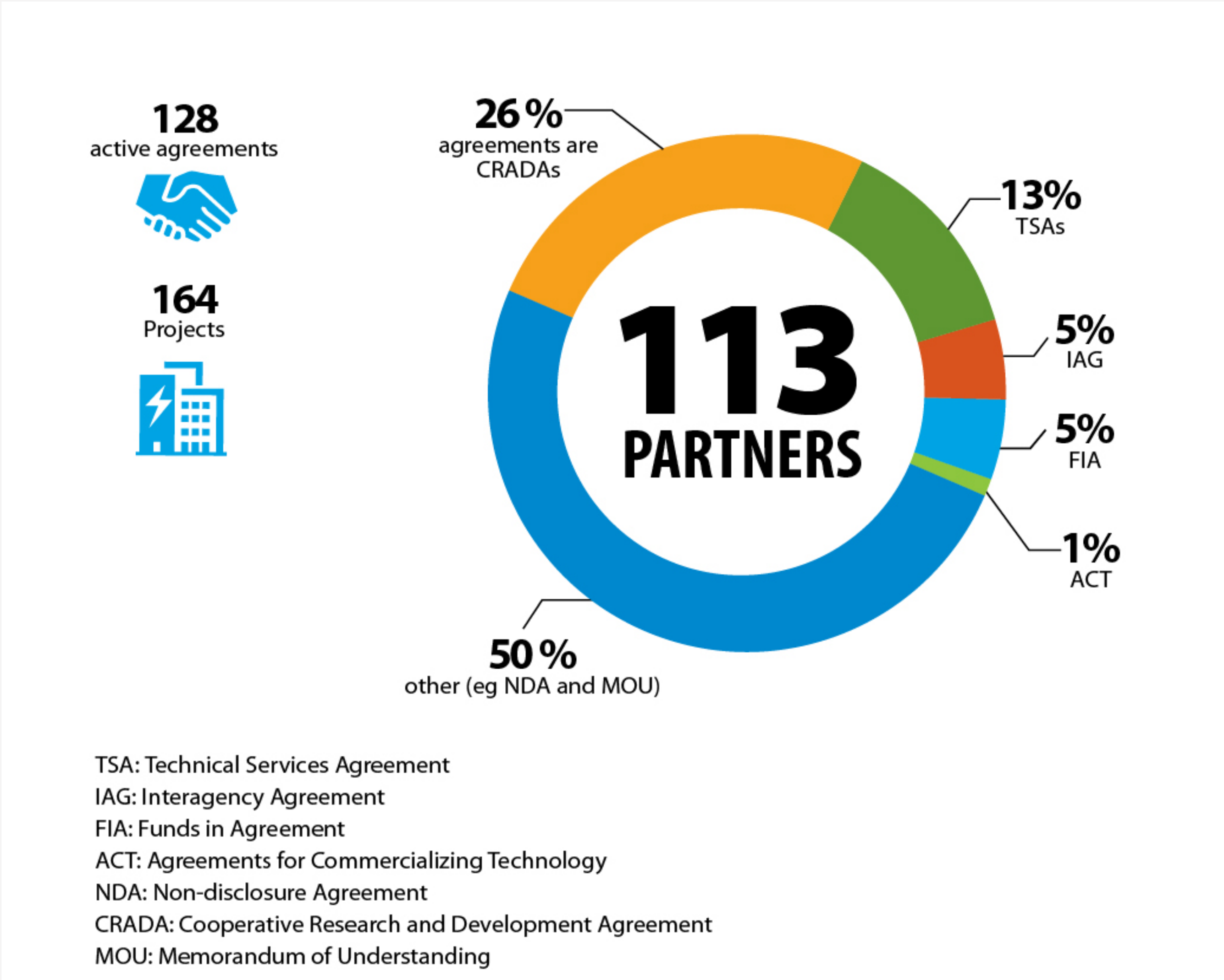

Chart by Jennifer-Breen Martinez, NREL

With expanding WETO support and enhanced business agility, NREL is well positioned to help move big ideas to market. The NREL wind staff successfully implemented innovative partnerships that leverage WETO investments to help accelerate wind energy research.

In addition, new NREL infrastructure investments increased other sources of funding such as industry partner cost-share, as recognized by the DOE Peer Review's recent highest ranking of the NWTC Testing Infrastructure project. Developing new, innovative ways to build partnerships also gives NREL the ability to work with industry in making wind a cost-effective electricity source for the world.

NREL Wind Energy Program staff produced technical and outreach publications in FY20, all of which help inform stakeholder groups and the public about wind energy.

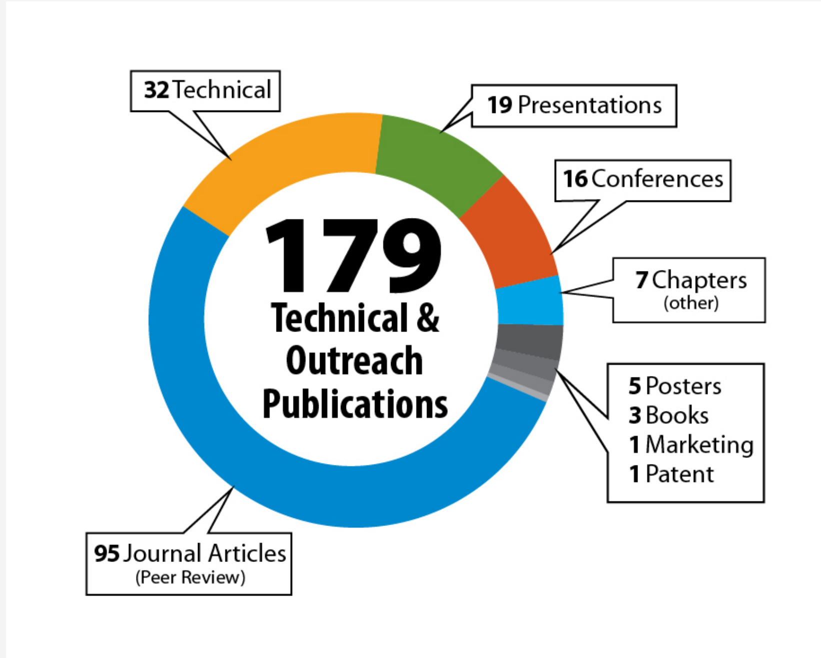

Chart by Jennifer-Breen Martinez, NREL

Notable Publications

1. Grand Challenges in the Science of Wind Energy.

Wind energy researchers from NREL and across the international wind energy industry wrote an article in *Science* inviting the scientific community to address three challenges that will drive the innovation needed for wind to become one of the world's primary sources of low-cost electricity generation. In addition to serving as a clarion call to the scientific community, this work sets forth a roadmap to help guide future wind energy research at NREL.

Available at https://science.sciencemag.org/content/366/6464/eaau2027.

2. Definition of the UMaine Volturn US-S Reference Platform Developed for the IEA Wind 15-Megawatt Offshore Reference Wind Turbine.

Funded by WETO and developed in collaboration the University of Maine and the Technical University of Denmark through the International Energy Agency Wind Technology Collaboration Programme (IEA Wind) Task 37 on Systems Engineering in Wind Energy, the multimegawatt reference turbine expands capabilities to assess technology for ever-larger and lower-cost offshore wind turbine designs.

Available at https://www.nrel.gov/docs/fy20osti/76773.pdf.

3. The Potential Impact of Offshore Wind Energy on a Future Power System in the U.S. Northeast.

Offshore wind energy could have a significant impact on power system performance of the Northeastern United States. Based on detailed modeling of power system operations in the Northeast, researchers found that the ISO-New England and NYISO control areas can accommodate offshore wind capacity injections of 2 GW and 7 GW in the mid-2020s. The power system impacts from 7 GW of offshore wind energy include a decline of regional wholesale power prices by 11% and an increase in the number of congestion events with varying impact on a subregional level. Assessing the sensitivity of these results to different points of interconnection and offshore wind's reliability contribution are identified as topics for further investigation.

Available at https://www.nrel.gov/docs/fy20osti/74191.pdf

Flatirons Campus

Research Facilities

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Adept Facilities Oversight and Preparation Spins Gears of Wind Energy Innovation

In FY20, NREL's Wind Program actively managed a broad R&D portfolio of 73 WETO-funded projects, many of which rely on access to state-of-the-art research facilities and capabilities at Flatirons Campus. NREL ensures that research facilities, assets, and equipment are primed for use by maintaining their mission-ready status so that they can be used by research projects across various DOE project portfolios, including wind. Activities include inspections, repairs, preventative maintenance, development of safe operating procedures and qualified operators.

This work includes providing detailed reports and status updates through monthly facilities briefings, and engaging the WETO leadership team with regular, open communications on the status of campus research facilities and upcoming projects.

Without the diligent oversight of the campus and facilities research team, many Water Power Technologies Office (WPTO), Solar Energy Technologies Office (SETO), Vehicle Technologies Office, Hydrogen and Fuel Technologies Office projects that lead the nation's early-stage R&D would not be possible. In a similar manner, NREL's broad wind energy research and development achievements would not be possible without the direct support of WETO. The following accomplishments are a sample of some of this year's highlights made possible by the Research Facilities and Capabilities team on behalf of WETO:

- Research Partnerships Provide Insight into Offshore Wind Blade Design and Improving Blade Service Life
- Fault-Tolerant Turbine Controller Innovations To Bolster Isolated Power System Support
- Volunteers Design and Print Face Shields for Colorado's Medical Workers and First Responders
- Shining (UV) Light on Inspired Innovation with Industry Partners
- Characterizing Drivetrain Failure Modes Reduces Wind Turbine Operations and Maintenance Costs
- NREL Creates First Wind Turbine Impedance Measurement System
- Technology Could Reduce Both Impacts on Bats and Unnecessary Curtailment

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Research Partnerships Provide Insight into New Innovative Blade Concepts

NREL completed two multiyear research partnerships with the University of Virginia, as well as the German Aerospace Center and Fraunhofer Institute for Wind Energy Systems, to conduct full-scale wind turbine aerodynamics research experiments utilizing the two-bladed and three-bladed 600-kilowatt (kW) research wind turbines (CART2 and CART3) at the Flatirons Campus.

The first project involved retrofitting DOE's CART2 with two highly flexible segmented ultralight morphing rotor blades designed in accordance with the objectives of the University of Virginia's project funded by DOE's ARPA-E, which supports the design of a 50-MW offshore wind turbine system with blades 200 meters long. The second project was conducted with the German Aerospace Corporation and funded by the German Federal Ministry for Economic Affairs and Energy. The CART3 wind turbine was used to validate the efficacy of SmartBlades, a new concept for intelligent wind turbine rotor blades using passive bend-twist coupling rotor control. These designs have the potential to greatly reduce materials and blade costs, which can lower the cost of wind energy.

In support of these innovative projects, WETO made significant investments in the operations and maintenance of these two turbines to ensure they were mission-ready, could be safely operated, and could produce required detailed research measurements.

Flatirons Campus Expansion and Capability Enhancements

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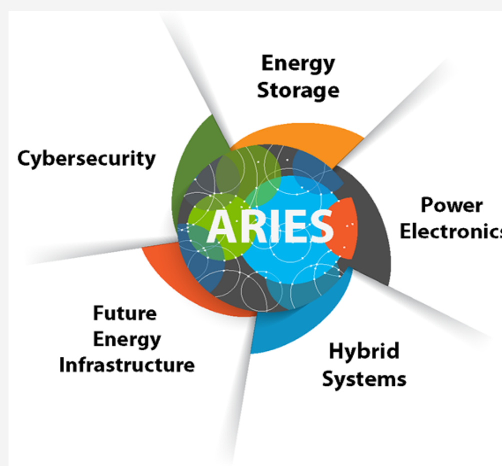
WETO Vision and Investments Pave Way for DOE's Crosscutting Strategic Initiative: ARIES

Stretching back to 2013, early insights and leadership from WETO on the strategic importance of grid integration research for renewable generation laid the foundation for what would result in a major DOE initiative unveiled this year: ARIES.



ARIES combines WETO's grid integration research capabilities at Flatirons Campus—referred to as Integrated Energy Systems at Scale (IESS)—with DOE's investments at NREL's Energy Systems Integration Facility. ARIES will bring clarity to how the millions of new devices—such as electric vehicles, renewable generation, hydrogen, energy storage, and grid-interactive efficient buildings—that are being connected to the grid daily will interact so we can maximize their impact and identify how to integrate things efficiently. Flatirons Campus provides ARIES an ability to scale the work, making possible consideration of opportunities and risks that come with the growing interdependencies between the power system and other infrastructures like transportation, water, and telecommunications.

Wind energy, water power, and grid integration research conducted at NREL's Flatirons Campus gained a boost with a recent upgrade to the power capacity at the facility. *Photo by Dennis Schroeder, NREL 58254*

Several specific projects helped set the stage for ARIES; projects that would not have been possible without WETO's grid integration research investments. These projects include:

- Implementation of the 6.3-MW controllable grid interface (CGI) and grid infrastructure to connect WETO wind turbines (DOE 1.5 MW, CARTs) and a megawatt-scale industry turbine to the CGI
- Investments in the 2.5-MW and 5-MW dynamometers
- Investments into digital real-time systems and ancillary grid control capabilities of DOE's GE 1.5-MW wind turbine.

The success of WETO's grid integration research capabilities have spearheaded significant major contributing investments from other DOE organizations (including the WPTO, SETO, Vehicle Technologies Office, Hydrogen and Fuel Cell Technologies Office, and DOE Facilities and Infrastructure) for the second 19.9-MW CGI, megawatt-scale hydrogen electrolyzer, PV arrays, Power Electronics Grid Interface platform, and behind-the- meter storage for extreme fast charging of electric vehicles.

To supplement DOE's investments, NREL has also contributed internal discretionary general purpose investment funding to provide six grid integration research pads, a 1-MW/1-MWhr battery energy storage system, research-grade data acquisition systems, a 3-MW load bank, and the 19.9-MW Flatirons sitewide power upgrade.

In FY20, with DOE approval, NREL also successfully transferred responsibility for funding annual operation and maintenance (O&M) of IESS facilities and capabilities from WETO to a new user fee model, where customers conducting IESS R&D projects are assessed a fee that provides funding needed to operate, maintain, and ensure mission readiness of all IESS assets at the Flatirons Campus.

ARIES will make it possible to understand the impact of and get the most value from the millions of new devices—such as electric vehicles, renewable generation, hydrogen, energy storage, and grid-interactive efficient buildings—that are being connected to the grid daily.

Distributed Wind

Research & Development

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Distributed Wind Turbines To Expand NREL Research Capabilities

NREL invited manufacturers to express their interest in installing 100-kW or smaller wind turbines as research hardware at the Flatirons Campus.

In addition to advancing distributed wind energy innovation and providing platforms for ongoing power system research at NREL, these distributed wind research turbines will support DOE's collaborative Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project, which works to develop wind-centered microgrids as plug-and-play components in hybrid systems with solar energy, energy storage, and other distributed energy resources.

NREL invited manufacturers to express interest in installing small wind turbines at NREL's Flatirons Campus (shown here) as part of a collaborative effort to improve wind-centered microgrids for distributed energy systems in remote locations. *Photo by Dennis Schroeder, NREL 37992*

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Competitiveness Improvement Project Awards Drive Distributed Wind Technology Innovation

Primus Wind Power has worked through the CIP program to continuously improve its Air series of wind turbines, including certification, design, and controller innovations. *Photo courtesy of Southwest Windpower*

NREL selected seven U.S. manufacturers to receive DOE Competitiveness Improvement Project (CIP) awards. Designed to accelerate deployment of small- and medium-sized wind turbines across the country and lower the cost of energy from distributed wind, these awards will help manufacturers optimize their designs, develop advanced components, assess innovative manufacturing processes, certify new turbine models, and improve unit reliability.

Through eight CIP funding cycles supported by DOE, NREL has awarded 36 subcontracts to 20 companies, totaling just over $7.75 million while leveraging additional millions in private-sector funding. Beyond funding, the CIP has also enabled manufacturers across the country to receive technical support provided by NREL.

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New Evaluation Process Streamlines Preprototype Development Projects

NREL developed a detailed review framework to systematically evaluate technologies submitted under the new preprototype award category within the CIP.

Used to evaluate four preprototype technology submissions under the 2019 CIP award cycle, this process provided detailed guidance to each submission. The review framework will also be used to improve the 2021 CIP solicitation and award process.

Tools Assessing Performance

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Weather Forecasting Simulations Enhance Distributed Wind Project Estimate Accuracy

NREL researchers performed a sensitivity study to identify the best parameters and inputs to conduct multiyear Weather and Research Forecasting (WRF) simulations across the United States, including Hawaii and Alaska. The study and subsequent analysis—part of a multilaboratory effort with Argonne National Laboratory, Los Alamos National Laboratory, and Pacific Northwest National Laboratory (PNNL)—helped researchers evaluate model drift, boundary conditions, and other relevant inputs that impact WRF outputs.

The WRF simulation will ultimately produce a 20-year wind resource data set with uncertainty quantification that can be used in grid intervention studies and to evaluate project performance for both utility-scale and distributed wind projects.

These efforts will enable researchers to provide resource forecasts to the distributed wind industry that more accurately estimate project performance and improve turbine reliability models, thus reducing construction estimate uncertainty and perceived financial risk.

Multiyear weather and research forecasting simulations across the United States will help the distributed wind industry more accurately estimate project performance and improve turbine reliability models. *Photo by Dennis Schroeder, NREL 36245*

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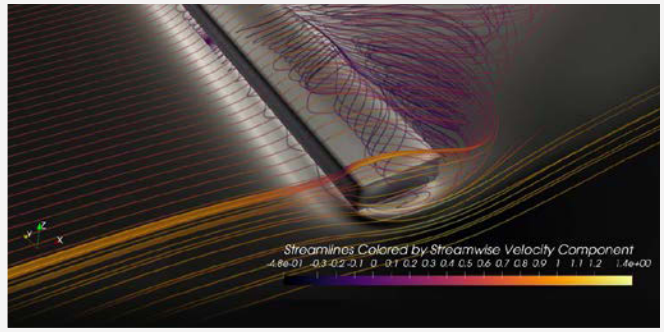
Detailed Obstacle Model Characterization Could Improve Energy Production Predictions

Distributed wind projects tend to be located closer to where the energy is used, increasing the likelihood that the wind resource will encounter obstructions before reaching the turbine. This makes modeling obstructions important to accurately predicting energy production prior to turbine installation.



This figure demonstrates wind speed around obstacles, which is critical to understanding the potential performance of distributed wind turbines placed in proximity to those obstacles. Warmer colors (orange) represent increased wind speed around the object, and cooler colors (blue and purple) represent decreased wind speed. *Image courtesy of NREL*

The multilaboratory Tools Assessing Performance team completed numerous large-eddy simulations around building obstacles. These simulations were used to evaluate their utility in producing a simplified obstacle model that could be easily used by the distributed wind industry. The simulations were also used to calculate the potential improvement of a new model over existing industry standard approaches. This later exercise indicated significant opportunity to reduce wind speed error estimates in the wake of building obstacles where distributed turbines are typically deployed.

Microgrids, Infrastructure Resilience and Advance Controls Launchpad

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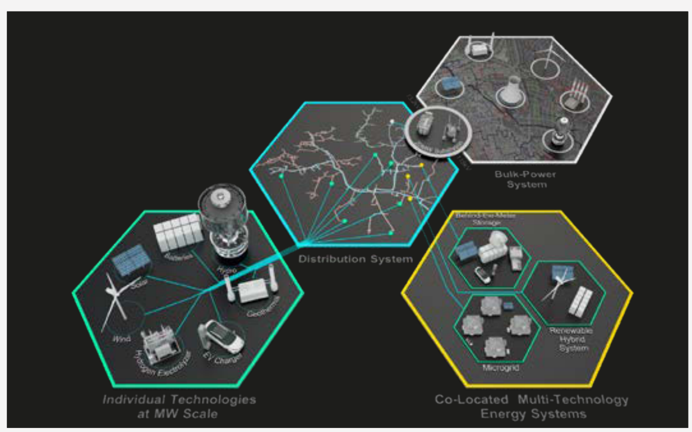
Information Designed To Explain Research to Project Partners

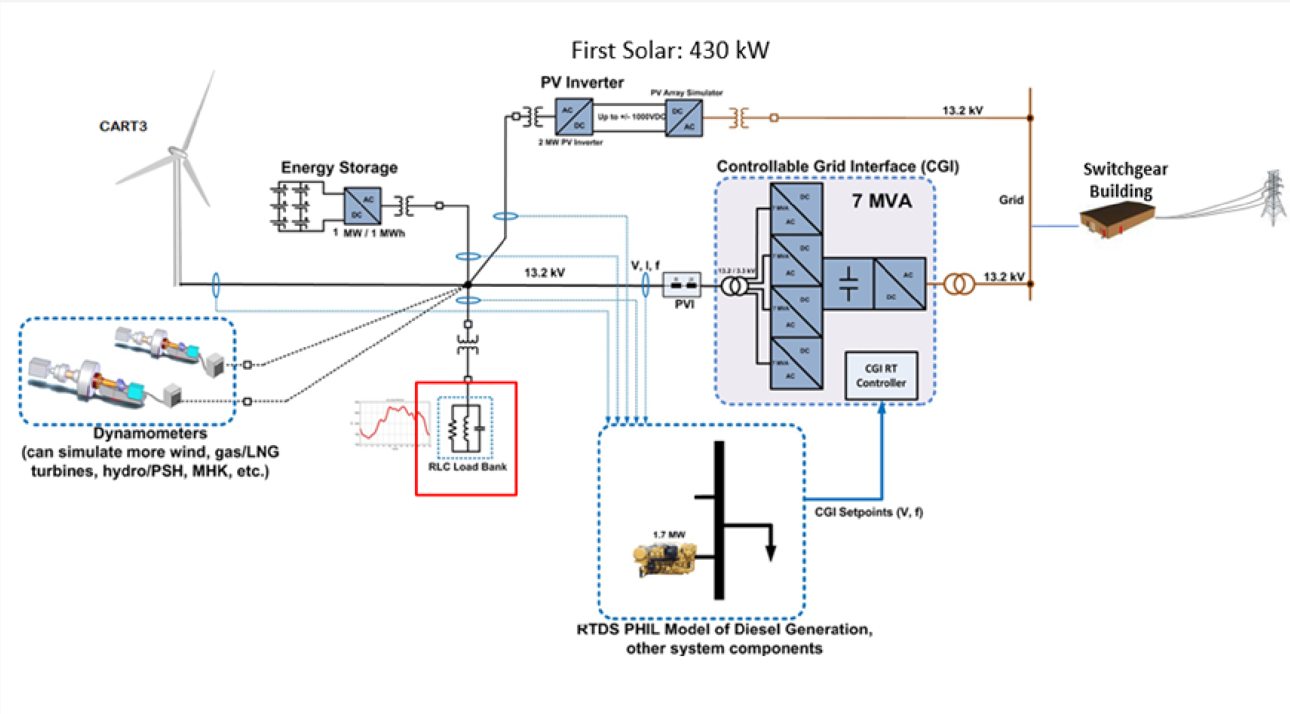
DOE and NREL initiated the Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project in 2018 in response to a request from the distributed wind industry to improve the operation, integration, and valuation of distributed wind in transactive environments, microgrids, and distribution system networks.



As part of the MIRACL project's research, distributed wind projects will be categorized into four use cases that will encompass wind turbines in isolated grids, front-of-the-meter deployments, grid-connected microgrids, and behind-the-meter deployments. *Graphic created by Josh Bauer, NREL*

On behalf of DOE, NREL leads the multi-year, multi-laboratory team that consists of Idaho National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories. The MIRACL effort also includes project advisors from the electric utility, wind, microgrid, and distributed energy resource industries. NREL developed a fact sheet designed to explain project objectives to potential project advisors and to promote the research to future project partners.

