# Accomplishments & Year-End Performance REPORT

WIND ENERGY PROGRAM: FISCAL YEAR 2019

NREL
Transforming ENERGY

The U.S. Department of Energy's (DOE's) National Wind Technology Center (NWTC) at the National Renewable Energy Laboratory's (NREL's) Flatirons Campus stands at the forefront of energy innovation. Since the earliest days of the wind industry, the Flatirons Campus has provided an ideal environment for the research and development (R&D) of advanced energy technologies.

Of ering broad-based technical expertise and world-class capabilities and facilities, NREL leverages these assets to provide the wind industry with a better understanding of fundamental physics, high-performance-computing-enabled simulation tools, and the physical validation necessary to significa tly lower the cost of wind energy.

NREL wind staff ork closely with other DOE national laboratories, government agencies, and academic institutions around the world—all with the common goal of developing better, more sustainable renewable energy for the future.

This report provides an overview of the many achievements NREL delivered on behalf of DOE's Wind Energy Technologies Ofc e (WETO) and other partners during Fiscal Year 2019 (FY 2019).

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# Technological Innovation and Adaptation with an Eye to the Future

# Top Wind Program Accomplishments Set a Strong Foundation for Industry Success

## Wind site's name change reflects expanding focus.

The 305-acre site just south of Boulder, Colorado, that houses the NWTC is now being referred to as NREL's Flatirons Campus. On March 26, NREL received a letter from DOE formally renaming the location of the NWTC to the Flatirons Campus. For several years, research at the NWTC site has been expanding beyond wind to include grid integration, water power, energy storage, solar photovoltaics, and advanced manufacturing. The new name and expanded campus will enable NREL to conduct the research needed to achieve an integrated energy system that can meet the complex energy challenges of the future. The NWTC will still be housed on the Flatirons Campus.

Looking to the horizon. The vision behind the Flatirons Campus opens possibilities as wide as the 305-acre site itself for advancing renewable energy technologies. *Photo by Dennis Schroeder, NREL 25929*

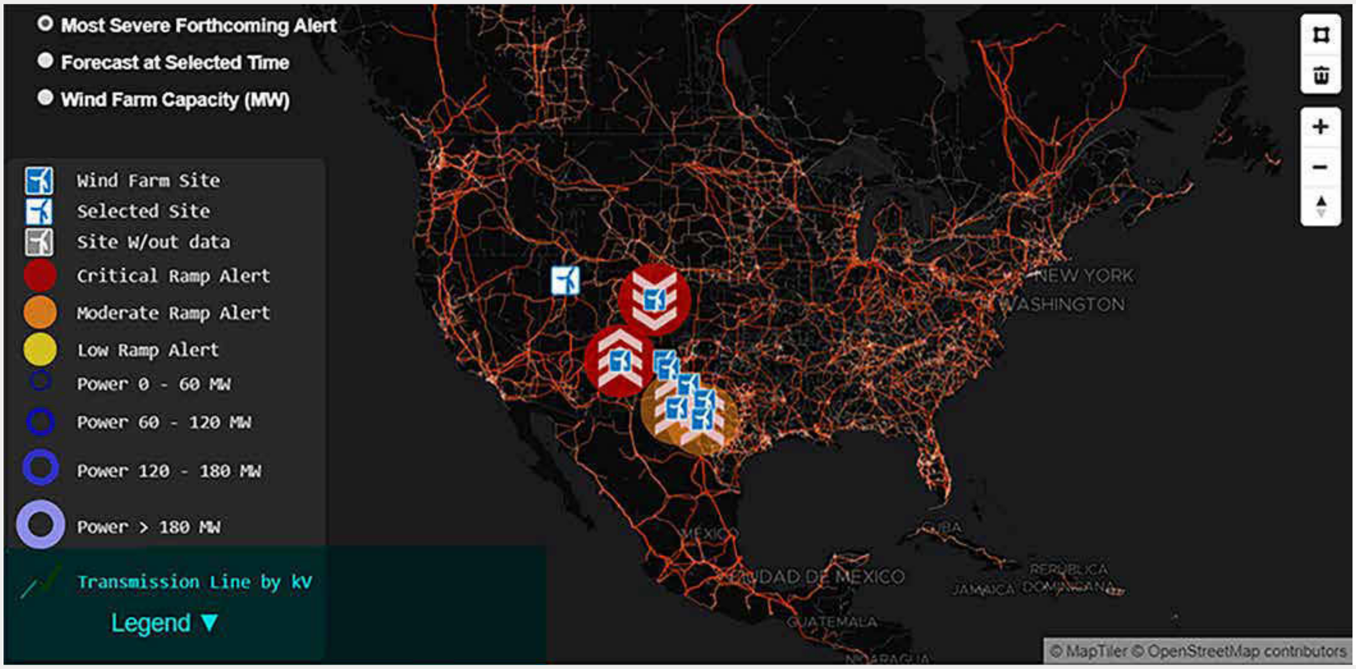

A view from on high. Jennifer King, along with other members of the Atmosphere to Electrons program, use algorithms that ensure reliable, robust, real-time, and efficiient operation of an entire wind farm by using local sensor information, such as supervisory control and data acquisition data; local meteorological stations; and nearby radars, sodars, and lidars. *Photo by Dennis Schroeder, 58254*

## Field validation studies demonstrate potential of wake steering and consensus control.

Wake steering field trials at a commercial wind plant improved energy capture at downstream turbines. Instrumenting turbines enables them to "talk" with each other and respond quickly to changes in wind direction, demonstrating the potential for turbine consensus control strategies. NREL enhanced its wind plant performance optimization software framework, FLOw Redirection and Induction in Steady State (FLORIS), to improve usability and flow physics. Wake steering and wind farm control strategies could increase wind plant annual energy production by 1%–2%, which amounts to yearly profits of about $1 million per year for a 300-megawatt (MW) wind plant.

## WindView provides a real-time look at wind data.

NREL researchers released the WindView software tool on GitHub to provide electric grid operators with free visual forecasting tools that display real-time probabilistic wind power forecasts. WindView's widespread use allows system operators to make control decisions based on the data the software provides. By making variable wind resources easier to track, WindView can contribute to further accessibility of wind energy in the United States.




A web of (inter)connections. WindView can analyze up to 200 wind farms and compare recent forecasts to actual outputs. *Image courtesy of Erol Chartan and Paula Edwards, NREL*

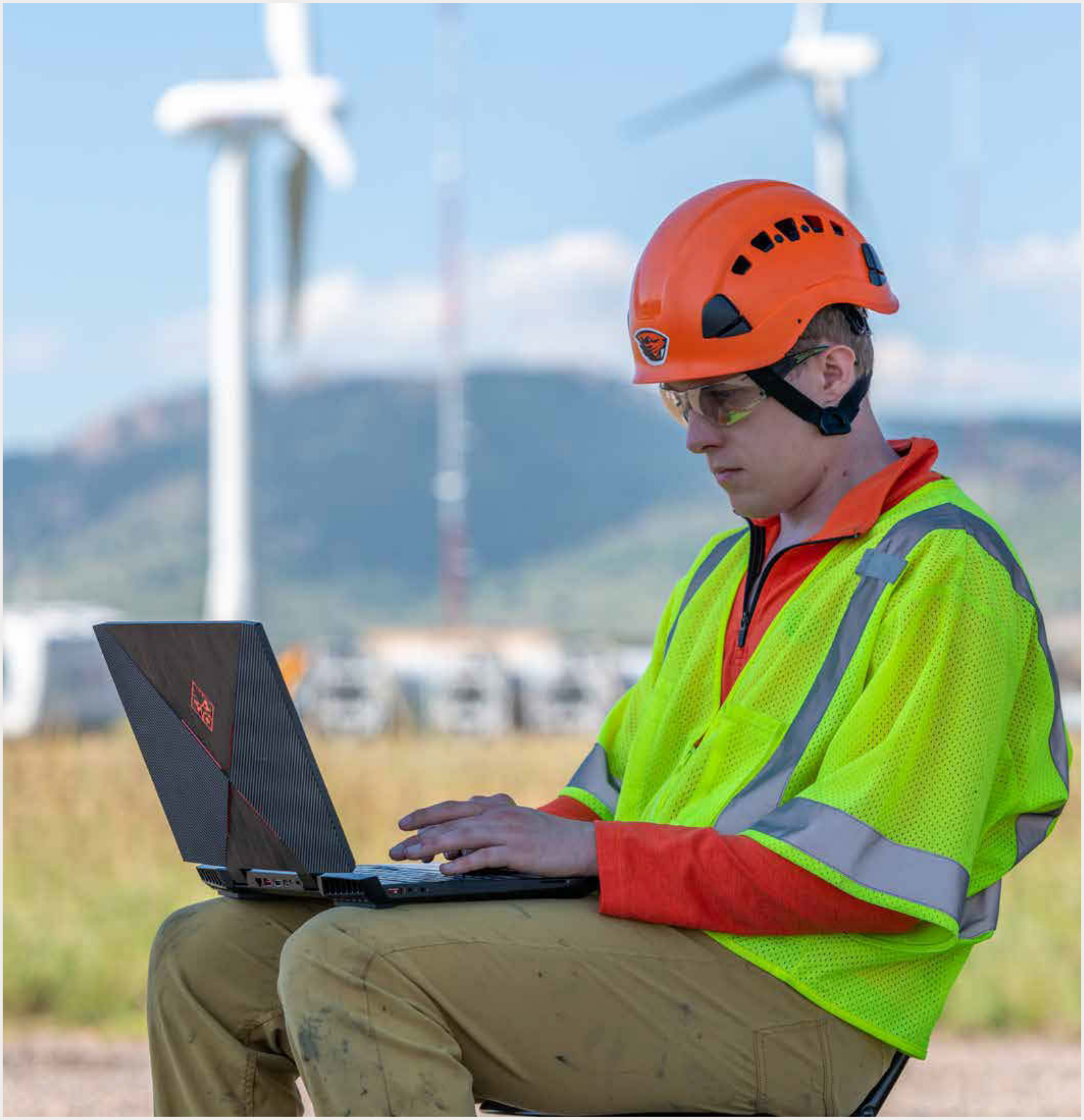
## Offshore wind market report projects accelerated growth.

The "2018 Offshore Market Technologies Market Report" provides detailed, unbiased data and analysis about the offshore wind market, technology, and cost trends. NREL researchers found the industry is primed for growth, with 25,824 MW of capacity in the project pipeline. In 2018, the global industry installed a record 5,652 MW of offshore wind capacity, and growth forecasts indicate 11–16 gigawatts of offshore wind energy capacity additions in the United States by 2030, thanks to technological innovation and favorable state policies. A trusted source of information for the offshore wind industry, the market report covers the status of the 176 operating offshore wind projects through Dec. 31, 2018, and analysis on a broader global pipeline of 838 projects in various stages of development. The report has been downloaded over a thousand times since its release in August.


On the rise. Of shore wind market projects indicate accelerated growth over next decade. *Cover design by John Frenzl, NREL*

## NREL facilities and staff spearhead early-stage wind-wildlife minimization research.

NREL's Flatirons Campus has become a hotbed of technological innovation for wind-wildlife minimization. Four separate research projects with Pacific Northwest National Laboratory (PNNL), Oregon State University (OSU), and the United States Geological Survey validated solutions to monitor, detect, and deter wildlife from approaching wind turbines. NREL's state-of-the-art equipment and renowned staff expertise help bring these technologies to market.

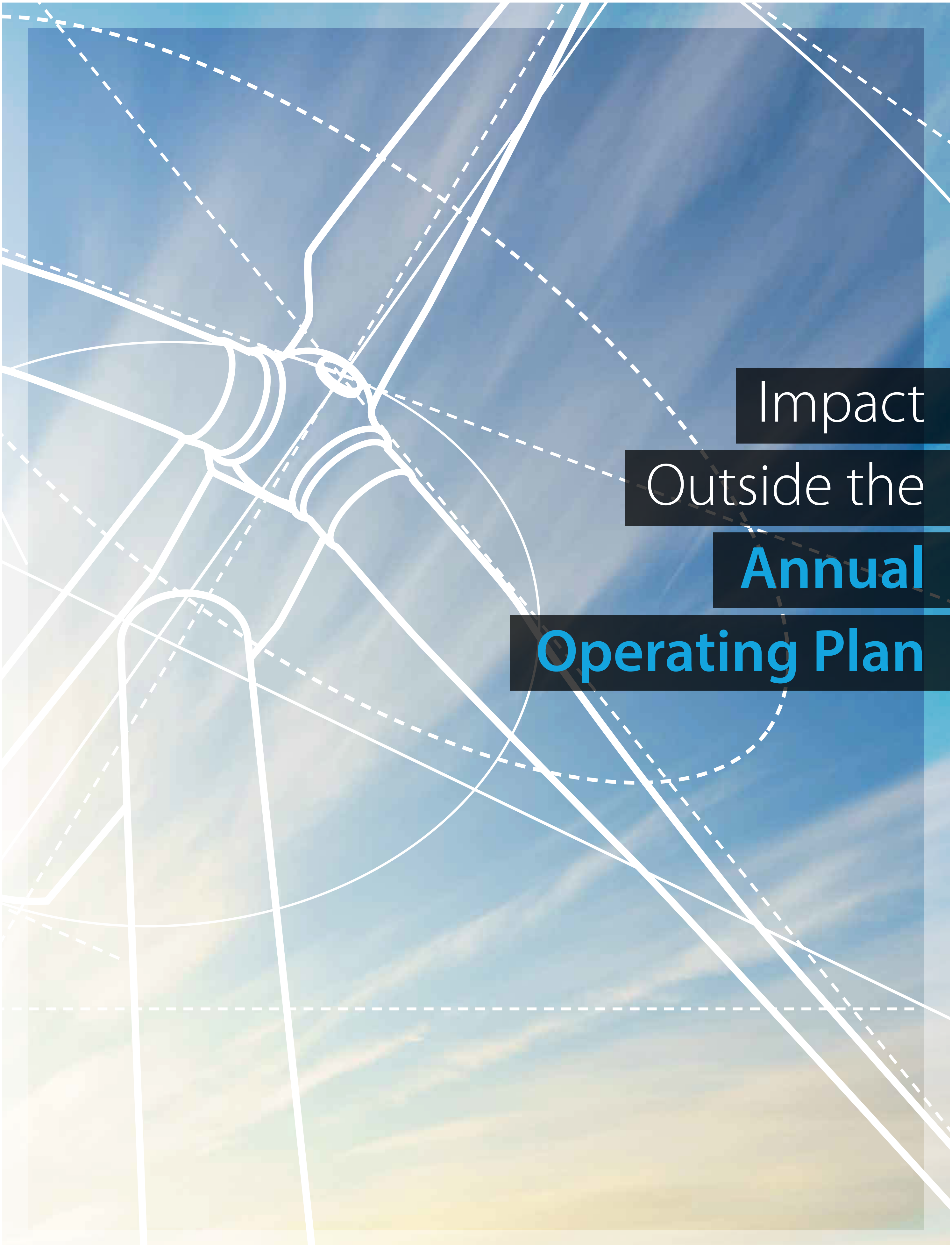


Time to concentrate. In between chasing down tennis balls, Oregon State University researcher Kyle Clocker monitors the wildlife detection sensors and cameras on each turbine blade from his laptop during system validation. *Photo by Joshua Bauer, NREL*

## NREL helps prepare workforce for energy needs of tomorrow.

Success and elation. Twelve college teams from around the country took part in the 2019 Collegiate Wind Competition at the Flatirons Campus.
*Photo by Werner Slocum, NREL*

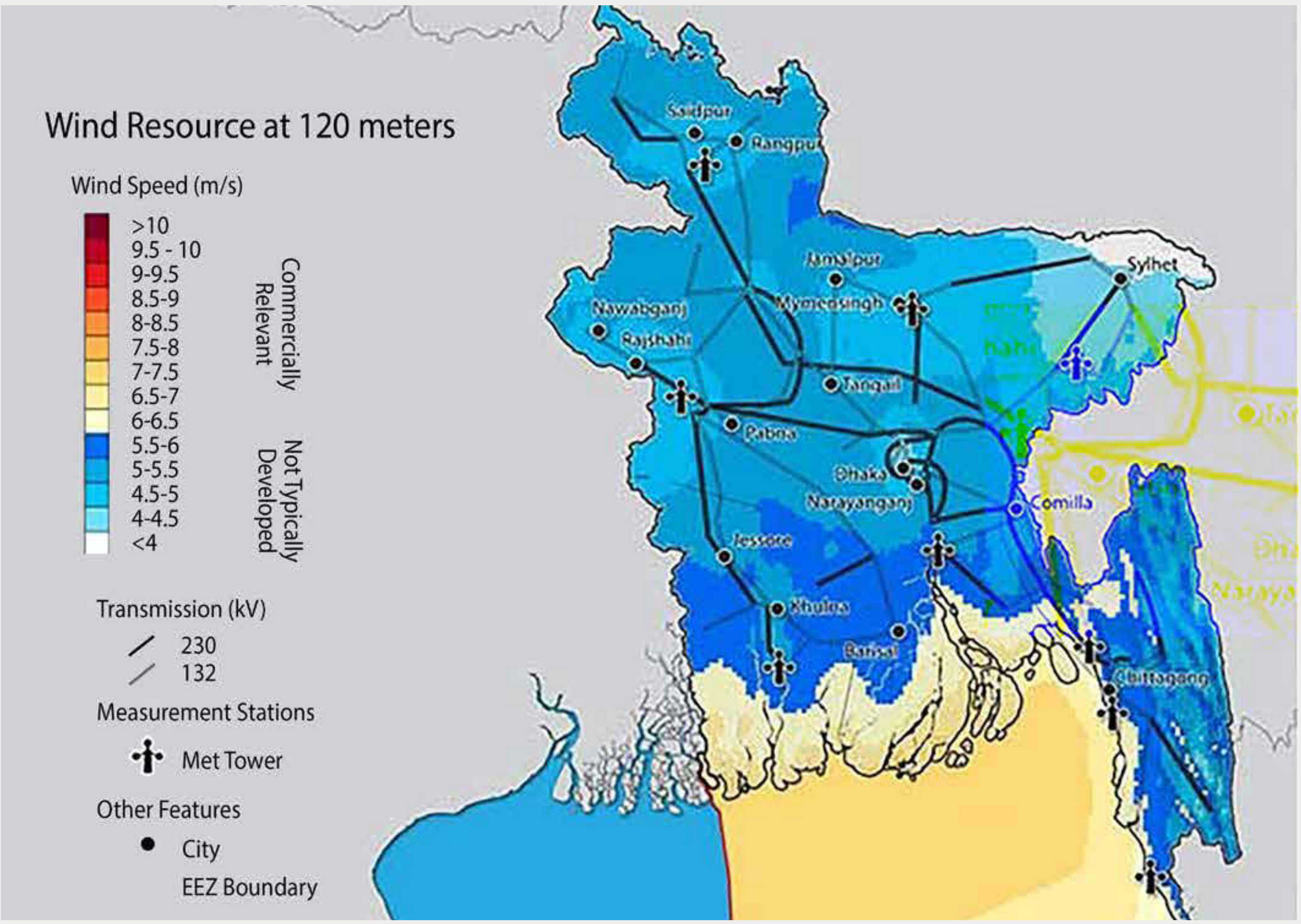
The Collegiate Wind Competition, coordinated by NREL, increases graduates' ability to find jobs in the wind industry by providing real-world technology experience and networking opportunities. With wind energy continuing to expand, experiences like the Collegiate Wind Competition will be critical to provide a steady stream of workers to the industry, which is explored in "*The Wind Energy Workforce in the United States: Training, Hiring, and Future Needs.*" Continued deployment of wind energy is somewhat contingent on community support, and another NREL report about construction of the Rush Creek Wind Farm highlights the economic impacts of wind energy development in rural Colorado and the importance of domestic manufacturing on jobs.



# Impact Outside the Annual Operating Plan

# Assessing Wind Power Potential in Bangladesh

A collaboration between the U.S. Agency for International Development and NREL used a unique combination of tools to determine the viability and risks involved in using wind power as a renewable energy resource in Bangladesh. The team published an analysis, "*Assessing the Wind Energy Potential in Bangladesh*," to explore a collaboration with the government of Bangladesh to help address significant challenges that include power shortages, increasing demand, decreasing domestic natural gas reserves, and an inadequate transmission infrastructure. This analysis improved the quality of modeled wind resource data for the country and made those data available to investors and the public through the *RE Data Explorer* tool that allows users to perform customized technical potential analyses.Significance and Impact




A detailed wind resource map of Bangladesh. Researchers from a U.S. Agency for International Development-NREL partnership collaborated with the government of Bangladesh to assess the country's potential and risks for using wind power as part of its renewable energy mix. This map and other data from the assessment are available to the public on the RE Explorer geospatial tool. *Map courtesy of NREL*

## Significance and impact:

The data gathered and analyzed in the assessment support the need for informed decisions by the government of Bangladesh ranging from policy and investment to reliable power sector planning. Research results will help reduce technical risk and encourage private sector investment in the emerging wind power industry in Bangladesh. The government of Bangladesh may also use the assessment to develop well-designed policies that could encourage domestic and foreign investment in renewable energy to achieve its commitment to using renewable energy for 10% of its total generating capacity by 2021.

# Partnership To Develop Model for Predicting Wind Turbine Blade Damage Utilized DOE Structural Research Facilities and Capabilities at NWTC

A partnership among Sentient Science, NREL, and Sandia National Laboratories (Sandia) aims to develop models and software that will predict damage progression on wind turbine blades. The project is part of DOE's Small Business Voucher program. The team completed a fatigue assessment on a 13-meter (m) blade by damaging the blade and then monitoring the damage as it progressed to failure.

### Significance and impact:

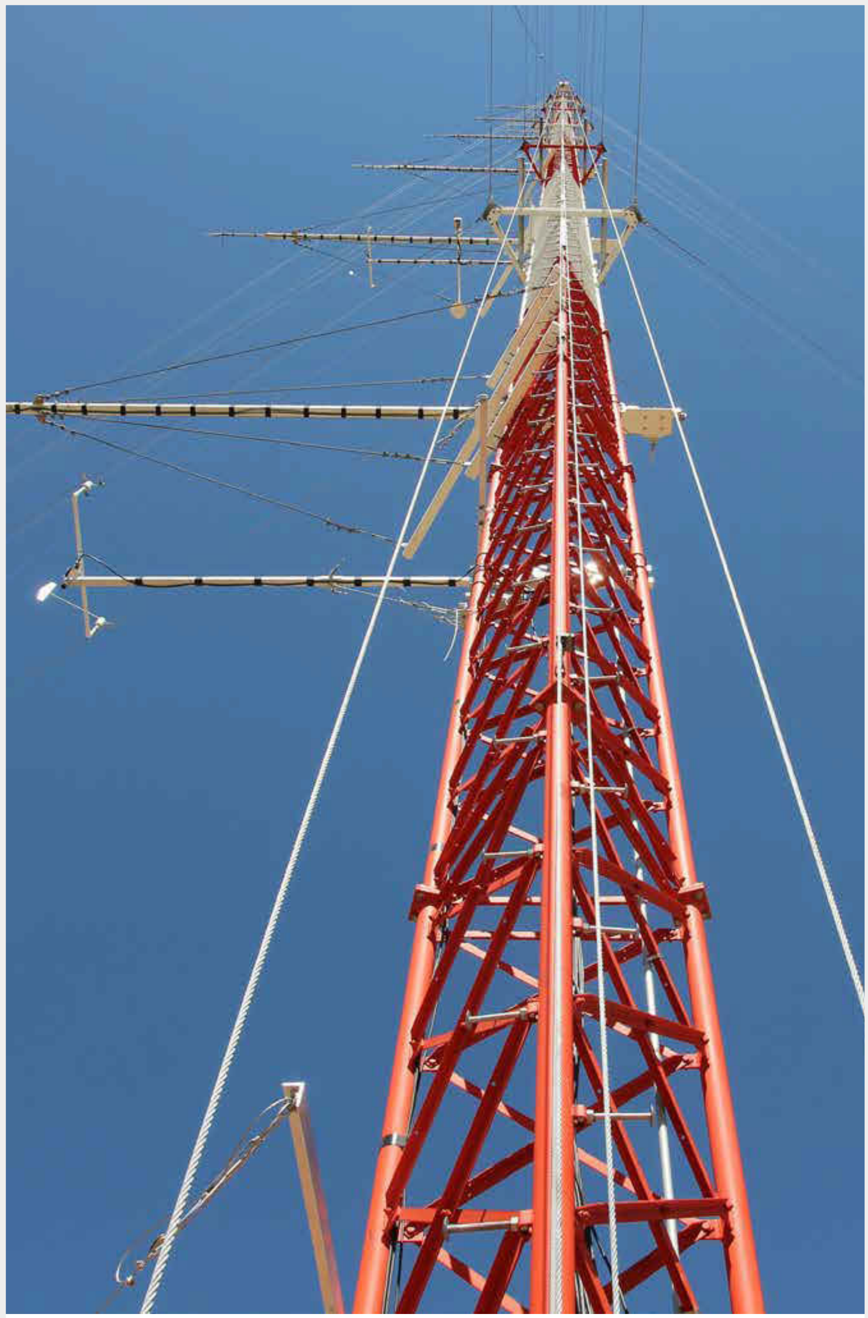
Sentient Science has developed damage progression models and software for use with wind turbine drivetrains. The company is now extending that capability with what it calls a "preventive-health tool for wind turbine blades." The tool will allow operators to plan for wind turbine blade maintenance and replacement, with minimal downtime, rather than respond to unexpected failure.

# U.S. Army Validates Drone Detection Models on M5

Through the U.S. Department of Defense, the U.S. Army used the NWTC's 135-m M5 meteorological tower to validate drone-detection models. Microphone booms attached to the tower measured vertical noise propagation under a range of atmospheric conditions.

### Significance and impact:

This project leveraged DOE's unique infrastructure investments at the NWTC to offer another federal agency an opportunity to conduct an experiment at the facility.



The U.S. Army utilized NREL's 135-meter meteorological tower to install instruments and collect data during a recent noise propagation experiment. *Photo by Lee Jay Fingersh, NREL 40950*

# Innovative, Flexible Blades Installed on Two-Bladed Turbine

Sponsored by DOE's Advanced Research Projects Agency-Energy, blade installation of NREL's partnership project with the University of Virginia, the Segmented Ultralight Morphing Rotor demonstration, kicked off in October 2018. The project explores two unique challenges to improving durability and reducing costs for offshore wind applications—flexible blades that can withstand strong, hurricane-force winds in the ocean and a downwind configuration so blades bend away from the tower to prevent it from being struck.

NREL engineers and technicians installed the Segmented Ultralight Morphing Rotor demonstration rotor onto the two-bladed Controls Advanced Research Turbine at the NWTC on October 5, 2018. *Photo by Dennis Schroeder, NREL 53473*

### Significance and impact:

This partnership enables NREL to work with outside researchers and highlights the laboratory's expertise and capabilities. It is the next phase of a much larger project working toward a record-breaking 50-MW turbine that demonstrates NREL's leadership in innovative offshore wind energy.

# New Materials Could Lead to Recyclable Wind Blades

NREL researchers are exploring the manufacturing process for specific parts of a thermoplastic wind blade that could ultimately improve the recyclability of turbine blades through a Laboratory Directed Research and Development project. The research team published their findings in Applied Composite Materials and noted that significant improvements in energy savings can be achieved by recycling retired materials and using thermal welding practices.

The team works to develop a blade using recyclable thermoplastic material. *Photo by Dave Snowberg, NREL*

## Significance and impact:

There are clear cost savings in the manufacturing process and potential savings could also be found by thermally welding the materials, ultimately reducing blade weight and cycle times. As blade materials become recyclable, repair and decommissioning costs will decrease as well. Eventually, recycling thermoplastic wind turbine blades could become a revenue generator for wind turbine farm owners and operators.

# NREL Receives Funding and Projects for Further Offshore Wind Research and Development

The U.S. National Offshore Wind Research and Development Consortium selected NREL to carry out a project focused on using shared moorings to improve the economic feasibility of floating wind technology. NREL has been awarded $300,000 (USD) for its Shared Mooring Systems for Deep-Water Floating Wind Farms project, in which it will assess the potential for reducing floating wind farm costs by connecting adjacent turbine platforms together and distributing the mooring loads throughout the wind farm.