Facility Models Set Groundwork for MIRACL Advanced Controls Research



This graphic provides a high-level overview of the major components included in NREL's Flatirons Campus model. *Graphic courtesy of NREL*

The MIRACL project seeks to equip and validate wind technology as a plug-and-play resource with electric grids, solar, storage, and other distributed energy resources in hybrid systems.

MIRACL research has been structured into three primary research areas:

1. Valuing and modeling grid system contributions from wind as a distributed energy resource

2. Developing advanced controls for wind and wind-hybrid distributed energy resource systems

3. Researching and creating methodologies for wind to drive a resilient and cyber-secure distribution system.

Advanced controls research will optimize existing wind turbine hardware to reduce downtime and increase overall power system stability in support of, or instead of, conventional generation sources. As part of this work, NREL and Sandia National Laboratories developed models of the NREL Flatirons Campus and Sandia's Scaled Wind Farm Technology Facility that feature distributed wind turbines, battery storage, solar photovoltaics, a diesel generator, and dynamic loads.

In FY21, these models will be used to perform dynamic desktop simulations, which will be validated with real hardware in FY22. Demonstration and documentation of distributed wind benefits in microgrids, isolated grids, and distribution-connected configurations will ultimately lead to increased valuation of distributed wind as an essential grid resource of the future.

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Fault-Tolerant Turbine Controller Innovations To Bolster Isolated Power System Support

Through the MIRACL project, NREL staff reimagined how turbines interact with isolated power systems. Rather than focusing on how turbines could support power systems, wind turbine controllers have historically been turbine-centric, which limits the potential contribution of wind energy into isolated power systems. Building on extensive experience in wind turbine controller design, NREL assessed the basic parameters that drive turbine operation to determine which parameters could be modified to provide power systems with warning and different operational considerations of potential turbine faults.

The resulting fault-tolerant controller will undergo systemwide simulation and hardware-in-the-loop assessments in FY21 to further document the potential value of these innovations.

NREL's research on fault-tolerant control systems will determine how wind turbines could support isolated power systems. *Photo by Rural Electric Convenience Cooperative*

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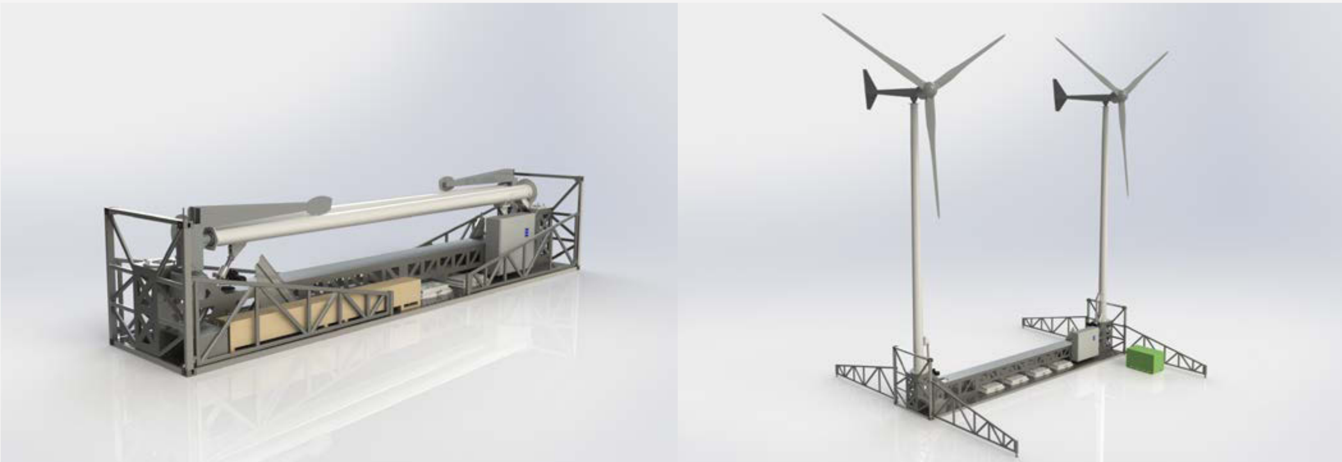

Providing quick access to energy during national defense and disaster recovery could look like this rapidly deployable wind energy system. Shown on the top is the system in its shipping configuration and on the bottom as it would be deployed on location. *Illustrations courtesy of Mike Bergey, Bergey Windpower Co.*

Turbines at the Ready: Multilaboratory Effort Creates Assessment for Deployable Turbines in Defense and Disaster Relief Applications

As part of DOE's Defense and Disaster Deployable Turbine (D3T) project to determine the viability of powering defense and disaster missions with rapidly deployable wind turbines, a team of NREL researchers assessed the disaster-relief market and reviewed deployable wind turbine technology constraints. To aid information dissemination, NREL also developed a D3T fact sheet for DOE. In addition, as part of an ongoing effort to create D3T design guidelines, NREL researchers reviewed the existing International Electrotechnical Commission (IEC) and American Wind Energy Association (AWEA) small wind turbine design standards (specifically IEC 61400-2 and ANSI/AWEA SWT - 1 [2016]) to determine if any modifications to these standards would be needed to accommodate deployable wind turbines.

A multilaboratory effort that includes Sandia National Laboratories, Idaho National Laboratory, and NREL, the D3T project collaborates with military and industry stakeholders to inform the development of deployable wind energy technologies. This work is part of a larger effort to help the U.S. Department of Defense identify and deploy renewable energy technologies to reduce fuel consumed in meeting operational energy needs. When completed, the effort will help determine whether a viable market for defense and disaster-deployable turbines exists, and if so, how to best meet the needs of that market.

Distributed Wind Strategic and Technical Engagement

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NREL Leads Revision to U.S. Small Wind Turbine Standard

The American standard for small wind turbines, last revised in 2009, required updating to allow for more rapid innovation by turbine manufacturers, help make the costs of meeting standards more consistent with the costs of distributed wind technologies, and ensure high-quality products to reduce financial risks associated with distributed wind technology investments.

The most expensive and time-intensive portion of the certification process was driven by a long-term operational requirement, called the duration test. Working in collaboration with distributed wind manufacturers, project developers, and research universities, NREL led an effort to assess, update, and implement the new American Wind Energy Association Small Wind Turbine standard, revision one, for 2020 (AWEA SWT-1 2020). To support the development of new duration test requirements, a detailed assessment of past certification tests was undertaken to determine how the duration test could be refashioned to lower the barrier to entry of new technology while still ensuring product performance.

The updated standard will lead to a more effective and cost-conscious conformity requirement for small and midsized wind technology.

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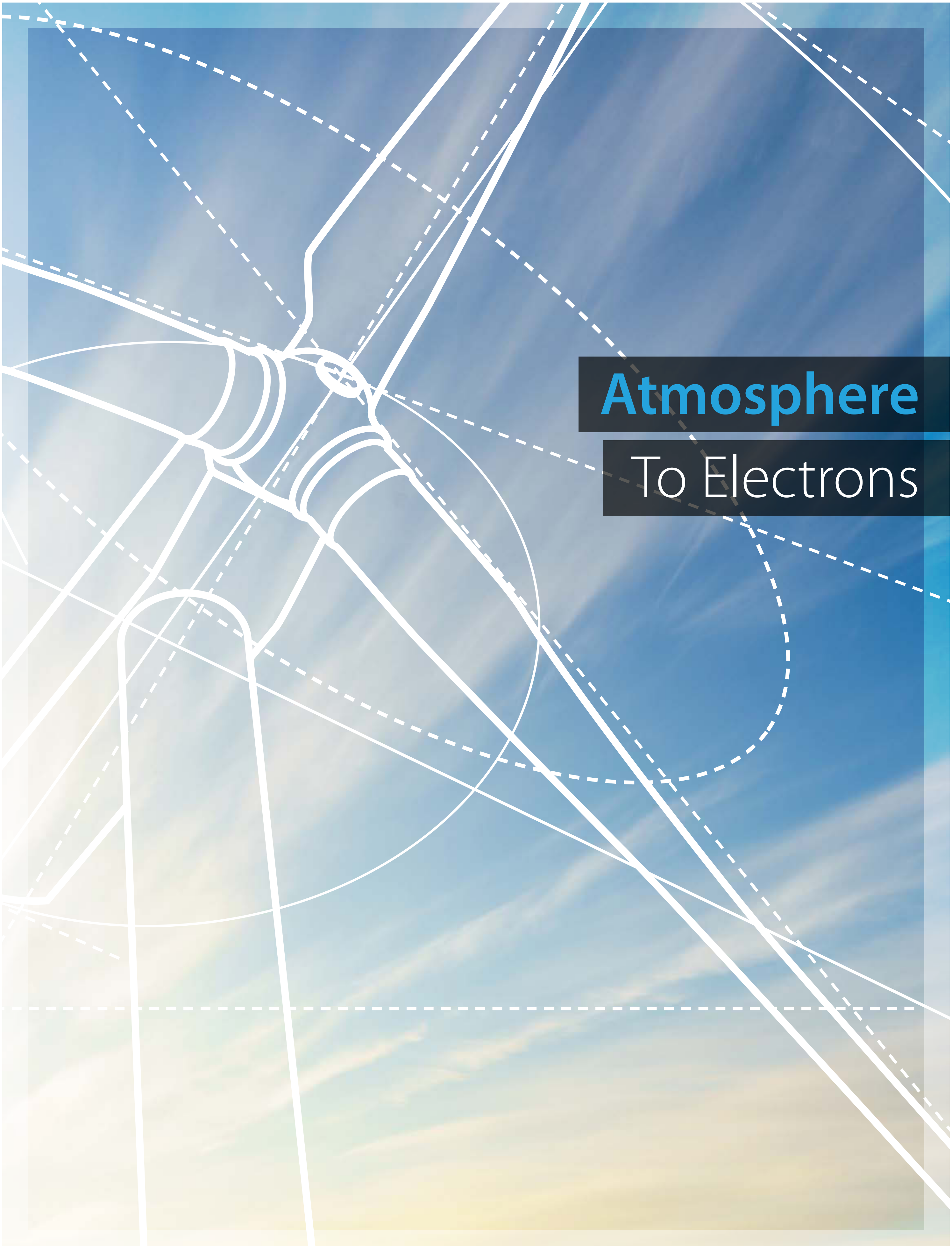
Collaboration Works To Mainstream Distributed Wind

NREL co-led a team of global wind experts in studying how wind energy can benefit distributed energy systems under IEA Wind Task 41, Enabling Wind to Contribute to a Distributed Energy Future. Working in collaboration with staff from the PNNL, NREL supported several international forums to highlight the role that wind energy, along with solar technologies, can play in supporting a distributed energy future while marshaling international research efforts to bolster U.S. investment in distributed wind innovation.

The 4-year project brings together research organizations from 11 participating countries.

Research convened by IEA Wind and sponsored by WETO is exploring how the highly successful distributed energy model employed by solar can be applied to wind energy. Team lead Ian Baring-Gould is in the first row, far left, in this photo of IEA Wind Task 41 team members at the project's kickoff meeting in Poland in late 2019. *Photo courtesy of IEA Wind Task 41*



Atmosphere
To Electrons

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Quantifying Impacts of Land Surface Modeling on Hub-Height Wind Speed Under Different Soil Conditions Improves Numerical Weather Prediction Models

By applying the WRF model and the extensive set of observations derived from the second Wind Forecast Improvement Project (WFIP2), researchers found ways for improvement in numerical weather prediction models for wind energy by investigating impacts of land surface models on hub-height wind speed under three different soil regimes (dry, wet, and frozen).

Understanding the impacts of land surface models on simulating turbine-height wind speed is a critical source of uncertainty in wind energy forecasting because of the physical connection between the land surface and wind speed through near-surface turbulent mixing. By reducing uncertainty and model errors, we can ensure for the sustainable growth and development of wind energy in the United States.

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Partnering with PNNL, NREL Provides Validation Code for Wind Energy Community

NREL and PNNL shared the verification and validation (V&V) methods and a framework for a case study validation with IEA Wind Task 36 (Forecasting for Wind Energy) and the larger wind energy community. The case study, a mountain wave case, and framework have been discussed and agreed upon with members of IEA Wind Task 36, the outcome of which demonstrates the importance of validation to the international wind energy community and can be used for evaluations of numerical weather prediction models used in wind energy forecasting. This V&V framework and validation code will be further discussed with IEA Wind Task 36 to keep making it useful, relevant, and adopted by the wider wind energy community.

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Forecasters Get Wind of Mountain Impacts on Performance of Wind Turbines and Power Plants

Collaborative research between NREL, the University of Colorado, the National Oceanic and Atmospheric Administration, PNNL, and industry researchers demonstrated that mountain waves not only occur frequently in areas of complex terrain, but they can be emulated with mesoscale models. These waves can impact wind turbine and wind power plant output; therefore, they should be considered when designing, building, and forecasting for wind power plants in areas of complex terrain.

The WFIP2 project field campaign in the Columbia Basin resulted in observing phenomena that impact wind conditions at turbine height in mountainous terrain. *Photo of Columbia Basin courtesy of Shutterstock*

By demonstrating the impacts complex terrain can have on the performance of wind turbines and wind power plants, researchers concluded that forecasters should be informed when mountain waves occur and receive information about wind variability so they can act accordingly (e.g., when setting day-ahead positions for balancing reserves and schedules). Information about the occurrence of mountain waves adds value by communicating the risk and probability of variability in power output, which helps when planning for possible extreme situations.

MMC Model Development and Validation

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Researchers Evaluate Procedures To Model Turbulence in High-Resolution Mesoscale Simulations

Wind researchers at NREL and the National Center for Atmospheric Research published "Simulating Real Atmospheric Boundary Layers at Gray Zone Resolutions: How Do Currently Available Turbulence Parameterizations Perform?" in the open-access journal, ***Atmosphere***, which sets forth a procedure other researchers can use to evaluate new or improved solutions to resolve gray zone issues.

Wind energy researchers now couple meso and microscale models, which have benefits for subkilometer resolution in the mesoscale model, but coupling can also complicate the task of turbulence modeling and lead to inaccurate outcomes. This is especially the case at horizontal resolutions between meso and microscales, known as the "gray zone," an area in which most mesoscale turbulence parameterizations perform poorly.

Researchers indicate that this modeling solution could take shape in a variety of ways, but that it should be evaluated against existing alternatives following the procedure they set forth. By laying this groundwork, this research advances the field toward developing a validated way to improve high-resolution mesoscale models that ultimately improve renewable energy output, including wind, with improved characterization, prediction, and understanding of atmospheric science under a wide range of realistic operating conditions.

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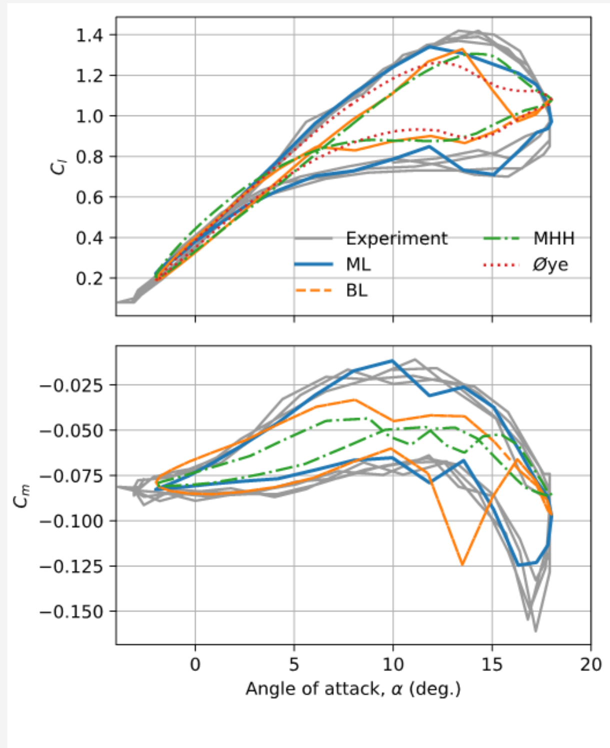
New Machine-Learning-Based Unsteady-Aerodynamics Model Demonstrates Leap in the State of the Art

Researchers Ganesh Vijayakumar, Shashank Yellapantula, and Shreyas Ananthan of NREL's High-Fidelity Modeling team created a new unsteady-aerodynamics model based on machine learning (a subset of artificial intelligence). The new model was trained using experimental data and comparisons with experiments outside the training set showed that the new unsteady-aerodynamics model performs much better than several state-of-the-art models available in engineering codes. The machine-learning model could have alternatively been trained on high-fidelity computational fluid dynamics data, and this work shows how machine learning can be an excellent pathway for taking the results and knowledge gained through high-fidelity modeling and high-performance computing to improve the tools used by engineering codes to design and optimize wind turbines and wind farms.

Unsteady-aerodynamics models are used in engineering simulations for design and certification with tools like OpenFAST, and in higher-fidelity actuator-line-type computational fluid dynamics simulations like those in Simulator fOr Offshore Wind Farm Applications (SOWFA) and Nalu-Wind. Unsteady-aerodynamics models are used to capture dynamic-stall effects, which become increasingly important with large rotors.



Comparison of the new, machine-learning unsteady-aerodynamics model, three state-of-the-art unsteady-aerodynamics models, and experimental data for coefficient of lift and moment (C_l and C_m) of a pitching N4415 airfoil. BL – Beddoes-Leishman model; MHH – Hansen et al. model; Øye – Øye dynamic stall model.

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Priority Access to Eagle Supercomputer Helps Wind Energy Research Soar

NREL worked closely with WETO to ensure WETO's $4-million investment over a 4-year period to allocate 288 nodes of the Eagle supercomputer for WETO-specific projects. This adds 7.2 million priority-access allocation units to pursue wind research projects with Eagle's high-performance computing capabilities. The world's largest supercomputer dedicated to energy efficiency and renewable energy, the Eagle can render computer models and simulations that would otherwise be impossible without its enhanced computational power. By allocating priority space and time on the Eagle, WETO projects have access to a critical research space that will help illuminate underlying complexities in wind energy systems and dynamics to help wind energy achieve its lowest cost.

High-performance computing systems like Eagle will allow wind researchers to model wind resources in a manner that more accurately captures the myriad of calculations to grasp the underlying physics at play at wind power plants. *Photo by Dennis Schroeder, NREL*

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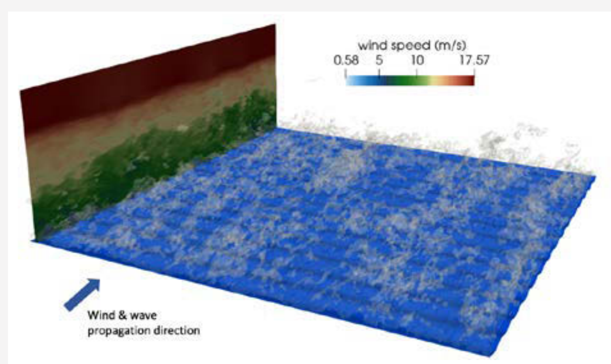
New ExaWind Capability Enables Simulation of the Marine Atmospheric Boundary Layer

Members of NREL's High-Fidelity Modeling team for wind comprised of Georgios Deskos, Shreyas Ananthan, and Ganesh Vijayakumar, and Michael Sprague implemented a new moving-wave boundary condition in the ExaWind modeling and simulation environment for offshore atmospheric dynamics. This is a key first step in preparing for high-fidelity simulations of offshore floating wind turbines and wind power plants.



Simulation of wind over waves using ExaWind's Nalu-Wind flow solver. This snapshot highlights how water waves can enhance wind turbulence, which is important in designing floating offshore turbines. *Graphic by NREL*

Offshore environments are characterized by complex interactions at the air-sea interface, such as large, nonlinear, wave propagation and wave breaking, which enhance the exchange of energy and momentum between the oceans and the atmospheric boundary layer above it. These interactions also play a key role in the hydrodynamic and aerodynamic loading of floating offshore wind turbines. The implementation of a new moving-wave boundary condition helps researchers obtain a deeper understanding of the coupling between wind and ocean waves, which contributes to improvements in offshore wind turbine design.

Energy Research and Forecast Modeling

Point of contact: Eliot Quon, Eliot.Quon@nrel.gov WETO 1.3.3.402-0

Foundation for Next-Generation Energy Research and Forecast Model Established

Working alongside Lawrence Livermore National Laboratory and PNNL, NREL researchers selected the AMReX framework as the foundation for the new Energy Research and Forecast (ERF) model. The multilab team arrived at this selection by leveraging experience from the High-Fidelity Modeling project. AMReX is also the foundation for AMR-Wind, an exascale-capable solver under development at NREL for simulating the wind power plant operating environment on the next generation of supercomputers, with which ERF will interface.

To facilitate ERF software development efforts and enable rigorous software quality assurance practices, the research team has taken the following steps:

- Establishing software verification protocols to guide ERF's development
- Working with PNNL to identify suitable verification cases for when ERF development has advanced.

This year's efforts lay a strong foundation for improving the accuracy with which we capture weather phenomena at regional and wind plant scales. By providing realistic simulations of wind plant aerodynamics and wind turbine aeroelasticity, ERF will enable efficient regional weather simulations that, in conjunction with AMR-Wind, form a high-fidelity, multiscale, wind-power-plant simulation framework that can improve wind plant performance and decrease the cost of wind energy.

New software for new hardware. Existing weather models are becoming outdated because of their incompatibility with next-generation supercomputing architectures; therefore, ERF aims to address this. *Photo by Dennis Schroeder, NREL 53208*

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

New Wake Identification and Characterization Methods Bring Order to Wake Analyses

NREL researchers unveiled a Python-based library of wake-tracking algorithms called the Simulated And Measured Wake Identification and CHaracterization ToolBox (SAMWICH Box), which helps bring order to the field of wake identification and characterization. The development and dissemination of SAMWICH Box can help resolve an issue whereby higher uncertainty in wake analyses results from researchers independently developing their own, distinct approaches to tracking wakes, resulting in difficulties with replicability and determining which wake methodology to apply and under what conditions.

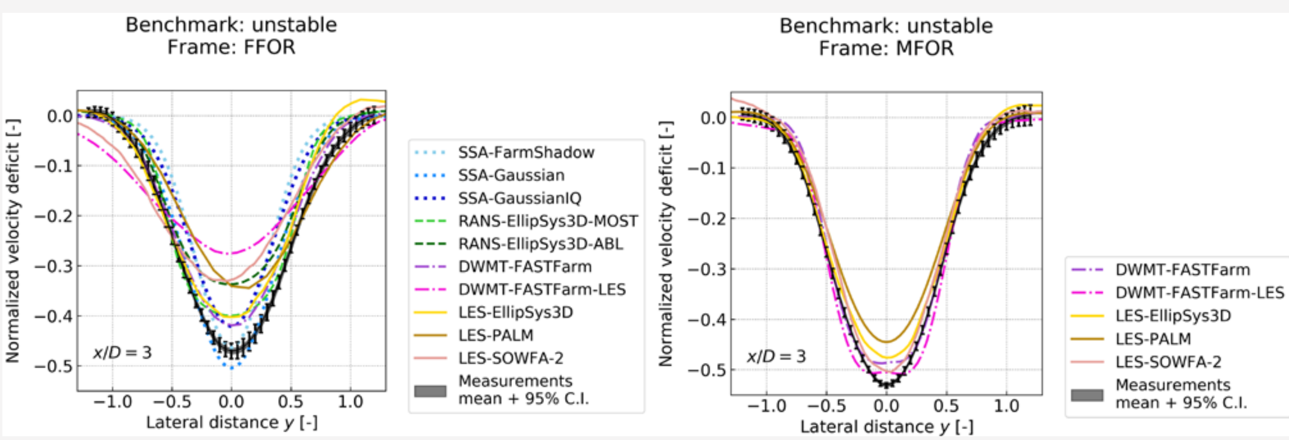
Rotor Wake Measurements

Point of contact: Paula Doubrawa, Paula.Doubrawa@nrel.gov WETO 1.3.4.401

Meandering Contradictions: Simulations Overestimate Movement of Wind Turbine Wakes

In a recent journal article for *Wind Energy*, researchers investigated the ability of nine different computational models to simulate the lateral and vertical movement of wind turbine wakes, as these movements directly affect the power and loading of downstream wind turbines. A range of different models and the simulation data were compared to a set of unique measurements—snapshots of the wake sampled every 2 seconds at the DOE Scaled Wind Farm Technology facility in Texas—finding that the simulations predicted more wake movement than was observed in the measurements.

Although some of this variation can be attributed to differences in the simulated turbulent inflow or computational setup, others may be caused by the underlying wake model. These results highlight the need for more dynamic measurements of wind turbine wakes and for more model validation studies that can single out the exact sources of model underperformance and guide ongoing model developments.

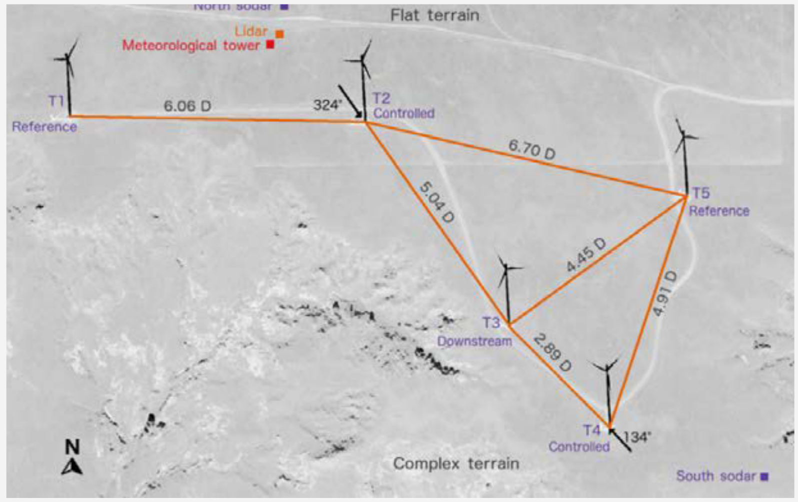


A side-by-side comparison of wake simulations in a fixed vs. meandering frame of reference reveals that the simulation wake strength errors come largely from wake meandering (i.e., better agreement is observed in the right panel)

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

Completion of 2-Year Wake Steering Field Campaign Helps Validate Atmospheric Flow Models

In partnership with NextEra, NREL completed a 2-year field experiment using a cluster of five wind turbines at an operational, utility-scale wind power plant in the continental United States. By deploying extensive instrumentation to measure flow conditions ahead of and behind the wind turbines, the study enabled researchers to measure and control wind turbine operation and evaluate the performance and structural response of the wind turbine system under different environmental conditions and operational strategies.



NREL measured the impact of steering individual turbine wakes away from downstream turbines. *Figure by Katherine Fleming, NREL*

This is the first public, long-term, wake-steering experiment conducted at an operational, utility-scale wind power plant. Rich in atmospheric and turbine measurements, the observational data set resulting from this campaign helps quantify the effect of wake steering as a control strategy on the performance and reliability of individual, utility-scale wind turbines. In addition, the data set collected will be used to validate a wide range of NREL flow models (from FLOw Redirection and Induction in Steady State [FLORIS] to FAST.Farm to ExaWind) and will be shared with the international community for validation of other codes, which helps ensure the accuracy of these computer models to reduce the levelized cost of wind energy.

Aeroacoustic Assessment Wind Plant Control

Point of contact: Pietro Bortolotti, Pietro.Bortolotti@nrel.gov WETO 1.3.4.403-0

Aeroacoustics Noise Generation Models Integrated in OpenFAST Platform

Along with the Big Adaptive Rotor project, the Aeroacoustics Assessment Project supported the development of a module for the aeroservoelastic model OpenFAST to estimate the aeroacoustics noise generated by wind turbines. As chronicled in an NREL technical report, the aeroacoustics module uses theoretical and experimental work from the past three decades to simulate noise emissions in the acoustic range. In addition to the model description, the report shows a code-to-code comparison conducted between the implementation in OpenFAST and the one available at the Wind Energy Institute of the Technical University of Munich, Germany. The noise emissions of the IEA Wind Task 37 land-based reference wind turbine returned a good match between the two implementations. Work is ongoing, which includes improving the model by adding a noise propagation model that can account for atmospheric and ground effects.

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

Changes in Wind Turbine Noise with Yawed Operation Could Improve Siting Decisions

Photo by Werner Slocum, *NREL 61701*

Aeroacoustic noise, the noise generated by a turbine as its blades cut through the air, depends on boundary layer properties along the length of the blade and the speed at which the rotor spins the blades. Using the OpenFAST aeroacoustics module, researchers find that changes in turbine noise output can arise through yawed operation, which reduces rotor speed for high yaw offset angles.

Modeling aeroacoustic noise with OpenFAST helps show how active control strategies such as yawing turbines could lead to practical noise reduction methods and technology for more widespread commercial deployment of wind turbines.

Noise generation is one of the key limitations on placement of new wind energy assets near populated areas and, as wind plant control strategies become more common, secondary effects to operating wind turbines under yaw misalignment will need to be considered.

American Wake Experiment AWAKEN

Point of contact: Patrick Moriarty, Patrick.Moriarty@nrel.gov WETO 1.3.4.404

NREL Organizes International Field Campaign To Study Wind Farm-Atmosphere Interactions

In its first full year, NREL assembled an international group of renowned researchers to join the American Wake Experiment (AWAKEN) to gather observational data to address the most pressing science questions about wind turbine wake interactions and aerodynamics, further understand wake behavior, and validate wind farm control strategies that have been shown to increase wind plant power production. The group comprises multiple institutes funded by U.S., Canadian, and European research agencies with atmospheric science and wind energy expertise. Researchers from across these institutes helped plan the experiment, submit proposals to augment available instrumentation and researcher participation, and establish the experiment location in wind farms around the DOE Atmospheric Radiation and Measurement Southern Great Plains facility in Northern Oklahoma.

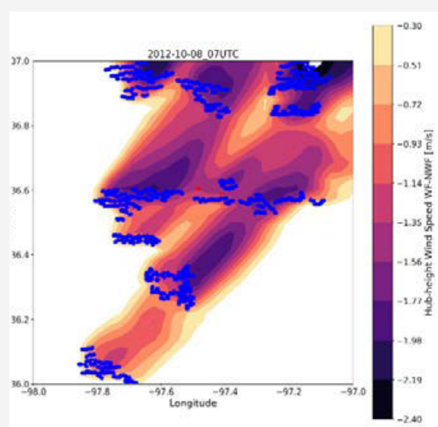


Image of wind speed losses caused by wake interactions between wind farms in the AWAKEN field campaign area. *Image courtesy of Julie Lundquist, NREL and University of Colorado Boulder*

The data gathered and complementary simulations of wind farms within the AWAKEN project can improve wind farm layout and enhance power production and plant reliability. By better understanding the physical processes at wind farms and improving modeling capabilities, AWAKEN can help lower the overall cost of wind energy.

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

Future Offshore Wind Power Plant Layouts Should Consider Turbulence and Veer Regimes

Using 13 months of lidar observations off the coast of Massachusetts, researchers determined that offshore wind power plants at the site of study will experience very low turbulence. However, large wind veer conditions that often occur during low-turbulence regimes can impact the effectiveness of wake-steering solutions. The study concludes that both turbulence and veer regimes should be considered when investigating optimal layout solutions for offshore wind farms currently being planned in the U.S. Eastern Seaboard to minimize wake losses and increase offshore wind energy production.

Advanced Flow Control Science

Point of contact: Paul Fleming, Paul.Fleming@nrel.gov WETO 1.3.5.401

NREL Boosts Speed and Accuracy of Wind Plant Optimization Model

NREL released a new version of its FLORIS model for wind plant performance optimization. The latest update combines the new three-dimensional physics of the curl wake-steering model with the analytical Gaussian model's speed to enhance FLORIS' ability to accurately design and analyze wind power plant control strategies for larger arrays of turbines.

Wake steering provides wind plants with important increases in power production for utility-scale wind farms. The new Gauss-curl hybrid model predicts the impact of a set of counter-rotating vortices on wake control, resulting in much greater potential to improve wake steering when turbines coordinate based on these vortices, which can help wind energy facilities to improve productivity and increase profits.

NREL's Jennifer King and her colleagues advance control strategies to improve the performance of wind power plants. *Photo by Dennis Schroeder, NREL 58254*

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

NREL Research Establishes Best Practices for Atmospheric Surveying for Wake Modeling

NREL researchers upgraded FLORIS to allow for inflow wind modeling to be spatially heterogenous in wind speed, wind direction, and turbulence. Details of this work are included in a journal article, "Design and Analysis of a Spatially Centered Wake," published in *Wind Energy Science*.

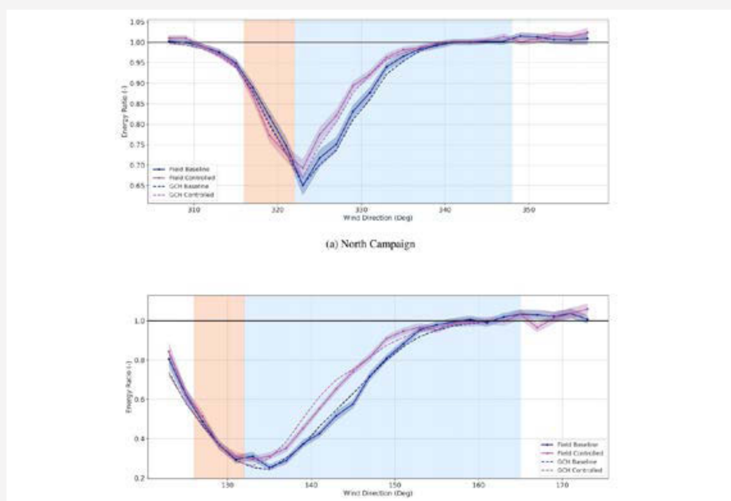
Modeling the power production of large wind farms accurately and completely is challenging because of the differing size and terrain of wind farms, along with changing weather patterns. Instead of using render inflow modeling based on homogenous inflow patterns, NREL researchers made critical improvements to FLORIS that allow for far more accurate, realistic modeling for large wind farms. They also validated these improvements to establish best practices for atmospheric surveying for wake modeling.

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

Results from Field Campaign Closely Match Latest FLORIS Model

In a second journal article centered on using FLORIS to model wake steering, NREL researchers documented a complete field campaign at a commercial wind site comparing the results with the latest FLORIS model, showing close alignment between field and model results.

In addition to allowing researchers to validate the gains in energy production predicted by the FLORIS tool with actual field results, data show an overall reduction in wake losses of approximately 6.6% for the regions of operation, which corresponds to achieving roughly half of the static optimal result.



These figures show the change in energy ratio (a metric of reduced energy production because of wake losses) from baseline operation (blue) to under wake-steering operation (magenta). Field results are shown in the solid line, whereas FLORIS predictions are shown in the dashed line, indicating good general agreement with the gain in energy production FLORIS predicts. *Graphic by Paul Fleming, NREL*

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Accounting for Wind Direction Variability and Uncertainty in Control Design Improves Accuracy of Wind Farm Controllers

Published in *Wind Energy Science*, the article "Design and Analysis of a Wake Steering Controller with Wind Direction Variability" discusses a new method for designing wind farm controllers assuming realistic uncertainty of critical wind measurements.

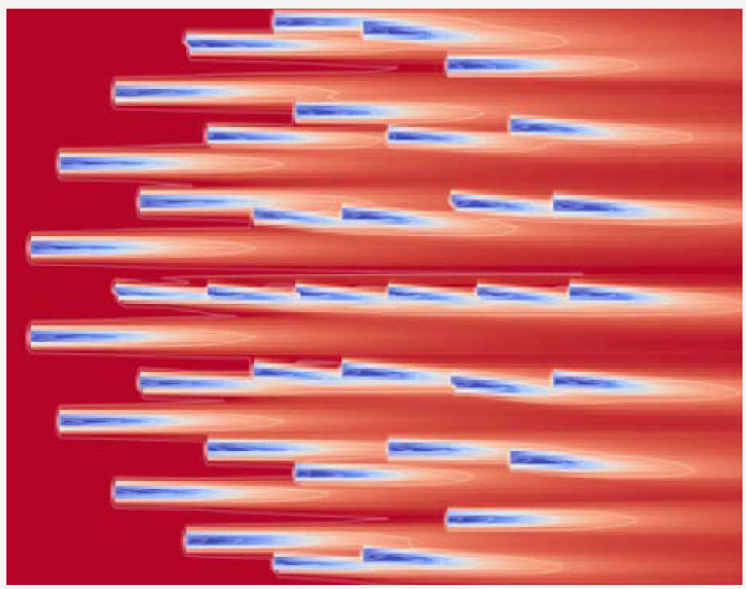
By accounting for wind direction variability, researchers found that energy production improved as the separation distance between turbines increased relative to designs that assumed no uncertainty. These methods enable the successful design of wake-steering controllers, even assuming the presence of uncertainty in critical measurements.

Enabling Auto Wind Plants Consensus Control

Point of contact: Paul Fleming, Paul.Fleming@nrel.gov WETO 1.3.5.402

New Wake Steering Model Predicts Critical Secondary Effects for Large Wind Farms

Wake steering is a wind farm controls concept that enables higher energy production of wind farms through coordination of the controls of individual wind turbines. Previously, much research and modeling efforts have focused on studying the change in the wake of a single turbine resulting from intentional wake steering. Recently, NREL has produced a new model of wake steering, called the Gauss Curl Hybrid, which models the way in which "steered" wakes interact with each other through the counter-rotating vortices generated in wake steering. Inclusion of these effects improves the accuracy of engineering models of wake steering when compared to higher-fidelity computational fluid dynamics simulations and increases the gains in power production for large arrays.



FLORIS simulation of a 38-turbine plant where second-order effects are modeled to maximize the benefit of wake steering. *Graphic by NREL*

Point of contact: Julian Quick, Julian.Quick@nrel.gov WETO 1.3.6.401

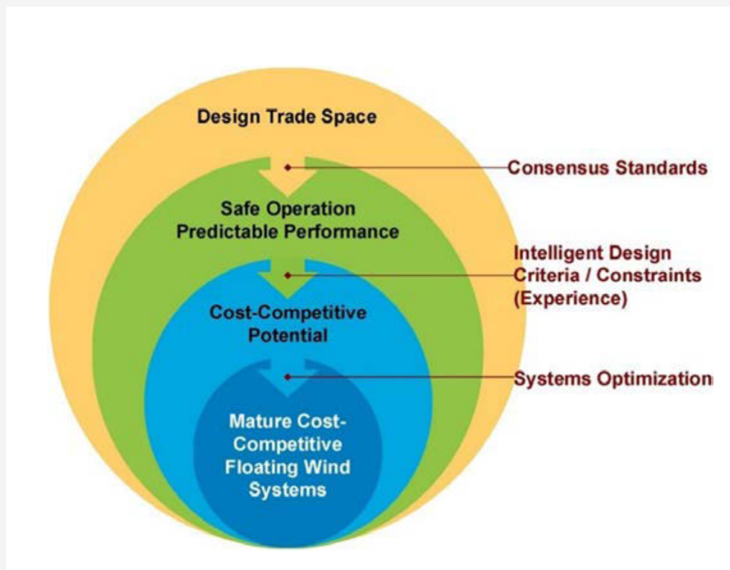
Optimization Under Uncertainty Strategy Produces More Power and Reduces Risk to Yawed Wind Turbines

NREL researchers formulated and solved an optimization under uncertainty problem for determining optimal plant-level wake-steering strategies in the presence of independent uncertainties in the direction, speed, turbulence intensity, and shear of the incoming wind, as well as in turbine yaw positions. The plant-level wake steering strategy formulated using an optimization under uncertainty approach produces more power in realistic conditions and reduces risk by prescribing strategies that call for less extreme yaw angles. *Wind Energy Science Discussions* published these findings.

Point of contact: Garret Barter, Garret.Barter@nrel.gov

Study Asserts Systems Engineering Vision for Floating Offshore Wind Cost Optimization

Many U.S. coastal areas have water depths that favor the deployment of floating over fixed-bottom offshore wind technology. Recognizing this, researchers articulated a long-term vision for a research program and design methodology that involves a fully integrated systems-engineering and techno-economic design approach to effectively account for the factors impacting floating offshore wind development, which can help push floating wind power plants toward a lower LCOE.



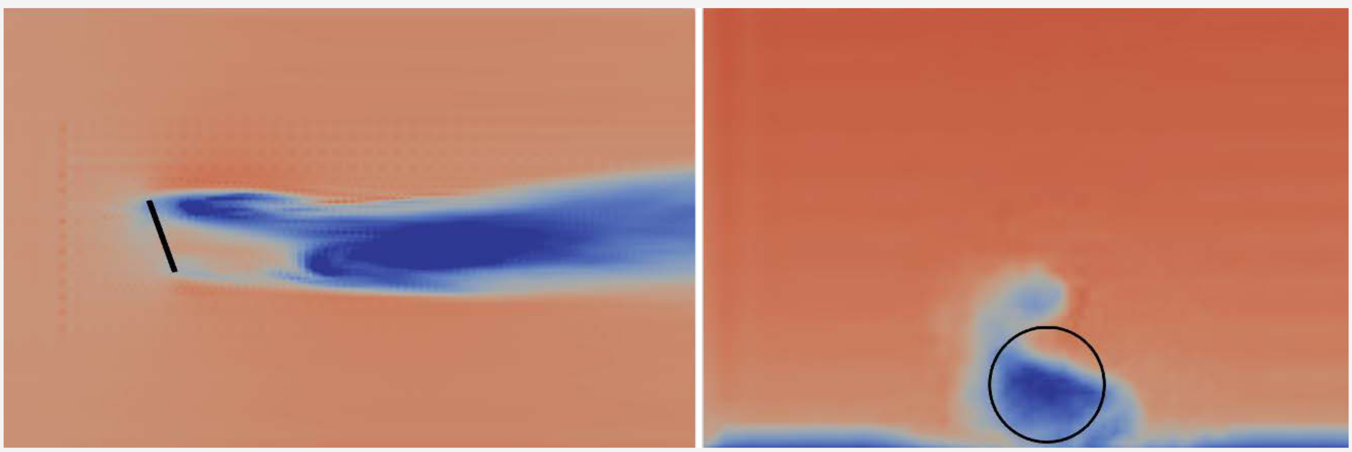
Narrowing the trade space to accelerate floating system optimization for wider offshore wind deployment. *Graphic by NREL*

Point of contact: Garrett Barter, Garret.Barter@nrel.gov

WindSE Unlocks New Possibilities for Plant Controllability Studies

A new unsteady solver has been created for the systems engineering model, WindSE, which allows it to resolve wind turbine blades (as "actuator lines") and wakes more accurately. Because WindSE provides adjoints, essentially sensitivities between user outputs and simulation parameters, there is now a direct connection between turbine blade lift and drag profiles and plant-level power production.

The new addition to WindSE unveils a new class of simulation, optimization, and sensitivity analysis studies that link wind-turbine-focused design to plant-level flow characteristics and power production. As a next step, this contribution empowers NREL to conduct blade design optimization to improve wake deflection when doing wake steering. Future work will focus on turbine-plant co-design, wherein the design geometry and the control strategy are developed in concert with one another to maximize performance in complex scenarios.



Top-down (left) and downwind (right) facing slices of wind turbine wakes show the unsteady actuator line method in WindSE. *Graphic by Ethan Young, NREL*

Offshore Wind

Research & Development

Point of contact: Amy Robertson, Amy.Robertson@nrel.gov WETO 1.3.6.403

New Soil/Structure Interaction Model Advances OpenFAST Accuracy for Fixed-Bottom Offshore Wind Systems

A new higher-fidelity model for representing the interaction between the soil and foundation of fixed-bottom offshore wind systems has been coupled to OpenFAST, providing a computationally efficient and more accurate approach for modeling soil/structure interactions. The Norwegian Geotechnical Institute developed the capability as part of the REDWIN (REDucing cost of offshore WINd by integrated structural and geotechnical design) project, which uses a macroelement approach to condense the response of the foundation and the surrounding soil to a force-displacement relationship at one point at the seabed. Phase II of the Offshore Code Comparison Collaboration, Continued, with Correlation and uncertainty (OC6) project focuses on verifying the OpenFAST coupling, as well as the coupling of the REDWIN model to other industry offshore wind modeling tools.

Traditional soil/structure models tend to underestimate soil stiffness and do not consider damping, which can lead to misrepresentation of the system frequencies and an underprediction of fatigue life. The new REDWIN modeling approach overcomes these limitations to provide a more accurate estimate of the load response of offshore wind systems, which will allow for the development of more innovative, cost-optimized fixed-bottom designs.

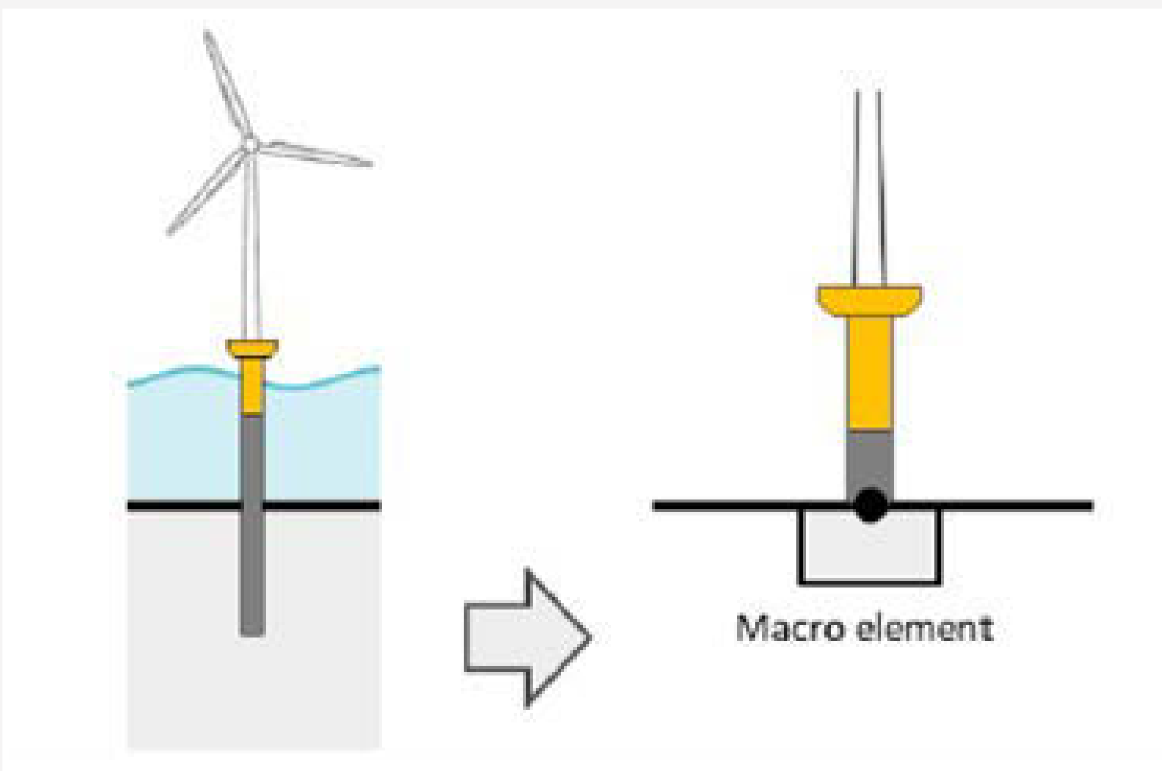
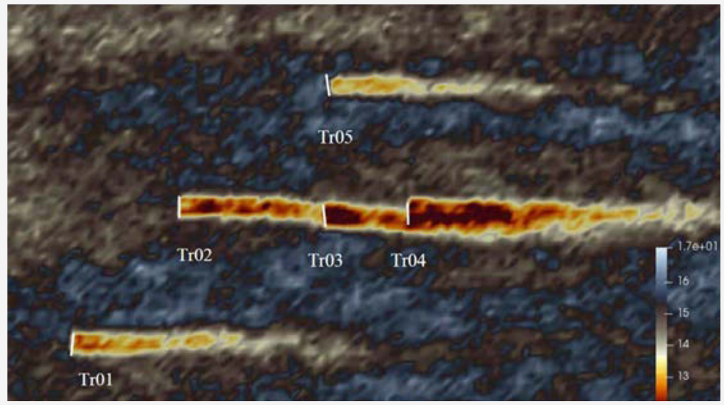


Illustration of a fixed-bottom offshore wind turbine (left) represented by the REDWIN macroelement approach. Image courtesy of the Norwegian Geotechnical Institute

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

Validation of FAST.Farm Supports Accurate and Efficient Prediction of Power Production and Structural Loading in Wind Plants

Two studies validating the FAST.Farm wind plant engineering tool's prediction of wind turbine power performance and structural loading in wind plants have been completed, finding that FAST.Farm can be an effective tool for assessing wind plant power performance and load analyses.