Of shore wind technology continues to advance through funded projects at NREL and across the national lab complex. *Photo by Dennis Schroeder, 40436*

## Significance and impact:

This feasibility study is expected to break new ground in offshore wind mooring innovations and help inform the future work of consortium partners and developers when considering mooring solutions for offshore wind in deep water. If successful, this work could help reduce the cost and extend the depth range of offshore wind farms.

The New York State Energy Research and Development Authority (NYSERDA) also announced five projects to expand knowledge regarding important environmental and fishery topics identified in New York's Offshore Wind Master Plan. Among these projects, NREL will develop collaborative strategies and tools to address commercial fishing access in U.S. offshore wind farms, specifically by identifying opportunities to reduce risk for fishermen working within or transiting through an offshore wind development.

## Significance and impact:

This fishing access study is expected to minimize the disruption of commercial fishing within offshore wind arrays while ensuring economical energy generation and safe operation for the industry. If successful, this work could help the two industries coexist in an economically meaningful way.

# Awards & Recognition

## NREL Researcher Received Women of Renewable Industries and Sustainable Energy Honors for Technology and Innovation

Jennifer King, a senior researcher in NREL's wind energy program, received a Women of Renewable Industries and Sustainable Energy Honors for Technology and Innovation award.

### Significance and impact:

The program celebrates individuals who have made a measurable impact on advancing renewable energy and serve as positive role models for women looking to enter the field. This award recognizes Jennifer's leadership and work toward a strong diversified workforce and a robust renewable energy economy.

## NREL Appoints Wind Pioneer as Senior Research Fellow

Paul Veers was elevated to senior research fellow because of his significant contributions to NREL and the larger scientific community.

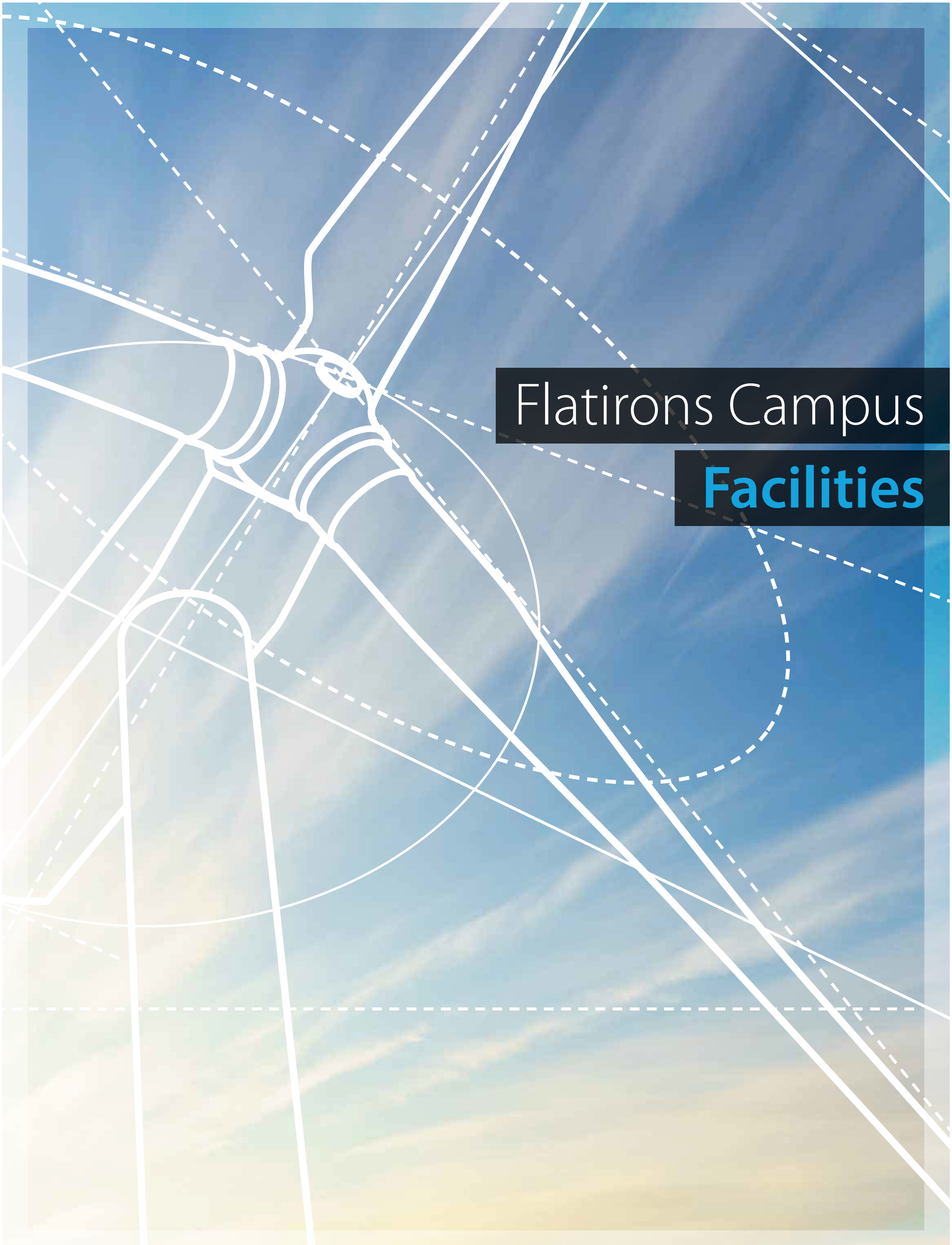
Chief engineer of the NWTC and manager of the Wind Energy Science Group, Paul came to NREL in August 2010. He previously worked at Sandia, where he led the research on innovations in wind turbine blade design.

### Significance and impact:

Along with other current research fellows, Paul will advise NREL executive management on the strategic direction of science and technology research and ensure NREL's work continues to meet the highest standards for quality and objectivity.

Wind pioneer Paul Veers, shown here at Flatirons, has been innovating wind power since the early 1980s. *Photo courtesy of Joshua Bauer, NREL*

# Flatirons Campus Facilities



Point of contact: David Simms, David.Simms@nrel.gov WBS: 1.1.0.401

# Improving Safety and Facilities To Optimize Operations

The equipment, facilities, and personnel at the Flatirons Campus needs to remain up to date to support fundamental research, development, experimentation, and validation of components and systems as well as to understand operation and failure modes.

Scott Wilde, NREL research operations manager, peeks out of the nacelle of the three-bladed Controls Advanced Research Turbine (CART3) as he directs the two-crane operation to remove the turbine's rotor. Rotor blades specially designed by a research partner were then installed on the CART3 for a field validation campaign to take place during the windy winter season. *Photo by Lee Jay Fingersh, NREL*

During the year, the project team maintained NREL's world-class research capabilities with the following accomplishments:

- The facilities team changed instruments on two of the meteorological towers (M-2 and M-5) to maintain calibration and traceability. They also supported partner research projects on the two Controls Advanced Research Turbines (CARTs) by completing required maintenance on each turbine, replacing a pitch drive, and updating the turbines' automated safety control systems. In addition, they purchased new lifting equipment to replace NWTC equipment no longer in service as a result of age and condition and enrolled new staff in Colorado Crane Operator School to receive necessary crane certification.

## Significance and impact:

NREL staff are responsible stewards of the significant specialized research infrastructure investments at the Flatirons Campus. Their diligence and expertise protect the safety and reliability of these investments, which upholds the integrity of the research performed there. In addition, rigorous staff training ensures that best practices are followed and supports DOE's objectives to ensure continued development and retention of research system engineers and technicians as well as technical subject matter experts.

- The NWTC at the Flatirons Campus conducts audits and implements quality assurance process upgrades in accordance with NREL Quality Management, Independent System Operator/International Electrotechnical Commission (IEC) 17025:2017, and the American Association of Laboratory Accreditation (A2LA) requirements to maintain accreditation. To receive accreditation from A2LA, an independent third party visited the site to audit operations covered under the scope of accreditation. The audit ensures that the facility fulfills regulatory requirements and demonstrates competence to industry stakeholders.

### Significance and impact:

An independent third-party auditor from A2LA evaluated all acoustic, electrical, and structural testing methods at the Flatirons Campus. Successful completion ensures that the Flatirons Campus fulfills regulatory requirements and demonstrates competence to industry stakeholders.

- The NREL facilities team completed operational modal characterization of the DOE 1.5-MW turbine to reflect drivetrain modifications to enable development of updated structural dynamics models for reliability and wake modeling research. The DOE Golden Office and Xcel Energy provided new guidance on the required future Flatirons Campus electrical configuration that will deliver additional flexibility for future research capabilities. NREL met this milestone by resolving required upgrades that impacted the second controllable grid interface (CGI) electrical design.

### Significance and impact:

The characterization of the DOE 1.5-MW turbine will enable development of updated structural dynamics models for reliability and wake modeling research. New power hardware-in-the-loop instruments and protection strategies expand options for collaborative monitoring and control of the Flatirons Campus grid integration research assets (e.g., generators, loads, storage) from NREL's Energy Systems Integration Facility and other national laboratories.

## Campus Expansion and Capability Enhancements

Point of contact: David Simms, David.Simms@nrel.gov WBS: 1.1.0.403

# Facility Enhancements Expand Flatirons Campus Research Capabilities

The Flatirons Campus and enhanced capabilities aim to meet next-generation technology demands and ensure that NREL's multimegawatt-scale research facilities will incorporate a comprehensive range of renewable energy technologies that meet the complex energy challenges of the future.

- NREL received approval from DOE to officially change the name of the 305-acre campus formerly known as the National Wind Technology Center (NWTC) to the Flatirons Campus. Although the NWTC will continue to be housed at the Flatirons Campus, the new name reflects the site's growth beyond wind to include grid integration, water power, energy storage, solar photovoltaics, and advanced manufacturing.

### Significance and impact:

The expanded campus will enable DOE and NREL to conduct the research needed to achieve an integrated energy system that can meet the complex energy challenges of the future.

- NREL continues to expand its research capabilities at the Flatirons Campus. Several system upgrades were accomplished in FY 2019, including an enhancement to the existing substation and procuring land rights in preparation for the energization planned for the spring of 2020. The existing substation was enhanced, and land rights procurement is in progress with energization expected in November 2019. Grid research pads, a new load bank, and a second controllable grid interface are also being designed and construction procurement is in progress. This project, done through a partnership with Xcel Energy, will expand the electrical generation capacity from 10 MW to 19.9 MW and will enable research related to the integrated energy systems at scale initiative.

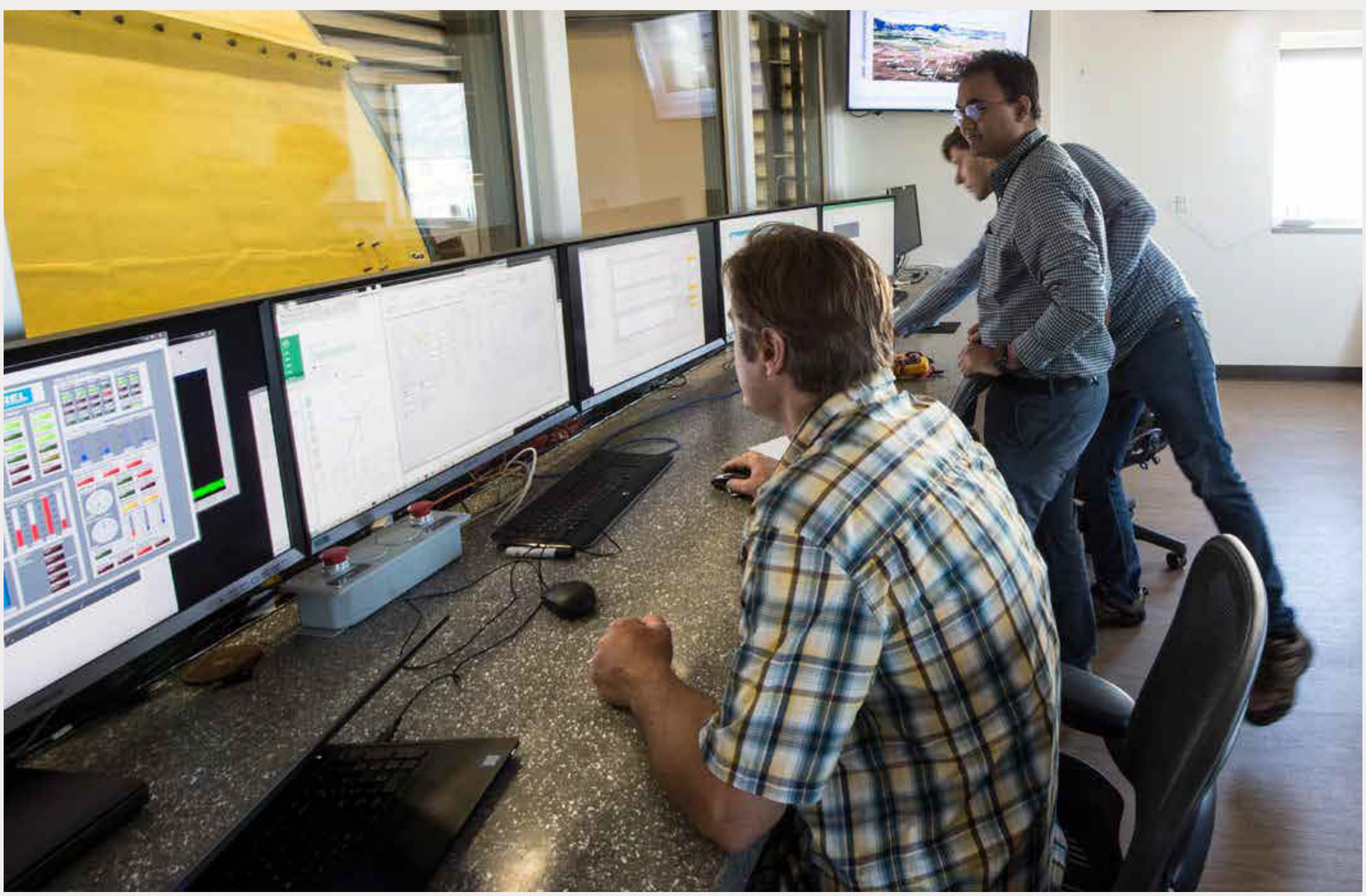
## Significance and impact:

These enhancements will help improve NREL's crosscutting research and drive new work and potential partners to the NWTC at the Flatirons Campus.

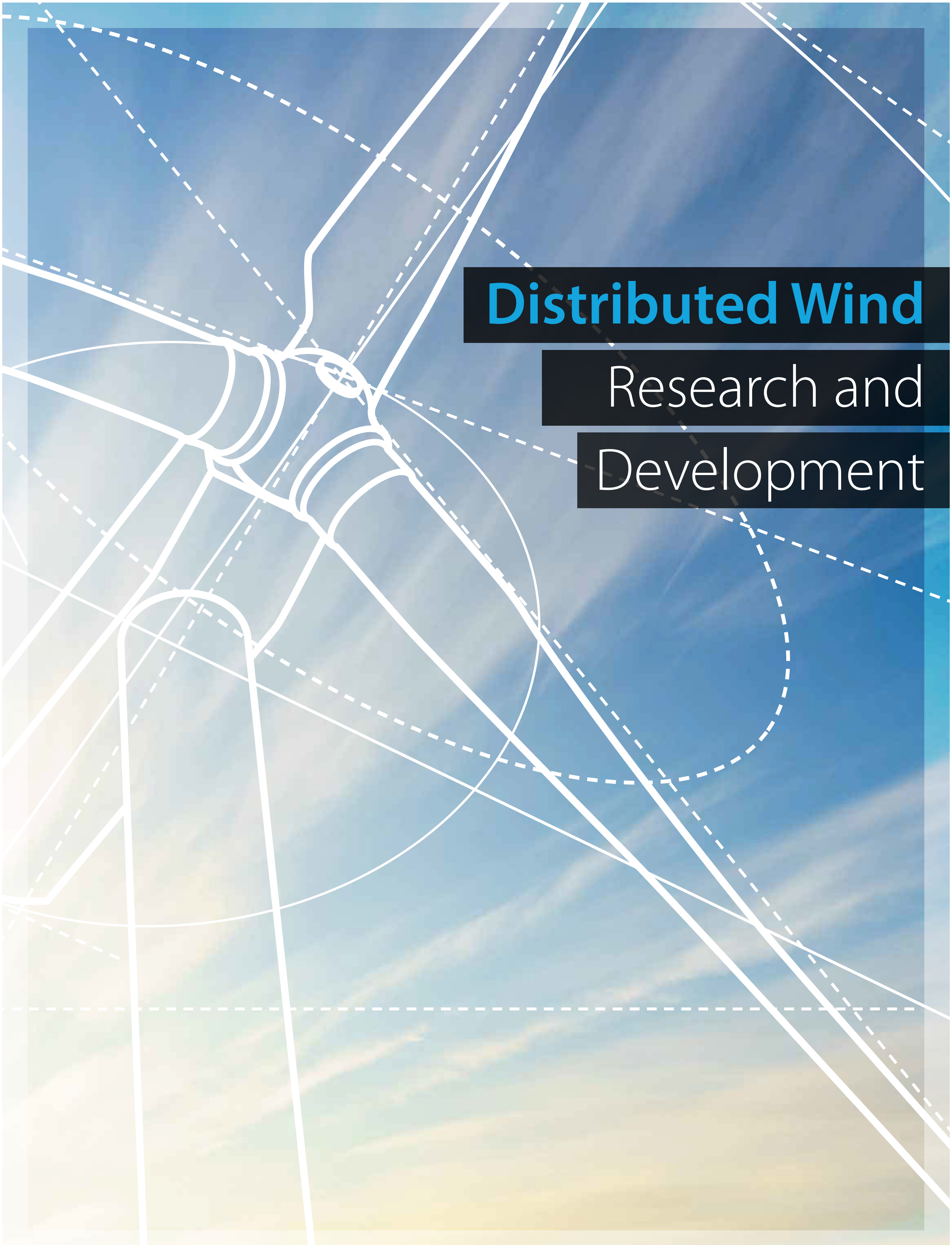
- The 3-MW grid simulator load bank and the second controllable grid interface (or CGI-2) are two significant projects helping to expand the research capabilities of the Flatirons Campus. Each of these foundational investments will provide significant support to anticipated future expansions for hydrogen, transportation, and grid integration research.

## Significance and impact:

The 3-MW grid simulator load bank and the CGI-2 are two of the first significant expenditures toward expanding the capabilities of the Flatirons Campus. Guidance from the DOE Golden Office and Xcel Energy related to the electrical configuration of the Flatirons Campus will allow NREL to design and build out the campus electrical infrastructure in support of planned future research. Projects like the simulator load bank and the CGI-2, as well as upgrading the site's electrical generation capacity from 10 MW to 19.9 MW, help enable future research to explore integrated energy systems at scale.



Analysis in the CGI Control room at the NWTC. *Photo by Dennis Schroeder, NREL*



# Distributed Wind Research and Development

Point of contact: Ian Baring-Gould, Ian.Baring-Gould@nrel.gov WBS: 1.2.1.401

# Bringing Low-Cost Distributed Wind Systems to Market

Companies developing distributed wind systems face challenges bringing the systems to market, including cost competitiveness, turbine reliability, and certification. The Competitiveness Improvement Project (CIP) helps distributed wind systems become more cost competitive and overcome barriers to market entry.

## During the fiscal year, the project team achieved the following:

- NREL conducted a design review and technically advised Pecos Wind Power in the design of an 85-kilowatt (kW), Class IV, low-cost wind turbine. NREL also provided technical monitoring and support to companies including Bergey Windpower, Windurance, Eocycle, RockConcrete, Intergrid, NPS, and Sonsight, Inc.

## Significance and impact:

The final production prototype design of the Pecos wind turbine marks progress toward WETO goals to improve performance and market share of certified small wind turbines in the United States.

- NREL continues to support the CIP as part of its multifaceted wind energy research portfolio to help the U.S. wind industry develop competitive, high-performance technology for domestic and global energy markets. NREL has begun planning for a CIP workshop focused on reviewing common topics of previous CIP solicitations, merit criteria, design evaluation requirements, and testing and certification standards.

## Significance and impact:

The CIP helps manufacturers of small and midsize wind turbines improve their turbine design and manufacturing processes while reducing costs and improving efficiency, as well as work toward certification. Certification is important because it demonstrates to consumers that these turbines meet performance and safety requirements.

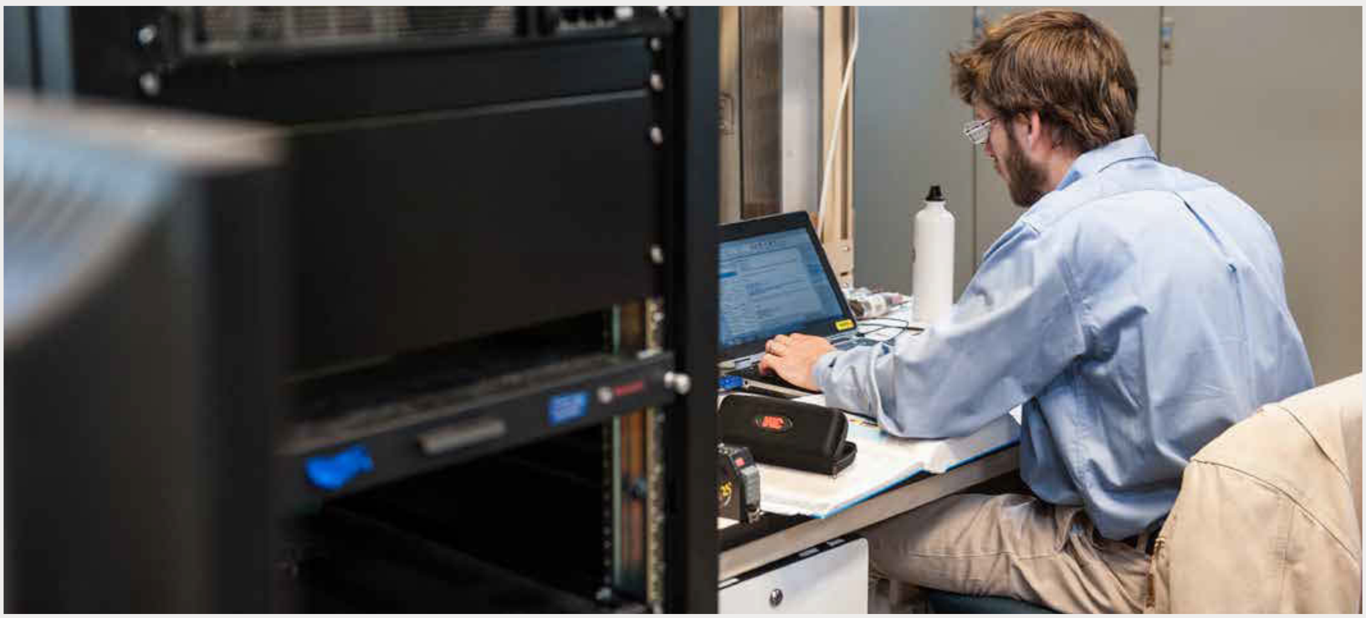

CIP project highlights improved design and reduced levelized cost of energy (LCOE) of the Bergey Excel 15 design. *Graphic courtesy of NREL*

Point of contact: Ian Baring-Gould, Ian.Baring-Gould@nrel.gov WBS: 1.2.3.401

# Enhancing the MIRACL of Distributed Wind

The Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project improves the integration of modern distributed wind equipment into microgrids, national lab testing capabilities, and other distributed wind networks. MIRACL also aims to develop secure standardized controls and interfaces to seamlessly integrate with other distributed energy resources in microgrid applications, and increase distributed wind capabilities to provide grid services.

## During the FY 2019, the project team achieved the following:



NREL Engineer Andy Hoke works on microgrid testing at the Flatirons Campus. *Photo by Dennis Schroeder, 31578*

- The NREL research team submitted a full R&D plan for the project to WETO and initiated planning for near-term infrastructure projects to improve the utilization of distributed wind technology on isolated and weak microgrids.

## Significance and impact:

The MIRACL project makes it easier to understand how distributed wind can be integrated into microgrids to capture more distributed wind potential across the United States. This project will ensure that distributed wind technology can play an active role in high-renewable-contribution, distributed-wind-energy-driven grids of the future.

- The MIRACL project now has an initial advisory board and a clear idea of what other industry representation should be added. NREL hosted team and advisory board meetings to obtain project feedback, conduct informational outreach, and test infrastructure needs from an industry perspective. Annual and semiannual meetings are scheduled.

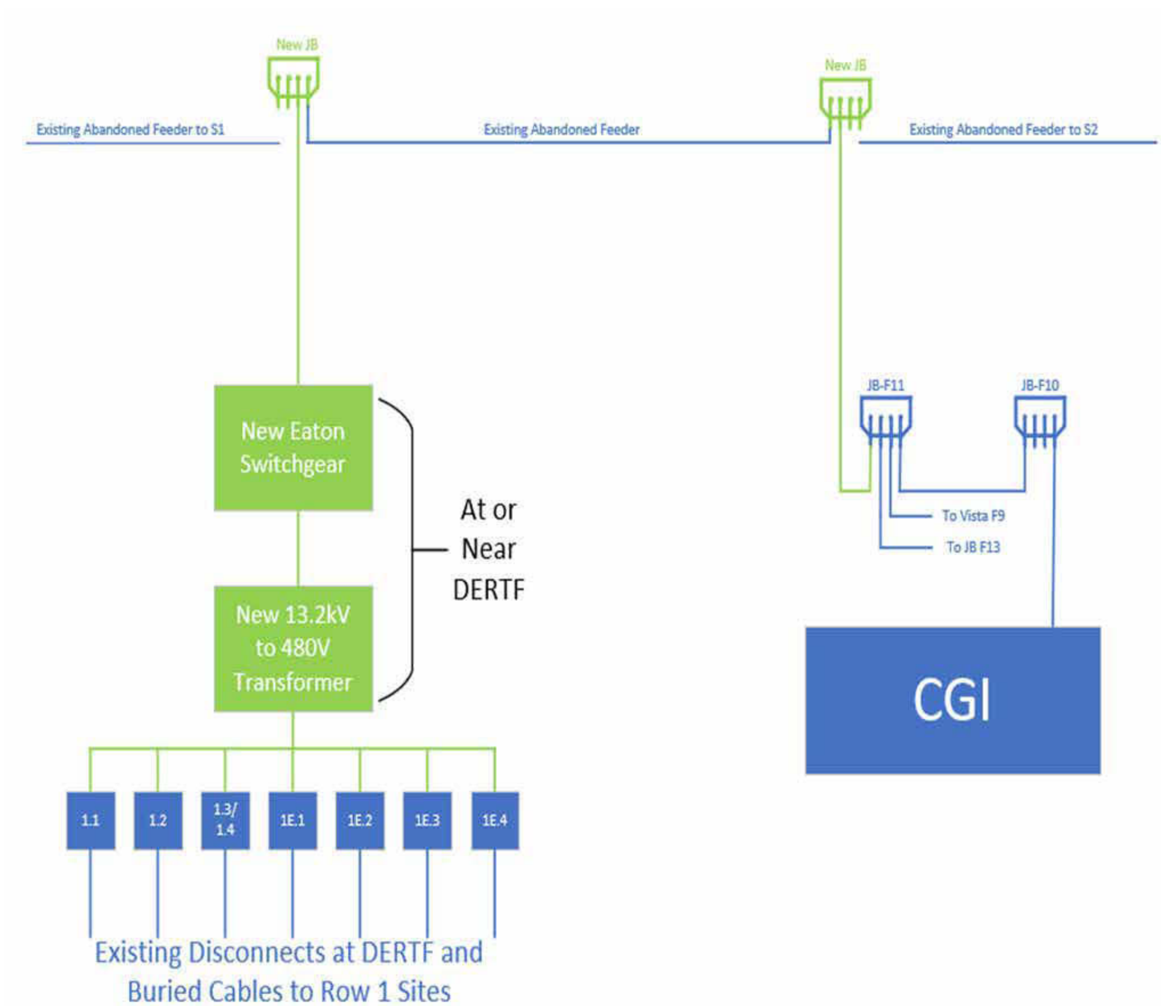
## Significance and impact:

The team is positioned to receive ongoing feedback in annual or semiannual in-person meetings, as well as periodic virtual meetings. Current advisory board members recommended adding utility members with real experience with distributed wind in their systems, or interest in adding it, as well as project developers who can provide insight into challenges such as permitting, financing, and interconnection. The advisory board also identified other key challenges, such as quantifying and demonstrating the value of distributed wind on a utility distribution system.