Instantaneous flow visualization of the five-turbine FAST.Farm simulation in turbulent 6.5-meter-per-second wind inflow, sampled at hub height and colored by velocity magnitude demonstrating wake impacts among wind turbines. *Image courtesy of Kelsey Shaler, NREL*

This finding follows two separate studies, one in which the structural response predicted by FAST.Farm was validated against high-fidelity coupled SOWFA-OpenFAST results for a series of small wind farm scenarios with structural flexible wind turbines and another in which FAST.Farm predictions of generator power, rotor speed, and blade pitch were **validated against supervisory control** and data acquisition measurements from five turbines at a full-scale wind farms. In addition to confirming FAST.Farm as an effective tool for assessing power performance and structural loading, the study helped to identify areas where further model validations and improvements should be targeted.

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

OC6 Phase I Dives Deep To Improve Offshore Wind Design Tools

The OC6 project has identified the largest sources for underprediction in hydrodynamic loading and response––an important first step toward more accurate modeling tools that help design more optimized, cost-effective offshore wind semisubmersible structures.

The group was able to identify the largest sources of underprediction by validating a variety of tools against two data sets, focusing on breaking apart the hydrodynamic load components. Results showed that the modeling approaches underpredicted all load components and attempts to tune models for one condition worsened results for other conditions, which indicates that some physics are missing in the current modeling approach. Further work with higher-fidelity tools is ongoing to understand what physical elements are missing.

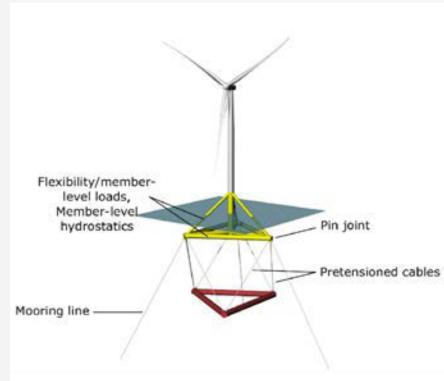
The validation campaign of the OC6-DeepC wind floating semisubmersible with rigid tower at the Maritime Research Institute of the Netherlands will help improve designs of semisubmersible turbine platforms. *Photo by Amy Robertson, NREL*

Demonstration of NREL Modeling Capability to Design Next Generation of Floating Offshore Wind Turbines (TCF)

Point of contact: Jason Jonkman, Jason.Jonkman@nrel.gov WETO 1.4.0.400

New OpenFAST Capability Addresses Impediment to Designing Floating Substructures for Offshore Wind Turbines

New functionality has been introduced in the OpenFAST wind turbine engineering tool for modeling floating substructure flexibility and member-level loads, which helps overcome an obstacle in which OpenFAST could predict global response of a floating substructure but not the structural loads within its individual members. The functionality supports hydro-elastic effects, together with coupling to the wind turbine and mooring system dynamics, for both nonlinear time-domain simulations and full-system linearization about an operating point. The new functionality is being verified and validated for the TetraSpar floating wind system in collaboration with industry partner Stiesdal Offshore Technologies.



New capabilities added to OpenFAST as applied to the TetraSpar. *Image courtesy of Stiesdal Offshore Technologies by Jason Jonkman, NREL*

The preexisting limitation is an impediment to designing floating substructures—especially newer designs that are more streamlined, flexible, and cost-effective, but the new capability in OpenFAST will enable the design and optimization of advanced floating wind technologies. This implementation is part of a larger effort at NREL to develop an open-source, multifidelity systems-analysis capability for floating offshore wind turbine analysis and optimization that captures the relevant physics and costs that drive designs and trade-offs.

Model Test of an Innovative Floating Wind System (TCF)

Point of contact: Caroline Draxl, Caroline.Draxl@nrel.gov WETO 1.4.0.401

East Coast Wind Resource Characterization Gets Boost from Multilab Project

National laboratories including NREL contributed to the development of a Funding Opportunity Announcement (FOA) for offshore wind energy. As part of this collaborative effort, researchers investigated and outlined the research requirements for the FOA, which focuses on two topic areas: improving wind resource modeling and predictions in offshore wind energy development areas, and enabling the demonstration of a novel technology and/or methodology that will advance the state of the art of offshore wind energy in the United States. In conjunction with this effort, NREL, in collaboration with National Oceanic and Atmospheric Administration labs, Argonne National Laboratory, Lawrence Livermore National Laboratory, and PNNL, produced a science plan to guide FOA responders and articulate strategies to address high-priority gaps in our current understanding of meteorological ocean phenomena impacting offshore wind energy production.

By laying the groundwork for this FOA project, NREL helps ensure that field campaign activities directly improve wind resource characterization in the U.S. East Coast offshore wind environment. With these improvements, researchers can incorporate the new understanding into foundational numerical weather forecasting models and other physics-based atmospheric and oceanographic models to improve wind energy forecasts to advance the offshore wind industry.

Offshore Wind Resource Sciences Work

Point of contact: Caroline.Draxl@nrel.gov WETO 1.4.1.401

Research Advances Marine Atmospheric Science and Works To Reduce Offshore Wind Costs and Risks

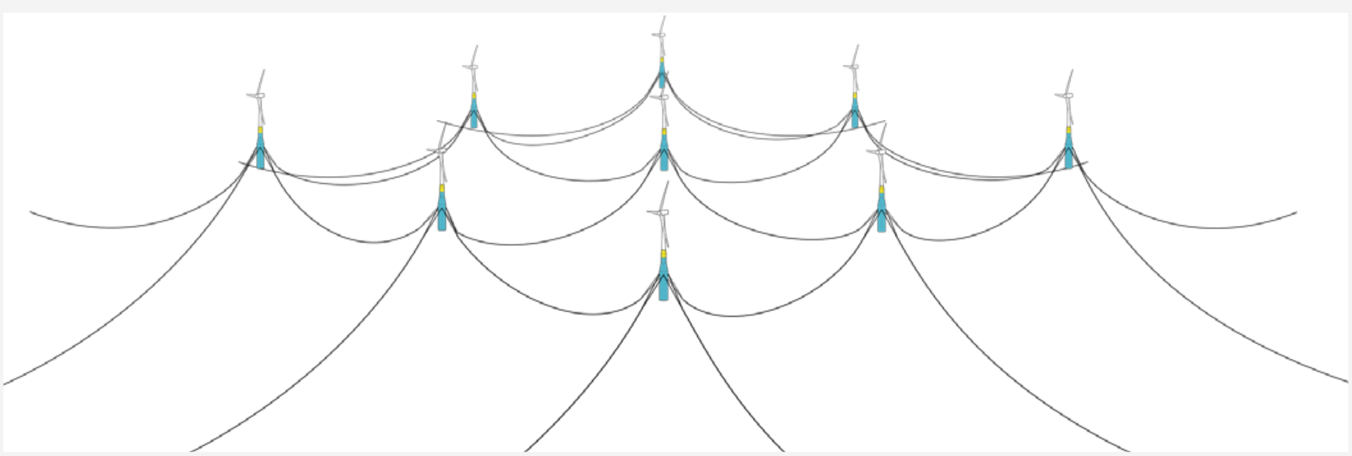
NREL researchers in offshore wind sciences are working to improve resource modeling and forecasting in offshore wind energy development areas. A workshop conducted jointly by NREL and other national laboratories convened representatives from the U.S. and European offshore wind industries, federal agencies, and the academic research community to discuss meteorological and oceanographic research to reduce costs and technology risks through improved offshore wind power resource and site characterization. Discussions provided valuable updates on state-of-the-art resources and techniques for assessing and forecasting wind energy offshore. This information aided in the development of a FOA to improve wind resource modeling and forecasting in offshore wind energy development areas by improving model physics for foundational wind forecasts and other applications in offshore wind energy areas.

Shared Mooring Systems for Deep-Water Floating Wind Farms (NYSERDA)

Point of contact: Senu Sirnivas, Senu.Sirnivas@nrel.gov WETO 1.4.91.401

Shared Moorings Project Explores New Approaches to Mooring System Design

The Shared Mooring Systems for Deep-Water Floating Wind Farms project team is exploring the potential for cost savings for offshore wind by mooring floating wind turbines to each other within an array. As part of this effort, the team created a new quasi-static mooring model, MoorPy, suitable for shared mooring arrays and interfacing with mooring design optimization tools currently under development, which will help provide a first assessment of the concept's feasibility. Using a 600-meter (m) water depth and site conditions based on the Humboldt Bay Call Area, a baseline spar design was sized to support the Technical University of Denmark's 10-MW Reference Wind Turbine, which will be used when exploring new shared mooring system configurations.



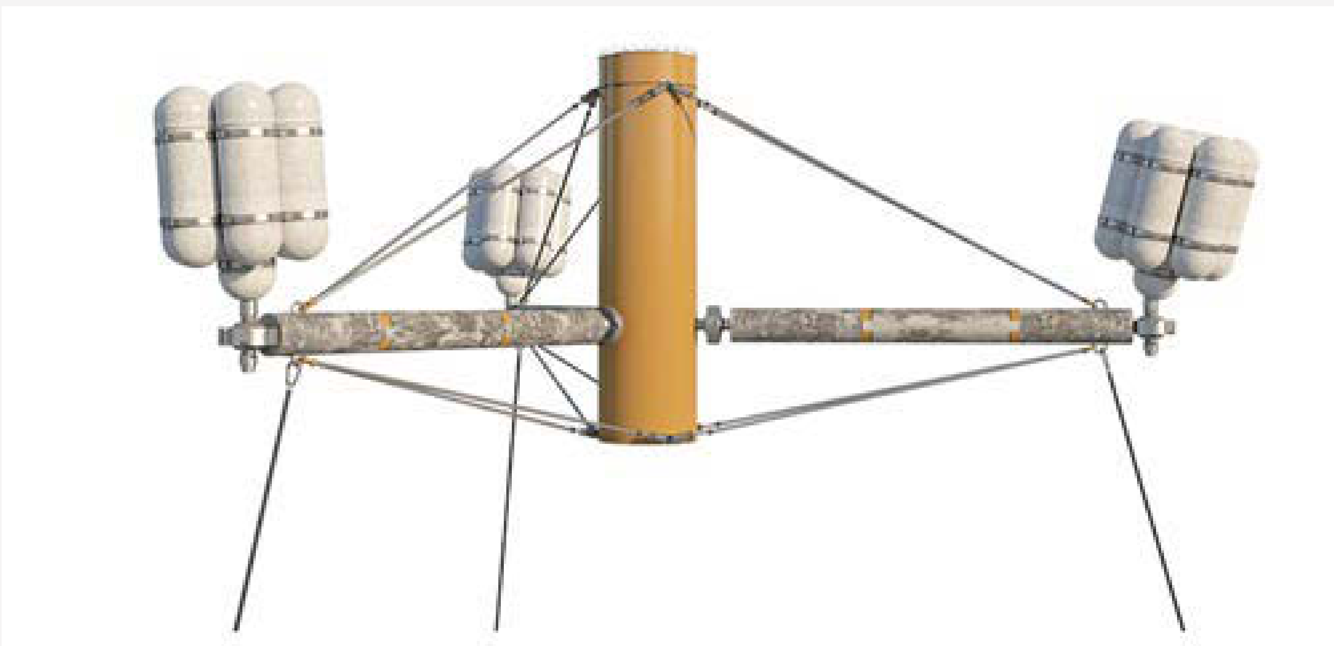
An example floating wind farm design featuring shared mooring lines connecting adjacent platforms. *Illustration by Matthew Hall, NREL*

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

SpiderFLOAT Spins Web of Innovation To Catch More Offshore Wind

An NREL-developed scalable offshore floating wind system, dubbed "SpiderFLOAT" for the system's spider-like components, could help drive down the cost of deep-water wind energy. SpiderFLOAT challenges the existing paradigm of offshore energy production—historically influenced by oil and gas project design—by drastically reconceptualizing what is possible for an offshore wind platform and spinning a web of new innovations to accompany the system. Funds from the Technology Commercialization Fund and Energy I-Corps helped launch SpiderFLOAT as an internal NREL project before becoming part of DOE's ATLANTIS program to develop a 10-MW USFLOWT.

SpiderFLOAT's modular design means it can meet the needs of various offshore wind systems and make it possible to capture the planet's abundant deep-water wind resources more effectively, helping provide more low-cost wind energy to coastal communities.



Named for its spider-like appendages, SpiderFLOAT aims to reduce the cost of energy by combining its scalable offshore floating wind substructure with a 10-MW reference turbine. *Illustration by Josh Bauer, NREL*

Advanced Components, Reliability, and Manufacturing

Fusion Joining of Thermoplastic Composites Using Energy Efficient Processes

Point of contact: Robynne Murray, Robynne.Murray@nrel.gov WETO 1.5.0.403

Bolt of Inspiration Charges Improvements for Lightning Protection System

To help protect thermally welded blades from lightning strikes, NREL researchers designed a 5-m blade tip section and determined the optimum joining methodology to accelerate learning, or "mock weld" the blade. This facilitated the design of a lightning protection system that will be infused into the blade skin. Plans are also underway for additional 1-m two-panel evaluations to accelerate learning in the National Technical Systems (NTS) Pittsburgh Lightning Test Center during the 5-m blade tip strike trial.

Having designed the lightning protection system component and created the mock welding method with materials at NREL's Flatirons Campus, the lab can move toward manufacturing the blade tip section. Once manufactured, researchers can validate the new section at NTS, with the ultimate goal of protecting turbines from lighting strikes in the field.

The team has manufactured panels with lightning protection systems. The panels were mock welded and sent to NTS for testing. The first set of panel tests has been completed by NTS and results are being used to inform the design of a lightning protection system for the 5-m tip section.

NREL researchers designed a 5-m blade tip section to protect thermally welded turbine blades from lighting strikes. *Photo by Andrew Scholbrock, NREL 34113*

This project was delayed because COVID-19 shutdowns and is now anticipated to end December 31, 2020. The team is on track to meet the deliverables to do so.

3D Printed Core Structures for Wind Turbine Blades

Point of contact: Scott Carron, William.Carron@nrel.gov WETO.1.5.0.404

NREL Establishes Online Collaborative Tools To Advance Large-Scale 3D Printing Applications

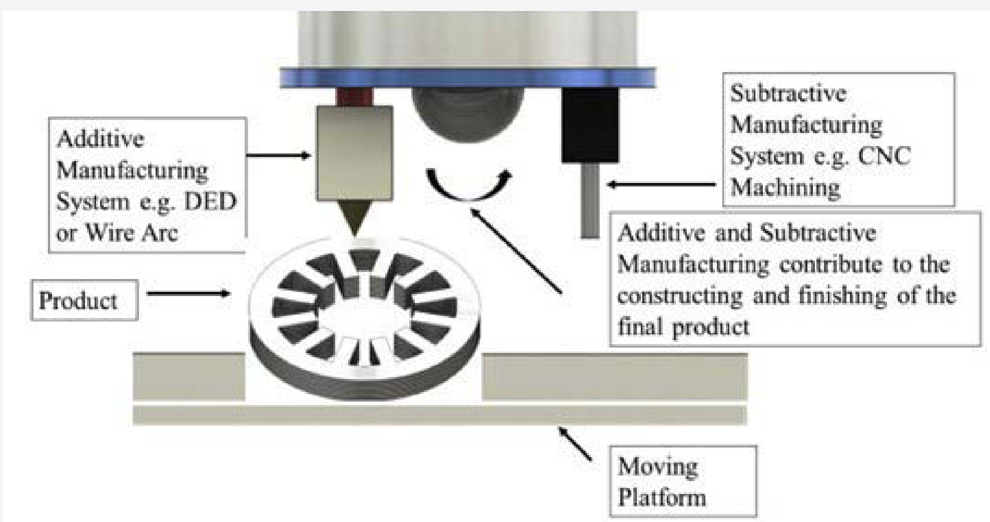
NREL, in collaboration with Oak Ridge National Laboratory (ORNL), launched the 3D-Printed Blade Core Material project at a kickoff meeting held at ORNL's Manufacturing Demonstration Facility. This meeting established how the two labs can share data to advance large-scale 3D printing applications in the wind industry. These data-sharing efforts will help the labs further reduce the levelized cost of wind energy, simplify blade manufacturing processes, and explore how emerging 3D-printing technologies can be used to increase the strength and stiffness of turbine blades with little impact to blade mass.

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

Lighter Wind Turbine Generators Made Possible by Machine Learning and Additive Manufacturing

In FY20, NREL researchers developed a software that utilizes advanced machine learning (AML) algorithms to perform a topology optimization that resulted in alternative 3D printable designs with reduced weight for electromagnetically active parts of the rotor of a radial-flux permanent-magnet synchronous generator. The MADE3D-AML software can generate novel magnetic designs with better distribution of materials that also results in lowest weight, providing a better opportunity for design space exploration. This included replacing existing materials with an air cavity or replacing those portions with lower strength and lighter weight electrical steel or high-performance magnets enabled by a multimaterial design and printing process. Given recent advances in the additive manufacturing of soft and hard magnets—pioneered by team members at ORNL and described in the article "Additive manufacturing of soft magnets for electrical machines—a review"— such complex designs are now possible to manufacture. The MADE3D-AML software has been given a closed-source copyright, whereas the approach to multimaterial design optimization has been specified in an application for a nonprovisional utility patent filed by NREL in US 2020/0188996 A1.

Using this technology, the team evaluated the active materials in the rotor of the direct-drive generator of the IEA Wind 15-MW reference wind turbine. A reduction of over 40% in the mass of the electrical steel was identified with the MADE3D-AML technology. Additive manufacturing cost models are currently being developed, which in FY21 would lead to an evaluation of the capital cost of this optimized generator, the resulting mass benefit in the turbine tower and substructure, and the cost of energy for both fixed and floating wind turbines. The MADE3D technology is applicable to advanced design optimization of both motors and generators used in other industries, in which size and weight of the powertrain are critical. NREL is considering partnerships between the MADE3D team and applicable industries.



NREL's MADE3D-AML software generates designs with better distribution of materials that can be printed using multiple techniques including hybrid manufacturing, as illustrated in the figure. Hybrid manufacturing includes a combination of additive manufacturing methods and computer numerical control (CNC) lathe machines.

Point of contact: Jonathan Keller, Jonathan.Keller@nrel.gov WETO.1.5.2.401

Characterizing Drivetrain Failure Modes Reduces Wind Turbine Operation and Maintenance Costs

Land-based and offshore wind power plant O&M costs are higher than anticipated and at an unacceptable level to operators based on current business models. The objective of the Wind Turbine Drivetrain Reliability Project is to conduct research to characterize main bearing, pitch bearing, and gearbox failure modes and validate technology to increase turbine availability, ultimately reducing wind power plant O&M costs.

Resolving issues like bearing axial cracking and gear tooth micropitting increases drivetrain reliability, turbine availability, and reduces operation and maintenance costs. *Photo by Dennis Schroeder, NREL 49408*

In FY20, NREL researchers published an article in the journal Tribology International. With this model, designers can evaluate the effectiveness of bearing design and lubricant property changes to reduce slip in the rollers of bearings—the predominant failure mode of bearings in wind turbine gearboxes. Furthermore, the model was integrated into an interdisciplinary methodology to conduct a reliability assessment for each individual bearing in each turbine of a wind power plant. This model connects the reliability forecast with turbine design and operations and was validated with 10 years of wind plant operational data and bearing failure records, a process described in another article in the journal Renewable and Sustainable Energy Reviews.

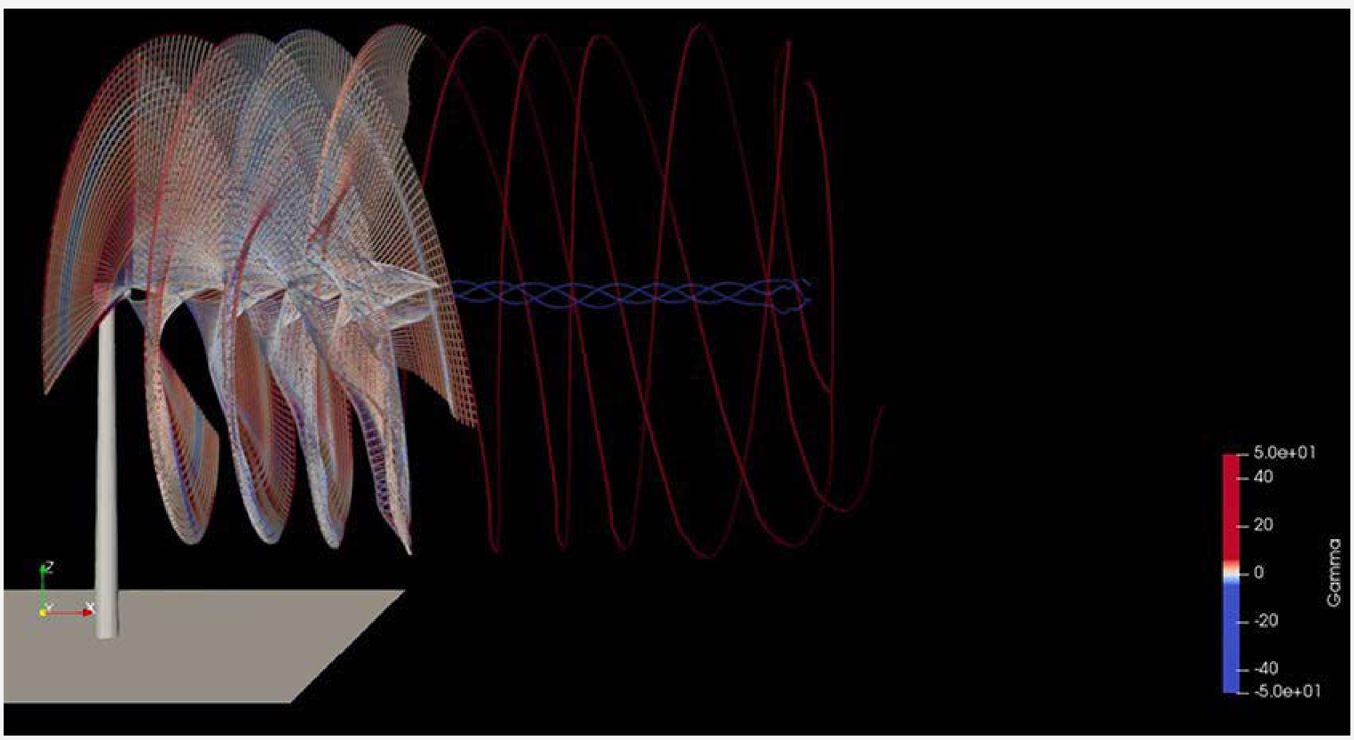
Another important root cause of gearbox failures is gear-tooth micropitting, which was observed in the General Electric (GE) Transportation Systems gearbox installed in the DOE 1.5 turbine. Micropitting is a fatigue phenomenon with many different causes and that manifests itself in many different ways, depending on operating conditions such as load, speed, and operating temperature. Factors such as gear geometry and accuracy, tooth-flank roughness, percentage of tooth sliding, and lubricant composition can also contribute to this phenomenon. With such a wide range of causes and manifestations, micropitting is extremely difficult to predict in service. This information informed a case study, published by the American Gear Manufacturers Association, of the ISO/TS 6336-22 micropitting safety factor method when applied to this and other gear sets that have experienced micropitting in service. The ISO/TS 6336-22 method did not predict the micropitting that occurred because of limitations in the method B for the wind turbine application, which operates at low speeds.

Point of contact: Nick Johnson, Nick.Johnson@nrel.gov WETO.1.5.4.401-0

New Open-Source Modeling Tool Enables Design of Large, Flexible Wind Turbine Blades

NREL released cOnvecting LAgrangian Filaments (OLAF), a new wake module included in NREL's OpenFAST wind turbine simulation tool. OLAF models the turbine wake using particles connected via filaments and is programmed to generate realistic representations of the wakes of large, flexible turbine blades, providing users an alternative to traditional aerodynamic models. Developed by NREL researchers Kelsey Shaler, Emmanuel Branlard, and Andy Platt, OLAF provides a better representation of the physics of turbine wakes produced by highly flexible blades.

As a collaboration with Lawrence Berkley National Laboratory and Sandia National Laboratories, OLAF was initially developed with funding from DOE's Big Adaptive Rotor project. The project seeks to create the next generation of land-based wind turbines with 206-m rotors, which will increase capacity factors by 10% or more over a typical land-based turbine. OLAF is a step forward in helping resolve the science and engineering challenges associated with large, highly flexible blades. Resolving these challenges will facilitate the development of blades that can accommodate the bends and shifts of the railway on their journey to a wind power plant, which is a current barrier for increasing the size of land-based turbine rotors.



This video shows how OLAF uses filaments to represent a turbine's wake. OLAF is programmed to generate realistic representations of the wakes of large, flexible turbine blades, providing users an alternative to traditional aerodynamic models. *Video by Kelsey Shaler, NREL*

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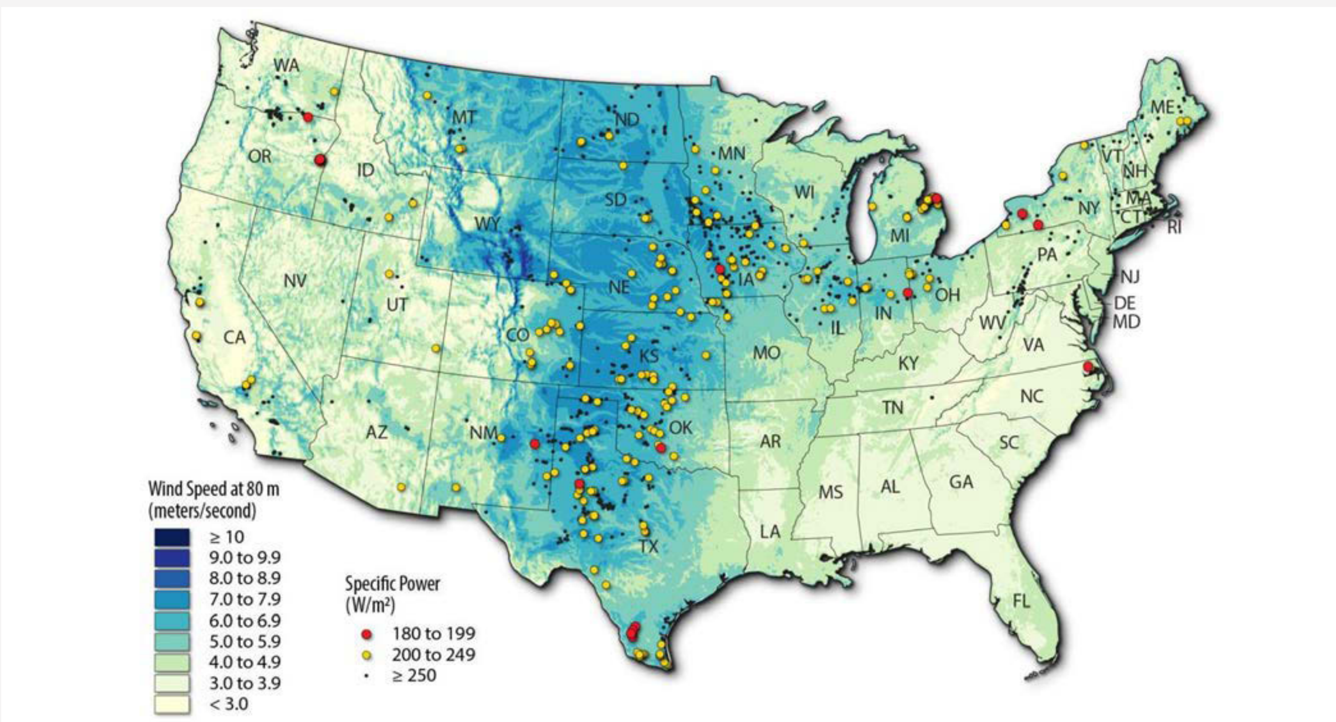
Demand for Low-Specific-Power Turbines Likely To Persist as Wind Penetration Grows

In land-rich but capacity-constrained wind power markets like the United States, developers have an economic incentive to maximize megawatt-hours per constrained megawatt, and so have favored turbines with ever-lower specific power. For the uninitiated, a machine's specific power refers to the relationship between the maximum nameplate capacity—or the amount of total generation plausibly generated by a wind turbine—relative to the swept rotor area of the blades. The larger a turbine's blades get, and the smaller its generator, the smaller its specific power is going to be. To explore whether the trend toward lower specific power machines will continue, NREL researchers employed geospatial LCOE analysis across the United States.

The team found that under reasonable cost scenarios, the demand for low-specific-power turbines may persist. Beyond LCOE, the boost in market value that low-specific-power turbines provide could become increasingly important as wind penetration grows. These results were published in the journal *Wind Engineering*.



Map of wind speed as estimated based on typical meteorological year conditions for the period of 1997–2010. *Graphic by Ryan Wiser and Mark Bolinger, Lawrence Berkeley National Laboratory*

High Efficiency Ultra-Light Superconducting Generator (SCG) for Offshore Wind (DE - 8787) – GE,

Advanced Next Generation High-Efficiency Lightweight Wind Turbine Generator (DE-8788) – AMSC

Advanced Lightweight HE Permanent Magnet DD Generator for Wind Turbine App (DE-8785) – WEG

Point of contact: Jonathan Keller, Jonathan.Keller@nrel.gov WETO.1.5.91.401. WETO.1.5.91.402, WETO.1.5.91.403-0

NREL LCOE Analyses and Modeling Tools Help Reduce the Cost of Wind Energy

As part of the "Advanced Next-Generation, High-Efficiency, Lightweight Wind Turbine Generator" FOAnnouncement projects led by American Superconductor, General Electric Global Research, and WEG Electric Corporation, NREL performed a third-party analysis and forthcoming summary of the key performance indicators for the generators developed by each company. This included a cost of energy analysis comparing advanced generators to a baseline synchronous, permanent-magnet generator, which was developed by NREL for both the reference turbine and a company-specific turbine rating.

NREL researchers also published a technical report, "Definition of the IEA Wind 15-Megawatt Offshore Reference Wind Turbine," in collaboration with the Technical University of Denmark and University of Maine, through IEA Wind. Among many projects, the conceptual design for the IEA Wind 15-MW direct-drive generator was used for the Advanced Lightweight Generator FOA 1981 projects and the annual-operating-plan-funded MADE3D project.

NREL researchers will use the IEA Wind 15-MW direct-drive generator design to help reduce the cost of offshore wind energy. *Graphic by Joshua Bauer, NREL; photo by Werner Slocum, NREL*

Standards Support and International Engagement

Point of contact: Jeroen van Dam, Jeroen.van.Dam@nrel.gov WETO 1.6.1.401

International Wind Energy Standards Development Leadership Extended Through 2024

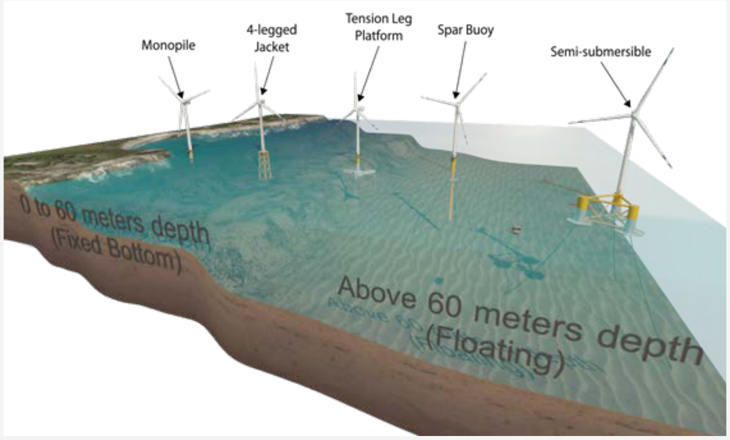
Demonstrating their confidence in his leadership, the Standards Management Board of International Electrotechnical Commission Technical Committee 88 (TC 88) voted to approve a 3-year extension of Jeroen van Dam's position as IEC TC 88 Chair through May 2024. Under van Dam's leadership, IEC TC 88 has created the IEC 61400 series of standards, which span the lifecycle of wind energy power plants and cover designs ranging from kilowatt-sized distributed wind turbines to offshore turbines of 10 MW and larger. About 1,000 appointed wind experts from 32 countries actively participate in standards development through TC 88.

Picture-perfect representation. Van Dam (right) stands tall as a leader among an international body of members who ensure standardization in the field of wind energy generation systems including wind turbines, land-based and offshore wind power plants, and interaction with the electrical system(s) to which energy is supplied. *Photo by Dennis Schroeder, NREL*

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

U.S. Wind Energy Standards Summit Explores Standards for Offshore Wind Deployment

NREL collaborated with the American Renewable Energy Standards and Certification Association to organize the annual U.S. Wind Energy Standards Summit in San Diego. Approximately 40 industry stakeholders (including representatives from original equipment manufacturers, owner/operators, insurance companies, consultants, universities, national laboratories, and government organizations) participated in the event, which informed future design requirements for offshore wind with a U.S.-specific lens. By setting forth standards for offshore wind including consideration of issues like hurricanes, or floating systems related to water depth, the greater the chance that wider offshore wind deployment will take hold in the United States.



Above a water depth of 60 m, floating offshore wind turbine platforms become more common than their fixed-bottom cousins, but they face challenges. NREL helped organize the U.S. Wind Energy Standard Summit to address U.S.-specific offshore wind issues, such as hurricanes. *Illustration by Josh Bauer, NREL*

Grid Intergration

North American Renewable Integration Study

Point of contact: Greg Brinkman, Gregory.Brinkman@nrel.gov WETO 3.1.0.409

NREL Completes Landmark Study of North American Power System Modernization

NREL completed analysis for two major components of an examination of the interconnection of U.S., Canada, and Mexico power systems that is the largest study of its kind from a geographical standpoint. A collaborative effort of Natural Resources Canada, Secretaría de Energía, and DOE's Grid Modernization Initiative, the North American Renewables Integration Study explores the potential to build a modern, reliable grid through increased use of wind, solar, hydropower, and other technologies across North America.

The North American Renewables Integration Study examined how renewable energy sources such as wind and solar could help create a power system across North America. *Photo by Dennis Schroeder, NREL 62227*

NREL researchers finished their analyses of Canadian and U.S. perspectives of the continental-scale power system and completed associated draft reports. Technical review of these reports will be conducted over the next several months. NREL also made available new open-source tools and data for stakeholders to use. Follow-on work with Mexico is also possible.

Atmosphere to Electrons to Grid (A2e2g)

Point of contact: David Corbus, David.Corbus@nrel.gov WETO.3.1.0.417

Optimized Wind Plant Controller Could Maximize Grid Services and Lower LCOE

NREL researchers created a platform for a new optimized wind plant controller (or "optimizer") that maximizes energy output while valuing provision of grid services. The optimizer is being demonstrated at NREL's Flatirons Campus grid integration research facility for different turbine and plant controls, integrating wake management, real-time measurements, grid services for different markets, short-term forecasts, and plant power output.

This novel wind power plant optimizer provides for maximum energy and full grid services under any aerodynamic condition and can lead to a lower LCOE by increasing the value of the power output of a wind plant.

Wind Grid Integration Stakeholder Engagement

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NREL Unveils Probabilistic Resource Adequacy Suite

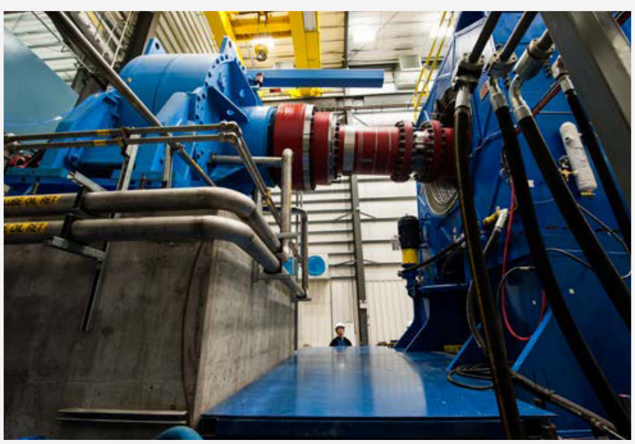
NREL researchers presented their Probabilistic Resource Adequacy Suite at a North American Electric Reliability Corporation forum, highlighting key aspects of the lab's groundbreaking work in adapting and developing new probabilistic methods and tools in anticipation of the needs of a future with higher penetrations of variable resources like wind power.

This work draws on NREL's activity in probabilistic assessment, which has been conducted for many key long-term studies that characterize future power systems. It allows NREL to assist NERC in accessing future sources of resource adequacy risk for systems with high amounts of wind power, which makes it possible to evaluate the reliability of future wind scenarios and realize a resilient, reliable future power grid.

NREL's probability assessment work makes it possible to evaluate the reliability of future wind scenarios and help ensure a resilient, dependable future power grid. *Photo by Dennis Schroeder, NREL 55200*

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

Point of contact: Shahil Shah, Shahil.Shah@nrel.gov WETO.3.1.0.420



NREL and GE partnered to develop an effective power-domain impedance theory that could help prevent blackouts. Researchers conducted experiments on a 4-MW wind turbine drivetrain, similar to the one in this photo, to analyze active and reactive power oscillations in wind power plants. *Photo by Dennis Schroeder, NREL 28250*

Wind Power Plant Electrical Oscillations Analysis Theory Proves Effective

NREL researchers, in partnership with GE, conducted experiments on a 4-MW wind turbine drivetrain to analyze active and reactive power oscillations in wind power plants. Their work resulted in a power-domain impedance theory, which proved to be effective for analyzing and mitigating wind power plant low-frequency oscillations similar to those at a United Kingdom offshore wind power plant that caused a major blackout event in August 2019. The theory could also help prevent the loss of bulk generation from wind during grid events, thereby increasing grid flexibility to achieve higher penetration levels for wind energy.

In addition, the team developed a research platform for evaluating and mitigating impacts of a wind power plant on the stability of a bulk power system and published a journal article with GE in *Frontiers in Energy Research*.

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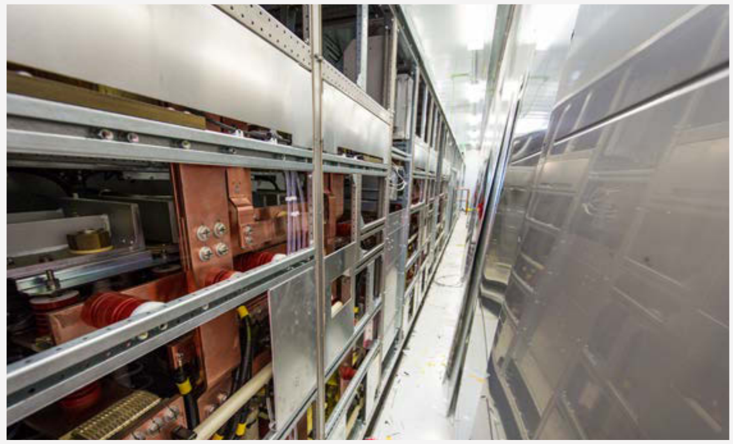
NREL Creates First Wind Turbine Impedance Measurement System

NREL has developed an impedance measurement system that is the first of its kind worldwide to characterize the electrical behavior of multimegawatt wind turbines and inverters at different frequencies. The system leverages a 7-MW grid simulator and Global-Positioning-System-synchronized, medium-voltage data acquisition system at the Flatirons Campus to measure wind turbine impedance responses.

The impedance measurement platform will help evaluate different dynamic stability problems, including subsynchronous, supersynchronous, and near-synchronous resonance problems; serve as a platform for high-fidelity model validation; and support the development of new technologies, such as grid-forming wind turbines.



NREL's controllable grid interface (shown here), which is the centerpiece of the laboratory's grid integration testbed, was used to develop the world's first wind turbine impedance measurement system. *Photo by Dennis Schroeder, NREL 27442*

Wind Power as Virtual Synchronous Generation (WindVSG)

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NREL collaborative research proves that wind power plants have the necessary controls in place to supply essential reliability services to the electric grid. *Photo courtesy of Avangrid Renewables*

Demonstration Shows Wind Energy Can Help Maintain Reliable Grid

NREL collaborated with Avangrid Renewables, the California Independent System Operator, and GE on a 3-day evaluation to show that utility-scale wind power plants can provide essential grid services that ensure smooth and continuous flow of electricity on the power grid.

The demonstration, conducted at Avangrid's 131-MW Tule Wind Farm in Southern California, proved that wind resources, like solar, can be used to actively manage the electric grid with higher levels of renewable generation. The findings will inform future research on the use of inverter-based resources to increase the variety of reliability services and accelerate progress toward a sustainable electric grid.

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Interarea Oscillation Damping Could Improve Power Grid Stability

NREL researchers published a journal article on the potential for wind power plants to damp interarea modes, which can cause power system oscillations, system instability, and blackouts.

The research, which was conducted in partnership with GE, found that power conversion devices, particularly megawatt-scale converters that connect wind turbines and photovoltaic power plants to the grid, could be used to damp these oscillations and improve grid stability. By injecting power into the system out of phase with the potentially unstable mode, this power can be provided by a wind power plant without affecting the plant's energy production.

NREL research determined that power conversion devices that connect wind turbines and photovoltaic power plants to the grid could be used to improve grid stability by minimizing power fluctuations. *Photo by Dennis Schroeder, NREL 62260*

North American Energy Resiliency Model (NAERM)

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First-of-Its-Kind Wind Resource and Power Forecasting Model To Improve Energy Resilience

NREL created the first iteration of the wind and solar resource and power forecast as a service to the North American Energy Resiliency Model (NAERM), which will be a first-of-its-kind tool to improve energy resilience and national security. This first iteration featured day-ahead forecasts for all wind generator sites across the 48 contiguous United States using a numerical weather prediction model, assumed an initial power curve of a GE 1.5-MW wind turbine across all sites, converted wind resource into power depending on atmospheric conditions, and created an automated set of scripts that linked these processes together for eventual deployment on cloud services.

The automated scripts are designed to run once a day to align with the load forecasts and eventually will be visualized on the NAERM dashboard.

Point of contact: Gregory Brinkman, Gregory.Brinkman@nrel.gov

Polar Vortex Impacts Can Be Additive, Analysis Shows

After completing the first phase of the NAERM, the NREL team presented the lab's modeling of the bulk electric system with impacts from extreme events—particularly polar vortex events. The model used information from DOE and industry to appropriately capture loss of wind turbines, gas pipelines, and other infrastructure.

The modeling showed that the potential impacts of a polar vortex can be additive, causing reductions in gas availability, reductions in wind availability (as a result of low-temperature or icing cutouts), and the inability to precisely forecast reductions that contribute to potential unserved energy.

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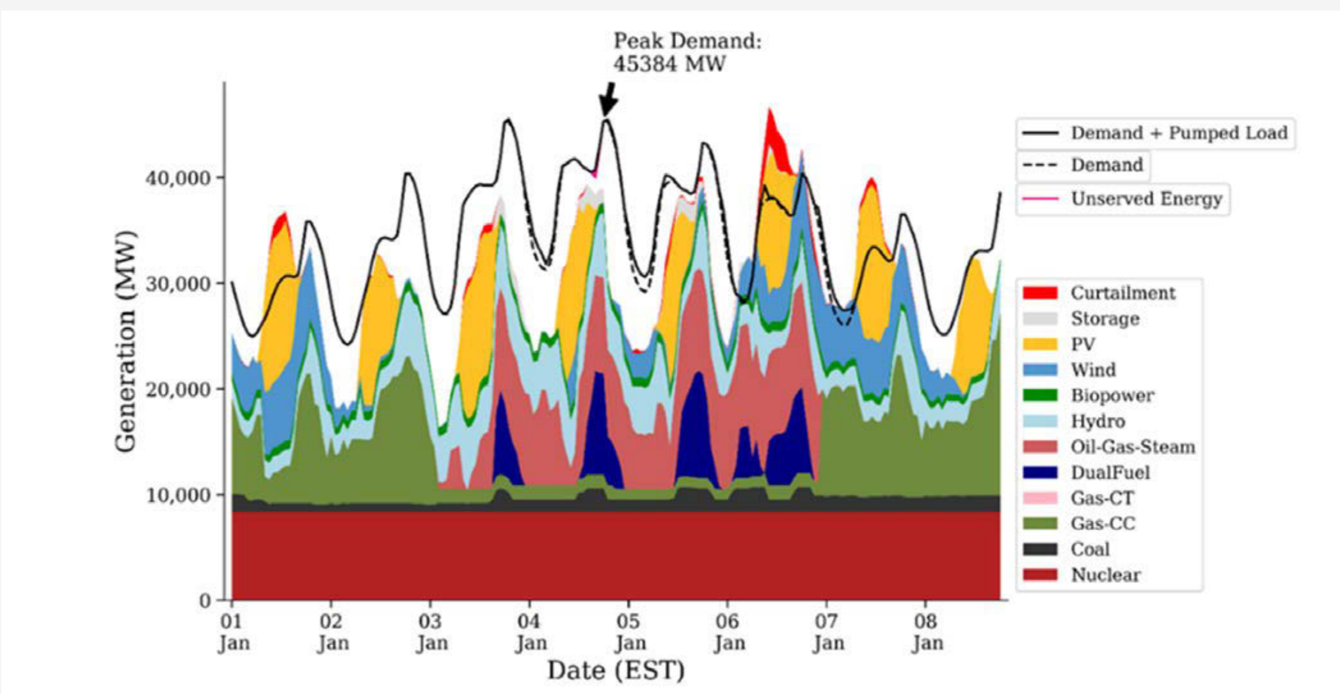
Modeling Visualization Showcased at House Energy and Water Appropriations Committee

In a presentation to the House Appropriations Committee on the FY21 DOE proposed budget, Office of Electricity Assistant Secretary Bruce Walker presented an NREL grid modeling visualization of a polar vortex visualization video. Walker had a brief exchange with Chairwoman Marcy Kaptur, who emphasized the need for such visualizations to communicate complex energy concepts to the American people.

By presenting this graphic to the committee, Walker demonstrated NREL's cutting-edge visualization work, which can provide essential data and information to those making critical decisions about the U.S. energy grid.