- The initial design of the NREL small wind (Row 1) site interconnection to the CGI was also completed, using an existing abandoned feeder line, which significantly reduced costs.

## Significance and impact:

Interconnecting the existing Row-1 distributed wind test sites to the CGI will allow the distributed wind industry to take advantage of the unique capabilities of this multimillion-dollar DOE grid simulation investment. It also provides connection to all additional system capabilities and equipment currently connected to the CGI, as well as all planned additions.




Schematic (green represents new and blue represents existing) showing the planned connection of the Row-1 distributed wind sites to the CGI. *Image courtesy of Robert Preus, NREL*

Point of contact: Robert Preus, Robert.Preus@nrel.gov WBS: 1.2.4.401

NREL worked with Sandia National Laboratories on a report that evaluated using wind to power U.S. military bases. *Photo by Dennis Schroeder, NREL*

# Defense and Disaster Deployable Turbine Project Protects Military Personnel Through Renewable Energy

The Defense and Disaster Deployable Turbine project aims to enable successful deployment of wind turbines for forward-operating military bases and disaster areas where quick deployment is critical. The team is working to add wind energy to military base energy portfolios by ensuring that renewable energy generation can happen at night and on cloudy days or seasons in which solar power is not viable. Through this project, military and wind industry stakeholders have been able to collaborate to develop wind turbine systems that meet military needs, especially for forward-operating bases.

## During FY 2019, the project team achieved the following:

- Wind energy has the potential to offset the use of diesel fuel to supply power to remote military installations. With input from NREL, Sandia submitted a report on the modeling and simulation scenario for a specific army forward-operating base configuration.

## Significance and impact:

Using wind to power U.S. military bases and overseas installations can reduce both the costs and risks involved in the use and transport of conventional fuels. Evaluating the needs and developing specifications for specific base configurations will enable safe, cost-effective, and successful deployment of wind energy systems on military bases.

Point of contact: Ian Baring-Gould, Ian.Baring-Gould@nrel.gov WBS: 1.2.5.401

# International Energy Agency Wind Task 41 Contributes to a Global Distributed Energy Future, New Model To Reduce Levelized Cost of Energy

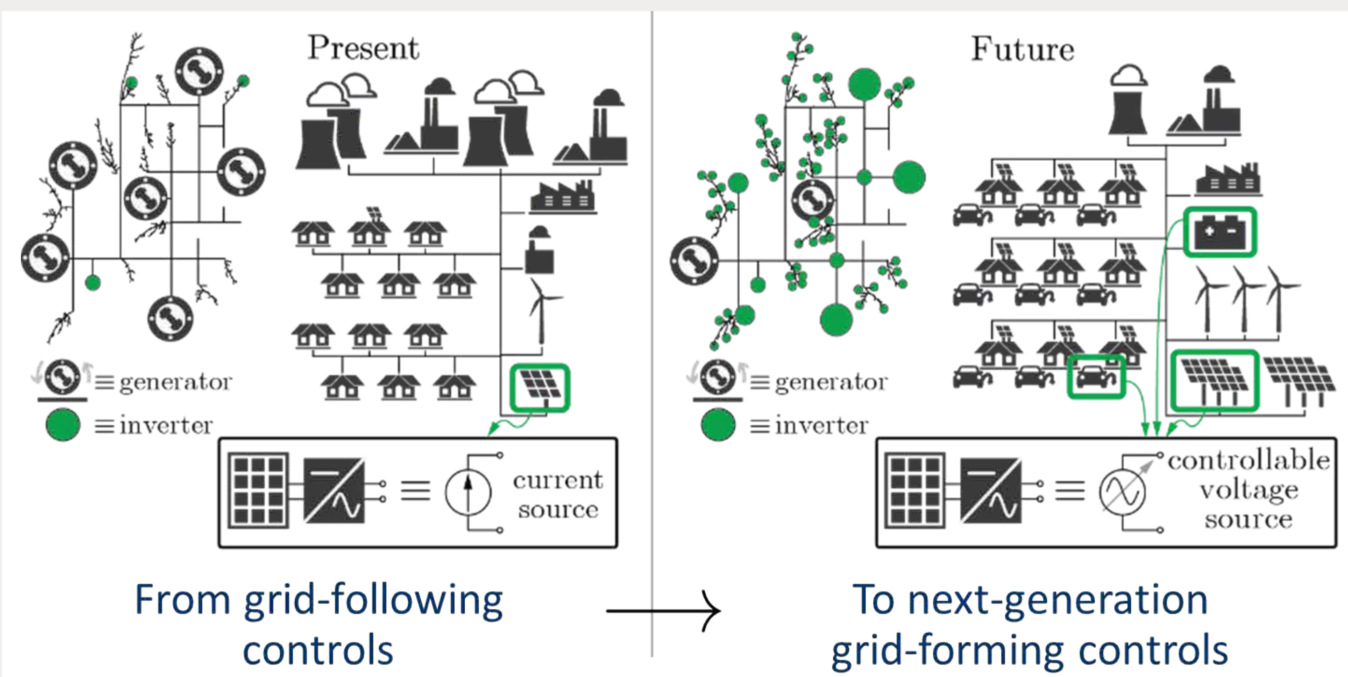
Through distributed wind strategic and technical engagement, NREL is reducing technical, economic, and market barriers that have limited the use of distributed wind. The International Energy Agency (IEA) Wind Task 41 aims to enhance collaboration among countries and companies to better integrate distributed wind technologies into the energy systems of the future.

## During FY 2019, the project team achieved the following:

- A final work proposal for IEA Wind Task 41 was approved in March at the 83rd IEA Wind Technology Collaboration Programme Executive Committee meeting in Bilbao, Spain, where it was well received. Canada, China, Denmark, Ireland, Korea, Spain, and the United States agreed to participate, and Austria, Belgium, Japan, and Poland expressed their interest in the project. NREL and PNNL are helping lead the United States' efforts on this project to enable wind to contribute to a distributed energy future.

## Significance and impact:

Mirroring an approach that was successful for photovoltaic technologies, IEA Wind Task 41 enhances collaboration with distributed wind experts across countries and companies to lower the costs of distributed wind and mitigate technology deployment barriers. Targeted improvements to distributed wind technologies include improved management and coordination, improved design standards for small and midsize wind turbines, enhanced data sharing for research, and expanded support for distributed wind integration into evolving electricity systems.




Vision for the future. Next-generation grid-forming controls radically alter the way distributed energy technologies work with the electric grid.

- NREL conducted work on the forthcoming balance-of-station model for distributed wind applications. Recent efforts have focused on megawatt-scale distributed applications, but future efforts will include distributed applications as small as 20 kW. This model allows for a more structured comparison of the LCOE impacts of different foundation and installation strategies and solutions. NREL also supported development, implementation, and reporting for an ongoing U.S. standards assessment.

### Significance and impact:

The new model evaluates the potential impact of turbine scale on distributed wind applications, among other balance-of-station considerations. At the megawatt scale, single turbine installations of 4-MW class turbines could lead to 20+% LCOE reductions relative to 1-MW class single turbine installations.

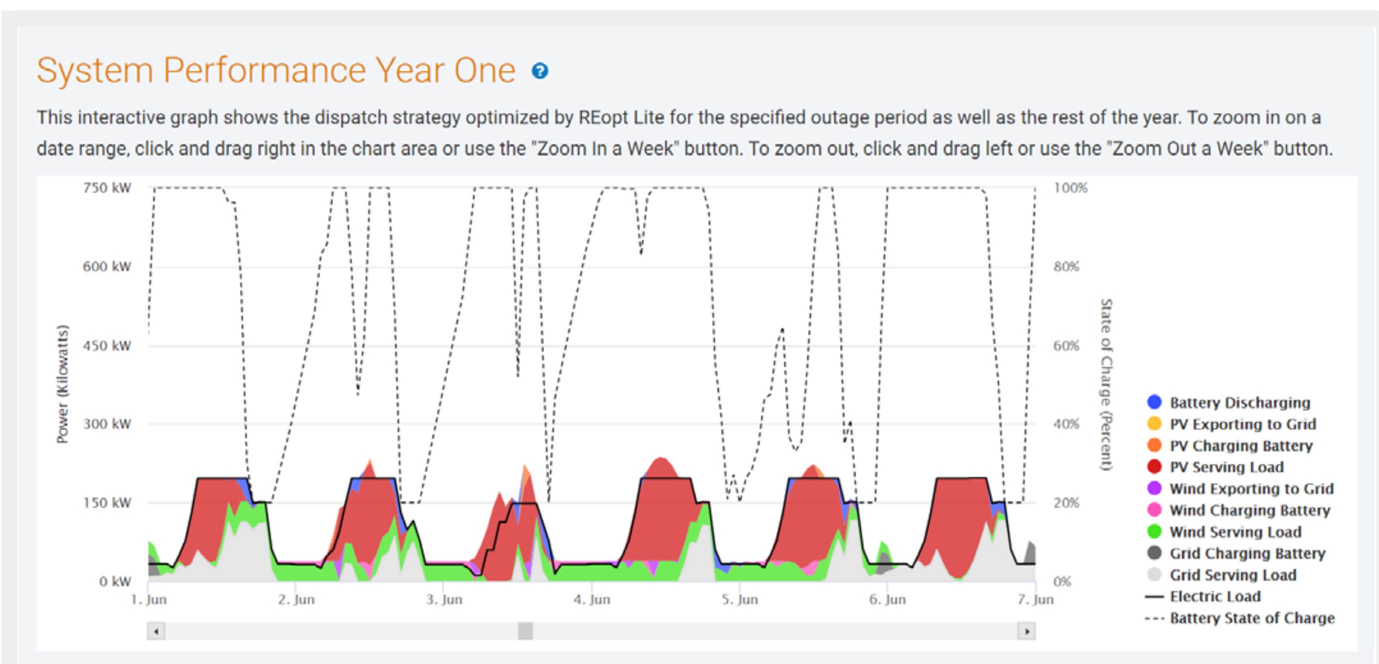
## Tools Assessing Performance

Point of contact: Heidi Tinnesand, Heidi.Tinnesand@nrel.gov WBS: 1.2.2.401

# REopt Lite Adds Wind as New Energy Optimization Capability, Workshop Addresses Challenges of Distributed Wind Resource Assessment

Through modeling and application development, this project aims to address the challenges of resource assessment in distributed wind by improving resource characterization capabilities and estimate precision. This team supports distributed wind energy cost savings and resilience by increasing the accuracy and reducing cost and risks of distributed wind site assessment, project development, and performance.

### During FY 2019, the project team achieved the following:




Vision for the future. Next-generation grid-forming controls radically alter the way distributed energy technologies work with the electric grid.

- NREL's REopt Lite web tool now has a wind optimization module for commercial building managers. Users can model four different wind size classes, including residential, commercial, midsize, and large turbines. The tool includes default values for wind system capital cost, along with inputs for federal, state, and utility capital cost and production-based incentives.

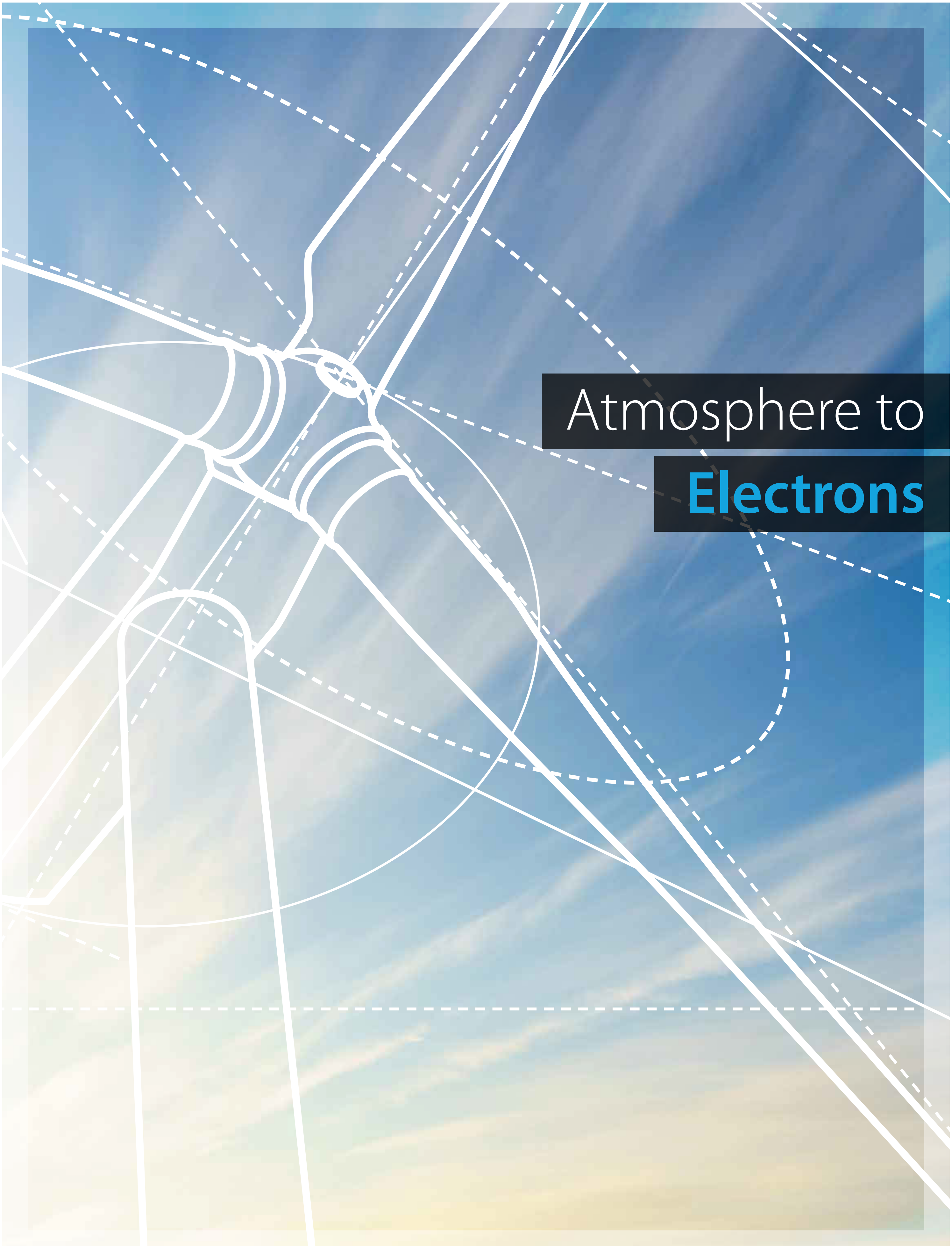
## Significance and impact:

Adding wind to REopt Lite allows building owners and energy managers to further diversify resilient power technologies at a site by evaluating the economic viability of distributed wind alongside solar photovoltaics and battery storage.

- The Tools Assessing Performance team hosted a workshop to discuss preliminary analysis and priorities with participants from the PNNL, Argonne National Laboratory, Los Alamos National Laboratory, DOE, and industry. Plans are underway to develop a high-fidelity wind resource data set that could be used in production and cost estimates for distributed wind systems.

## Significance and impact:

Better data on wind resources will allow developers and contractors to provide potential adopters with credible performance estimates, thereby boosting consumer and investor confidence and opening the door to low-cost financing.



# Atmosphere to **Electrons**

# Improved Wind Forecasting Boosts Plant Performance

NREL is one of five national laboratories that are collaborating to improve predictions of wind speeds and power within the Second Wind Forecast Improvement Project (WFIP 2). The goal of the project is to refine the physics used in current forecast models for more accurate wind forecasts in complex terrain.

## During FY 2019, the project team achieved the following:

- In conjunction with WETO.4.1.0.406, the Atmosphere to Electrons (A2e) Performance Risk, Uncertainty, and Finance (PRUF) program area, WFIP 2 closed out the NREL portion of WFIP 2 by preparing a journal article on the best-performing statistical models of wind plant power productions for application to Columbia Gorge Wind Farms. Analysis was based on measured atmospheric data. With the project closing out, efforts will now shift to supporting the WFIP 2 extension project.

NREL researchers check the weather forecast and review safety plans before inspecting wind turbine blades. *Photo by Dennis Schroeder, NREL*

## Significance and impact:

Considerable improvement in hourly power predictions can be experienced when including some measure of turbulence or stability in statistical models of wind farms. Turbulent kinetic energy was found to be the most important variable apart from wind speed and more important than wind direction, pressure, and temperature. This research helps to enable a new generation of wind power plant technology, in which wind power plants optimize performance through improved statistical analysis.

- NREL completed a literature review and industry survey about the best practices in machine learning for wind power forecasting. This review is part of NREL's work to translate advances in modeled wind forecasts to improvements in power predictions. Additionally, NREL contributed to two journal articles in the Bulletin of the American Meteorological Society. One article presents an overview of this project, and the second article describes the observational field campaign, highlighting several meteorological phenomena that occur frequently in complex terrain and for which model predictions have been enhanced.

### Significance and impact:

The journal articles help advance the field's understanding of how to better characterize and forecast winds affected by specific weather phenomena to lower overall project costs by reducing uncertainty and increasing accuracy of models.

MMC - Model Development & Validation

Point of contact: Matthew Churchfield, Matthew.Churchfield@nrel.gov WBS: WETO.1.3.2.401

# Researchers Aim To Understand Full Range of Atmospheric Flow Conditions at Wind Power Plants

The goal of the Mesoscale-Microscale Coupling (MMC) project is to create new predictive numerical simulation capabilities that represent the full range of atmospheric flow conditions impacting wind power plant performance. Coupling microscale wind plant simulation tools with mesoscale atmospheric models will enable the incorporation of these important missing factors on microscale wind plant flow simulations, providing improved characterization, prediction, and understanding of wind plant performance under a wide range of realistic operating conditions.

### During FY 2019, the project team achieved the following:

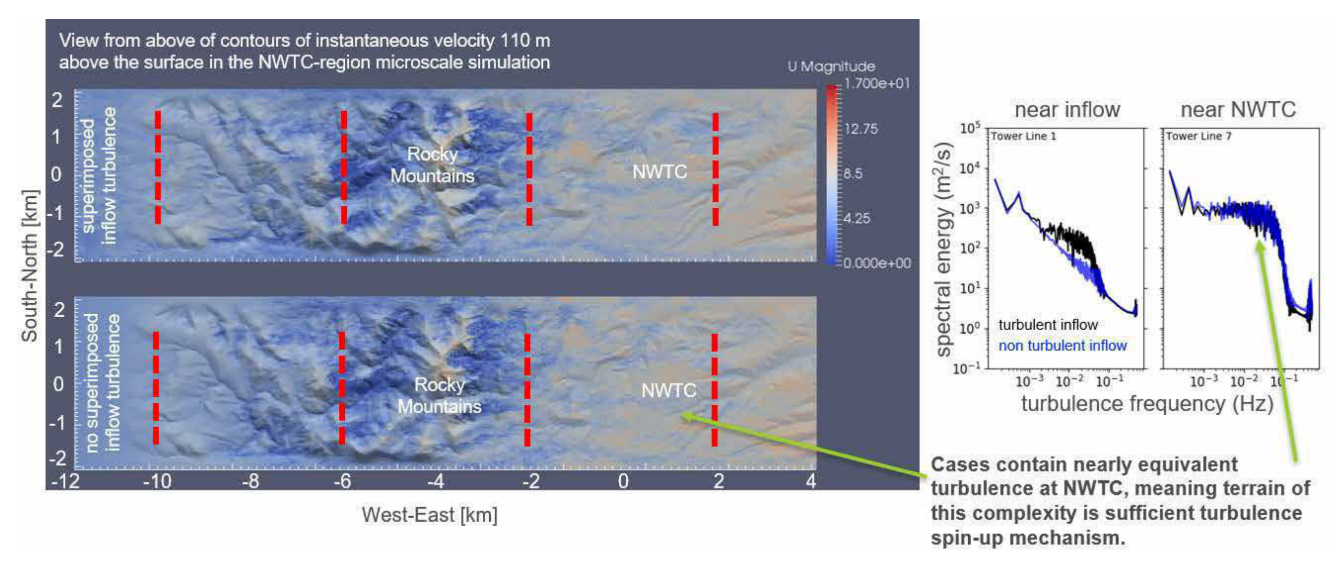
- NREL researchers made progress in the development of a profile assimilation coupling method. The goal of this project is to drive a microscale simulation, given the mean vertical profiles of the winds. Although a previously developed simple method works well in reproducing the given mean winds, it does not predict turbulence effectively. The researchers developed more advanced methods for performing profile assimilation coupling that show great improvement in predicting wind turbulence.

  Researchers also advanced the interface between the mesoscale and microscale in complex terrain. The team is working to determine how terrain ruggedness affects the formation of turbulence within the microscale domain and under what terrain conditions sophisticated methods are necessary for initiating turbulence at the mesoscale-microscale interface. The terrain west of the NWTC is being used as a case study.

  The team also discovered that offline microscale codes like the Simulator for Wind Farm Applications and Nalu-Wind can resolve gravity waves, which are three-dimensional atmospheric waves that exist. Researchers made significant progress in understanding gravity waves and in formulating methods to deal with boundary reflection problems.

### Significance and impact:

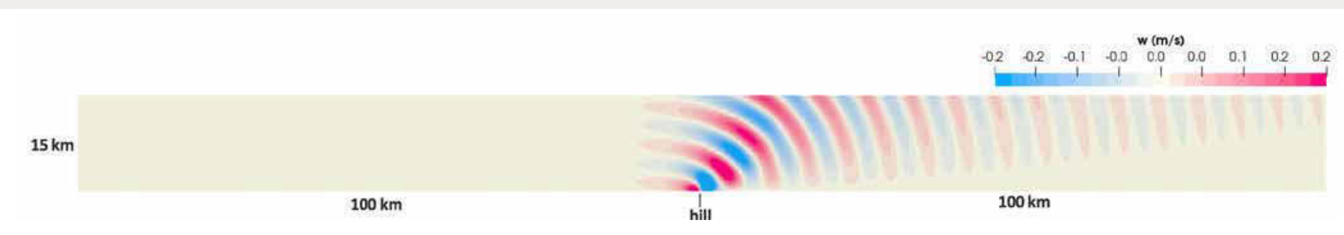
The development of the profile assimilation method will significantly enhance the range of conditions that we can simulate within the microscale beyond just the canonical cases we simulate now. This is useful for other A2e tasks, such as controls science, in providing a wider range of situations to simulate wind plant advanced control. Studying coupling needs within complex terrain is important because those needs are not well understood yet and best practices should be established. Recent findings for the MMC project have been published in the *Bulletin of the American Meteorological Society*.




Terrain view and data from research on how complex the terrain needs to be to completely rely upon it as the mechanism for turbulence "spin-up."
*Graphic courtesy of NREL*

- A key to increasing the range of atmospheric flow conditions that can be simulated is to incorporate the mesoscale (regional-scale) weather impacts on the microscale (wind-plant scale). There is no "one-size-fits-all" mesoscale-microscale coupling method, and coupling comes with significant challenges. One such challenge arises when gravity waves form in the microscale solution when performing mesoscale-microscale coupling in complex terrain.

  Atmospheric gravity waves are three-dimensional (3D) disturbances in atmospheric flow that are a combined result of flow over terrain and background atmospheric density stratification in which more dense air lies below less dense air. In initial work to simulate complex flow cases, realistic gravity waves form but reflect off of simulation domain boundaries polluting the flow field. In reality, the atmosphere has no defined boundaries like in simulations, so real gravity waves should not reflect like this. NREL has made progress addressing this issue by implementing gravity-wave-absorbing boundary regions in mesoscale-microscale simulations to keep the waves from erroneously reflecting.




A vertical slice of a 200-kilometer-long atmospheric simulation containing gravity waves caused by a small 100-m tall hill. The waves are shown as disturbances in the vertical velocity field. The winds are from the left to right. *Figure by Matt Churchfield, NREL*

## Significance and impact:

Proper treatment of atmospheric gravity waves within a mesoscale-coupled wind-plant flow simulation makes for more accurate mesoscale-microscale coupling in complex terrain with realistic flow phenomena. Not only does complex terrain initiate gravity waves, but researchers are finding that wind farms themselves can create gravity waves. These gravity waves can contribute to wind-farm blockage effects that reduce power output. Understanding these waves can help to optimize power output at wind farms.

Point of contact: Michael Sprague, Michael.A.Sprague@nrel.gov WBS: WETO.1.3.3.401

# High-Fidelity Modeling and Simulation Project Enhances Knowledge of Flow Physics at Wind Plants

The goal of the High-Fidelity Modeling project is to reduce wind plant losses and drive significant reductions in the cost of wind energy. By improving our understanding of the fundamental flow physics governing whole wind plant performance—including wake formation, complex terrain impacts, and turbine-turbine interaction—new technologies can be developed that mitigate adverse effects and enhance energy capture potential.

## During FY 2019, the project team achieved the following:

- As a part of the High-Fidelity Modeling project and the ExaWind Exascale Computing Project objectives, NREL researchers demonstrated the ability of the Nalu-Wind and OpenFAST codes to perform a full-physics geometry-resolved simulation of a single wind turbine in turbulent atmospheric flow.


Cutting through the haze. This graphic shows velocity magnitude in the full-physics resolved single-turbine simulation. *Graphic by NREL*

## Significance and impact:

Nalu-Wind and OpenFAST capabilities raise the bar for high-fidelity modeling around the world. Using these codes, NREL demonstrated the first full-physics simulation of its kind—a significant step toward full-scale predictive wind farm simulations that factor in both complex flow dynamics and turbine structural dynamics. Getting the full-scale picture of the physics and variables at play at a wind farm is essential to understanding how wind farms function in different atmospheric conditions. This simulation moves the field one step closer to this understanding, which will be essential for improving how wind farms are optimized for energy extraction, increased turbine life, and improved resource availability forecasting.

- Ganesh Vijayakumar, an NREL researcher, implemented a flexible blade modeling capability into high-fidelity modeling simulations that capture how wind turbine blades bend and deform as they would in real life. Shreyas Ananthan, also from NREL, presented the results of these simulations at the 2019 Wind Energy Science Conference in a paper titled, "Effect of Fluid-Structure-Interaction Algorithms on Wind Turbine Loads."

### Significance and impact:

Blade-deformation coupling helps predict the behavior of advanced, flexible, adaptive blades that might have blade deflections and curvatures greater than turbine blades in the past. This behavior pushes the limits of traditional design tools based on engineering approximations and can improve the accuracy of high-fidelity simulations. Flexible blade modeling can help improve how wind farms and turbine blades are optimized for energy extraction, increased turbine life, and improved resource availability forecasting.

## Rotor Wake Measurements & Predictions for Validation

Point of contact: Paula Doubrawa, Paula.Doubrawa@nrel.gov and Patrick Moriarty, Patrick.Moriarty@nrel.gov WBS: WETO.1.3.4.401

# Researchers Improve Understanding of Wind Turbine Wakes Through Measurements at Wind Plants

The ability to understand and predict wind power plant flows needs to be improved to enable the design and optimization of the next generation of high-performance wind plants that will significantly reduce the cost of wind energy. Achieving this goal requires integrating high-quality wind plant experimental data with simulations to study relevant physical phenomena. It also requires validating current and future (i.e., in development) computational modeling tools through the development and implementation of a verification and validation framework.

### During FY 2019, the project team achieved the following:

- In "Benchmarks for Model Validation based on LiDAR Wake Measurements," researchers offer the wind energy industry and research communities the data and methodology that they need to validate wind turbine wake models of any type. The publication defines three benchmarks of increasing complexity in the atmospheric environment: near neutral, slightly unstable, and very stable. It is difficult to perform a full-system validation of wind plant simulations that consider atmospheric inflow, the response of wind turbines, and their wakes without freely available, high-quality measurements.

### Significance and impact:

This work provides a robust wake model validation exercise open to anyone, which will serve to minimize uncertainty in model validation practices related to varying methodologies across simulation tools and users. When the three benchmarks are combined, they can be used to identify shortcomings in model performance and drive the direction of model development.

- Lidar devices can only provide wind measurements along the laser beam (i.e., the "line-of-sight" velocity). Retrieval of horizontal wind speed from the line-of-sight measurements of a single lidar in the wind turbine wake is difficult because of the complexity of the flow within the wake, and requires making assumptions that introduce errors in the wind speed estimates. In the paper, "Evaluation of Wind Speed Retrieval from Continuous-Wave Lidar Measurements of a Wind Turbine Wake Using Virtual Lidar Techniques," NREL researchers quantify errors associated with the retrieval processes and provide guidelines for best practices when using lidar to measure wakes. The analysis is based on high-fidelity simulations of the IEA Wind Task 31 Scaled Wind Farm Technology benchmark. A virtual lidar is incorporated in the simulation to mimic the behavior of the real lidar, which is mounted on the turbine hub in the Texas facility.

The high level of mixing found in the wind turbine wake creates larger variations of wind speed in the volume of air that is measured by the laser. Because of these flow complexities and instrument limitations, the lidar tends to overestimate the wind speed in the near wake and underestimate it in the far wake. The location of the transition from an overestimation to an underestimation of wind speed in the wake depends on how fast the wake dissipates. Both near wake and far wake retrieval errors result from laser beam angled measurement decreasing with downstream distance, and the error resulting from the volume-averaging increases with downstream distances. These findings are critical for interpreting lidar-derived wind estimates at wind power plants.

### Significance and impact:

This research helps quantify errors associated with both real lidar data and postprocessing of the lidar data, providing researchers with a better understanding of wake measurement data in the context of cutting-edge remote-sensing technology. In addition, this work ultimately creates a better numerical model validation platform for future research.

Advanced Flow Control Science for Wind

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

## Advanced Flow Control Software Advances Wake-Steering Capabilities and "Smart Plant" Control Design

The advanced flow control project develops the technical capabilities, methods, and approaches that enable "smart plant" control design to optimize wind plants with respect to energy capture and loads. This wind-power-plant-focused controls capability is one of the primary mechanisms to utilize much of the physics-based understanding generated by A2e, and to put into effect the actual performance improvements in the wind plant systems.

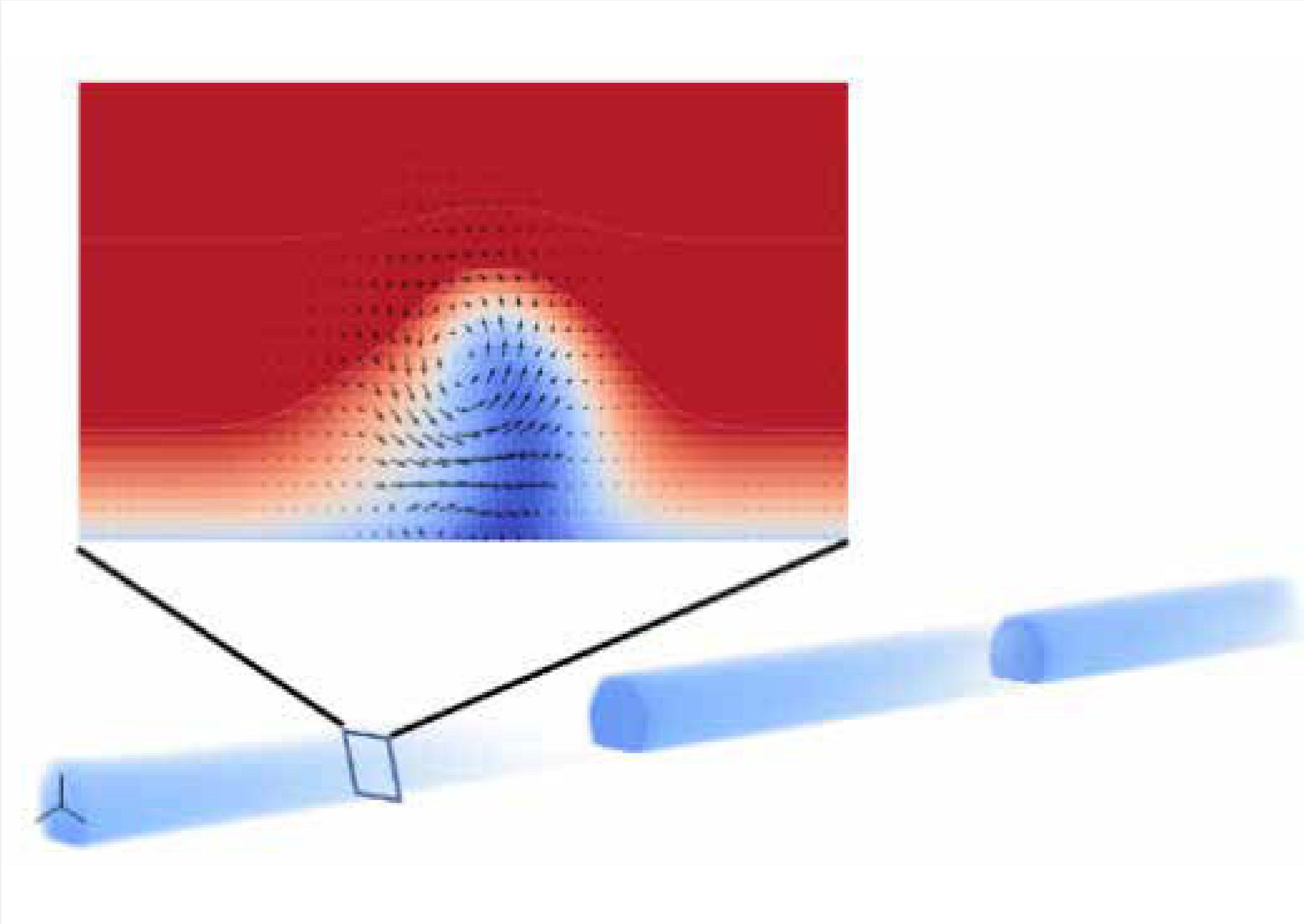
### During FY 2019, the project team achieved the following:

- NREL released the fourth-generation FLORIS software, which has accuracy and usability improvements. Developed in collaboration with the Delft University of Technology, FLORIS models turbine-wake interactions at wind power plants and allows for the design and analysis of wind farm controllers using a user-specified wake model. NREL software engineers also introduced a modular approach that enables features to be added quickly and a redesigned interface that gives researchers more control over simulations.

  Among these improvements is incorporation of the curled wake model, which provides additional methods for designing wake-steering controls at wind power plants, unlocking new potential for wake steering not previously captured in any engineering wake model.

### Significance and impact:

Advanced flow control science develops the technical capabilities and methods for smart plants, where the activities of wind turbines are coordinated by a central wind farm controller. Made available through GitHub, the ability to use information from turbines and adjust in real time can substantially improve performance, optimize energy capture, and minimize loads of existing and new wind farms. FLORIS exists in an evolving code environment, responding to the latest advances in advanced flow control science, enabling wind farm developers to design controllers and estimate their impact on annual energy production.

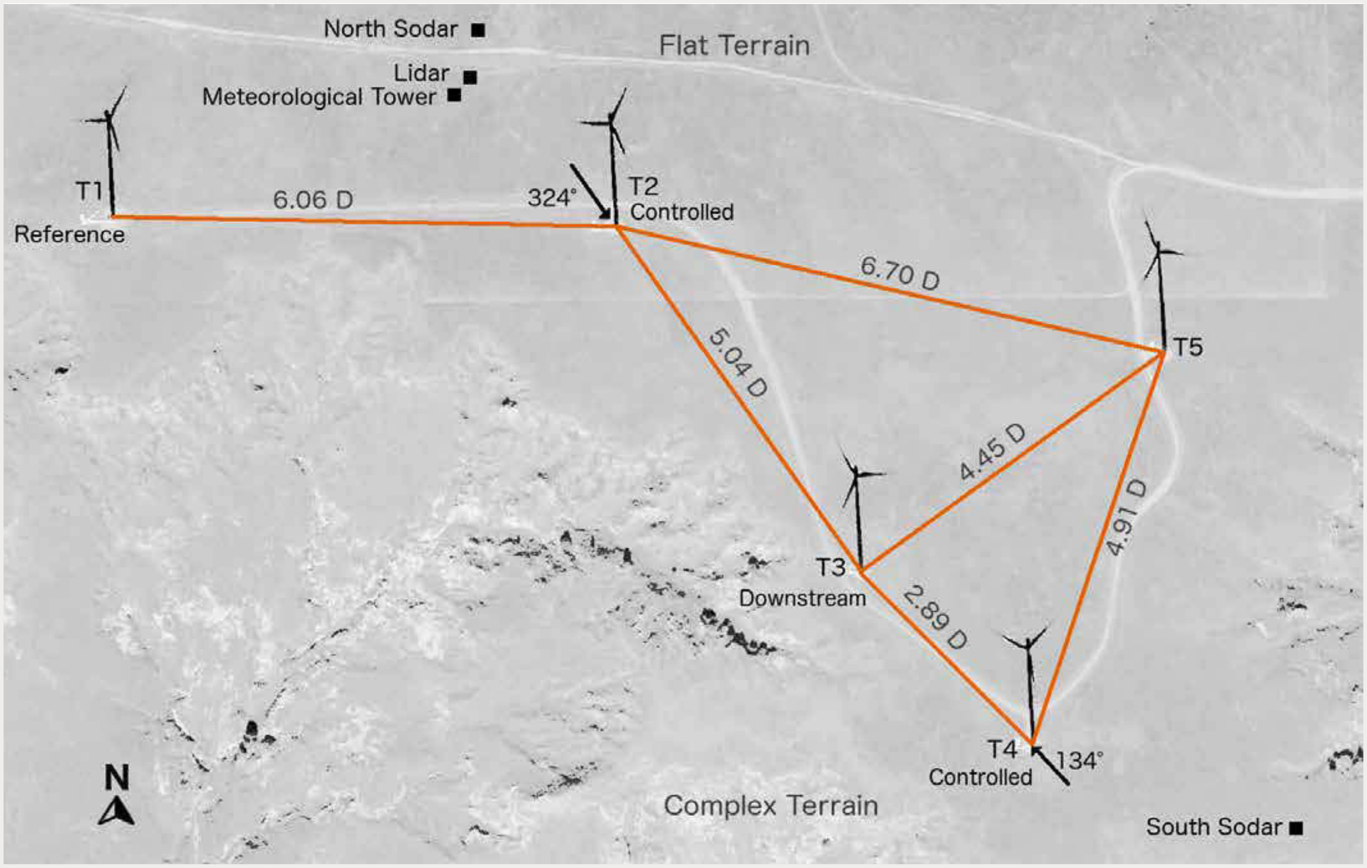


This 3D illustration shows a FLORIS simulation of three turbines generated using the new curled wake model. Shown above the three turbine wakes is a single-plane visualization featuring the in-plane vortex flows that lead to the curled shape of the wake. *Illustration by Paul Fleming, NREL*

- In partnership with NextEra Energy and the University of Colorado Boulder, NREL measured the impact of wake steering on a subsection of a commercial wind power plant. The field trials were consistent with simulated predictions, which suggest that annual energy production gains of 1%–2% are achievable for existing facilities implementing wind-plant-level controls. NREL and NextEra deployed a range of sensing equipment for the field trial—including a ground-based lidar, meteorological tower, and two sodars—which allowed researchers to quantify the atmospheric inflow during the test and investigate the effect of different conditions on performance. Research findings are published in *Wind Energy Science*.

## Significance and impact:

A collaborative effort between WETO 1.3.5.401 and WETO 1.3.4.401 (Rotor Wake Measurements & Predictions for Validation), efficiency improvements associated with wake steering can increase annual profits by $1 million or more, depending on the plant size and design. Several pathways for refining controller designs resulted from the field validation campaign. Given that a 2% gain at a typical 300-MW wind plant could represent $1 million per year in additional profits, there is widespread interest in implementing optimized controls.




NREL measured the impact of steering individual turbine wakes away from downstream turbines at NextEra Energy Resource's Peetz Table Wind Energy Center.
*Figure by Katherine Fleming, NREL*

Point of contact: Paul Veers, Paul.Veers@nrel.gov WBS: WETO.1.3.6.401

# Optimizing Energy Capture Through Centralized Wind Farm Controls

The Systems Engineering and Optimization project advances multidisciplinary analysis and optimization for wind energy applications by enabling wind turbine and plant design to improve overall wind turbine and plant performance.

- The Wind-Plant Integrated Systems Design and Engineering Model (WISDEM®) software created by NREL is making a name for itself by capturing important system interactions through foundational mathematics that will be widely used by the industry. Not only did the open-source software receive a trademark on its name, it also was nominated for a prestigious R&D 100 Award. WISDEM takes an integrated plant perspective by assessing how a new technology or operational or control strategy impacts whole plant performance, cost, and other system metrics.

## Significance and impact:

WISDEM could bring LCOE improvements when integrated into wind plant layout design. It incorporates advances in computational algorithms and simulation methods, physics-based improvements, and updated cost and performance modules to assess new technology opportunities and advance best practices in multidisciplinary design, analysis, and optimization for wind energy applications. The potential users are diverse and include the value chain for the wind industry—component suppliers, turbine manufacturers, developers, owner-operators, and consultants.

More efficient wind farms use algorithms that ensure reliable, robust, real-time, and efficient operation using local sensor information, such as supervisory control and data acquisition data; local meteorological stations; and nearby radars, sodars, and lidars. *Photo by Dennis Schroeder, NREL*

- NREL researchers maximize turbine performance and wind farm control strategies with technologies that allow wind turbines to share information with one another in real time. Published in the journal *Wind Energy Science*, data already acquired at the turbine level through SCADA are communicated with nearby turbines and provide them with the ability to respond more quickly and effectively to changes in wind direction. This has implications for a variety of wind farm activities, such as potentially decreasing dynamic yaw misalignment and the amount of time a turbine spends yawing, enhancing resiliency to faulty wind-vane measurements, and increasing the potential for success of wind farm control strategies such as wake steering.

## Significance and impact:

By incorporating measurements from multiple nearby turbines, we can get more reliable estimates of wind direction than we can from an individual turbine. This consensus-based approach uses information from nearby turbines to estimate wind direction in an iterative way rather than averaging all the information in a wind plant at once. This has the potential to increase power production of the wind farm by better aligning turbines with the wind.

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

- NREL researchers published a technical report titled, "A Detailed Wind Turbine Blade Cost Model" that details a cost model for wind turbine blades between 30 and 100 m in length. The model, which is significantly more detailed than the models available in the public literature, estimates the bill of materials; the number of labor hours and cycle time; and the costs related to direct labor, overhead, buildings, tooling, equipment, maintenance, and capital. The model is implemented within WISDEM and will now be used as starting point for more sophisticated studies like process optimizations for wind turbine blade factories and rotor design studies, such as the ones that are being conducted within the Big Adaptive Rotor project.

## Significance and impact:

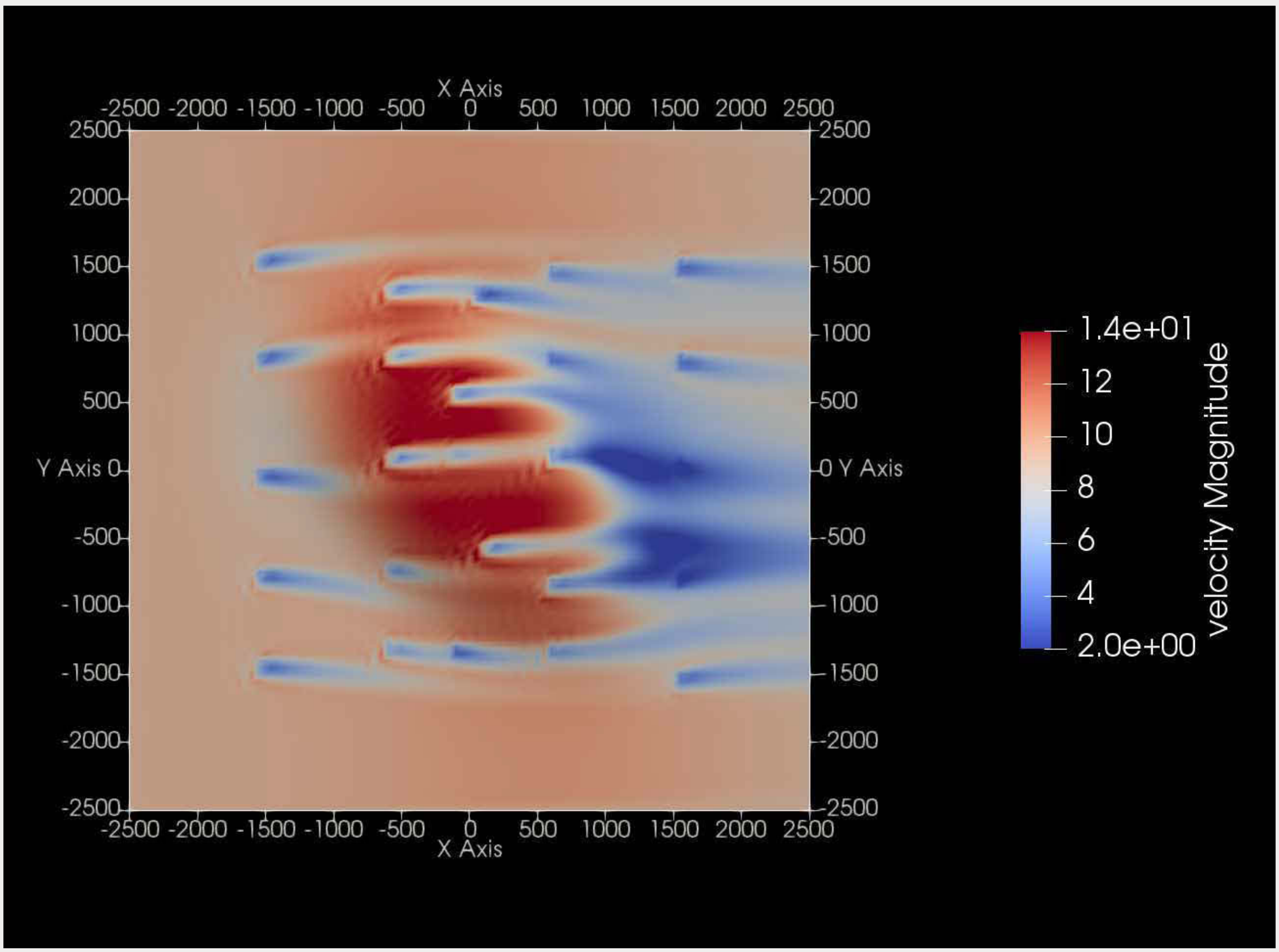
The report describes a model that can be adopted by the wind industry, research community, and academia to estimate wind turbine blade costs. Thanks to the model, design processes can help optimize the design of the blades and the manufacturing processes, ultimately reducing blade and wind turbine costs.

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

- NREL researchers demonstrated the ability to simulate the effects of mild terrain with attached flows on intraplant flow fields and examine the impact on array losses and overall plant energy production. This wind turbine layout optimization study maximizes power in complex terrain by accounting for complex three-dimensional wind velocity fields in Wind Systems Engineering (WindSE), a tool for modeling atmospheric fluid flow within a wind power plant and optimizing turbine positions and settings. It demonstrates how ignoring terrain effects will not generate optimal layouts. The team also finalized and drafted reports on Phase I work and developed and presented a Phase II work plan proposal for IEA Wind Technology Collaboration Programme Task 37, which coordinates international research activities to analyze wind power plants as holistic systems.

## Significance and impact:

This milestone moves WindSE and the NREL plant flow modeling and optimization suite closer to supporting real-world wind power plants. Studies have previously ignored these real-world complexities, but the team can now provide insight into when simplified terrain can be used and when it is detrimental to the accuracy of a resource assessment.




Velocity magnitude showing wind acceleration over a mesa (red region) and the wakes from 25 optimally placed wind turbines (blue regions). *Image by Jeffrey Allen and Ryan King, NREL*

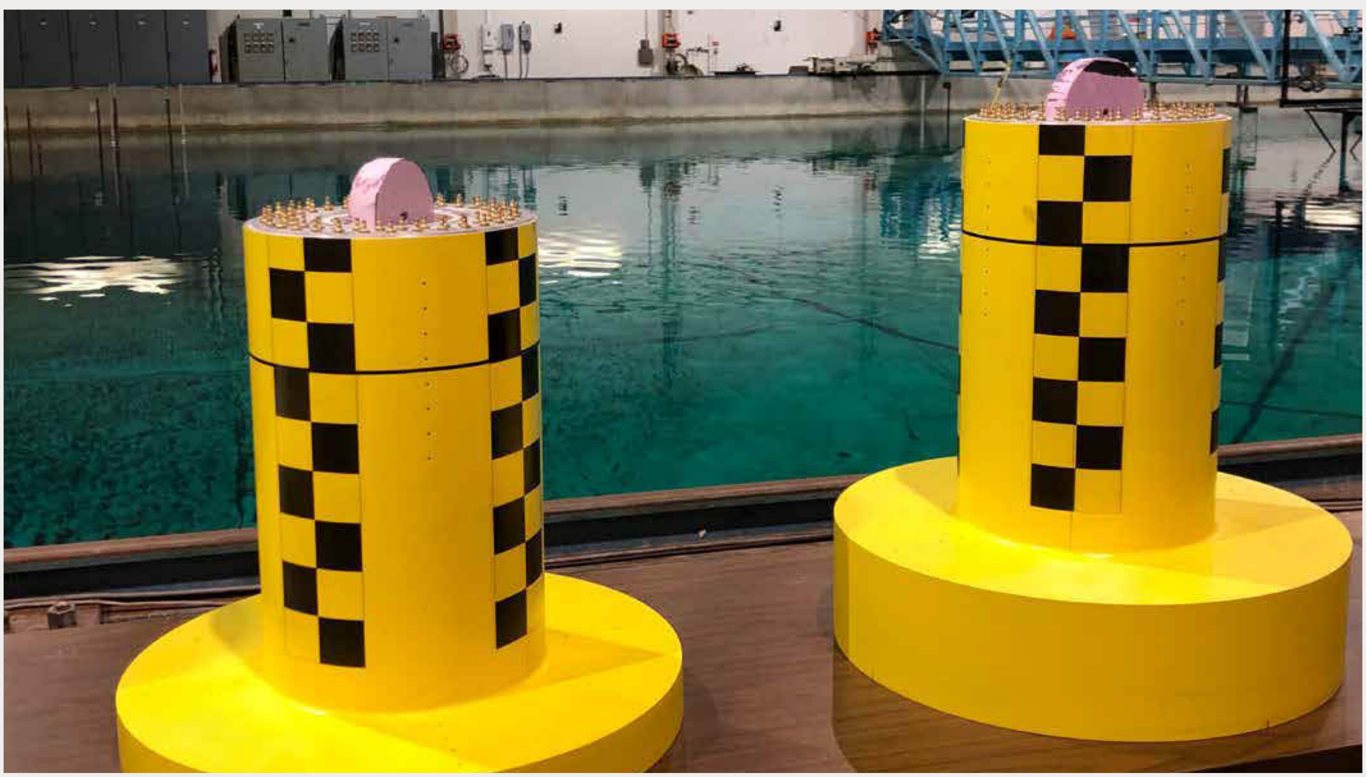
Point of contact: Amy Robertson, Amy.Robertson@nrel.gov WBS: 1.3.6.403

# Advancing Offshore Wind Technologies Through Modeling and Validation

This project aims to advance innovative offshore wind technologies to commercial maturity by validating the current suite of modeling tools used for designing offshore wind systems with high-quality data sets under a variety of conditions. An international research project run under IEA Wind Task 30 has been working to address the need for validated offshore wind modeling tools. The Offshore Code Comparison Collaboration, Continuation, with Correlation and unCertainty (OC6) project, which runs from January 2019 to January 2023, involves participants from across the offshore wind industry, including offshore wind designers, consultants, certifiers, developers, and research institutions.

As part of the OC6 project, NREL developed a set of load cases that can be used to validate the nonlinear dynamic behavior of a floating semisubmersible. The cases will be used to perform a three-way validation among engineering-level simulations (e.g., OpenFAST), higher-fidelity computational fluid dynamics simulations, and experimental measurements.

During the year, NREL researchers examined how bichromatic wave cases can be used to effectively examine low-frequency responses of floating wind systems at the surge and pitch natural frequencies. Bichromatic wave cases can be more easily implemented in computational fluid dynamics tools than a full irregular wave spectrum, providing a means for the three-way validation with engineering tools and experimental data.



As part of the OC6 tank test, cylinders with heave plates attached to the bottom were individually validated to gather data to better understand the physics that interact on dif erent components of an of shore wind system. *Photo by Amy Robertson, NREL*

NREL also held an open test day at the Offshore Technology Resource Center at Texas A&M University, which allowed the public to witness the new floating wind, component-level validation campaign to better understand phenomena that have an influence on an offshore wind platform. Representatives from the following offshore industry companies attended the demonstration: Shell, DNV GL, SBM Offshore, Bentley, Maritime Research Institute Netherlands, Atkins, and London Offshore Consultants.

### Significance and impact:

Although offshore wind is a mature market in Europe and costs are rapidly decreasing globally, innovative and optimized offshore wind technologies have the potential to reduce costs further. Validated design tools make rapid technology innovation and the resulting cost reduction in the offshore wind industry possible. Validation will also provide a better understanding of design tool uncertainties, identify areas of improvement, and increase acceptance of these tools within industry and wind research communities.

## A2e EMC Support

Point of contact: Paul Veers, Paul.Veers@nrel.gov WBS: 1.3.9.401

The objective of this project is to provide laboratory-based leadership to the management of the A2e initiative through travel and participation in international work groups.

# A2e Researchers Advance Scientific and Technical Understanding of Wind Power Plant Optimization at the International Wind Energy Conference

NREL researchers attended the 2019 Wind Energy Science Conference in Cork, Ireland, to discuss the latest research in the field of wind power plant optimization. By providing an interactive forum for international collaboration and multidisciplinary discussion, the conference encourages researchers to discuss cutting-edge research and existing work, and brainstorm solutions to industry challenges  by hosting a wide array of multidisciplinary experts in wind energy.