Graph of the modeled dispatch during a 2019 polar vortex event that affected the Northeastern United States. *Image by Daniel Levie, NREL*

Mitigating Market Barriers

Point of contact: Cris, Hein, Cris.Hein@nrel.gov WETO.3.3.0.401

Collaborating with International Partners To Resolve Wind Energy and Wildlife Interactions

NREL's 4-year extension proposal for Task 34-Working Together to Resolve Environmental Effects of Wind Energy, or WREN, was approved by the IEA Wind TCP. WREN leverages international perspectives and research to support the deployment of wind energy technology around the globe through a better understanding of environmental issues, particularly those related to wildlife, efficient monitoring programs, and effective mitigation strategies.

NREL's Task 34 WREN leverages perspectives and research to support understanding, monitoring, and mitigation of wind energy interactions with wildlife like the hoary bat pictured here. *Photo by Kathleen Smith, Florida Fish and Wildlife Conservation*

Since its inception, WREN has conducted 16 webinars, distributed 7 fact sheets or short science summaries, and published 2 journal articles and 2 technical reports. WREN also manages the Tethys knowledge base. Going forward, WREN will continue to 1) identify priority international needs for further research, 2) aggregate, synthesize, and disseminate information on the global state of the science and recommended practices, and 3) assess the technical readiness and effectiveness of solutions and explore the feasibility of transferring technologies and practices across jurisdictions.

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Researchers Explore if Wind Turbines Cause Barotrauma in Bats

The perception that wind turbines cause barotrauma (harmful exposure to rapid pressure variation) in bats persists in the published literature and news media. NREL researchers investigated the likelihood of this phenomenon by performing a computational fluid dynamics simulation of a wind turbine and analytical calculations of blade-tip vortices to estimate characteristics of the sudden pressure changes bats may experience.

Research results indicate that for bats to experience the largest possible magnitude of low or high pressures, they would almost assuredly collide with the blade. This finding, paired with publications documenting the physiological evidence of blunt-force trauma by wind turbines to bats, suggests that barotrauma is unlikely to be a significant contributor to bat mortality at wind energy facilities. These findings are to be published in a forthcoming publication.

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

Conserving Grouse Species and Advancing Wind Deployment

In partnership with the American Wind Wildlife Institute and Western Ecosystems Technology, Inc., researchers conducted a meta-analysis of 10 studies of grouse behavior near wind turbines. The team's findings informed a technical report for the National Wind Coordinating Collaborative that will soon be submitted to a journal. The technical report and additional studies can be used to inform siting decisions that avoid, minimize, or mitigate impacts to grouse and their habitat.

Grouse populations benefit from large, intact, and undisturbed habitats; they are adversely affected by the influence of humans on the natural environment, but there is uncertainty as to the extent and magnitude of the impact caused by wind energy development. Through their meta-analysis, researchers found that grouse habitat selection, survival, and lek attendance (where courtship behaviors are displayed) were negatively impacted in habitats near wind turbines. However, the magnitude of the effect was small and variable across studies.

Increasing our nation's wind energy infrastructure in ways that protect and conserve wildlife depends on finding solutions to wind-wildlife challenges that are scientifically sound and statistically valid. A meta-analysis of 10 studies of grouse behavior in habitats near wind turbines indicates negative impacts but is inconclusive regarding the magnitude of those impacts. *Photo by Tom Kerner, United States Fish and Wildlife Service*

Wind Turbine Curtailment Field Test

Point of contact: Cris Hein, Cris.Hein@nrel.gov WETO 3.3.0407-0

Technology Could Reduce Both Impacts on Bats and Unnecessary Curtailment

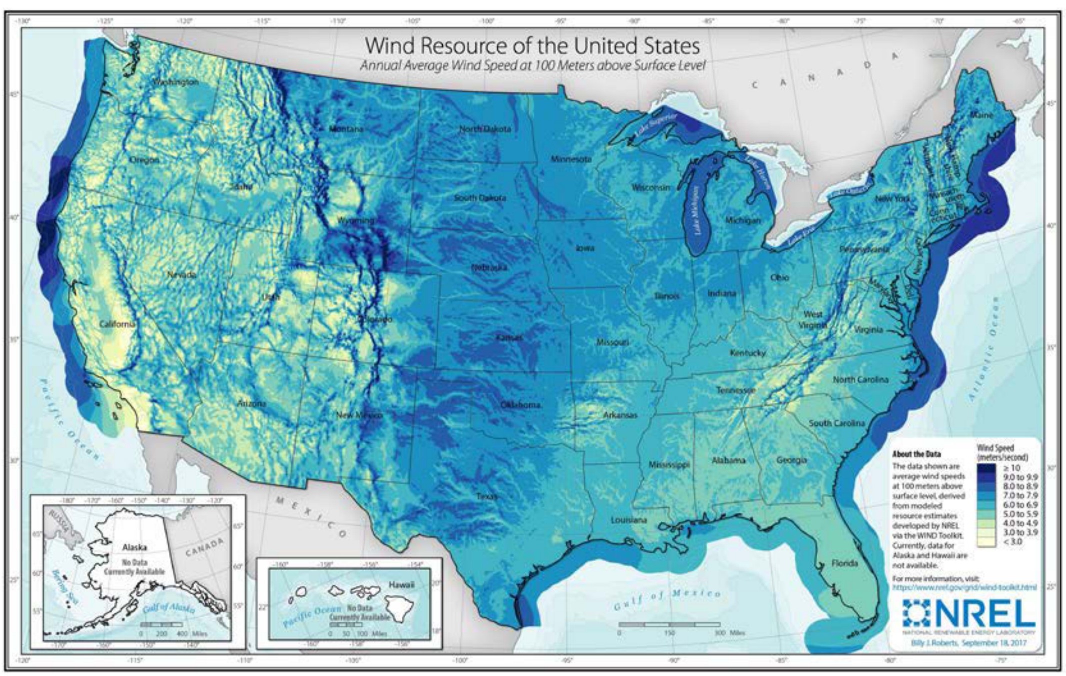
To develop smart curtailment methods that use additional variables to limit curtailment to the highest periods of risk, NREL is working with the Electric Power Research Institute and Natural Power to develop the Turbine-Integrated Mortality Reduction system and the Bat Smart Curtailment system, respectively. These technologies use real-time data on bat presence and wind speed to determine whether a turbine should be curtailed. Once completed, these systems will reduce both impacts on bats and unnecessary curtailment while reducing loss in annual energy production (AEP).

Point of contact: Mary Hallisey, Mary.Hallisey@nrel.gov WETO 3.4.0.401 WIND

Rollout of New 100-Meter Wind Resources Maps

NREL recently announced the first release in a series of new and improved wind resource maps. The initial suite covers the Northeast region of the United States. Land-based maps are available for Vermont-New Hampshire, Massachusetts-Connecticut-Rhode Island, Maine, and New York, and new offshore wind resource maps are available for the Gulf of Maine (Maine-New Hampshire-northern half of Massachusetts) and New York-Connecticut-Rhode Island-Massachusetts. Built on the foundation of the Wind Integration National Database (WIND) Toolkit, which was developed by NREL, these maps provide a comprehensive picture of the wind speed at 100 meters above surface level for stakeholders to better understand the wind resource potential in the Northeast.

The ability to assess and characterize available wind resources is critical to the development, siting, and operation of a wind power plant. WETO supports efforts to accurately define, measure, and forecast the nation's land-based and offshore wind resources. In support of these efforts, NREL has produced offshore and land-based wind speed maps for many years. Offshore wind resource maps are especially important now: with a significant percentage of the U.S. population living along a coast adjacent to an ocean or one of the Great Lakes, there are strong economic incentives for exploring offshore wind development near coastal communities. These incentives may include revenue for communities, temporary jobs, and lower cost of energy for consumers. NREL's wind resource maps can help stakeholders understand the potential for wind energy development in their area.



Graph of the modeled dispatch during a 2019 polar vortex event that affected the Northeastern United States. *Image by Daniel Levie, NREL*

Point of contact: Mary Hallisey, Mary.Hallisey@nrel.gov

Rollout of New WINDExchange National Strategy

In FY20, the NREL WINDExchange team developed a national strategy to mitigate barriers associated with wind energy siting and planning. Targeted for launch in FY21, the strategy will help address a myriad of impacts that intersect with community values, risk assessment, and planning processes. Outcomes will include an expanded network of experts and decision makers with the information resources needed to make informed decisions. The WINDExchange program will focus on six priority challenges: Lifecycle considerations

- Technically sound information
- Offshore wind energy technologies
- Technology today
- Economic development
- Balancing the impacts of community planning and decision-making.

Turbines at the Block Island Wind Farm. *Photo courtesy of Mary Hallisey, NREL*

Stakeholder engagement activities and development of information resources conducted by WETO focus on providing science-based information to help communities make informed decisions about wind energy deployment. Since the WINDExchange regional effort ended in 2018, the NREL team has been transitioning to a national strategy that examines priority wind energy issues so communities can accurately assess the appropriate deployment of this clean energy resource by providing fact-based, credible information on which to base their planning and siting decisions. The lack of fact-based information outside of WINDExchange has the potential to increase the LCOE and result in development projects being scaled back, delayed, or denied. Providing information resources to community officials facing complicated decisions provides a pathway for community values to be integrated with their energy mix to increase project acceptance and local economic viability.

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Collegiate Wind Competition Organizers Transition to Virtual Format and Select 2021 Teams

Collegiate Wind Competition (CWC) organizers, led by NREL, facilitated the competition's move to a virtual format to accommodate health concerns related to a pandemic. Organizers also selected the university teams that will participate in the 2021 competition, including 10 returning teams and three new teams.

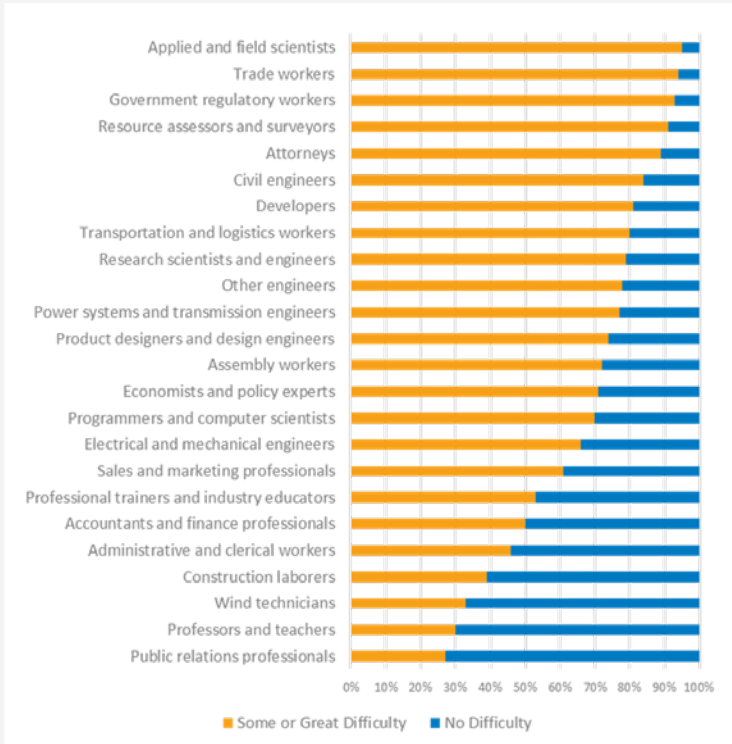
The CWC provides an opportunity for college students to link academic coursework with tangible, hands-on, collaborative learning. Through the competition, students gain valuable real-world experience as they prepare to enter the workforce, ideally the wind energy workforce. Many CWC alumni who now work in the wind industry attribute much of their success in finding a job in this industry to the experience they gained from the event; individuals like Alana Benson.

The Collegiate Wind Competition provides college students with the real-world experience needed to enter the wind industry workforce. Organizers moved the competition to a virtual format and selected the 13 university teams that will participate in the 2021 CWC. *Photo by Werner Slocum, NREL*

Point of contact: Jeremy Stefek, Jeremy.Stefek@nrel.gov WETO.3.4.0.403

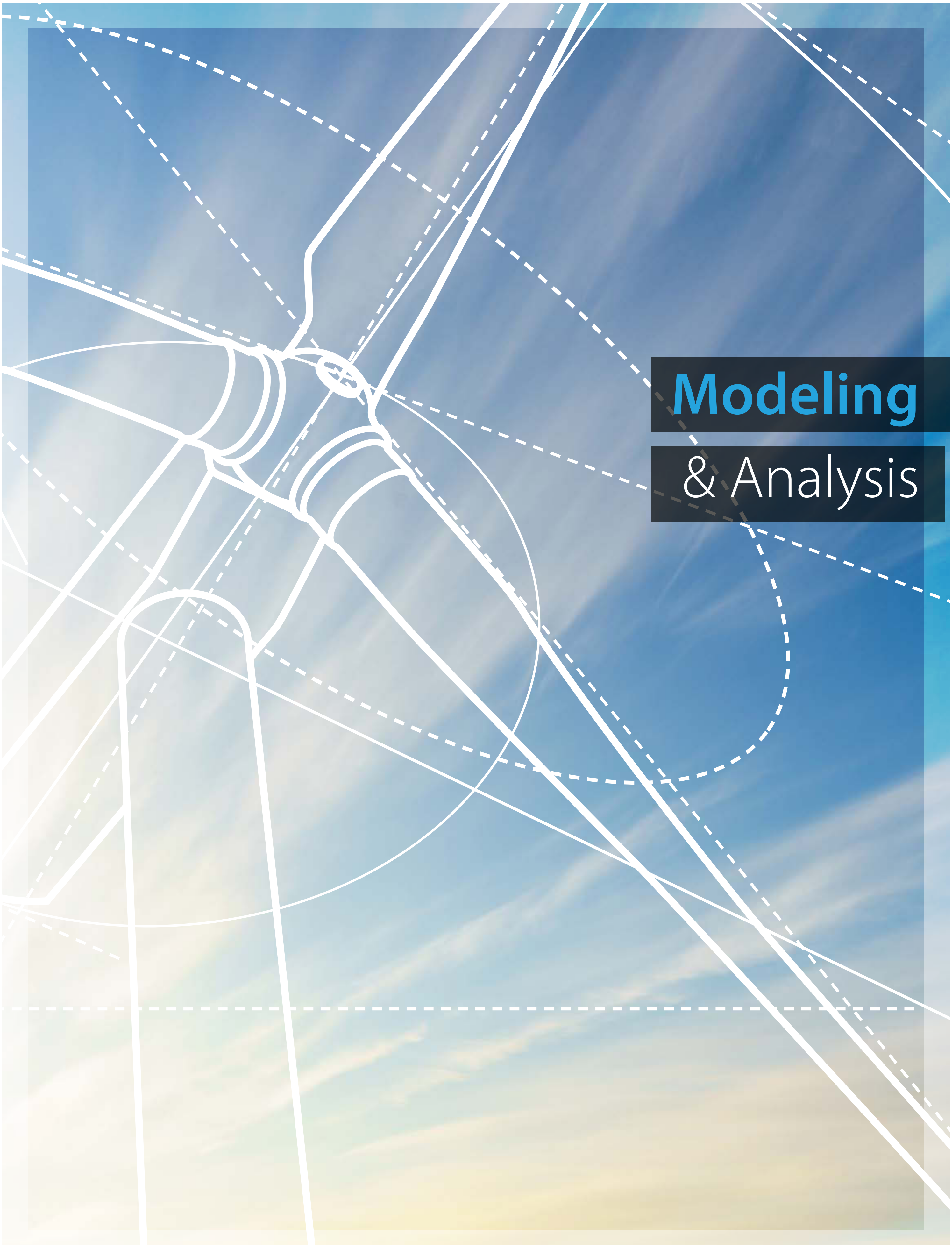
NREL Researchers Survey Wind Industry To Better Understand Wind Workforce Gap

NREL researchers surveyed wind industry employers and the potential workforce (i.e., students and recent graduates) to understand the industry's needs, awareness of U.S. wind educational programs, and hiring processes, and to gather students' and recent graduates' perspectives on the difficulty of finding jobs and interest in the industry as part of an effort to address the wind energy workforce gap. Survey results showed that students and job seekers are more interested in careers in wind energy than other industries but also need assistance connecting to wind energy employers. Furthermore, participating in a DOE-sponsored wind energy program, such as Wind for Schools or the CWC, will make students two times more likely to work in the wind energy industry than those who do not participate.



The difficulty of employers identifying well-qualified candidates while wind and renewable energy graduates report difficulty finding jobs in the wind industry suggests a potential gap in the wind industry workforce that the survey helps uncover. *Graphic by Jeremy Stefek, NREL*

NREL received approximately 300 responses from industry and 770 responses from students and recent graduates. The top reasons employers cited as challenges to finding qualified entry-level applicants included lack of training and education (30%), and lack of experience (28%). Meanwhile, students and recent graduates with experience seeking entry-level work in the wind industry cited difficulty getting relevant industry experience (67%), the geographic location of jobs (67%), and getting hands-on training specific to the wind energy industry (62%) as obstacles to entry. The results of this research will be shared with industry, educational institutions, and the potential workforce to provide insights on the primary reasons for the land-based wind workforce gap and to find solutions to bridge the gap through workforce development programs.



Modeling & Analysis

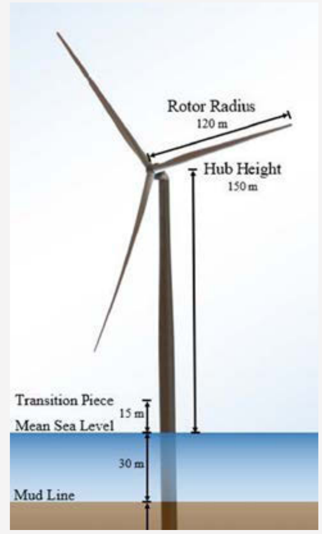
Point of contact: Garrett Barter, Garrett.Barter@nrel.gov WETO.4.1.0.401

Offshore Wind Reference Turbine Accelerates Development of Offshore Wind Systems

NREL led an international research team to develop an open-source conceptual design for a 15-MW offshore reference wind turbine with a fixed-bottom monopile support structure. The IEA Wind 15-MW reference wind turbine can be used by researchers, original equipment manufacturers, and project developers to explore new technologies or design methodologies that lower costs, improve performance, and reduce project risk. As these innovative designs are applied to the same reference turbine, their relative impact can be evaluated to identify the most promising pathways for expanded offshore wind deployment.

Policymakers and analysts can use the reference turbine to estimate future costs and deployment scenarios as well as associated infrastructure needs. In addition, the IEA Wind 15-MW reference turbine provides a valuable educational tool to help wind industry newcomers understand the challenging trade-offs and design optimizations inherent to wind turbines.

The project culminated in an IEA Wind report that summarizes the results.



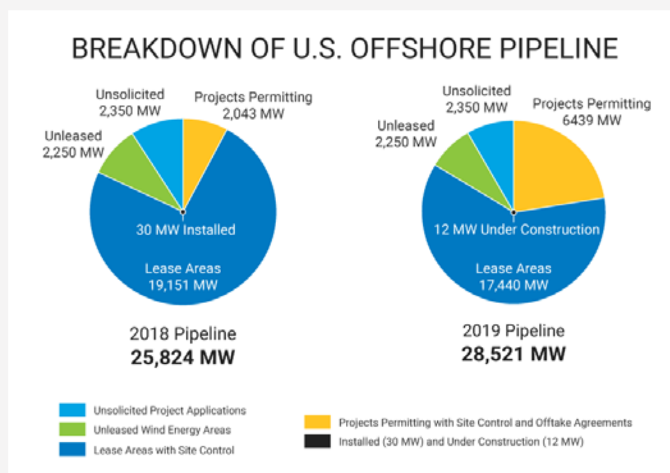
An artistic rendering of the IEA Wind 15-MW reference turbine. The open-source offshore wind turbine design allows wind industry contributors to share their designs and innovations with other researchers to accelerate technological development.

Point of contact: Walt Musial, Walt.Musial@nrel.gov

Offshore Wind Data and Trends Reflect Accelerated Growth

NREL researchers analyzed 2019 global offshore wind market, technology, and cost trends to develop the "*2019 Offshore Wind Market Data Update*. Their research found that global installed offshore wind capacity grew by 19% in 2019, reaching 27,064 MW, with a U.S. project pipeline of 28,521 MW. Turbine size grew as well—from a capacity-weighted average of 3.5 MW in 2010 to 6 MW in 2019, with industry announcements of new prototypes indicating this average will increase to 10 MW by 2025. Industry analyst projections estimate that the LCOE of fixed-bottom offshore wind will continue to decline to a range of $50/MWh to $75/MWh by 2030.

Collected yearly since 2015, NREL's offshore wind research provides objective, up-to-date information about offshore wind in the United States and worldwide.

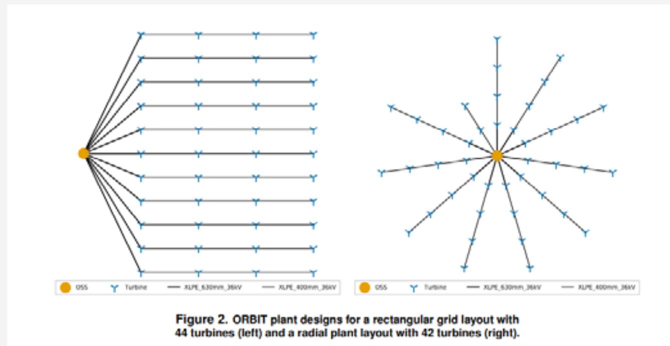


The U.S. offshore wind project pipeline grew more than 10% between 2018 and 2019. *Graphic by NREL*

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

New Modeling Tool ORBIT Enables Assessment of U.S. Offshore Wind Power Plant Balance-of-System Costs

NREL developed a new open-source modeling tool that enables project developers to evaluate balance-of-system (BOS) costs for offshore wind power plants—such as project characteristics, technology solutions, and installation methodologies. The Offshore Renewables Balance-of-system and Installation Tool (ORBIT), available on GitHub, provides a bottom-up approach to modeling all construction and installation costs outside of the capital expenditure of the turbine itself. ORBIT captures key drivers of offshore wind project decisions by considering cost trade-offs of major components, weather delays during installation, exclusions resulting from marine mammal migration, operational constraints and capabilities of individual vessels, and quayside production and assembly restrictions.



ORBIT plant designs for a rectangular grid layout with 44 turbines (left) and a radial plant layout with 42 turbines (right).

The tool provides current information critical to supporting decision-making for state policy and private-sector investments, which is important for understanding the market trajectory of offshore wind in the United States. NREL researchers describe ORBIT in this technical report.

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Land-BOSSE Identifies Further Cost-Savings Opportunities

NREL's open-source Land-based Balance of System Systems Engineering (LandBOSSE) model helps users estimate BOS costs for land-based wind power plants and explore how various design parameters, labor and equipment rates, and other factors might change those costs. NREL researchers executed thousands of scenarios with LandBOSSE to explore how five key wind power plant parameters—turbine rating, hub height, plant size, labor rate, and terrain complexity—affect BOS costs for land-based wind plants.

LandBOSSE helps users explore potential opportunities for reducing a wind project's total investment costs, including labor costs. *Photo by Dennis Schroeder, NREL 53924*

Results show that increasing the size of a baseline plant from 150 MW to 400 MW could reduce BOS costs by 21%. In addition, because foundation and erection costs scale appreciably faster than all other types of land-based BOS costs, advancements in erection and foundation technologies (e.g., alternative tower or foundation designs) present greater opportunities for reducing BOS costs as wind plant sizes and turbine ratings increase. For example, if foundation costs decreased by 50%, building a wind plant with 5-MW turbines (with rotor diameters of 166 m and hub heights of 120 m) could decrease LCOE by 5%.

Point of contact: Parangat Bhaskar, Parangat.Bhaskar@nrel.gov

LandBOSSE Extension Enables Deep Dive into Distributed Wind Balance-of-System Costs

NREL expanded its open-source LandBOSSE model to accommodate 15-kW to multimegawatt distributed wind projects, whose BOS costs can make up half of their total capital expenditures. The model's extension into distributed wind now enables users to estimate total BOS costs using a combination of user-defined inputs, such as project road length, distance to interconnection, and hub height. LandBOSSE can estimate costs of individual components like foundation, site preparation, and project management, and dive even deeper into cost of labor, material, equipment rental, mobilization, and more. This ability enables users to explore opportunities for innovations and BOS cost reductions.