### Significance and impact:

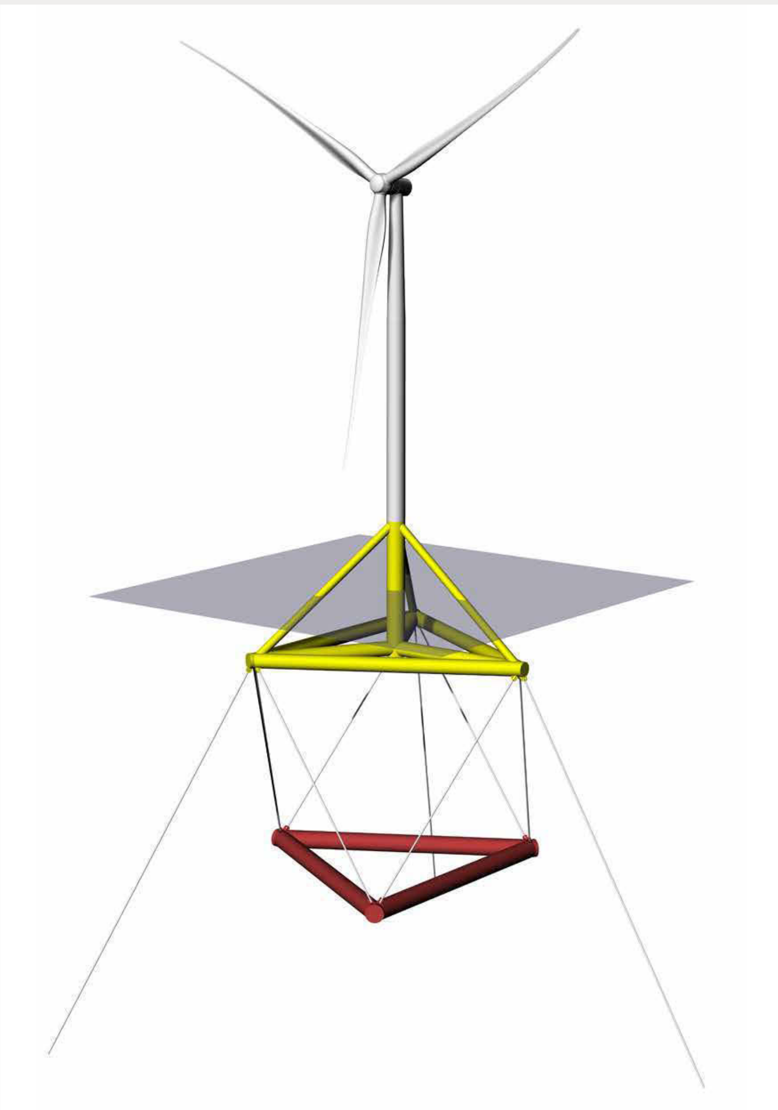
NREL researchers continue to provide international leadership in advanced flow control science, with several NREL researchers attending the conference to discuss the latest in consensus-based optimization strategies, wake steering, turbine blade deformation, simulated structural loads, and mesoscale-to-microscale coupling. Working alongside global experts through a series of workshops and panels, NREL researchers learned about the latest findings in the field and identified several potential ways to solve critical problems that help to bridge knowledge gaps that present obstacles to further technological and scientific advancements. Researchers attending the event benefited the program and colleagues not in attendance by gathering information to help advance A2e research, sharing their findings with other NREL colleagues, and uncovering future areas of work.

# Offshore Research and Development

Point of contact: Jason Jonkman, Jason.Jonkman@nrel.gov WBS: 1.3.6.402 and 1.4.0.400

# OpenFAST Upgraded To Enable Design of Next-Generation Floating Wind Turbines

Floating technology may be the key to deploying offshore wind turbines where the water is too deep to use bottom-mounted foundations. Under a DOE Technology Commercialization Fund project in partnership with Stiesdal and Magellan Wind, NREL researchers worked to develop, validate, and demonstrate improvements to NREL's OpenFAST wind turbine simulation tool that enable design and optimization of the next generation of floating offshore wind systems.



With 58% of the United States' viable of shore wind resources in deep water, floating technologies like the Stiesdal TetraSpar are likely to be cost ef ective. NREL is upgrading and validating the OpenFAST software to enable the wind energy community to design and optimize next-generation floating wind technologies. *Image courtesy of Stiesdal*

## During FY 2019, the team:

- Compared structural configuration and resulting multiphysics modeling needs against the modeling capability already available in the OpenFAST software to establish the functional requirements and modeling approach to upgrade the modeling capability
- Completed implementation plans for computing floating substructure flexibility and member-level loads within OpenFAST that meet the functional requirements
- Validated the OpenFAST upgrade by reviewing a data set from a 1:43-scale trial of the Stiesdal TetraSpar system
- Evaluated a scaled version of the Stiesdal Tetraspar with a 3.6-MW Siemens turbine, a flexible tower, and pitched blades (but no active control) under a variety of wind and wave load cases.

## Significance and impact:

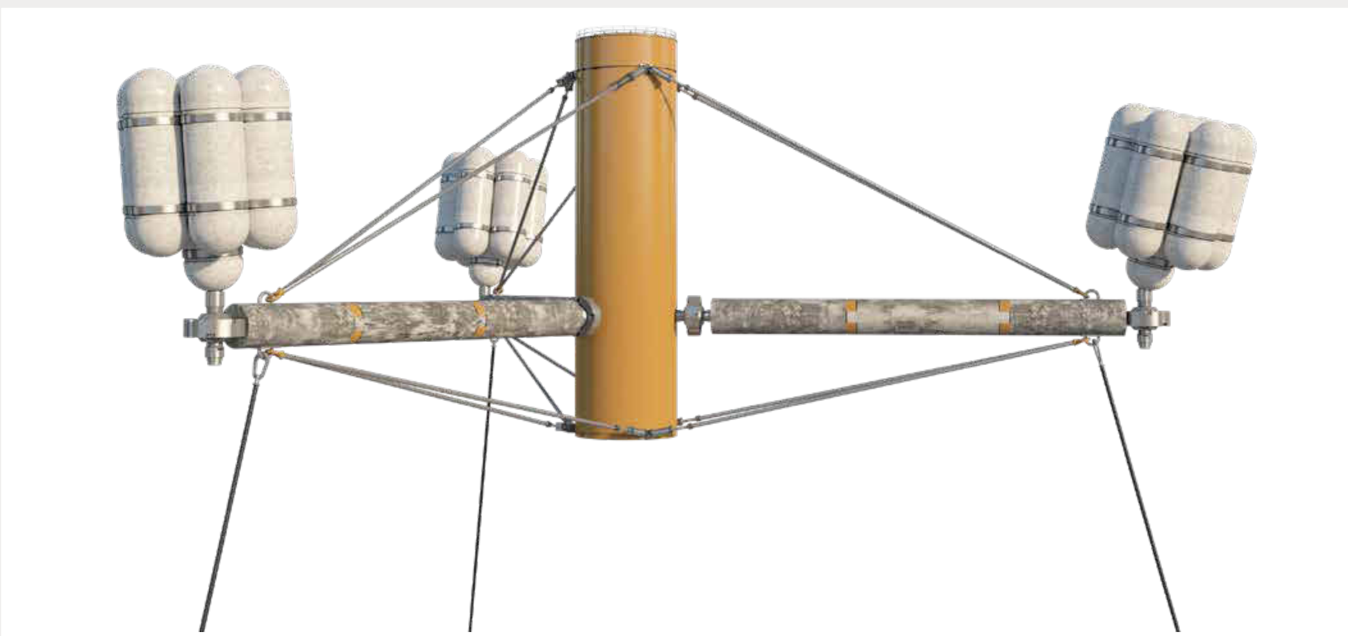
This work will enable the wind industry to use the upgraded OpenFAST modeling tool to design the next generation of floating offshore systems that are likely to be more streamlined, flexible, and cost effective to advance offshore wind energy deployment.

Point of contact: Senu Sirnivas, Senu.Sirnivas@nrel.gov WBS: 1.4.0.401

# NREL Develops Patent-Pending Design for Floating Offshore Wind System

Work on NREL's patent-pending offshore floating wind system called SpiderFLOAT, which features modular components that resemble spider legs, continued throughout the fiscal year. The NREL research team that developed the SpiderFLOAT technology updated the actual model configuration for co-simulation, revised the final validation matrix, delivered a presentation to the WE TO team showcasing the development of the technology, executed a nondisclosure agreement with Texas A&M University to conduct a subscale model evaluation of the technology at the university's wave basin, and received an Advanced Research Projects Agency-Energy ATLANTIS award focusing on new system controls options.

SpiderFLOAT, designed as a support platform for wind turbines ranging from 6 MW to more than 20 MW, began as an internal NREL Laboratory Directed Research and Development project and was then selected to participate in the DOE Energy I-Corps and Technology Commercialization Fund programs.



SpiderFLOAT has the potential to substantially reduce costs by simplifying construction and maintenance logistics for deep-water wind systems in challenging of shore marine environments. *Image by Josh Bauer, NREL*

## Significance and impact:

The SpiderFLOAT substructure reduces costs and improves performance by minimizing the use of steel and limiting transmission of wave motions to the wind turbine. The flexible technology can also be paired with a range of turbine designs and anchoring methods to accommodate numerous system configurations. SpiderFLOAT's modularization and simplified mooring allow for partial on-site manufacturing and easy towing of the entire system for installation and maintenance. In addition, by minimizing construction activities at the installation site, SpiderFLOAT helps reduce pile driving and other environmentally sensitive activities typically associated with fixed-bottom installations.

# Advanced Components, Reliability, and Manufacturing

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

# Improving Wind Turbine Drivetrain Reliability

The objective of the wind turbine drivetrain reliability project is to conduct research and validate turbine drivetrain technology to enable reductions in wind power plant operation and maintenance costs. This can be accomplished by identifying, developing, and verifying mitigation strategies for the dominant failure modes to increase inherent reliability, and developing and verifying monitoring and prognostic tools to increase operational reliability and turbine availability. The mechanisms of the predominant and unaccounted failure modes subject to real-world wind plant influences, including grid events, must be characterized.

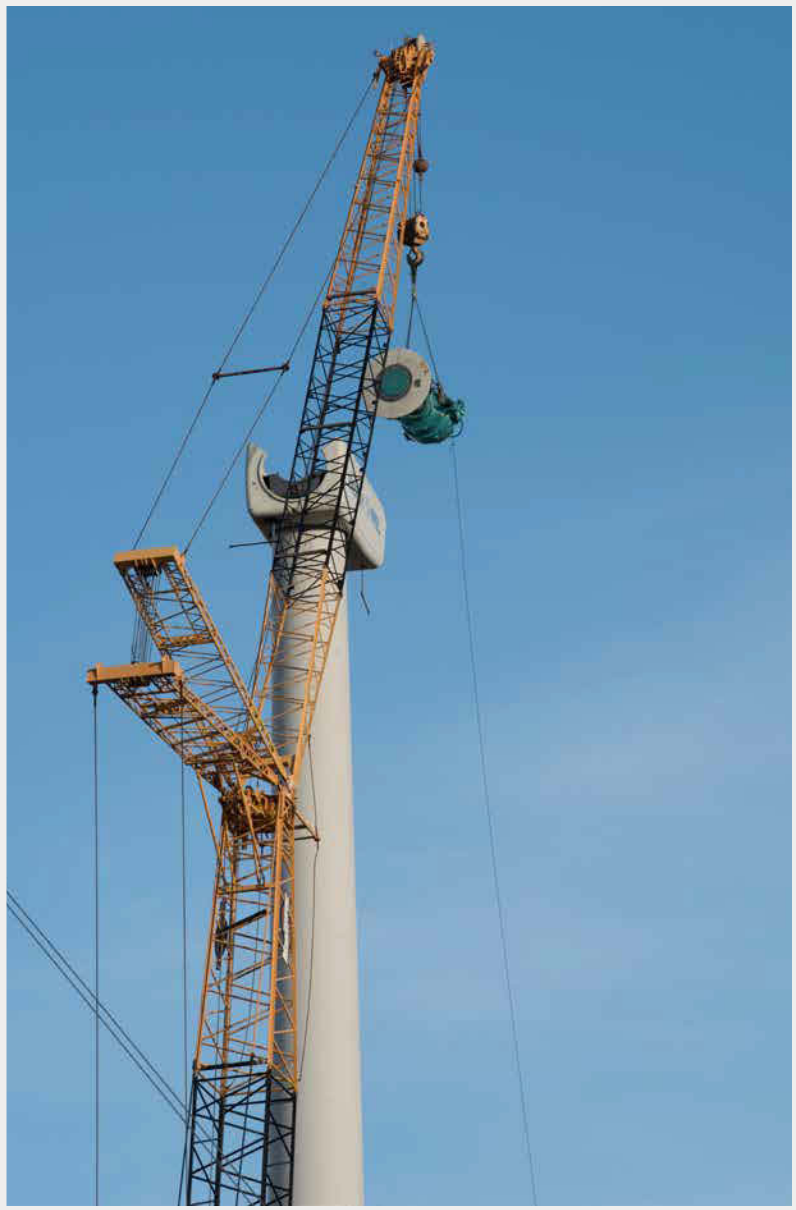
## During FY 2019, the team achieved the following:

- NREL coordinated with researchers at Argonne National Laboratory to address the lack of drivetrain component failure models in design standards. Researchers examined roller sliding models that enable evaluation of accumulated frictional energy loss and are used in the probability of failure modeling work. An article on planetary-load-sharing behavior and resulting reliability was published in *Wind Energy Science*.

## Significance and impact:

Both the probability of failure and roller sliding models address bearing axial cracking, the most prevalent failure mode observed in the field. The probability of failure modeling fills an industry gap in evaluating component reliability, and the roller sliding model is scalable to different turbine and gearbox platforms. This research will help increase reliability, reduce operation and maintenance costs, increase turbine availability and energy capture, and reduce the LCOE for wind power plants.

NREL submitted a collaborative research and development agreement (CRADA) with The Timken Company for the Drivetrain Reliability Collaborative research activity. The collaborative will undertake dynamometer validation on the 1.5-MW drivetrain at the Flatirons Campus to collect main bearing validation data in controlled but accelerated loading conditions. The CRADA is still in the review and approval process.



A wind turbine gearbox is replaced with a new, instrumented gearbox at the Flatirons Campus. *Photo by Dennis Schroeder, NREL 49416*

The team also hosted a Drivetrain Reliability Collaborative workshop with more than 170 attendees from DOE, labs, universities, and industry. The workshop included panels and talks on land-based wind and offshore wind, gearbox and main bearing reliability, current drivetrain reliability R&D activities, operation and maintenance research, condition monitoring, and data analytics.

- Failures in gearbox bearings have been a primary source of reliability issues for wind turbine drivetrains, leading to costly downtime and unplanned maintenance. The most common failure mode of gearboxes is attributed to white-etching cracks, which the NREL report, "Investigation of Roller Sliding in Wind Turbine Gearbox High-Speed-Shaft Bearings," investigates.

## Significance and impact:

Mitigation strategies for dominant failure modes in wind turbine gearboxes can increase turbine operational reliability and availability. Collaborative work from NREL, the Flender Corporation, and SKF measured high-speed bearing loads, sliding, and the lubricant environment, which helped to validate two different modeling approaches for bearing sliding—one analytical dynamic model and one multibody model that can be used to evaluate roller slip losses or cumulative frictional energy that are potential driving factors for white-etching cracks.

Making the change. Wind power plant operation and maintenance costs account for as much as 20% to 50% of the wind power purchase agreement price and generally increase as wind power plants age. Photo by *Dennis Schroeder, NREL 49409*

- Published in the journal Wind Energy Science, "Sensitivity analysis of the effect of wind characteristics and turbine properties on wind turbine loads," assesses which wind inflow and turbine input parameters have the greatest influence on turbine power, fatigue loads, and ultimate loads during normal turbine operation. Using the NREL 5-MW baseline wind turbine, separate case studies were performed on wind-inflow conditions and turbine structural and aerodynamic properties.

## Significance and impact:

This research can be used to help establish uncertainty bars around the predictions of engineering models during validation efforts and provide insight on probabilistic design methods and site suitability analyses.

Point of contact: Nick Johnson, Nick.Johnson@nrel.gov WBS: 1.5.4.401

# Increasing Rotor Sizes Through Big Adaptive Rotor

Larger rotors capture substantially more energy both through a greater swept area and accessing increased wind speeds at higher above ground levels. Rotor growth also leads to higher capacity factor wind plants, yielding less variability in power production. With limited high wind resource sites, future development will depend in part on deployment in lower wind resource sites, requiring further increases in rotor size for cost-effective energy production. A multilab team of NREL, Sandia, Oak Ridge National Laboratory, and Lawrence Berkeley National Laboratory researchers working on the Big Adaptive Rotor project will help develop technology to further drive down the cost of wind energy through a 10% increase in capacity factor.

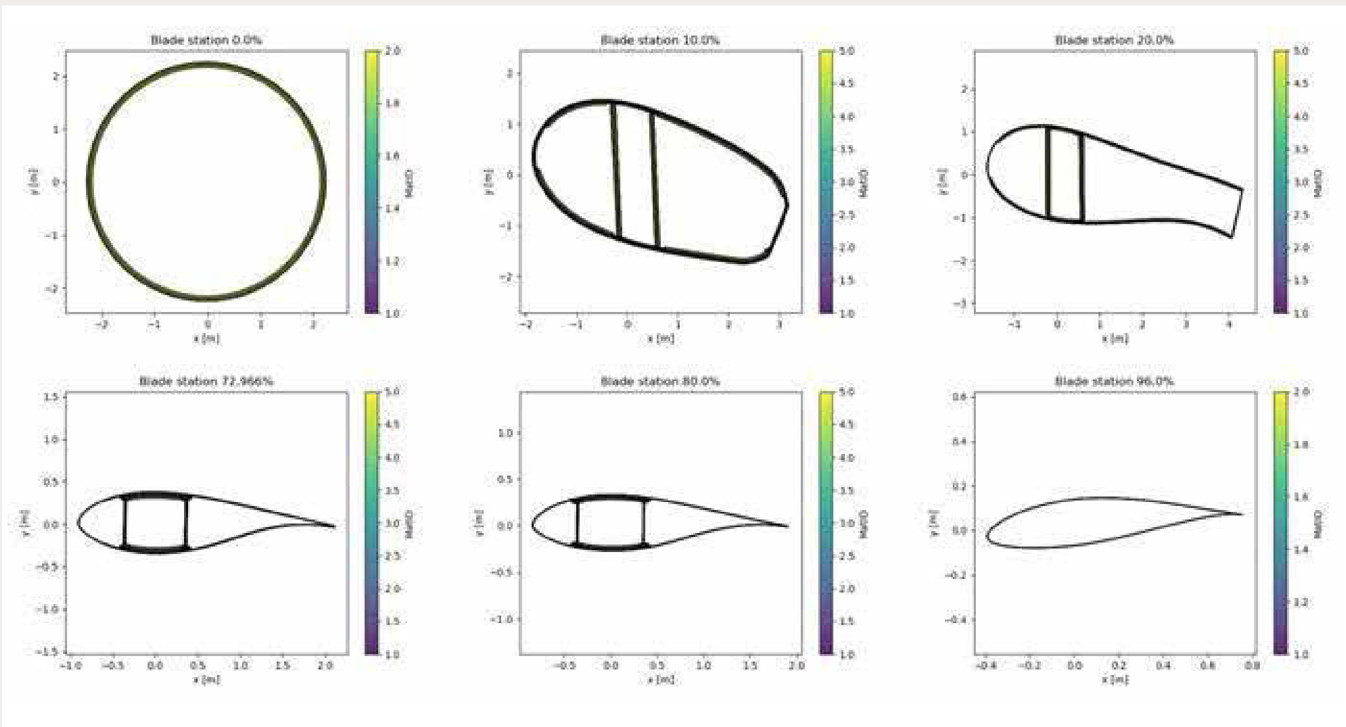
## During FY 2019, the project team achieved the following:

- In relatively capacity-constrained markets, lower specific power has been the most direct way to boost megawatt-hours and revenue per invested dollar, supporting large reductions in LCOE. In "Opportunities for and Challenges to Further Reductions in

Wind turbine blades wind their way by train through Denver, Colorado. *Photo by Dennis Schroeder, NREL 20894* the "Specific Power" Rating of Wind Turbines Installed in the United States," analysis from NREL and Lawrence Berkeley National Laboratory researchers finds that under plausible cost scenarios (where the low-specific-power technology has an additional cost of $320/kW, relative to higher-specific-power technology, and another where the low-specific-power technology has an additional cost of $640/kW), low-specific-power turbines could continue to play an important role in the United States and global energy markets of the future.

## Significance and impact:

This research illuminates historical trends in wind turbine specific power and characterizes future conditions under which lower- or higher-specific-power technology could prevail. It also sets the foundation for further work that examines the value boost from low-specific-power turbines at wind project sites across the United States, which can provide greater insight into the relative economics of large-rotor turbines generally and low-specific-power technology specifically.




The cross-sectional airfoil shape of a blade at different locations along the span. *Graphic by Pietro Bortolotti, NREL*

- In, "Investigation of Innovative Rotor Concepts for the Big Adaptive Rotor Project," NREL researchers analyze novel concepts that have the potential to reduce the LCOE for 100-m (and above) land-based wind turbines. The concepts were evaluated at a 2018 workshop and by national lab experts, and six concepts are recommended for future research and development: downwind turbines, distributed aerodynamic devices, multielement airfoils, highly flexible blades, flexible high tip-speed-ratio blades, and inflatable blades.

## Significance and impact:

Future wind developments depend on deployment in lower wind resource sites, requiring further increases in rotor size for cost-effective energy production, and this research advances six concepts for future research and development to make future wind deployment possible.

# Standards Support and International Engagement

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

# Standards Development Helps Ensure Wind Industry Safety and Growth

As the U.S. wind industry continues to grow and mature, international standards need to be supplemented with domestic standards to address U.S.-specific needs. This project works to ensure that all standards that apply to wind turbine design, manufacturing, installation, and operations are effective in supporting a high-quality and reliable electricity supply from wind for the nation.

NREL makes major contributions to wind standards at the international and national levels and focuses on standards that have a large impact on the market and those with links to the DOE wind program.

## During FY 2019, the project team achieved the following:

- Hosted the U.S. Wind Energy Standards Summit in San Diego, California, to convene and update the U.S. wind energy standards and certification community on standards efforts and potential areas for coordination.

- Provided an overview of the Offshore Wind Standards initiative, which is developing a set of roadmaps to navigate existing standards and guidelines, with the aim of facilitating safe designs and orderly deployment of offshore wind in the United States.

- Held a meeting with the Offshore Wind Technical Advisory Panel and presented to the standards community about progress and issues being addressed.

- Hosted 25 wind turbine blade experts at the IEA Wind Topical Expert Meeting #94 on Large Component Testing for Ultra-Long Wind Turbine Blades. The purpose of the meeting was to identify near-term and future needs for the validation of wind turbine blades and consider whether existing assessment methods and facilities can keep pace with industry growth needs.

- Participated in several International Electrotechnical Committee meetings at locations across the globe. These meetings focused on standards topics ranging from offshore wind and gearboxes to rotor blades and noise at receptor locations.

## Significance and impact:

Standards assure minimum levels of safety, remove market barriers, and provide high-quality, reproducible test methods and facility use that could enable high levels of reliability and reduced time to market. Standards not only guarantee a level playing field for international markets, but are also critical for ensuring that the operating fleet of turbines in the United States is highly reliable regardless of the hardware's source.

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

# International Engagement Strengthens U.S. Influence, Accelerates Wind R&D

Throughout the year, NREL continued to represent the United States by holding key leadership positions in the International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP), which shares information and research activities to advance wind energy research, development, and deployment in member countries.

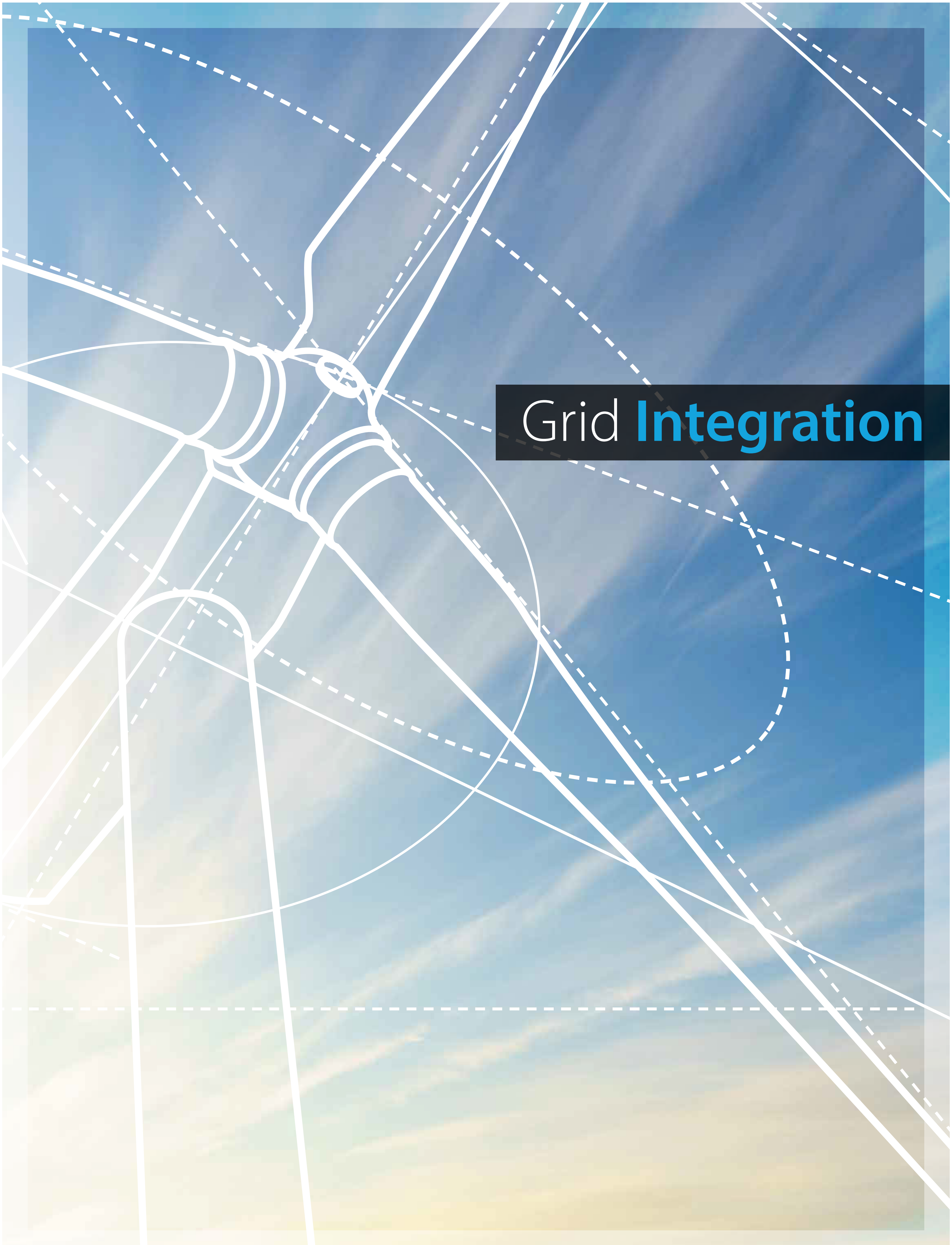
NREL's active participation in IEA Wind TCP includes collecting critical information on the most recent wind research, development, and demonstration activities in IEA Wind member countries and providing valuable feedback to U.S. industry on the status of this work to further innovation in R&D and accelerating wind deployment.

The extensive leadership NREL provides to IEA Wind includes Laboratory Program Manager Brian Smith serving as Vice Chair of the Executive Committee and several staff serving as task operating agents. In all, NREL staff participated in research for 14 IEA Wind TCP tasks in 2019. Key among these were Task 30: Offshore Code Comparison Collaboration, Continuation, with Correlation, and unCertainty (OC6); and Task 34: Working Together to Resolve Environmental Effects of Wind Energy (WREN); and new tasks, Task 41: Enabling Wind to Contribute to a Distributed Energy Future and Task 43: Digitalization of Wind Energy.

In addition, NREL's communications department researched and wrote the U.S. chapter of the IEA Wind TCP 2018 Annual Report.

## Significance and impact:

NREL's IEA Wind activities strengthen U.S. presence and influence among 21 member countries, the European Commission, the Chinese Wind Energy Association, and WindEurope. This work demonstrates NREL's leadership in the research community and wind industry worldwide.



# Grid Integration

# Market and Reliability Opportunities for Wind on the Bulk Power System

Point of contact: Jessica Lau, Jessica.Lau@nrel.gov WBS: 3.1.0.408

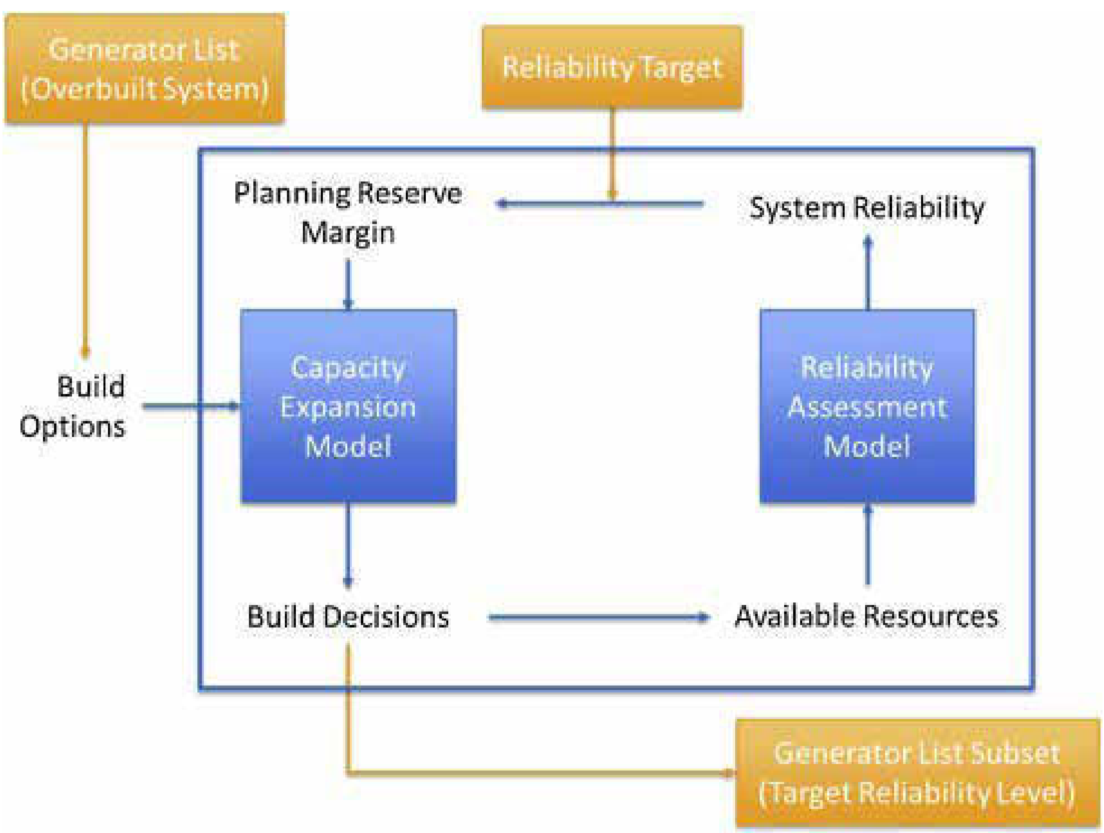
This project aims to understand the impact of wind and other zero-marginal cost resources on long-term resource adequacy and revenue sufficiency under a wide range of market design options and revenue sources. Higher penetration levels of zero-marginal cost resources can result in suppressed energy prices, or "merit order effect."

## During FY 2019, the project team accomplished the following:

- The journal article, "Evaluating Resource Adequacy Impacts on Energy Market Prices Across Wind and Solar Penetration Levels," highlights an NREL study showing that when more capacity exists in a system, prices tend to be lower and less volatile. To present these findings and join the industry conversation, researcher Bethany Frew chaired a panel at the Energy Systems Integration Group Fall Technical Workshop titled, "Resilience, Price Formation, and Market Design."

## Significance and impact:

NREL is leading discussions and creating primary resources on the impacts of wind energy on overall energy market pricing. The team is developing insights into the key drivers of wholesale electricity and ancillary services that will be used in future research and by the industry for the price formation process. By considering a wide range of resource adequacy levels within a test system, the NREL team highlighted the need to interpret price outputs within the context of the system reliability level.




The figure shows a feedback loop between capacity expansion and resource adequacy assessment models. Given a set of existing generators on the system, the process will iterate until it converges on a subset of generators that together provide the desired level of resource adequacy.

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

North American Renewable Integration Study project team members at a kickoff meetingat NREL in October 2016. *Photo by Werner Slocum, NREL*

# New Model To Support the North American Renewable Integration Study

Using the Probabilistic Resource Adequacy Suite, the North American Renewable Integration Study developed reliability modeling to address a variety of future scenarios, including those with higher penetrations of meteorologically driven energy sources, such as wind and solar. The new model produces visualizations of high-stress periods and an impact analysis of capacity expansions. It can help identify potential renewable energy development zones for the most cost-effective resources in all three countries and quantify potential benefits from changes in operational and planning practices.

## Significance and impact:

This body of work seeks to create a detailed analysis of cross-border and interregional integration that will help power systems planners and operators, government agencies, and regulators understand the impact of cooperation between nations and grid operators. The new model allows researchers to quantify potential benefits of changes in operational and planning practices and large-capacity cross-border interconnections to support the integration of renewable energy. Pending research completion, this project plans to highlight how the North American Renewable Integration Study could impact future energy collaboration among the United States, Canada, and Mexico in a future publication.Power System Reliable Integration Support To Achieve Large Amounts of Wind Power (PRISALA)

Point of contact: Dave Corbus, David.Corbus@nrel.gov WBS: 3.1.0.411

# Grid Integration Researchers Collaborate for Stronger Wind Energy Penetration

This project focuses on disseminating key results from NREL analysis to utilities and the power systems industry to limit integration barriers and enable wind energy to reach high penetrations. The Power System Reliable Integration Support to Achieve Large Amounts of wind power project helps stakeholders by removing barriers that might otherwise prevent the use of wind energy and providing cost-effective solutions to encourage market-place adoption.

## Significance and impact:

Research from this project educates decision-makers on operational and market impacts of wind energy and dispels common misconceptions. NREL researchers attended the Energy Systems Integration Group (ESIG) Fall Technical Workshop in late 2018. ESIG is the leading technical organization in the U.S. for advancing the state of knowledge of variable generation integration and transmission and NREL's attendance was critical for the development. Future collaborations with fellow workshop attendees resulted from NREL's attendance at the workshop.

# WindView Tool Provides Real-Time Look at Wind Data

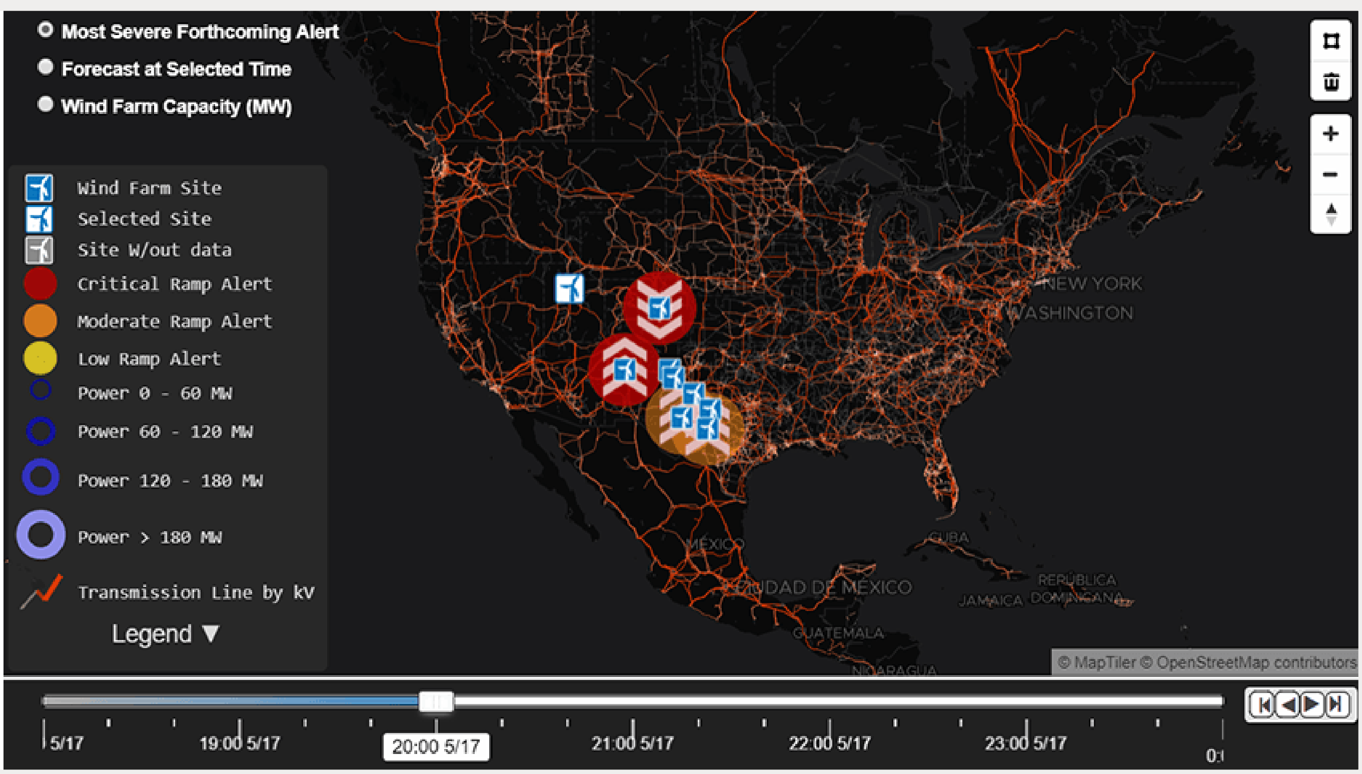
NREL researchers released the WindView software tool on GitHub to provide electric grid operators with free visual forecasting tools that display real-time probabilistic wind power forecasts. WindView's widespread use allows system operators to make control decisions based on the data the software provides. By making variable wind resources easier to track, WindView can contribute to further accessibility of wind energy across the United States.

## During FY 2019, the project team achieved the following:

- NREL researchers released the WindView software tool on GitHub to provide electric grid operators with free visual forecasting tools that display real-time probabilistic wind power forecasts. WindView allows system operators to make control decisions based on the data the software provides. By making variable wind resources easier to track, WindView can contribute to further accessibility of wind energy in the United States.

## Significance and impact:

WindView's approach sets it apart as a forecasting tool. It helps operators to understand probabilistic wind forecasts over different spatial domains with sophisticated visualization tools. WindView is ready for use by utilities, system operators, researchers, or forecast providers.




The new WindView tool provides real-time visual forecasting. *Graphic by NREL*

Understanding the Role of Short-Term Energy Storage and Large Motor Loads for Active Power Controls by Wind Power

Point of contact: : Vahan Gevorgian, Vahan.Gevorian@nrel.gov WBS: 3.1.0.413

# Researchers Work To Reduce Wind Power Costs Through Active Power Controls

NREL researchers developed and tested coordinated controls of active power by wind generation, short-term energy storage, and large industrial motor drives for providing various types of ancillary services to the grid and minimizing loading impacts. Through modeling use cases for a fast-frequency response provision by wind-storage systems for a multiarea power grid, NREL's team completed a report on a large wind power plant demonstration for the provision of essential reliability services.

## Significance and impact:

This project is expected to reduce operation and maintenance costs and subsequently the cost of energy generated by wind power.

NREL researchers Przemyslaw Koralewicz, David Corbus, Shahil Shah, and Robb Wallen work on microgrid integration analysis in the CGI control room at the NWTC. *Photo by Dennis Schroeder, NREL*

Point of contact: Jonathan White, Jonathan.White@nrel.gov WBS: 3.1.0.416

# Discussions Build Awareness of Cybersecurity Needs on Wind Farms

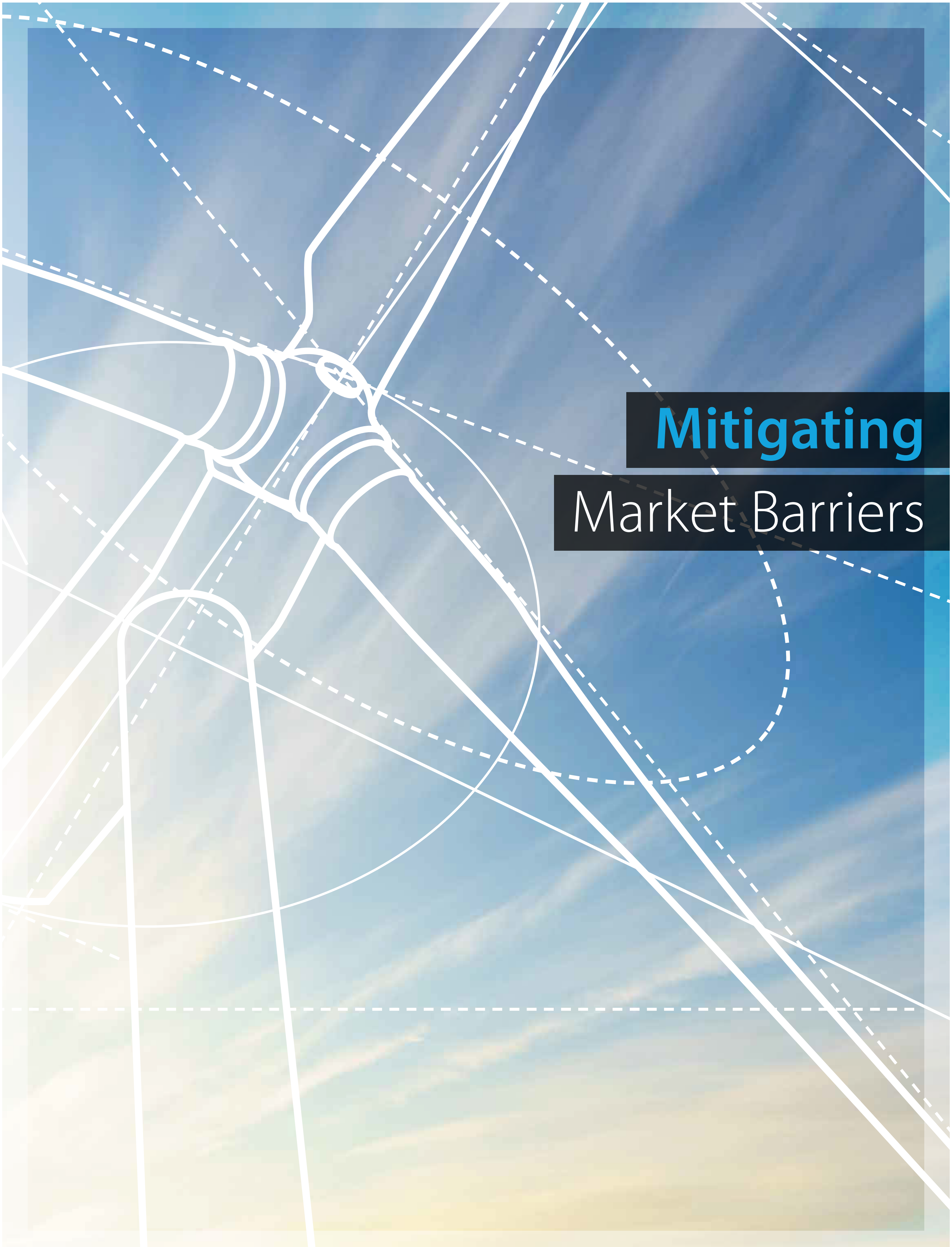
NREL hosted a multistakeholder workshop to evaluate the growing potential for cybersecurity vulnerabilities on U.S. wind farms. The workshop, "Assessing the Impact of Cybersecurity on the Nation's Wind Farms," brought together industry panelists who represent a variety of organizations, including GE Renewable Energy, Vestas, and Siemens Gamesa Renewable Energy.

## Significance and impact:

With support from WETO and IECRE, NREL organized a platform to evaluate the growing potential for cybersecurity vulnerabilities within U.S. wind farms. The workshop initiated a productive discussion on the current state of cybersecurity for the wind industry—and where there are research gaps.


Representatives from the national lab complex, wind industry, manufacturers, cybersecurity product vendors, and standards organizations came together at NREL's Flatirons Campus for a workshop evaluating cybersecurity vulnerabilities on U.S. wind farms. *Photo by Josh Bauer, NREL*

# Mitigating Market Barriers



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

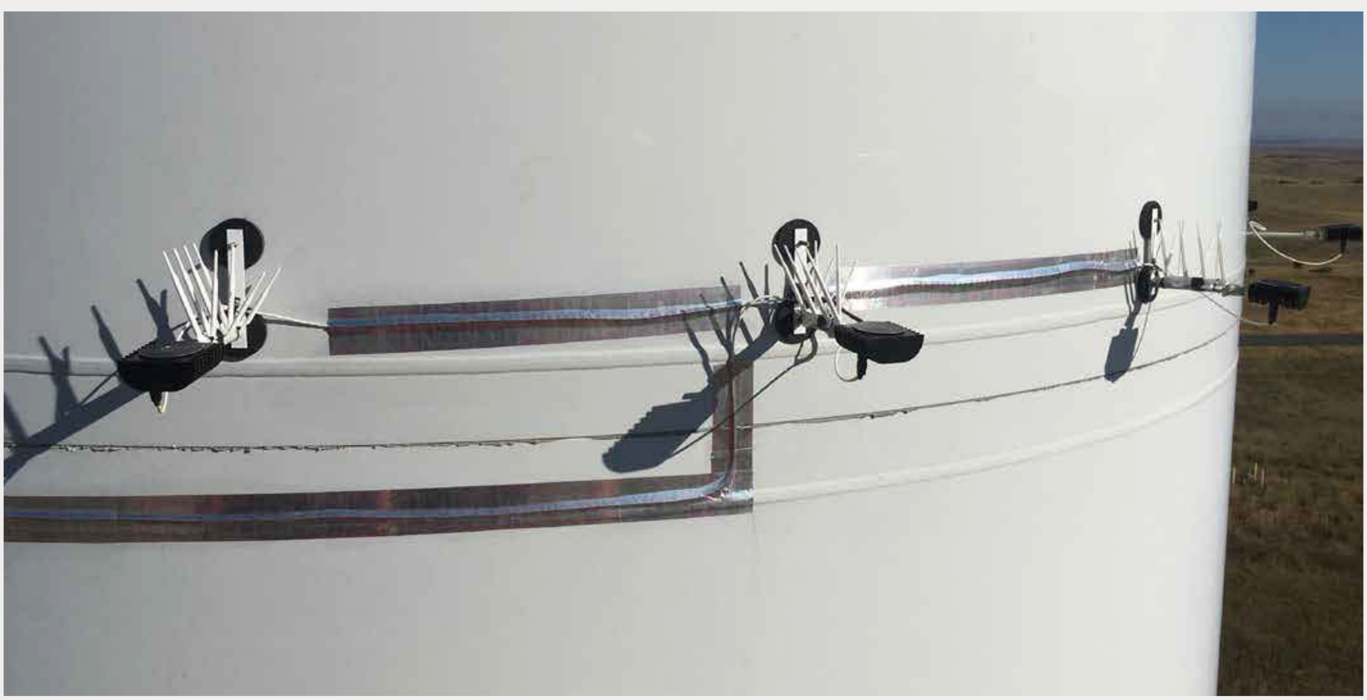
# Wildlife Impact Minimization Project Facilitates Broader Wind Energy Deployment and Species Protection

The Wind Operational Issue Mitigation Project facilitates more efficient wind energy deployment across the United States. Through R&D of wildlife minimization technology, cost-effective solutions for the wind industry are developed to help detect and deter birds and bats at wind energy facilities. A primary focus of this project involves partnering with technology innovators as part of the Technology Development and Innovation (TD&I) effort to support the advancement of experimental technologies aimed at reducing bird and bat impacts at wind turbines, a barrier to wind development in some parts of the United States.

## During FY 2019, the project team achieved the following:

- Led by United States Geological Survey Research Scientist Paul Cryan, TD&I staff and researchers installed an ultraviolet (UV) light onto two utility-scale research turbines at Flatirons to see if this dim illumination will prevent bats from approaching the wind turbines. Although, the extremely dim UV light used in this experiment is invisible to humans and birds, prior tests showed that bats can see it.

  The TD&I program selected a project from the Mide Technology Corporation to improve bat impact minimization technologies that are ready for validation. The Mide Technology Corporation research team has proposed the development of a self-powered, self-contained, ultrasound device that can be mounted on a turbine blade. This device will produce ultrasound at the tips of wind blades to expand the range of influence of the ultrasound deterrent as compared to deterrents located just in the nacelle. This would ideally create a much more effective mechanism to deter approaching bats.



Not your bat cave. Installed UV lights may help bats distinguish wind turbines from other objects, such as trees where they might want to roost. *Photo by Dave Swartz, NREL*

## Significance and impact:

The TD&I program matches technology developers with NREL facilities and expertise to develop, validate, and engineer emerging technologies that detect and deter birds and bats at wind farms. NREL's work in environmental wind-wildlife impact minimization continues to put the lab at the forefront of wind energy research, thereby helping further wind energy deployment.

- WREN, also known as Task 34, established by the International Energy Agency Wind Committee, focuses on the development and characterization of monitoring and mitigation solutions to better understand wind-wildlife interactions and strategies to reduce fatalities at wind energy facilities. WREN members have prioritized and sequenced the informational webinars and deliverables for 2020 and developed a draft proposal for Phase 3 of the project.

  NREL researcher Cris Hein led a 90-minute expert forum that brought together wind energy experts from national labs, academia, and industry to review and discuss available research on barotrauma and whether the phenomenon contributes a substantial proportion of fatalities.

## Significance and impact:

Participation in WREN helps to facilitate international collaboration that advances global understanding of environmental effects of offshore and land-based wind energy development. By participating in WREN, NREL can help better understand and advance research regarding the potential impacts of barotrauma,  minimization strategies, and where additional investigation is needed.

- Minimizing environmental impacts of wind turbines is a priority for the industry, and technologies to detect and deter eagles help reduce barriers to the deployment of wind facilities. NREL worked with PNNL researcher, Shari Matzner, to validate her ThermalTracker system in the presence of wind turbines. ThermalTracker uses thermal imaging cameras to track flight paths of wildlife to help further develop detection technology and prevent wildlife interactions with wind turbines.


Time for a checkup. Stereoscopic vision from ThermalTracker provides more accurate tracking of wildlife. *Photo by Werner Slocum, NREL*

## Significance and impact:

Field validation of the ThermalTracker system and software at the Flatirons Campus allow for a sustained installation with data collection in a variety of weather and landscape conditions. Findings will enable enhancements to the software that will support better detection of wildlife and could also prove useful in offshore wind energy facilities.

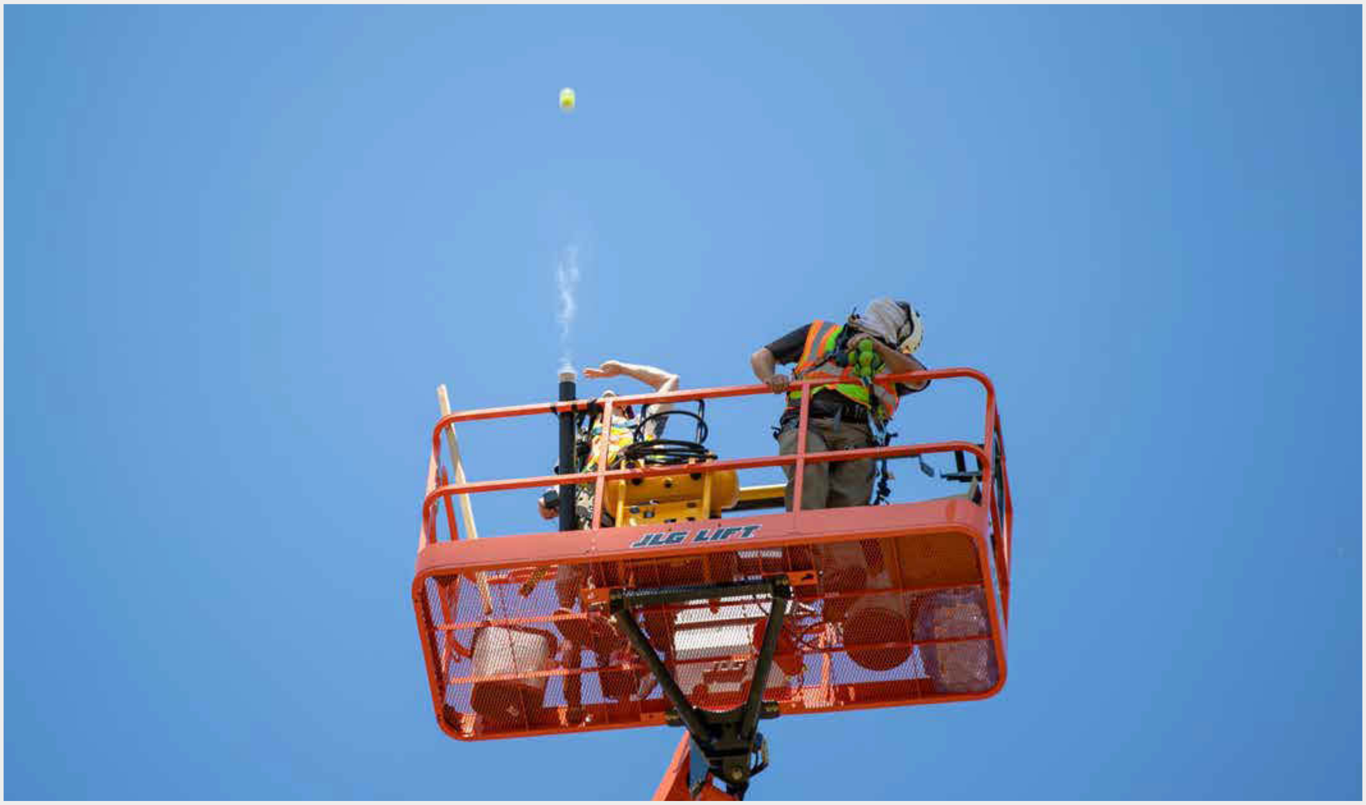
NREL hosted a workshop for nearly 30 members of WETO, as well as experts from across the national lab complex, wind energy industry, academia, nonprofit sector, and private consultants to share challenges they face and possible solutions to address wind-wildlife issues. The workshop also included a large share of members of the Wind-Wildlife Land-Based Collaborative, a 4-year funded effort to reduce wildlife impacts at wind energy facilities to increase deployment of wind energy responsibly through collaboration with federal, state, private, and nonprofit organizations. The workshop provided an opportunity to highlight cutting-edge work supported by NREL and DOE in this area and helped to identify several challenges that require further attention—chiefly data collection and analysis.

## Significance and impact:

Data collection at both regional and local scales is necessary, with regional wildlife data needing to be more generalized so that it can be applied in localized contexts when making wind plant siting decisions—which is difficult, considering the unique behaviors and interactions wildlife species exhibit near wind facilities in various geographic contexts. Despite these challenges, training participants set their sights on the future, discussing research questions about how wildlife will interact with the future fleet of wind turbines and tomorrow's hybrid power plants.

Using tennis balls, Oregon State University researcher Kyle Clocker demonstrates to DOE employees the impact detection technology he and his team have developed to protect eagles and other wildlife species. *Photo by Brendan Davidson, NREL*

Point of contact: Jason Roadman, Jason.Roadman@nrel.gov WBS: 3.3.0.406



NREL's Jason Roadman and Mark Murphey fire tennis balls at the GE 1.5-MW turbine at the Flatirons Campus. *Photo by Joshua Bauer*

# OSU Researchers Partner with NREL To Protect Eagles with Potato Cannons

The Eagle Take Minimization Project, funded by DOE, incorporates three disciplines—computer science, mechanical engineering, and electrical engineering—that work together to minimize bird and bat encounters with wind turbines. Through a combination of cameras and sophisticated software algorithms, we can detect wildlife species like eagles and trigger a response to dissuade them from approaching a wind turbine.

OSU's system is designed to reduce wind energy impacts on wildlife, a market barrier to further wind energy deployment. The researchers simulated bird flight paths toward turbines by firing tennis balls and small potatoes from a manlift at the research turbine's blades. A series of sensors, cameras, and software captured each tennis ball impact, providing data to further refine wildlife minimization technology at turbines.

## Significance and impact:

The opportunity to leverage the expertise and state-of-the-art equipment at NREL helps researchers test their technologies. NREL's facilities and staff make it easy to install equipment and gather the information necessary to help minimize wildlife impacts for both land-based and offshore wind energy developments, helping to break down this market barrier for wind energy deployment.

# Stakeholder Engagement and Workforce Development

Point of contact: Ruth Baranowski, Ruth.Baranowski@nrel.gov WBS: 3.4.0.401

# Accelerating Wind Deployment with Community Exchange and Research

This work supports R&D efforts to reduce the costs of renewable energy technologies and accelerate the large-scale use of domestic energy sources, helping to further enable American energy independence and domestic job growth over the next 3–7 years.