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

Building from LandBOSSE, HybridBOSSE Allows Estimates of Potential Costs Savings at Hybrid Wind Power Plants

NREL used the LandBOSSE architecture as the basis to develop Hybrid Balance-of-System Systems Engineering (HybridBOSSE), a new tool that can be used to estimate potential BOS cost savings at hybrid wind power plants. Hybrid plant designs—such as those that use wind and solar and battery storage systems—have the potential to increase the value of renewable energy systems and lower their BOS costs through shared infrastructure. Prior work has identified potential cost savings at solar PV + storage plants and the technical and economic performance of solar PV + storage plants. However, additional work is needed to understand cost drivers that are specific to hybrid wind plants.

The HybridBOSSE model, which is still under development, currently includes Storage Balance-of-System Systems Engineering (StorageBOSSE) and Solar Balance-of-System Systems Engineering (SolarBOSSE) modules and is able to execute LandBOSSE. SolarBOSSE is a bottom-up, component-based BOS cost model for solar PV and StorageBOSSE currently models the BOS costs of battery storage. The modular, integrable model design of HybridBOSSE will allow it to be extended to include other energy technologies and integrate with other projects or tools in the future. The model is also scalable and can be used to explore a wide range of plant sizes and hybrid scenarios. Preliminary results from HybridBOSSE (under baseline cost assumptions) indicate that BOS costs per kilowatt would be reduced by 10% for a co-located 100-MW wind and 100-MW solar PV hybrid, versus two independent (not co-located) 100-MW wind and 100-MW solar PV plants.

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

Levelized Cost of Wind Energy Continues Downward Trend

To provide insight into current component-level costs as well as a basis for understanding variability in the LCOE across the country, NREL researchers used representative utility-scale wind projects to estimate the LCOE for land-based and offshore wind power plants in the United States.

The team found that LCOE estimates continue to show a downward trend from the ***2010 Cost of Wind Energy Review.*** These findings were published in NREL's ***2018 Cost of Wind Energy Review***.

NREL's analysis of the cost of wind energy in 2018 shows a downward trend since 2010. *Photo by Dennis Schroeder, NREL 57711*

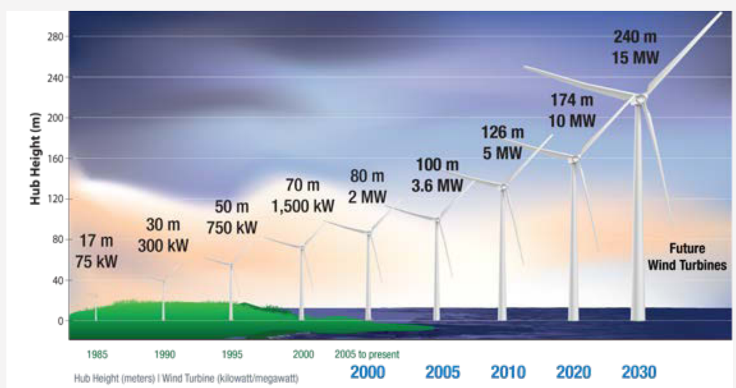
Wind Analysis for Priority Needs

Point of contact: Walt Musial, Walt.Musial@nrel.gov WETO.4.1.0.402

Floating Possibilities: Introductory Webinar Presents Floating Offshore Wind Technologies

A webinar conducted by NREL offshore wind lead Walt Musial covered a critical public knowledge gap on floating offshore wind technology, which has rapidly accelerated its commercialization potential in recent years. The webinar drew 338 live participants and since its release has become the fourth-most viewed NREL video to date, with over 30,000 views (at the time of this publication).

By publishing the content in a highly accessible video form, the webinar can serve as a valuable educational and public reference resource on floating offshore wind now and for the foreseeable future. It can also support constructive dialogue around opportunities for floating offshore wind development in deep-water coastal regions of the United States.

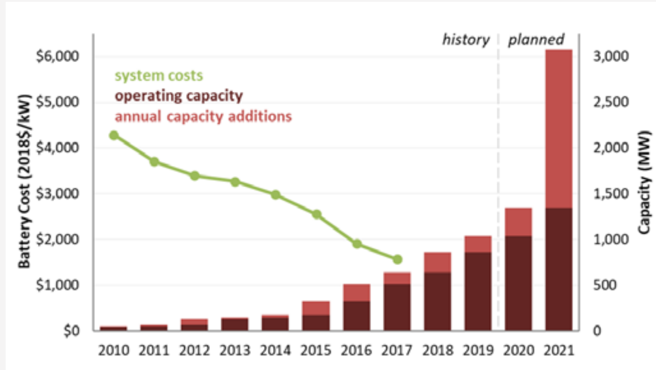


NREL research has helped drive the technology powering increasingly large offshore wind turbines. For example, a single GE 12-MW Haliade-X offshore wind turbine can now power up to 4,500 average U.S. homes. *Illustration by Josh Bauer, NREL*

Point of contact: Wesley Cole, Wesley.Cole@nrel.gov WETO.4.1.0.405

A Collaborative Approach To Improve Storage Modeling in Planning Studies

Energy storage can provide many grid services, but such widespread application introduces modeling challenges that need to account for time chronology to assess the ability of (energy-constrained) storage to provide grid services at the times when they are most needed. NREL researchers—in collaboration with other top grid modelers from the U.S. Energy Information Administration, Environmental Protection Agency, Electric Power Research Institute, and North Carolina State University—authored a paper in *Progress in Energy* presenting recent advances in storage modeling in long-term planning models.



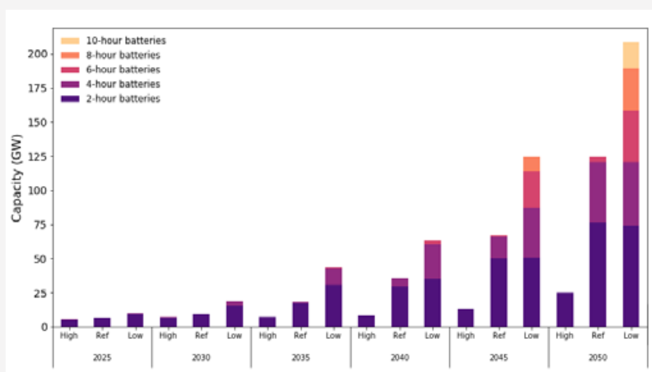
This graph shows declining battery system costs correlating with recent and planned battery deployment. *Figure courtesy of the U.S. Energy Information Administration*

Accurately modeling the cost and value of storage is important to assess the implications of increasing variable renewable energy, including wind. This research was co-funded by multiple EERE offices, including WETO, SETO, Strategic Priorities and Impact Analysis, and WPTO.

Point of contact: Wesley Cole, Wesley.Cole@nrel.gov

Assessing the Role of Energy Storage as a Peaking Resource

As wind and solar comprise a larger share of total U.S. generation, the need for complementary technologies such as energy storage and transmission will grow. Understanding the potential growth in battery storage capacity is one of the key questions around this power system transition. NREL researchers developed new state-of-the-art methodologies for modeling storage and applied these methods to assess the potential for batteries to provide peaking capacity. The methods and analysis consider storage systems with multiple durations to understand the impacts of growing wind and solar.



This graph shows the estimated amount and type of battery storage deployed over time and with storage cost assumptions (high, reference, and low). *Image by NREL*

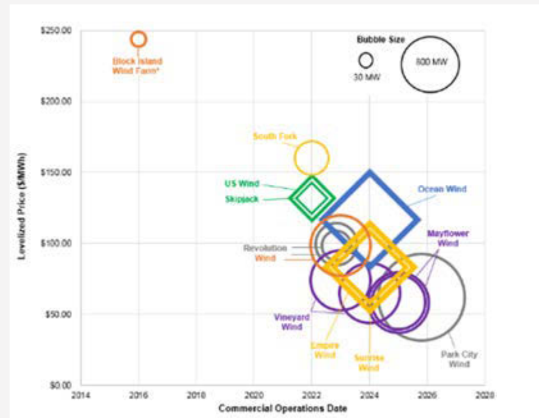
Such studies inform decision makers and power system planners of the dynamic interactions between multiple technologies and how they can be utilized together in an optimized energy future.

Point of contact: Jenny Heeter, Jenny.Heeter@nrel.gov

Procuring Offshore: Understanding Offshore Wind Policies in the United States

The nascent U.S. offshore wind industry is expected to experience unprecedented growth over the next decade spurred in part by state policies. To compare the policy support mechanisms and procurement schemes used across U.S. states and Europe, NREL researchers defined and applied a common taxonomy.

This approach can be used to inform cost modeling and enable a systematic comparison of revenues between U.S. and global offshore projects. The study provides the information decision makers need to assess and design policy instruments.



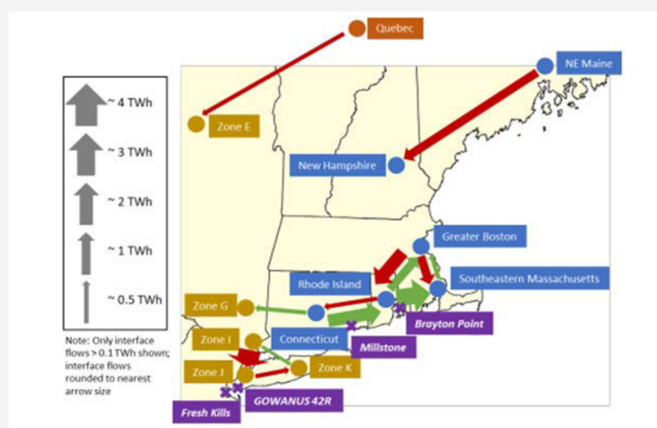
Declining contract prices for recently announced U.S. offshore wind projects. *Graphic by Paul Spitsen, DOE*

Point of contact: Jessica Lau, Jessica.Lau@nrel.gov

Pinpointing Potential: Bringing Offshore Wind onto Tomorrow's U.S. Northeast Grid

NREL researchers conducted an impact assessment of adding up to 7 gigawatts (GW) of offshore wind energy on a future electricity system in the U.S. Northeast.

Using a minimal upgrade philosophy for offshore wind deployment and assuming each offshore wind project would fulfill the interconnection infrastructure requirements, the study found that there may be minimal reliability and operational impacts with offshore wind capacity injections of 2 GW and 7 GW. The study provides power system planners and decision makers with a better understanding of the benefits and disadvantages of offshore wind under various system conditions.



Depiction of how transmission flows in the U.S. Northeast might change with the interconnection of 7 GW of offshore wind capacity in the region. *Figure by Philipp Beiter, NREL*

In addition, the team found that the characteristics of offshore wind resource and location can lead to grid value beyond energy, with reliability and resource adequacy support in high congestion areas. More in-depth studies should be conducted to fully explore these values.

PRUF - Wind Plant Performance Benchmarking Improving Turbine Performance with Power Curves

Point of contact: Jason Fields, Jason.M.Fields@nrel.govWETO.4.1.0.406

Improving Turbine Performance with Power Curves

NREL researchers teamed up with external authors to assess wind turbine power performance prediction methods in a Wind Energy Science article that documents activities of the Power Curve Working Group, which aims to advance the modeling of turbine performance.

Modeling approaches that accurately predict wind turbine power output in comprehensive atmospheric conditions can help reduce the uncertainty associated with energy yield predictions of future wind farms. The article provides access to well-documented power curve methods for modifying wind turbine performance considering different atmospheric parameters, discusses the effectiveness of power curve methods across 60 real-world power performance evaluations, and documents the 7-year evolution and findings of the Power Curve Working Group.

Point of contact: Mike Optis, Mike.Optis@nrel.gov

Round-Robin Validation Sets the Standard for Machine-Learning-Based, Wind-Speed Extrapolation Methods

The increasing size of commercial wind turbines makes measuring hub-height wind speed more challenging and costly, yet the accurate assessment of wind resource at hub height is critical to forecasting generated power. NREL researchers implemented a round-robin validation approach to assess the performance of machine-learning-based vertical extrapolation of wind speeds against conventional methods. The team trained and evaluated a random forest machine-learning model at different sites and then compared the model against the power law and logarithmic profile.

Researchers found that the random forest outperforms the standard extrapolation approaches and concluded that round-robin validation should be the standard for machine-learning-based wind-speed extrapolation methods. Their findings were published in the journal *Wind Energy Science*.

Point of contact: Jason Fields, Jason.M.Fields@nrel.gov

OpenOA Upgrade Identifies, Analyzes Wind Plant Performance Drivers

NREL released an updated version of Open Operational Assessment (OpenOA), an open-source, nonproprietary, transparent, and standardized software tool for analyzing wind power plant operations. OpenOA v2.0, now available on GitHub, offers users an enhanced capability to identify and analyze the drivers of wind farm performance, providing useful wind plant operational data and modeling tools that will enable wind industry professionals to make more accurate predictions and informed decisions in their work, thereby reducing investment risk.

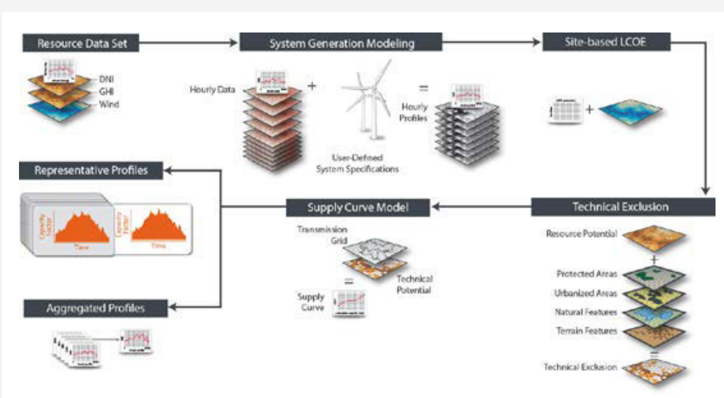
OpenOA v2.0 features updates for identifying and analyzing the drivers of wind power plant performance. *Photo by Josh Bauer, NREL*

OpenOA v2.0 also features augmented annual energy production calculation, methods for performing partial gap analysis, and quality control automation. In addition, the new version features updated examples highlighting the main OpenOA methods and low-level toolkits.

Spatial Analysis for Wind Technology Development

Point of contact: Galen Maclaurin, Galen.Maclaurin@nrel.gov WETO.4.1.0.407

Envisioning Renewable Expansion: Open-Source Release of the Renewable Energy Potential Model



The reV module diagram. The open-source model will help wind industry stakeholders assess the potential and risks involved with land-based and offshore wind projects. *Graphic by NREL*

NREL's Renewable Energy Potential (reV) model is a first-of-its-kind, detailed, spatio-temporal modeling assessment tool that empowers users to assess renewable energy resources and their geospatial intersection with grid infrastructure and land-use characteristics.

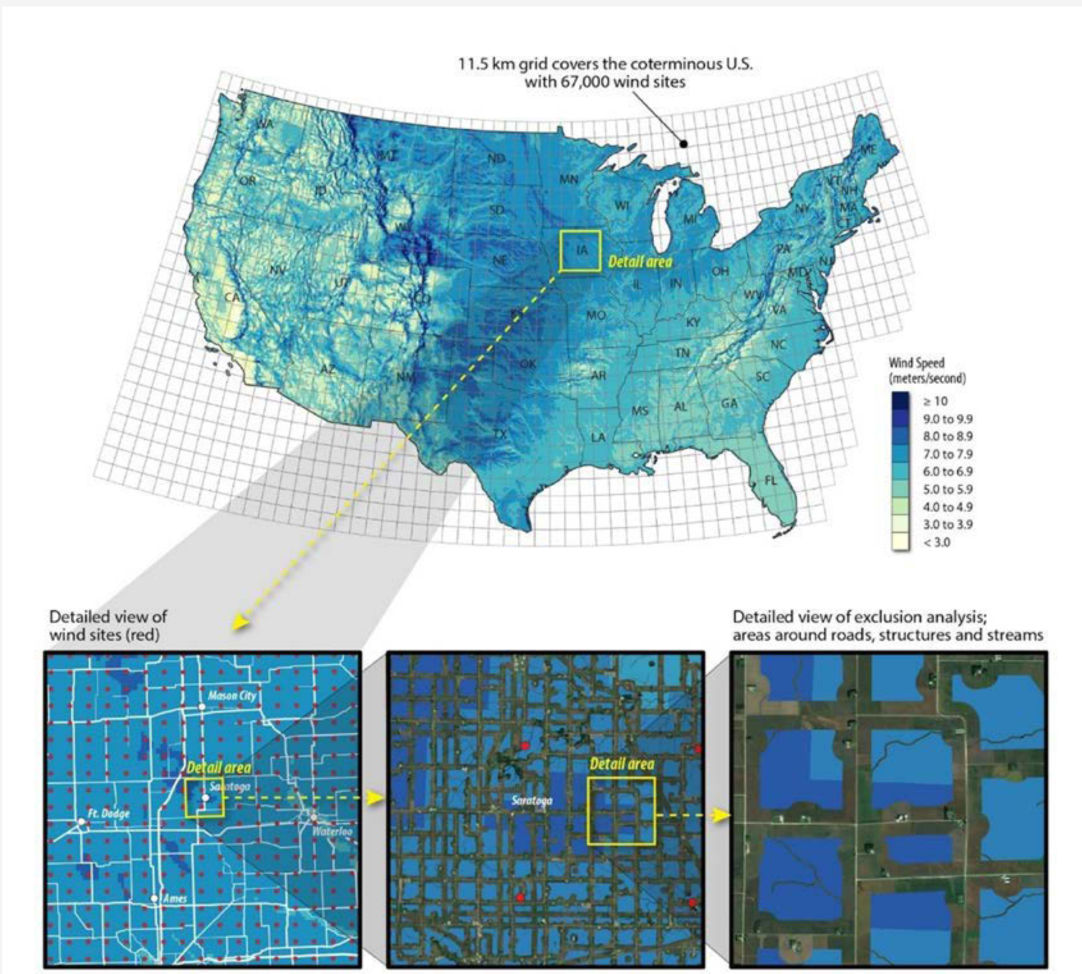
The open-source release of reV will increase its use among wind industry stakeholders, which will improve model data and enhance the tool's usefulness. Now, industry stakeholders can assess technical potential, spur-line distances and costs, and opportunities for new turbine technologies at both regional and national scales.

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

Updated National Wind Potential Using Unprecedented Spatial Resolution

NREL researches have updated the national wind technical potential assessment using increased spatial resolution to represent technical, social, and ecological siting constraints that developers face. The new assessment includes three siting regimes that capture a broad range of deployment barriers, illustrating the bookends of wind potential estimates along the gradient of siting restrictions. The ***Reference*** siting regime resulted in a land-based wind technical potential of 7.8 terawatts.

Ongoing research finds that U.S. wind technical potential estimates can vary by multiple terawatts with different assumptions about the level of siting restrictions and wind turbine advancements.



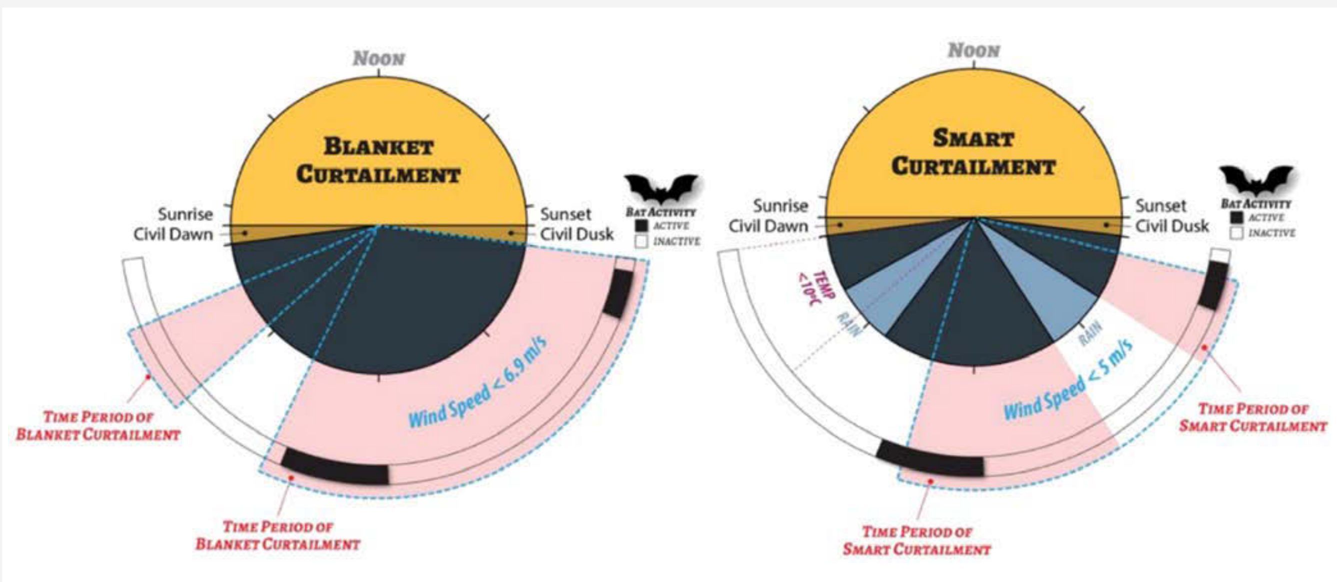
The geographic scope and multiple spatial resolutions of the reV model used to estimate national wind technical potential.
Image by Billy J. Roberts, NREL

Point of contact: Galen Maclaurin, Galen.Maclaurin@nrel.gov

National-Scale Impacts on Wind Energy Production Under Curtailment Scenarios To Mitigate Bat Fatalities

Curtailment to reduce bat-turbine collisions is an evolving practice predominantly founded on an association between wind speed and bat activity during high-risk months of the year. NREL-led research applied different curtailment regimes across the contiguous United States and examined sensitivities of potential reduction in AEP and how that related to costs and financial viability for new wind projects.

Results showed that AEP reduction can range across the country from less than 1% to as high as 8% for different curtailment regimes. Although the moderate curtailment regime typically resulted in less than 1% AEP reduction, during the period of curtailment (summer to early fall), monthly power production was reduced by up to 5%. This research brings the question of bat curtailment into national-scale modeling and long-term energy planning through improved representation of operational constraints for wind energy deployment.



The blanket modeling scenario applied curtailment based solely on wind speed during the night across high-risk months of the year. The Smart scenario also considered temperature (>10°C) and precipitation rate (<1 mm/hour) thresholds to represent periods of increased risk of bat-turbine collisions.
Images by Billy Roberts, NREL

Programmatic Support

NREL Technology Management and Support

Point of contact: Brian Smith, Brian.Smith@nrel.gov WETO.5.1.0.401

Skillful Progammatic Support Broadens Wind Research Impact

The NREL Wind Program actively managed a broad R&D portfolio of 73 WETO-funded projects. This work included providing detailed quarterly reports that assessed the technical and financial performance of each project and engaging the WETO leadership team in regular, open communications to review progress and facilitate early identification and mitigation of issues. In addition, NREL Wind Program leadership evaluated potential impacts of COVID-19 on research projects quarterly, ensuring the health and safety of staff and contractors.

Skillful project management enables all activities in NREL's broad wind energy research and development portfolio to directly support the WETO mission and lead the nation's efforts in early-stage R&D, helping develop and deploy technologies that enable growth of the U.S. wind industry, enhance U.S. competitiveness, increase U.S. energy security and independence, strengthen domestic manufacturing, and provide local economic opportunities across the country.

Achievements include serving in a strategic leadership role of the IEA Wind TCP, overseeing NREL's research presentations and posters, guiding conference panel participation, developing and delivering the annual NREL wind accomplishments report, and producing ongoing communications products, such as *The Leading Edge*, NREL's wind portfolio newsletter.