## During FY 2019, the team accomplished the following:

- As part of an ongoing effort to provide resources to help communities weigh the benefits and impacts of wind energy, several pages on the WINDExchange website were updated. The radar interference page now includes detailed information on the process for mitigating wind energy's interference with radar systems, and the state profile pages now include information on wind turbine component manufacturers, number of megawatts under construction, renewable portfolio standards, and cities with 100% renewable energy commitments.

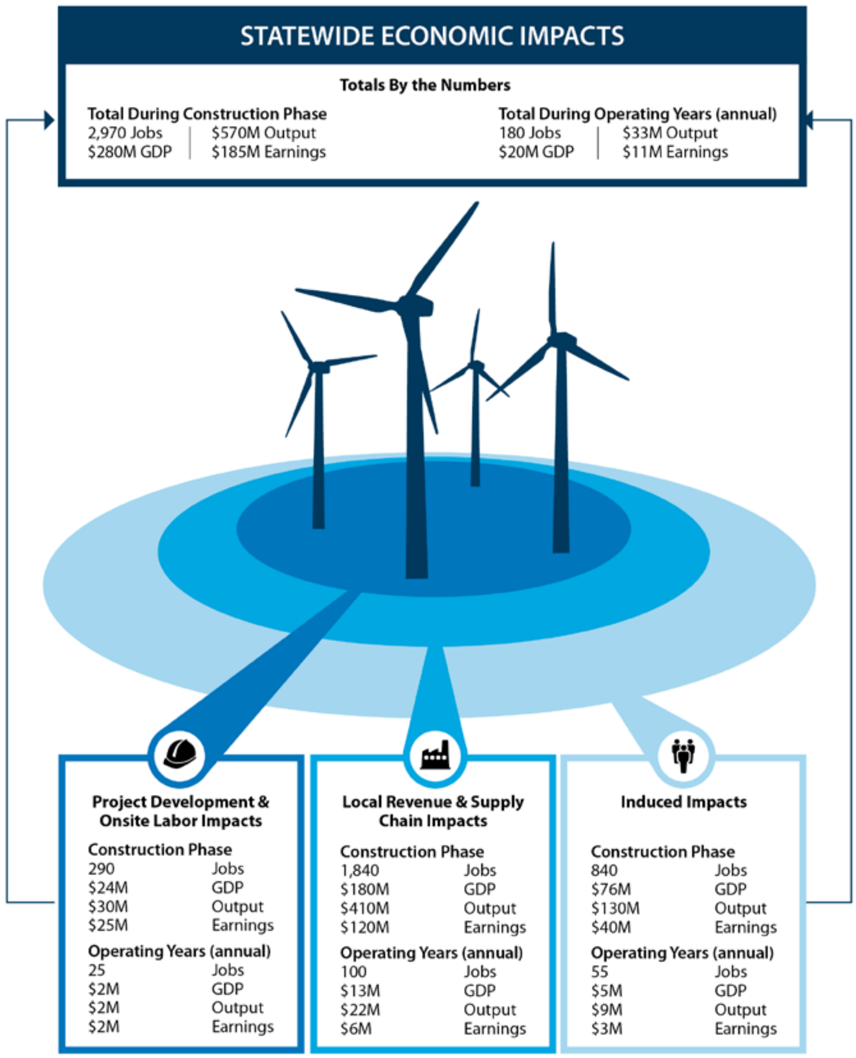
## Significance and impact:

Wind energy is one of the fastest-growing sources of new electricity supply in the United States. As wind development continues to expand to new areas of the country, tracking requirements by state become more critical, and the likelihood that some turbines will be located within the line of sight of radar systems increases. If not mitigated, such wind development can cause potential interference for radar systems involved in air traffic control, weather forecasting, homeland security, and national defense missions.

Early coordination with the Federal Aviation Administration, National Oceanic and Atmospheric Administration, Department of Homeland Security, and the U.S. Department of Defense during the siting process can help prevent a radar interference issue long before a wind power plant is built. *Photo by NREL*

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

- NREL published a report, "Economic Impacts from Wind Energy in Colorado—Case Study: Rush Creek Wind Farm," a case study of Xcel Energy's 600-MW Rush Creek Wind Farm—Colorado's largest wind energy project. By using modeled and empirical data from NREL's Jobs and Economic Development Impact (JEDI), the team developed an informative picture of the economic impacts of wind energy development in rural Colorado—results that could apply to other states as well. The JEDI analysis shows that it is not just the construction phase of a wind plant that creates economic impact. The Rush Creek Wind Farm will support 180 long-term jobs and $20 million in gross domestic product in Colorado annually throughout the operation and maintenance phase of its anticipated 25-year lifespan.




Statewide economic impacts from Rush Creek according to the Jobs and Economic Development Impact model. *Image courtesy of NREL*

## Significance and impact:

In-state wind turbine manufacturing and installation support both short-term and long-term jobs and account for other economic impacts. This work helped gain a deeper understanding of how wind plant construction impacts the economies of rural communities, where wind plant construction often occurs.

Point of contact: Elise DeGeorge, Elise.DeGeorge@nrel.gov WBS: 3.4.0.402

# Preparing the Next Generation of Wind Professionals Through Real-World Experience

The DOE Collegiate Wind Competition (CWC) challenges interdisciplinary teams of undergraduate students from a variety of academic programs to offer unique solutions to complex interdisciplinary wind energy challenges.

## During FY 2019, the project team accomplished the following:

- CWC 2019 Technical Challenge organizers from NREL have brought another successful year to a close in May 2019. Some schools needed to overcome significant obstacles to compete this year, but nothing stopped the 12 returning teams from the 2018 competition from learning the skills they needed to put up a solid performance during the event. NREL has already started preparing for the 2020 CWC, taking place at the American Wind Energy Association (AWEA) WINDPOWER Conference in Denver, June 1–4, 2020.

The DOE Collegiate Wind Competition team from Virginia Tech adjusts their turbine to prepare for a final run in the tunnel. All their hard work paid off when they took home a second-place trophy. *Photo by Werner Slocum, NREL*

The University of Wisconsin–Madison team works together on their turbine design during the Technical Challenge, held at the NREL Flatirons Campus in May 2019. *Photo by Werner Slocum, NREL*

## Significance and impact:

The CWC prepares participating college and university students to enter the wind energy workforce by providing them with real-world technology experience. The technical challenge pushes students to think critically about wind plant siting and project development, in addition to wind turbine design, building, and testing. During the competition, students are challenged to learn complex skills that directly contribute to their ability to earn a job in wind energy after graduation.

- NREL released a request for proposals for students interested in competing in the C WC in the spring of 2021. Teams from a variety of backgrounds will design, build, and test a model wind turbine that can stand up to the challenge of a massive wind tunnel and plan, financially analyze, and present research on a wind power plant. By March 2020, organizers will select up to 12 teams to compete in the challenge, which will be co-located with AWEA's WINDPOWER Conference in Indianapolis, Indiana, or held at the Flatirons Campus in Colorado in the spring of 2021.

## Significance and impact:

The release of the request for proposals is a shift to an annual—versus biennial—competition. This shift will allow for more students from a variety of universities to participate in the competition and help spread the knowledge students need to enter the wind energy workforce even further throughout the country. The team is accepting applications through December 2019.

Point of contact: Elise DeGeorge, Elise.DeGeorge@nrel.gov WBS: 3.4.0.403

# Assessing the Wind Energy Workforce and Developing Future Industry Professionals

Wind for Schools helps improve workforce development for the wind industry, ensuring that a broad range of individuals consider wind energy as a career option across the spectrum of industry needs, from wind plant technicians to wind energy R&D innovators. Through the support of university programs, tool and curricula development, and workforce research, this initiative helps to prepare the future wind energy workforce.


Participants from academia, industry, and national laboratories gather in the Workforce Pavilion for a discussion on the educational needs to prepare the next generation of wind energy workers. *Photo by Alex Lemke, NREL*

## During FY 2019, the team accomplished the following:

- To help bridge the disconnect between academia and industry, NREL partnered with AWEA to hold the first Workforce Pavilion at the AWEA WINDPOWER Conference in May 2019. This pavilion was created to leverage AWEA's interest in the future wind energy workforce. It brought together students, professors, and wind industry representatives interested in addressing long-term concerns about graduating students who are underprepared for a career in wind energy.

## Significance and impact:

This pavilion not only helped identify some of the missed connections between academia and industry, but also took steps toward solving them while highlighting NREL's and DOE's role in preparing the next generation of wind workers.

- To assess the national wind energy workforce, the hiring needs of the industry, and the educational programs that are preparing students for work, researchers interviewed educational institutions offering wind programs, as well as industry representatives, to identify gaps in the workforce and path to employment. The team published their findings in "The Wind Energy Workforce in the United States: Training, Hiring, and Future Needs."

## Significance and impact:

Hiring companies are not finding qualified applicants for open entry-level positions, and students are not being offered jobs that allow them to enter the industry. The published report highlights wind energy workforce gaps and proposes the need for creative

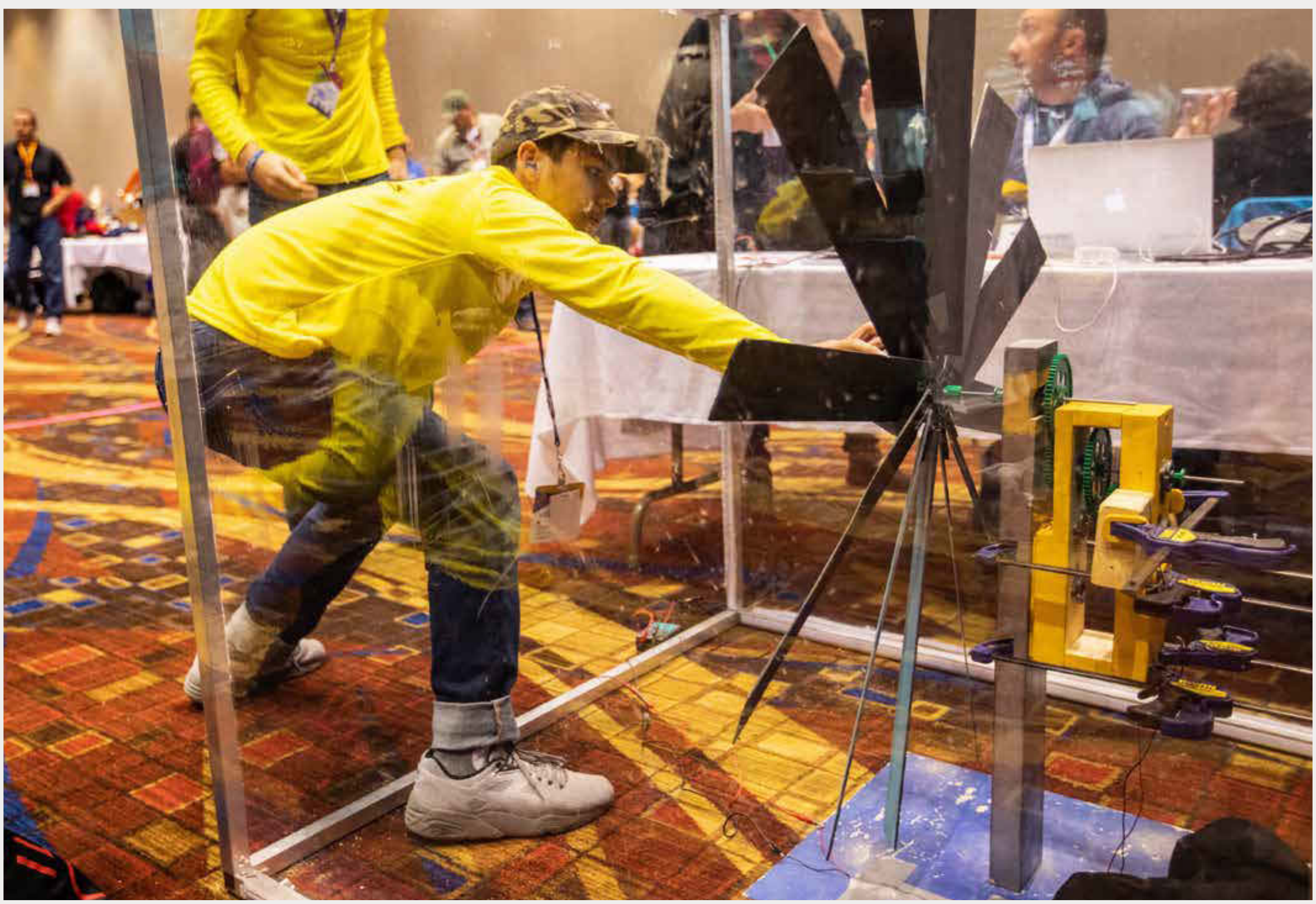
While some programs—such as the Collegiate Wind Competition—are available to connect students with industry representatives and provide real-world experience, more solutions are needed to prepare students to enter the wind energy workforce. *Photo by Werner Slocum, NREL* solutions to meet the needs of job-seeking students and a growing industry. Narrowing this workforce gap—decreasing hiring difficulty while increasing graduates' ability to find jobs in the industry—could reduce recruiting costs, better satisfy employer needs, and grow the domestic wind workforce. In addition to assessing the current state of the wind industry's workforce and training, the report looks ahead to future needs of the industry and the potential education programs needed to support its growth.

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

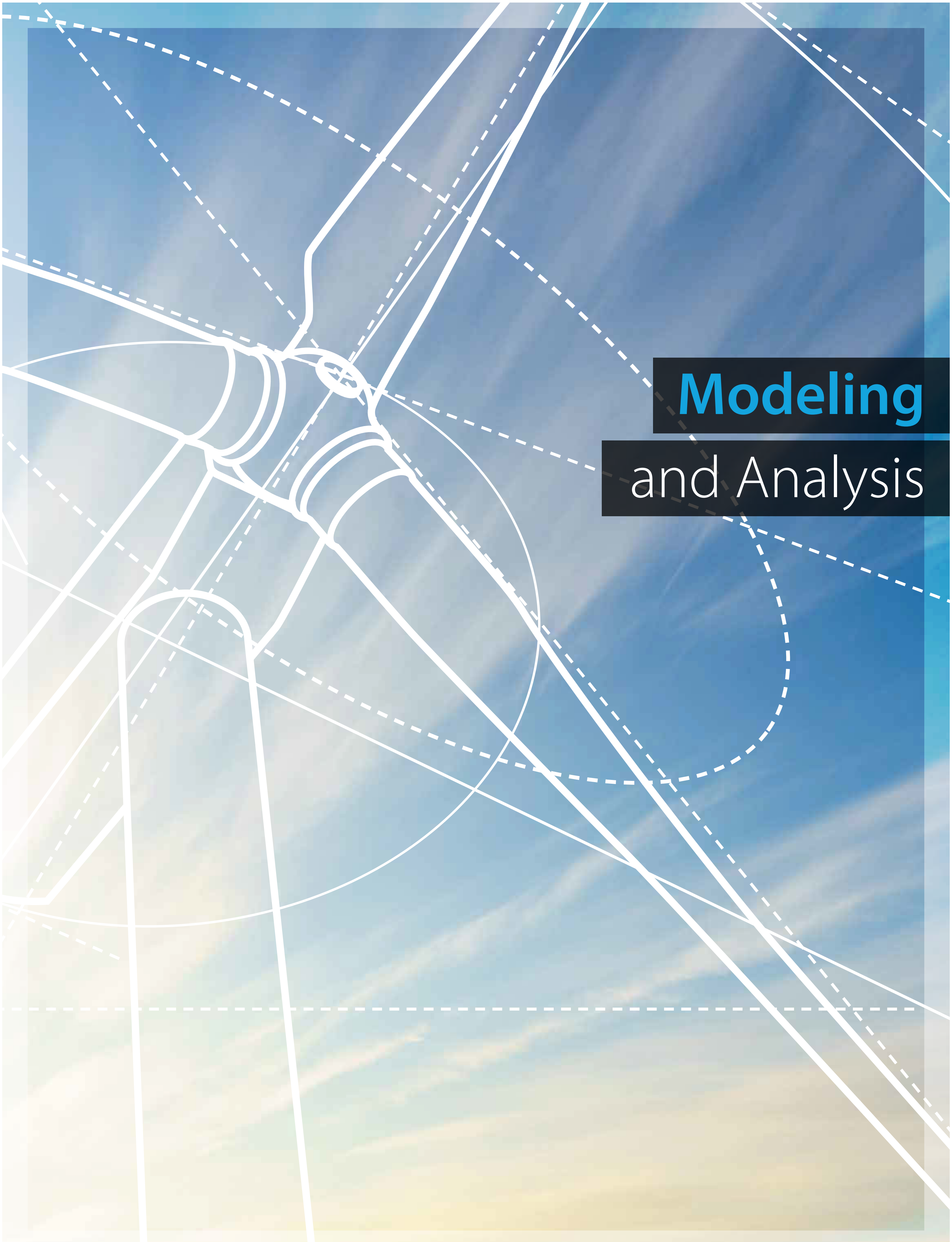
- To help develop the future wind energy workforce, NREL researchers planned the Wind for Schools Summit in January 2019, bringing together participants of the Wind for Schools initiative, a project with nearly 15 years of history. This event focused on how universities can better support the rapidly expanding need for motivated and trained workers for the wind industry. For the first time, representatives of the new Renewable Energy Powering Schools organization—a project tasked with expanding financial and technical support for educational institutions within Wind for Schools—also participated.

## Significance and impact:

By offering educational programming like the Wind for Schools Summit, NREL engages directly with the institutions that will train many future wind workers while opening pathways to allow for an expanded understanding of the applications, benefits, and challenges of wind energy to communities and younger students who are just starting to think about career choices. The summit also allows NREL and DOE to hear firsthand about challenges faced by educational institutions, especially how to better collaborate and engage directly with the larger wind industry. The team is creating wind-focused activities that help introduce K–12 teachers and students to wind energy and prepare college juniors and seniors for careers in the industry.



Participants in the National KidWind Challenge test out the turbines they created during AWEA WINDPOWER 2018 in Chicago. *Photo by Werner Slocum, NREL*



# Modeling and Analysis

Point of contact: Eric Lantz, Eric.Lantz@nrel.gov WBS: 4.1.0.401

# Analyzing Historical Wind Technology Trends To Illuminate the Electric Sector of the Future

This body of work focuses on characterizing land-based and offshore wind technologies based on historical trends and innovation potential to illuminate the future cost of wind power, considering an array of potential technology and market conditions.

## NREL researchers accomplished the following during FY 2019:

- Produced an open-source version of the Land-Based Balance-of-Systems Engineering model, a novel tool that can help researchers, analysts, wind power developers, government agencies, and the public understand the potential for cost reductions in a wind project's total investment costs. Also published a related technical report.

- Revamped several offshore models and planned and scoped the development of a 15-MW offshore wind reference turbine.


The Wind Plant Technology Characterization project's main objective is to develop and apply capabilities that assess the value of future innovation opportunities and to track trends in recent wind technology and deployment. *Photo by Suzanne Tegan, NREL*

- Informed decision makers at local, state, and federal levels on developments in global land-based and offshore wind during the IEA Task 26 meeting in Germany.
- Delivered a sensitivity output module for the Offshore Regional Cost Analyzer model that represents a first-of-its-kind systematic sensitivity analysis of comprehensive offshore wind spatial cost modeling and fills a critical gap in cost modeling literature.
- Published the "2018 Offshore Wind Technologies Market Report," which provides unbiased data and analysis about the offshore wind market, technology, and cost trends.
- Published a new study, "Increasing Wind Turbine Tower Heights: Opportunities and Challenges," in which researchers examine opportunities for increasing the height of wind turbine hubs.
- Cowrote with researchers from Lawrence Berkeley National Laboratory a journal article in Renewable Energy Focus, which finds that reducing operational expenditures of U.S. land-based wind power plants is essential to achieving lower LCOE and making wind even more cost competitive.

### Significance and impact:

NREL analysis like this helps guide future wind energy development to reduce the cost of wind energy and increase the contribution of wind to the electrical grid; inform WET O's scientific research and technology development strategy; and, by providing market and cost benchmarks for wind technology, advise other public and private sector investments in wind technology and related innovation opportunities.

Wind Analysis for Priority Needs

Point of contact: Eric Lantz, Eric.Lantz@nrel.gov WBS: 4.1.0.402

## Informing Public Sector Investment in Wind Technology

This project is designed to provide subject-matter expertise to WETO in technological, economic, and policy analysis, especially for high-priority responsive analysis to meet executive, congressional, and senior management priorities. The project also supports economic impact research and modeling tools that provide stakeholders with detailed and robust information on the economic impacts of development and operation of wind energy in the United States.

### During FY 2019, the project team:

- Started compiling data and documenting outcomes for 11 case studies of significant U.S. wind power innovations
- Created a public version of an offshore wind LCOE memo that characterizes anticipated costs for what is expected to be the first commercial-scale offshore wind project in the United States
- Completed a memo exploring different research, development, and deployment efforts that would help achieve a 50% cost reduction on land-based wind
- Delivered a draft summary report of the case study, "Bend-Twist Coupled Blades and Flatback Airfoils" for inclusion in WETO's contribution to a Nature Energy special report featuring DOE/Office of Energy Efficiency and Renewable Energy (EERE) success stories

- Conducted communications and dissemination efforts about these research and analysis activities, which helped to raise awareness of and support for the work among a variety of stakeholders, including Congress, industry, universities, and the general public

- Published a technical report, "Increasing Wind Turbine Tower Heights: Opportunities and Challenges," which assesses how higher hub heights could increase wind energy viability across the nation.

## Significance and impact:

By providing expertise in technological, economic, and policy analysis, NREL helps inform WETO's investment in wind technology research. These analysis activities provide insights and intelligence around both current and future priority questions, including potentially providing an enhanced understanding of WETO contributions to wind industry R&D and new capacity expansion analysis associated with changes in WETO program cost targets.


One of the case studies of significant U.S. wind power innovations included in this work focused on a series of test turbines built and operated from 1975 to 1996. Shown here is a 2.2-MW, two-bladed, fixed-speed turbine called Mod-1 but nicknamed "Old Thumper," which in the late 1970s taught lessons on drivetrain reliability, noise, and community engagement. *Photo courtesy of the National Aeronautics and Space Administration*

WETO.4.1.0.405 - Energy Sector Modeling and Impacts Analysis

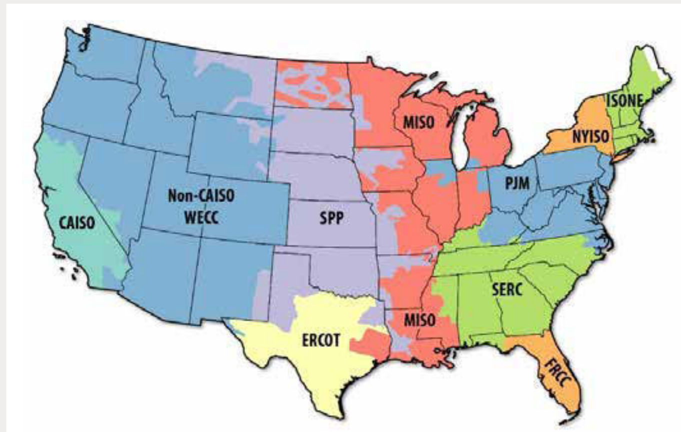
Point of contact: Trieu Mai, Trieu.Mai@nrel.gov

# Guiding Long-Term Technology Design To Increase Variety, Quantity of Grid Services

This project includes multiple tasks designed to evaluate the technical system needs of the future energy system and how wind technology—including future turbine and plant design—can economically service those needs.

## During FY 2019, the project team:

- Published four reports:
  - "An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind," which provides an overview of grid services needed around the country and wind energy's role in contributing to those services.
  - "The Vineyard Wind Power Purchase Agreement: Insights for Estimating Costs of U.S. Offshore Wind Projects," a detailed examination of the estimated costs for one of the first major offshore projects in the United States.
  - "Cost Projections for Utility-Scale Battery Storage," which documents the development of cost and performance projections for utility-scale lithium-ion battery systems, with a focus on 4-hour duration systems.
  - "The Potential for Battery Energy Storage to Provide Peaking Capacity in the United States," finds that the addition of renewable generation can significantly increase energy storage potential by changing the shape of net demand patterns with technologies like solar, but the impact of wind generation is less clear and likely requires more detailed study considering the exchange of wind power across multiple regions.
- Developed a new methodology to quantify the technology cost targets needed for electricity generation technologies to achieve certain penetration levels in the energy market that was published in *Applied Energy*. NREL researchers presented the methodology and initial estimates of competitive cost targets for offshore wind energy—referred to as the "required costs," or the LCOE needed to achieve a specific annual generation level.
- Released a publicly available version of one of NREL's flagship tools, the Regional Energy Deployment System (ReEDS) model. ReEDS is a capacity planning model for the North American electricity system that simulates the evolution of the bulk power system—including changes to deployment of wind, all other major generation technologies, storage, and transmission—from present day through 2050.




A map of the regions studied in "An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind," by Paul Denholm, Yinong Sun, and Trieu Mai, includes the seven U.S. independent system operator/regional transmission organization market regions, along with other aggregate nonmarket regions.

## Significance and impact:

This work improves underlying wind energy models and data for national-scale long-term planning and provides a foundational understanding of the U.S. power system and how wind contributes to the energy and grid needs.

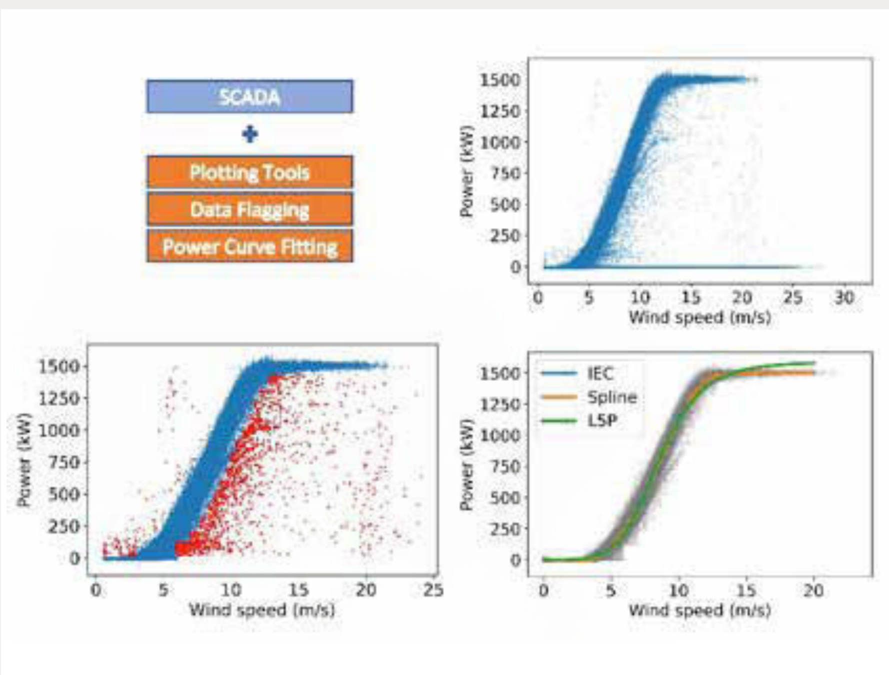
Point of contact: Jason Fields, Michael.Fields@nrel.gov WBS: 4.1.0.406

# Analysis Improves Wind Power Plant Performance To Identify and Reduce Uncertainties.

The Performance Risk, Uncertainty, and Finance (PRUF) multiyear project works to enhance understanding of financial risks and uncertainties around wind plant investment decisions to improve wind plant energy production and operational cost estimation methods and reduce uncertainties around return on investment. Work within PRUF includes investigating the magnitude of wind plant performance losses and uncertainties along with their impact on financial structures, the cost of capital, the cost of ownership and operations, and LCOE.

Over the year, PRUF researchers completed work on multiple activities, including publishing a journal article in Wind Energy Science titled "Assessing variability of wind speed: comparison and validation of 27 methodologies." In a *Renewable and Sustainable Energy Reviews* journal article, NREL researchers examine the impact of atmospheric turbulence and stability inputs on machine-learning model predictions of wind farm power output and find that considerable improvement in hourly power predictions results from the inclusion of turbulence or stability measures—especially turbulent kinetic energy—in forecasting models.