NREL Experts Lead Global Wind Efforts

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

In partnership with DOE, NREL experts led or co-led 10 IEA Wind collaborative research efforts including two new tasks—Wind Farm Flow Control and Enabling Wind Turbine Blade Recycling—and three new topical expert meetings on floating offshore wind arrays, hybrid power plants, and airborne wind energy. The wind research efforts NREL staff are leading or co-leading include:

Task 26: Cost of Wind Energy

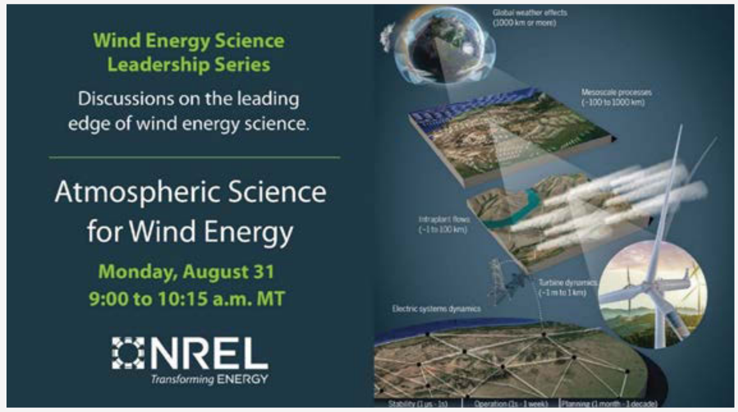
- Task 28: Social Science of Wind Energy Acceptance
- Task 30: Offshore Code Comparison Collaboration, Continuation, with Correlation, and uncertainty (OC6)
- Task 31: Wakebench: Benchmarking Wind Farm Flow Models
- Task 34: Working Together to Resolve Environmental Effects of Wind Energy (WREN)
- Task 37: Wind Energy Systems Engineering
- Task 41: Enabling Wind to Contribute to a Distributed Energy Future
- Task 43: Digitalization of Wind Energy
- Task 44: Wind Farm Flow Control.
- Task 45: Enabling Wind Turbine Blade Recycling

Additionally, NREL Wind Energy Laboratory Program Manager Brian Smith served as vice chair of the IEA Wind Executive Committee, and NREL communications staff wrote the U.S. chapter of the IEA Wind annual report. NREL's leadership with IEA Wind strengthened the nation's presence and influence among member countries, the European Commission, the Chinese Wind Energy Association, and WindEurope.

Point of contact: Alexsandra Lemke, Alexsandra.Lemke@nrel.gov

Launch of Wind Energy Science Leadership Series Provides Insight into Future of Wind Energy

NREL launched the Wind Energy Science Leadership Series as an ongoing series of educational webinars that includes presentations and discussions on wind-energy-related topics, featuring speakers from the lab, strategic partners, and the energy industry, further demonstrating NREL's international leadership in the wind energy sector.



NREL invited members of the scientific community to take part in conversations about wind energy science by posting promotional content across social media channels.
Design by Jennifer Breen-Martinez; illustration by Joshua Bauer and Besiki Kazaishvili

By attending each webinar in the series, participants gained a better understanding of the challenges facing wind energy and the pathways forward for making wind one of the most prevalent energy sources of the future. Individuals interested in learning more about wind energy science can catch up on past webinars in the series by visiting NREL's Learning Channel.

Point of contact: Alexsandra Lemke, Alexsandra.Lemke@nrel.gov

NREL Leaders Act As Strategic Advisors Supporting WETO Through Management and Operations Detail Assignments

Alexsandra Lemke, Mike Robinson, Jon Keller, and Rich Tusing provided strategic support and guidance to WETO through management and operations detail assignments aimed to define, develop, shape, and support the implementation of WETO's R&D portfolio. These individuals served in various leadership roles, including contributing to high-quality deliverables such as the Multi-Year-Program Plan; advising on strategic planning and roadmap initiatives including wind-hybrid technologies, wind-storage technologies, and wind-circular economy technologies; coordinating U.S. national laboratory collaborative activities; providing timely and effective management of analytical and technical support activities; and exhibiting strong leadership in targeted areas (early-stage R&D, high-performance computing, technical and economic analysis, external affairs, and communications) with high market impact. These NREL leaders are trusted advisors and assist with effectively achieving WETO's high-level initiatives that provide strategic technical direction and offer a robust scientific engagement strategy with internal and external stakeholders.

Point of contact: Kiki Carpenter, Kiki.Carpenter@nrel.gov WETO.5.1.0.402

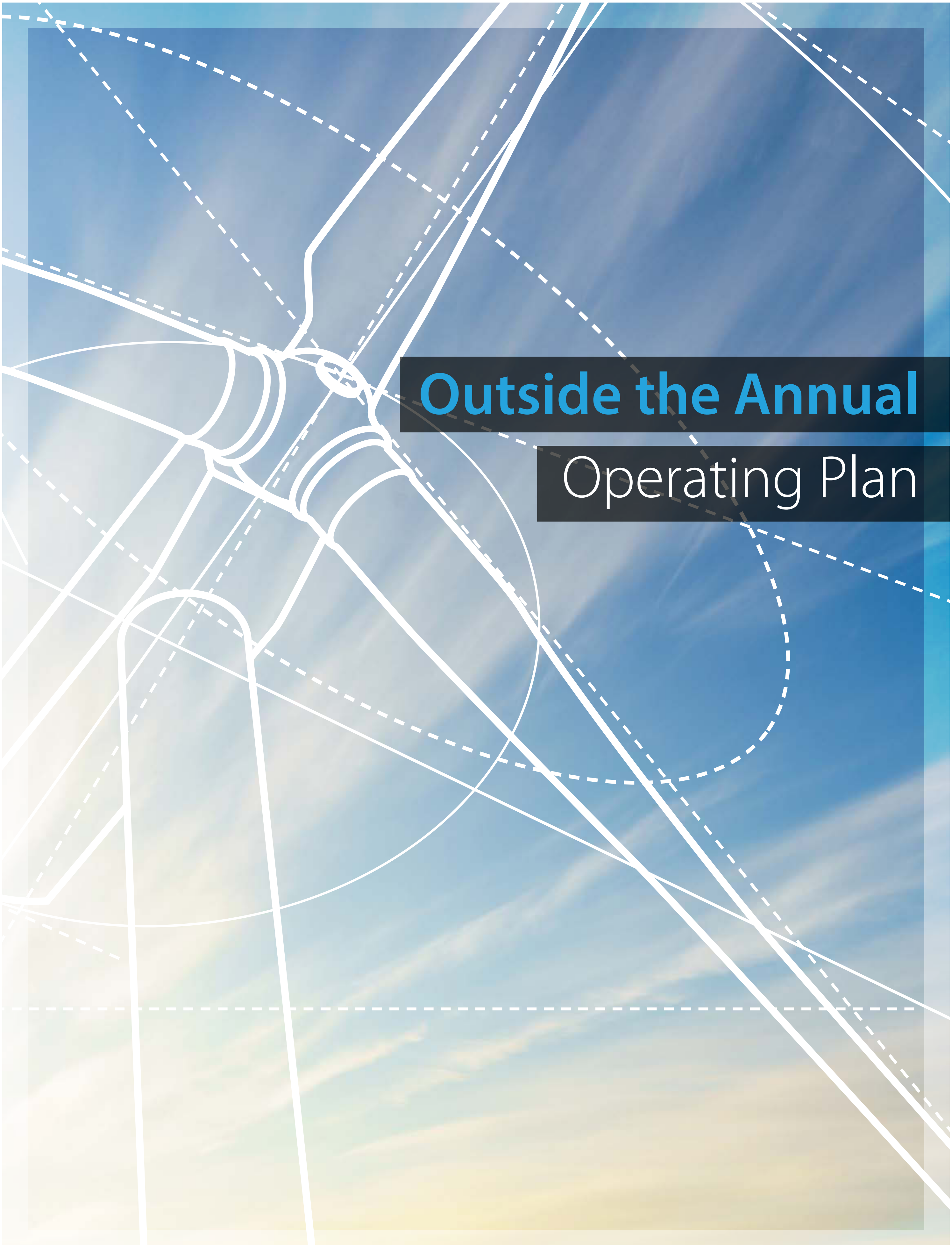
Strategic Communications Amplify the Wind Energy Technologies Office Mission

Through the dissemination and amplification of wind research activities, NREL's communications team supports WETO and its efforts to foster a greater understanding of the benefits of wind energy technologies. The communications team reinforces WETO's mission by creating a variety of materials consumed by thousands of stakeholders, such as fact sheets, technical reports, brochures, web content, newsletters, and social media posts, and disseminating them to relevant stakeholders. By delivering WETO news through a multitude of channels, the team increases stakeholder awareness of WETO's R&D priorities and improves the American public's understanding of the benefits of wind energy technologies.

How Wind Works Animation on energy.gov help keep people of the United States informed about what wind power is capable of in an interactive, simple to understand manner. *Animated by Charles Joyner, Accenture Federal*

The team developed top-level publications such as the U.S. chapter of the "2019 IEA Wind Annual Report" and twice-yearly R&D newsletter. Additional achievements include creating interactive graphics for market report pages, writing web articles and event listings, coding and disseminating breaking news emails, providing strategic content guidance on priority web pages, and leading website animation improvement projects such as the revised "How a Wind Turbine Works" animation, and supporting the successful re-branding of WETO's wind energy newsletter, "Catch the Wind," helping to elevate its name recognition. The rebrand took the newsletter from an average open rate of 8% to 15%.

Outside the Annual Operating Plan



Point of contact: Daniel Laird, Daniel.Laird@nrel.gov

Volunteers Design and Print Face Shields for Colorado's Medical Workers and First Responders

Physician Claudia Kunrath of Denver Health Medical Center wears a 3D-printed face shield prototype while treating COVID-19 patients. *Photo by Claudia Kunrath, Denver Health*

Like most institutions, NREL has had to adjust to the new reality caused by a pandemic. Not the type who like to stand idly on the sidelines, NREL staff Jason Roadman and Scott Jenne along with a host of other volunteers, helped protect front-line medical workers and first responders by designing and manufacturing face shields and frames.

As we do our best to follow physical distancing and safer-at-home guidelines, essential workers and health care professionals continue to comfort, treat, and mitigate risk for those most impacted by the COVID-19 pandemic. While NREL's primary mission advances the science and engineering of energy efficiency, sustainable transportation, renewable power technologies, and the integration and optimization of energy systems; laboratories across the national laboratory complex have stepped up to help tackle COVID-19, providing a service to the community and advancing awareness and scientific knowledge in new pathways like three-dimensional (3D) printing.

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Groundbreaking Experiments To Influence Floating Offshore Wind Turbine Designs

Through the Floating Offshore-wind and Controls Advanced Laboratory (FOCAL) program, NREL and its partners are generating the first public floating offshore wind technology scale-model data set to include advanced turbine controls, floating hull load mitigation technology, and hull flexibility. In the first year, the team developed a plan for implementing advanced floating wind turbine control methods at model scale in a wind/wave tank—the first of four validation campaigns under this program. NREL is partnering with the University of Maine and DNV GL on this project, which is one of three NREL-led projects awarded by DOE's Advanced Research Projects Agency-Energy (ARPA-E) Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control (ATLANTIS) program. Data and findings generated from the FOCAL experiments will be made available to other groups within the ATLANTIS program and eventually to the general public to validate the tools and designs to achieve the ATLANTIS goal of light and efficient floating turbines with integrated controls.

The W2 Ocean Engineering Laboratory at the University of Maine will be used to conduct combined wind and wave testing of wind turbines with advanced controls. *Photo courtesy of the University of Maine*

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Researchers Achieve Faster Time to Solution for Running Wind Turbine Simulations

Working collaboratively, NREL researchers achieved a faster time to solution, the time needed to run a computer program simulation, for wind turbine simulations. By comparing the scaling performance on high-performance computing (the ability to efficiently split a program across multiple processors), researchers showed that solving the mass-conservation equation accounts for the majority of wind simulation time. The team examined and improved two common "preconditioning" algorithms that are key to accelerating the solution of the underlying equations: Smoothed aggregation algebraic multigrid (AMG) and classical AMG. Reducing the mass-conservation solve time is critical for optimizing programs to run simulations on high-performance computers so researchers can focus on the underlying scientific breakthroughs from the work, rather than tinkering "under the hood" to get those simulations to work. The paper on this work was published in the ***SIAM Journal on Scientific Computing***.

NREL Evaluates Accuracy of Rutgers University Real-Time Weather Model

An accurate characterization of the wind resource off the coast of New Jersey and neighboring states is critical to ensuring confidence in offshore wind analyses that require these data. NREL researchers completed an independent validation study of the performance of the Rutgers University Center for Ocean Observing Leadership's real-time Weather Research and Forecasting model (RU-WRF) for wind resource assessment work. The team categorized recommended improvements to the RU-WRF setup, Rutgers' custom coldest-pixel sea-surface temperature product, and the atmospheric observations and methods used to validate RU-WRF. These results were published as a technical report by NREL.

Ultraflexible Floating Offshore Wind Turbine Research Aims To Lower the Cost of Energy

The Ultraflexible Smart Floating Offshore Wind Turbine (USFLOWT) project, one of three NREL-led projects awarded by DOE's ATLANTIS program, is working to reduce the cost of wind energy production and provide an entirely new option for the offshore wind industry. In 2 years of ARPA-E funding, USFLOWT will first develop a co-designed controller for a 10-MW turbine. This controller will optimize elements of the turbine by accessing information about wind and wave environments. Using the control co-design approach, researchers will study the system costs and energy production of deploying such a design on a 600-MW wind turbine in a North Atlantic Coast wind power plant.

Revolutionary Toolset to Enable Floating Offshore Systems at Greatly Reduced Cost

Through the Wind Energy with Integrated Servo-control (WEIS) project, NREL and partner University of Illinois Urbana-Champaign are developing an open-source, user-friendly, and customizable toolset to enable control co-design optimization of floating offshore wind systems. The research team initiated development of a low-fidelity frequency domain model that will provide rapid prototyping of different turbine-platform architectures, which will then be passed to mid and high-fidelity models for thorough co-design optimization.

Next, the team added a free-wake vortex aerodynamic model to the tool to predict blade and system loads more accurately for very large rotor systems attached to a floating platform. The WEIS toolset will enable optimization and design of the system controller simultaneously with the other system components, resulting in significant levelized cost of energy (LCOE) reductions for floating offshore wind turbines. One of three NREL-led projects awarded by DOE's ATLANTIS program, WEIS aims to generate widespread use within the floating offshore design community. In addition, by capturing the designs being proposed in other ATLANTIS projects, WEIS will be indispensable for innovation in low-cost, efficient offshore wind turbines.

TThe WEIS project will develop a open-source, user-friendly toolset designed to enable offshore floating system engineers to design radically new systems at greatly reduced costs. *Photo by Senu Sirnivas, NREL*

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Synthetic Data Lay Groundwork for Improved Atmospheric Forecasting

Funded as a Laboratory Directed Research and Development project, researchers found that synthetic data—data generated by a computer system using inputs from real-world observations—could improve atmospheric forecasting for wind power. The larger set of inputs synthetic data provide can help researchers observe the full wind flow field in a specified region, and this study shows that short-term forecasts using this regional synthetic data perform comparably to studies that use observational data. These results provide motivation to use synthetic data for short-term forecasting in grid simulations and open the door to future algorithmic improvements.

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NREL Studies Determine Gulf of Mexico Well-Positioned for Offshore Wind Development

Two recent studies conducted by NREL and funded by the Bureau of Ocean Energy Management (BOEM) have yielded promising results for the future of offshore wind energy in the Gulf of Mexico. The studies assessed potential offshore energy resources and determined which technologies are the most promising to meet the region›s future energy needs. The results will inform national and regional strategic energy planning over the next decade.

Two studies conducted by NREL and funded by BOEM highlight the untapped potential of offshore wind energy in the Gulf of Mexico. *Image courtesy of BOEM*

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Over $10 Million Awarded for Projects Advancing Offshore Wind Research and Development

The National Offshore Wind Research and Development Consortium recently announced selection of 12 offshore wind research and development technology projects. NREL, along with collaborators DNV GL and the Business Network for Offshore Wind, was selected to create a comprehensive U.S. supply chain roadmap to achieve 20 GW of U.S. offshore wind by 2035. Details on some of the work resulting from this funding can be found in the offshore section of this report.

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New Research Explores Opportunities for Hybrid Wind and Solar Power Plants

Funded through a Laboratory Directed Research and Development Program, a new technical report titled "Opportunities for Research and Development of Hybrid Power Plants" summarizes state-of-the-art research concerning hybrid power plants. These plants could provide significant value to the electric grid system as the share of renewable energies increases from 10% to 20% or more and costs of wind, solar photovoltaics (PV), and battery storage continue to decrease. For more information about this work, visit our page dedicated to Hybrid Energy Systems Research.

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Chief NREL Engineer Paul Veers Named ASME Fellow

NWTC Chief Engineer Paul Veers has been named an American Society of Mechanical Engineers fellow. He received this distinction for his outstanding engineering achievements, active leadership with the society, and more than 10 years of diligent practice—40 years to be exact. Congratulations, Paul!

Paul Veers (right) has worked in wind energy technology since 1980 and has written more than 70 articles, papers, book chapters, and reports. He also served as the chief editor for *Wind Energy*, an international journal for progress and applications in wind power. From left: Eric Lantz, Katherine Dykes, and Tyler Stehly. *Photo by Dennis Schroeder, NREL*costs. *Photo by Senu Sirnivas, NREL*

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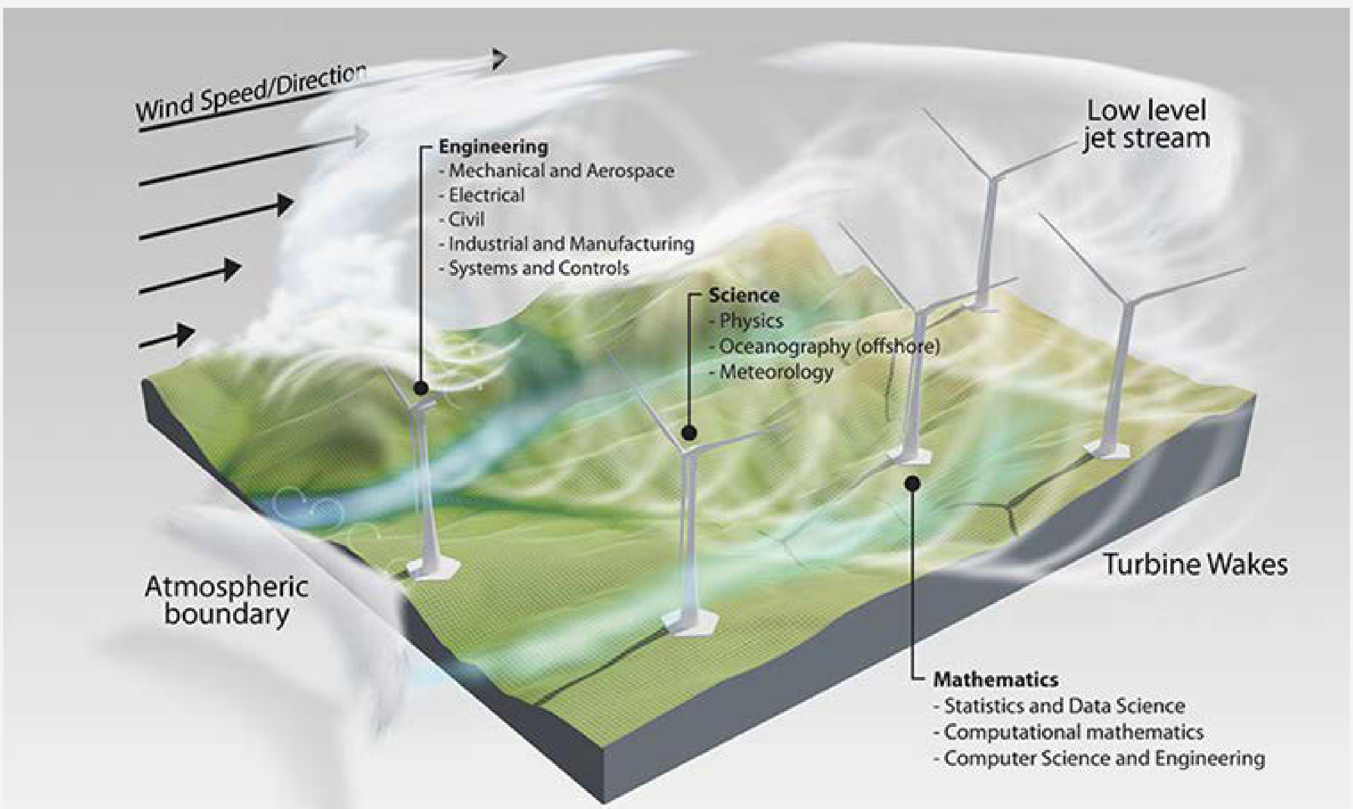
Wind Experts Write Book To Empower Development of Wind Power Plant System Models

Along with several other technical experts across the world, the NWTC's Chief Engineer, Paul Veers, wrote a two-volume book titled, "Wind Energy Modeling and Simulation Volume 1: Atmosphere and Plant and Volume 2: Turbine and System," as an end-to-end resource, covering every aspect of wind energy design, modeling, and simulation. NREL contributed to 10 of the book's 18 chapters, helping to explain the principle elements behind multiple subsystem models that are needed to create a fully optimized wind power plant.

Written with plain-language explanations and mathematical examples, the book allows practitioners with atmospheric, aerospace, mechanical, electrical, and other scientific backgrounds to learn directly from internationally recognized wind experts, empowering these individuals to develop their own wind plant system models. By providing a common language and baseline level of knowledge across the international wind community, NREL researchers empower fellow wind energy practitioners to pursue larger and more efficient wind power modeling systems to make wind one of the world's primary sources of low-cost electricity generation.



Authors of "Wind Energy Modeling and Simulation, Volumes 1 and 2," use this illustration to explain how a spectrum of science, engineering, and mathematical disciplines can help make wind energy one of the world's primary sources of electric power generation. *Illustration by Josh Bauer, NREL*

Shining (UV) Light on Inspired Innovation with Industry Partners

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For nearly 2 years, NREL researchers have supported a project that explores whether illuminating turbines with dim ultraviolet (UV) light will minimize bat impacts at wind energy power plants. But Scott Schreck, a systems design engineer from Siemens Gamesa Renewable Energy, saw another potential application.

No off-the-shelf UV light fit the specifications Schreck required for development work, so he reached out to NREL to see if he could use a custom-designed "bat light" for a wind tunnel trial to better illuminate air flow tufts. NREL contacted Dave Dalton from Bat Research and Consulting, who built the custom-designed bat lights and shipped Siemens Gamesa Renewable Energy an available unit.

The bat light presented several advantages for Schreck's wind tunnel application. The light enabled clearer visualization of the flow field, faster and more reliable interpretation of the results, and more efficient use of expensive wind tunnel evaluation time. Similar stories abound over the years as NREL serves as a knowledgeable resource and liaison with a global network of experts across the energy industry.

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NREL Models Predict Lower Costs for Floating Offshore Wind Plants on Oregon Coast

Funded by BOEM, the "Oregon Offshore Wind Site Feasibility and Cost Study" assesses the potential costs of floating offshore wind power plants at least 10 nautical miles from Oregon's coast, where wind speeds are some of the world's strongest. The LCOE for the hypothetical projects—600 MW each, outfitted with 15-MW wind turbines, and developed by 2032—ranged from $74 per megawatt-hour (MWh) in the north to $53 per MWh in the south, near the California border.

The study indicates the cost of deploying floating offshore wind in Oregon could be 30% to 40% less than previously estimated, which improves the prospects of offshore wind deployment in the region.

An NREL model predicts floating offshore wind could unlock new regions to offshore wind development, such as the Oregon coast. *Photo by Senu Sirnivas, NREL 27606*

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