PRUF researchers upgraded OpenOA, NREL's open-source code base for wind power plant operational analysis, to full public development. This work was featured in a news article and video posted to nrel.gov. In addition, NREL researchers implemented a wind plant energy-loss and uncertainty framework in the System Advisor Model, which will include an IEC-61400-15-compliant loss and uncertainty model that allows for further analysis and valuation of wind plant performance improvements.




Using different OpenOA modules to calculate idealized power curves for a sample wind turbine. In this example, supervisory control and data acquisition (SCADA) data are filtered and then fit using three different power curve models. *Graphic courtesy of NREL*

The PRUF team also released Phase 1 results of the Wind Plant Performance Prediction benchmark study; supported analysis for the Power Curve Working Group's intelligence-sharing exercise and presented preliminary results via webinar; and organized and facilitated the IEA Wind Topical Experts Meeting #92 on current trends in wind energy digitalization, which attracted 46 participants from 11 countries.

## Significance and impact:

PRUF is designed to increase the deployment of wind energy by lowering the actual and perceived risks and uncertainties associated with developing, investing in, owning, and operating wind power plants.

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

# Building Understanding of Wind Energy Potential To Maximize New Opportunities, reV Model

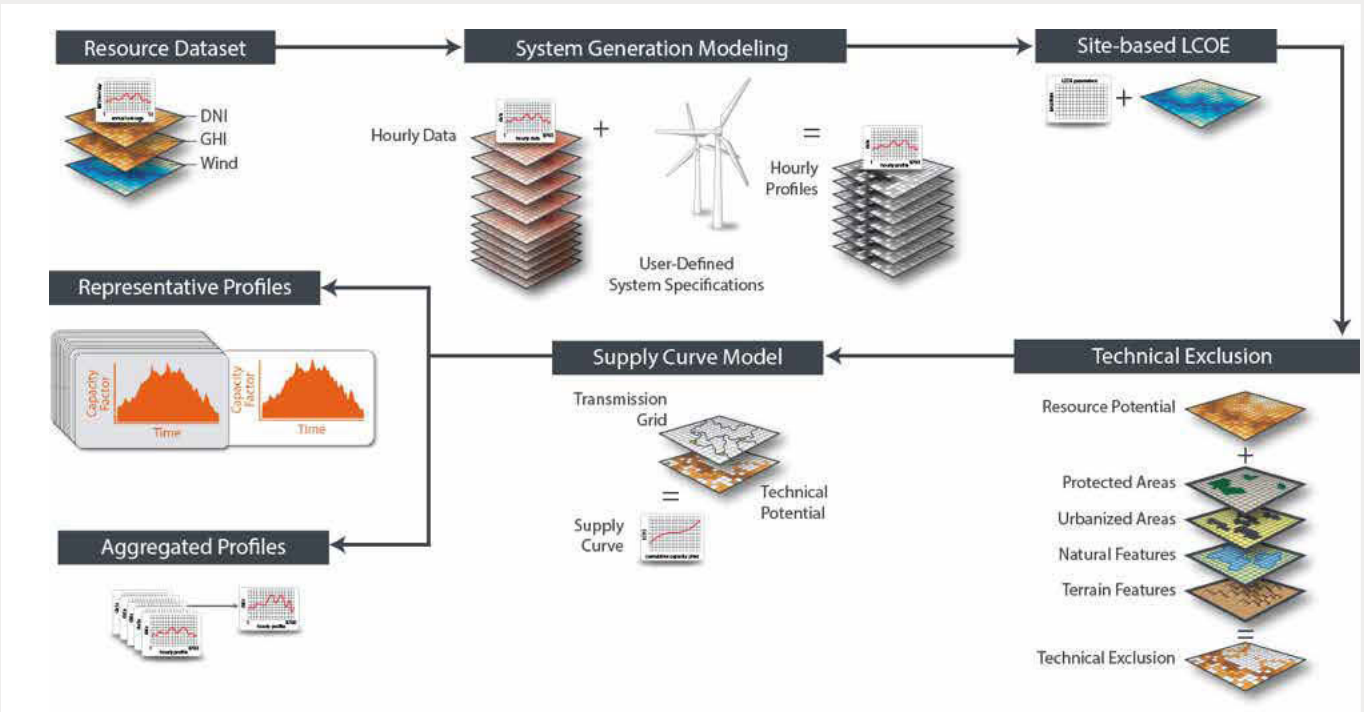
National-scale modeling of wind energy potential has made significant progress in the last 2 years with the development of the renewable energy potential (reV) model. This geospatial modeling platform has enabled researchers to dynamically examine wind energy production and cost improvements, with high spatial and temporal fidelity, by modifying turbine and financial parameters, spatial exclusions, and grid interconnection costs.

Research in FY 2019 addressed two separate areas for improvement in the reV model: 1) developing cost-based exclusions and wildlife mitigation modeling, and 2) site-specific modeling of wind farm characteristics for future build out. Accomplishments include the following:

- Published a technical report titled, "The Renewable Energy Potential (reV) Model: A Geospatial Platform for Technical Potential and Supply Curve Modeling"
- Refined the reV medium and high baseline scenarios to model smart curtailment for wildlife mitigation scenarios and added the temperature and precipitation rate from the Wind Integration National Dataset Toolkit to model bat activity
- Prepared a journal article describing the modeling framework for predicting variable power density across the lower 48 U.S. states, aiming to move beyond a long-standing modeling assumption that power density is constant across space
- Examined the spatially varying economic impacts of bat curtailment scenarios and presented these at the DOE wind-wildlife training on September 18
- Examined how cost-based exclusions and wildlife mitigation scenarios will change the addressable gigawatts of wind capacity (such as available land)
- Designed an offshore wind supply curve model in reV to increase flexibility in modeling assumptions and potential for assessing pathways for technology innovations
- Conducted a proof-of-concept analysis of simple balance-of-system costs across the country that account for terrain complexity, turbine layout complexity, and soil conditions
- Developed land-based and offshore supply curves with reV, documenting the inconsistencies between how land-based wind in reV is handled compared to offshore wind in the Offshore Regional Cost Analyzer
- Drafted a journal manuscript presenting work conducted on wind farm layout and resource characterization and relationships between wind deployment and land use, terrain, and major ecological (habitat) regions.

## Significance and impact:

By leveraging core reV model capabilities, this project builds a new foundation of knowledge and understanding that will feed future characterizations of wind energy potential considering both new opportunities presented by advanced technology and higher-fidelity characterizations of potential deployment barriers (e.g., wildlife, social acceptance, logistics, and site accessibility).




Flowchart illustrating the principal modules of the reV model. Processing starts with renewable energy resource data and culminates in the supply curve. Model interoperability is highlighted with representative profiles to couple with capacity expansion models and aggregated profiles to couple with production cost models. *Graphic courtesy of Billy Roberts, NREL*

# Technology Transfer

Allowing communication between wind turbines can improve the overall power performance of large-scale wind farms. *Photo by Warren Gretz, NREL*

## Small Business Vouchers – WindESCo

Point of contact: Jennifer King, Jennifer.King@nrelgov WBS: 5.1.0.407

# Wind Turbines Get Social To Improve Wind Power Plant Output

Wind turbines currently operate independently of one another, which makes diagnosing and addressing performance issues costly and difficult for operators. A partnership between NREL and the wind solutions company WindESCo, funded through the Small Business Voucher Project, gathered wind farm data and used it to simulate the process of using sensors that enable data sharing between turbines (collective consensus), allowing them to theoretically adjust to conditions in real time.

### Significance and impact:

The ability to adjust wind turbines in real time can improve power output and reduce wear and tear. When turbines can communicate with one another, their overall performance is more coordinated. The yaw motion of individual turbines is reduced as well, meaning turbines spend less time "chasing the wind" to find the optimal positioning. Use of these data would allow turbines to compare performance with one another, adjust to atmospheric conditions, and operate more efficiently. Wind farms could also see reduced maintenance costs.

Small Business Vouchers – Sentient

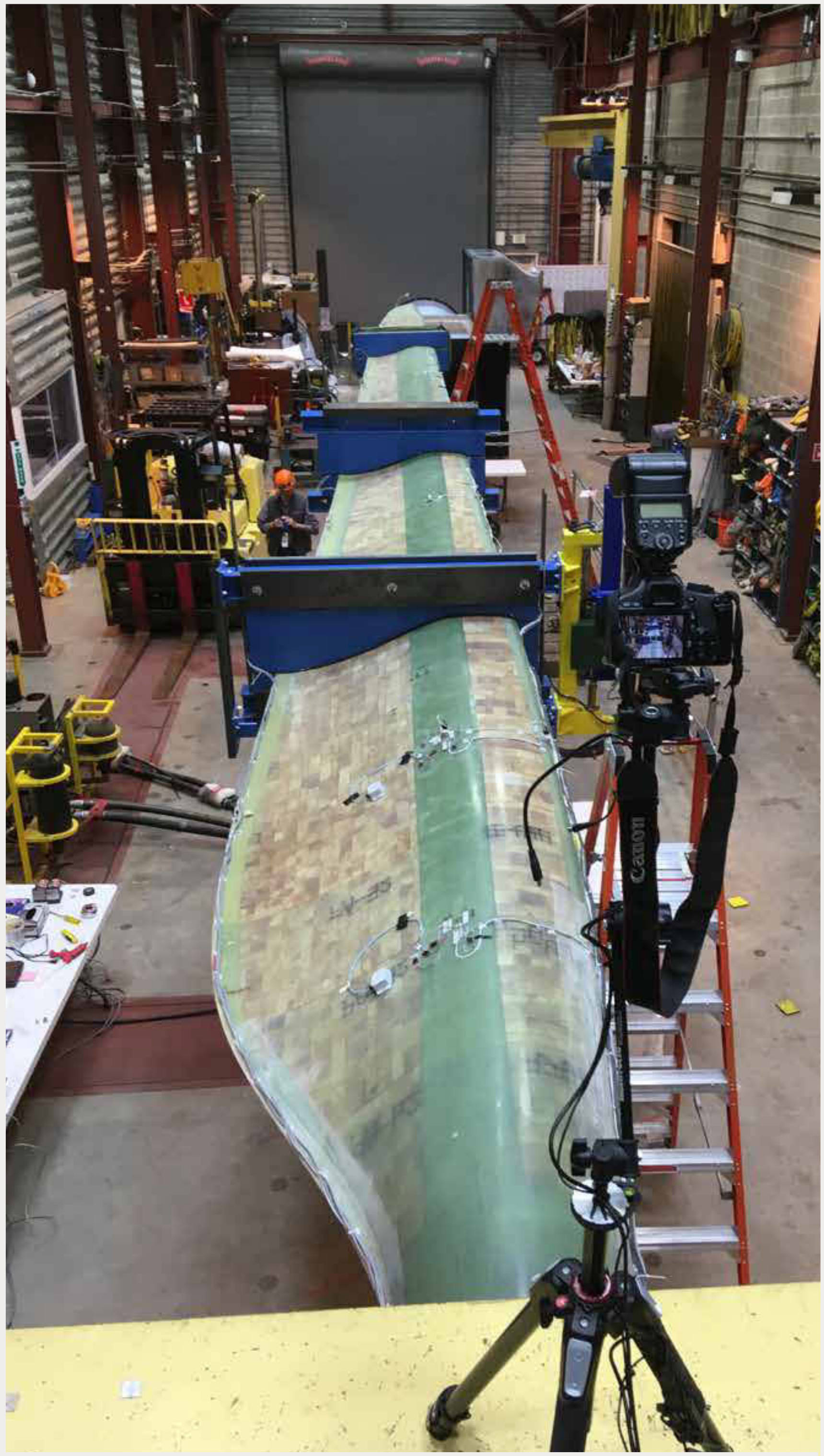
Point of contact: Scott Hughes, Scott.Hughes@nrel.gov WBS: 5.1.0.408

# Partnership To Develop Model for Predicting Wind Turbine Blade Damage

Predicting wear and tear on wind turbine blades is essential for saving money and ensuring smooth operation of a wind turbine. One defective wind turbine blade can cost up to $300,000 if the problem is not caught early enough to repair. A partnership among Sentient Science, NREL, and Sandia aimed to develop models and software that will predict damage progression on wind turbine blades. The project is part of DOE's Small Business Voucher program. In late 2018, the team completed a fatigue assessment on a 13-m blade by damaging the blade and then monitoring the damage as it progressed to failure.

## Significance and impact:

Sentient took the data that resulted from the structural fatigue validation test and compared it with data collected from their optically-based health monitoring system, with NREL supporting this effort through review and data comparison. This effort will eventually result in a tool that allows wind plant operators to plan for wind turbine blade maintenance and replacement, with minimal downtime, rather than respond to unexpected failure.




Preventive health for wind turbine blades. Sentient Science's wind blade fatigue assessment in NREL's Structural Testing Laboratory includes a 13-m blade and an optical measurement system, shown on top of the test stand. *Photo by Ryan Beach, NREL*

Point of contact: Latha Sethuraman, Latha.Sethuraman@nrel.gov WBS: 5.1.0.405

# Additive 3D Printing Technology To Enable Next-Generation Drivetrains

Manufacturing and Additive Design of Electric machines enabled by 3D printing (MADE3D) could allow equipment manufacturers to produce large electric direct-drive machines that weigh up to 50% less than those manufactured by traditional 2D methods. Latha Sethuraman, along with senior NREL researchers Jon Keller and Robert Preus and William Erdman from Cinch, Inc., underwent an intensive 2-month program as part of DOE's Energy I-Corps Program to assess market opportunities and investigate potential backers for MADE3D. Although 3D design techniques enable the use of new shapes, geometries, and design materials in the printing process, adoption of electric machine 3D design and printing is still in its nascent stages in many industries, including the wind industry.

Energy I-Corps trains national lab researchers to evaluate industry needs and potential market applications for their technologies. The program aims to accelerate the deployment of energy technologies by granting DOE laboratory scientists and engineers direct market feedback on their research. I-Corps helps researchers develop viable market pathways for their technology, which helps program participants like the NREL team better understand the technology's true potential for market application.

## Significance and impact:

After 78 interviews, Sethuraman and team identi¬fied electric aviation, urban air taxis, ship propulsion, and wind energy industries as potential adopters for MADE3D. Within the wind industry, the share of direct-drive turbines is expected to grow across global markets. Creating lightweight direct-drive generators through 3D printing technology could help ensure that American-made technology is on the cutting edge of this technological space. The next step for the project team is securing funding to help advance MADE3D's software and printer development.

Latha Sethuraman, part of the MADE3D team at NREL. *Image by Deb Lastowka*

# Programmatic **Support**

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

# Hands-On Support Broadens Wind Research Impact

This project team provides program management and operations support to effectively plan, integrate, implement, control, and report NREL's extensive portfolio of 74 active WETO-funded projects. During FY 2019, the project team achieved the following:

- Leading NREL's participation in the WETO 2019 Project Peer Review, which involved coordinating presentations of 20 NREL researchers, and documented results of 27 projects that represented $70,079,995 of combined FY 2017 and FY 2018 project budget
- Overseeing NREL's research presentations, posters, and panel participation for the AWEA WINDPOWER conference, hosting the Workforce Pavilion and supporting the WETO booth
- Delivering quarterly accomplishments reports and Wind Program status reports; responding to lab calls; updating budgets; participating in regular calls, meetings, and summits; and providing regular newsletters communicating NREL wind research progress accomplishments and travel
- Developing a Flatirons Campus re-branding and rollout strategy
- Serving in a strategic leadership role as vice chairman of the IEA Wind Technology Collaboration Programme and operating agent for IEA Wind Tasks 26, 30, 31, 34, 41, and 43
- Submitting a new "Flatirons Campus Expansion and Capability Enhancements" annual operating plan project for a second CGI procurement and installation
- Reviewing the FY 2019 Small Business Innovation Research Phase I proposals
- Meeting the FY 2019 WETO notable outcome performance objective by developing a comprehensive next-generation wind manufacturing research plan to transform next-generation wind manufacturing, ensure future industry growth, and increase domestic manufacturing competitiveness and jobs in America.

## Significance and impact:

This 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 opportunity across the country.

## Communications Support

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

# Strategic Communications Amplify the Wind Energy Technologies Office Mission

NREL's core communications team is at the forefront of WETO's efforts to reach its target audiences through a strategic blend of outreach activities involving traditional and digital media, conferences, and events. The team's support consists of developing, providing, and disseminating meaningful, impactful communications that bring stakeholder attention to DOE's efforts to lead the nation in accelerating the deployment of wind energy technologies through improved performance, lower costs, and reduced market barriers.


The team from Texas Tech watches as they test their model wind turbine in the tunnel. *Photo by Werner Slocum*

NREL's communications team leveraged a variety of tactics and channels to engage with stakeholders during FY 2019, including:

- Adding the Peer Review report pages to the WETO website, creating several web articles and event listings to ensure the most accurate and up-to-date program information is presented
- Coding and disseminating breaking news emails, which included auditing priority web pages, collecting subject matter expert opinion on improving site animations, managing the writing and dissemination process for both fall and spring R&D newsletters, and finalizing content for the U.S. chapter for the IEA Wind TCP 2018 Annual Report

- Supporting top-level publications, the "Wind Technologies Market Report," "Offshore Wind Technologies Market Report," and the "Distributed Wind Technologies Market Report" through editing, peer review coordination, graphic design, print finalization, and web publication.

The communications team also completed a quarterly milestone accomplishment of managing logistics and collateral creation for the AWEA WINDPOWER Conference. In addition to WINDPOWER, the team managed preparations for AWEA Offshore WINDPOWER, the Collegiate Wind Competition, and supported preparation for the Wind Peer Review. Finally, the team kept WETO Communications Lead Liz Hartman apprised of all NREL wind-related publications, social media, and Tier 1 reports.

### Significance and impact:

The NREL communications team amplifies WETO's mission by creating a variety of communications materials, such as fact sheets, technical reports, brochures, web content, newsletters, and social media posts, and disseminating them to relevant stakeholders. The team delivered WETO news to thousands of newsletter subscribers, website visitors, and conference attendees.

## M&O Support – Alex Lemke

Point of contact: Alex Lemke, Alexsandra.Lemke@nrel.gov WBS: 5.1.0.403

# External Affairs Project Advances WETO's Mission; Successfully Leads Peer Review Coordination and Execution

The senior advisor of WETO External Affairs provided a deep understanding of how to effectively represent the interests of WETO and communicate them to a diverse set of existing and potential stakeholders. Working closely with WETO leadership to identify opportunities that will result in enhanced partnerships and new business development, the advisor helped build, improve, or expand WETO's relationships to ultimately advance the WETO mission. During FY 2019, the senior advisor led or contributed to a variety of key projects, including:

- Serving as a core team member of the 2019 Wind Program Peer Review, providing guidance and support in event logistics, execution, communications, industry engagement, and project evaluation to ensure WETO's R&D portfolio is seen as necessary, valuable, and impactful; the Peer Review gave subject matter experts from the wind industry, academia, and federal agencies the opportunity to provide feedback on projects funded by WETO; as part of this effort, 20 NREL researchers presented results from 27 projects that represented more than $70 million of combined FY 2017 and FY 2018 project budgets

- Executing several successful, high-level events, including an industry engagement meeting with AWEA; the Research Needs for Offshore Wind Resource Characterization Workshop; the AWEA Project Siting and Environmental Compliance Conference; the International Partnering Forum; IEA Wind's Executive Committee bi-annual meeting in Washington, D.C.; the Drivetrain Reliability Collaborative; and AWEA's WINDPOWER, Offshore WINDPOWER, and Clean Energy Executive Summit

- Serving as a core contributor to the Multi-Year Program Plan, providing guidance and consulting on best practices in finalizing the report, project management, writing/editing, and consulting on design elements, ensuring the plan will effectively communicate a road map for WETO's work during the next 5 years

- Contributing to IEA Wind's TCP Secretariat application and working collaboratively the TCP to create an improved vehicle for member countries to exchange information on the planning and execution of national, large-scale wind system projects and to undertake co-operative research and development projects

- Developing a "Strategic Conference Planning Guide and Procedures" plan with the intent of educating WETO and other EERE technologies offices about the importance of identifying a strategy and messaging for every conference, workshop, or summit, and finding new opportunities for increased participation, messaging, and articulating the office strategy at core events.

### Significance and impact:

The close involvement of the external affairs advisor in key wind industry activities and events ensures that WETO, EERE executive leadership, and external industry partners are engaged in discussion  opportunities for increased awareness and understanding of WETO's R&D priorities. This will amplify the effectiveness and reach of WETO's research through guidance and support for cross-cutting communications; stakeholder engagement; workforce, legislative, international, and national lab collaboration; and many technology-to-market activities, ultimately accelerating the understanding and adoption of wind energy technologies.

M&O Support

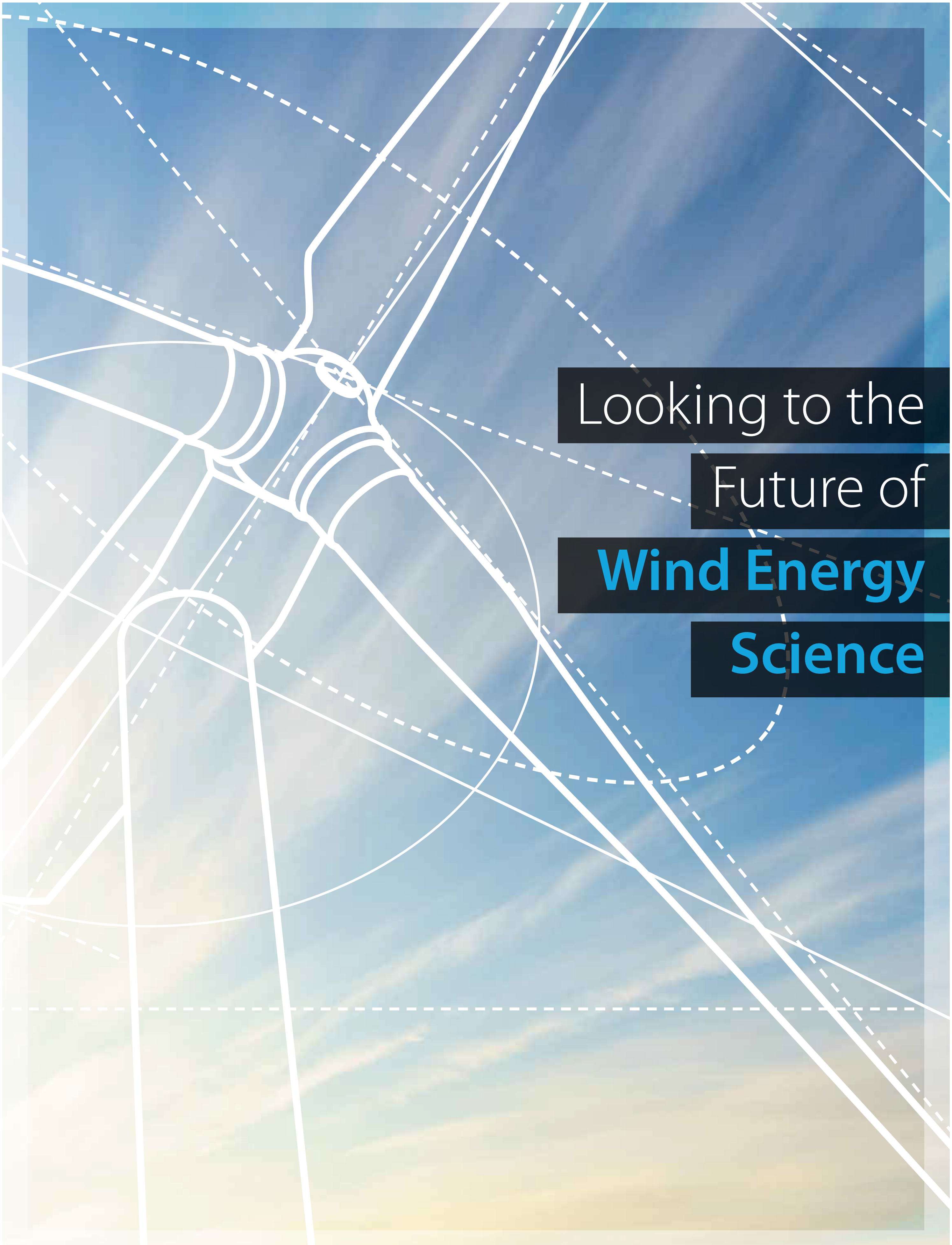
Point of contact: Alex Lemke, Alexsandra.Lemke@nrel.gov WBS: 5.1.0.403, 5.1.0.404, 5.1.0.410

## 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, 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.

### Significance and 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.



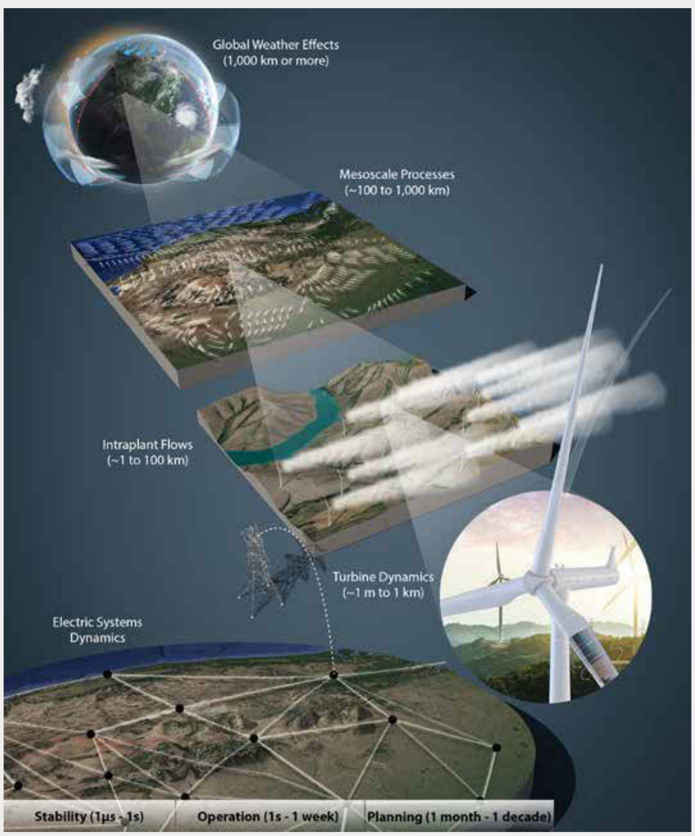
# Looking to the Future of Wind Energy Science

# Facing Upwind: Looking to the Future of Wind Energy Science at Flatirons

Earlier this year, DOE formally renamed the 305-acre site just south of Boulder, Colorado, that houses the NWTC to the Flatirons Campus, named after the distinctive reddish-brown sandstone formations nearby. For several years, research at the site has been expanding beyond wind to include grid integration, water power, energy storage, solar photovoltaics, and advanced manufacturing. The name change reflects a broader trend for NREL and the industry to pursue and advance integrated energy systems at scale—and part of this effort is learning how wind power plants can support and foster grid reliability and resiliency.

As wind becomes an increasingly large part of the electric system, the design and operation of more effective wind power plants requires substantial research with regard to wind plant control with larger electric system operations; something many researchers at Flatirons are focused on. The design and operation of wind power plants to support and foster grid reliability and resliency is so critically important to wind research that it was identified as one of three challenges in the science of wind energy.

Published in Science, "Grand challenges in the science of wind energy" invites the scientific community to consider the research needed to help wind become one of the world's primary sources of low-cost electricity generation, accounting for as much as a third and up to half of the world's electricity needs by 2050. The grand challenges are based on a workshop NREL hosted in 2017, which was attended by more than 70 wind experts representing 15 countries. Attendees discussed how wind could serve the global demand for clean energy in the electricity system of the future, which will increasingly rely on variable renewables like wind. Based on this workshop, article lead authors Paul Veers (NREL), Eric Lantz (NREL), and Katherine Dykes (Technical University of Denmark) identified the three grand challenges in wind energy research that require further study from the scientific community:




Wind energy's scientific grand challenges span vast scales both in terms of space and time. Mastering the physics and addressing the related research needs across these scales will position wind energy to serve as a primary source of future energy supply for the world. *Illustration by Josh Bauer and Besiki Kazaishvili, NREL*

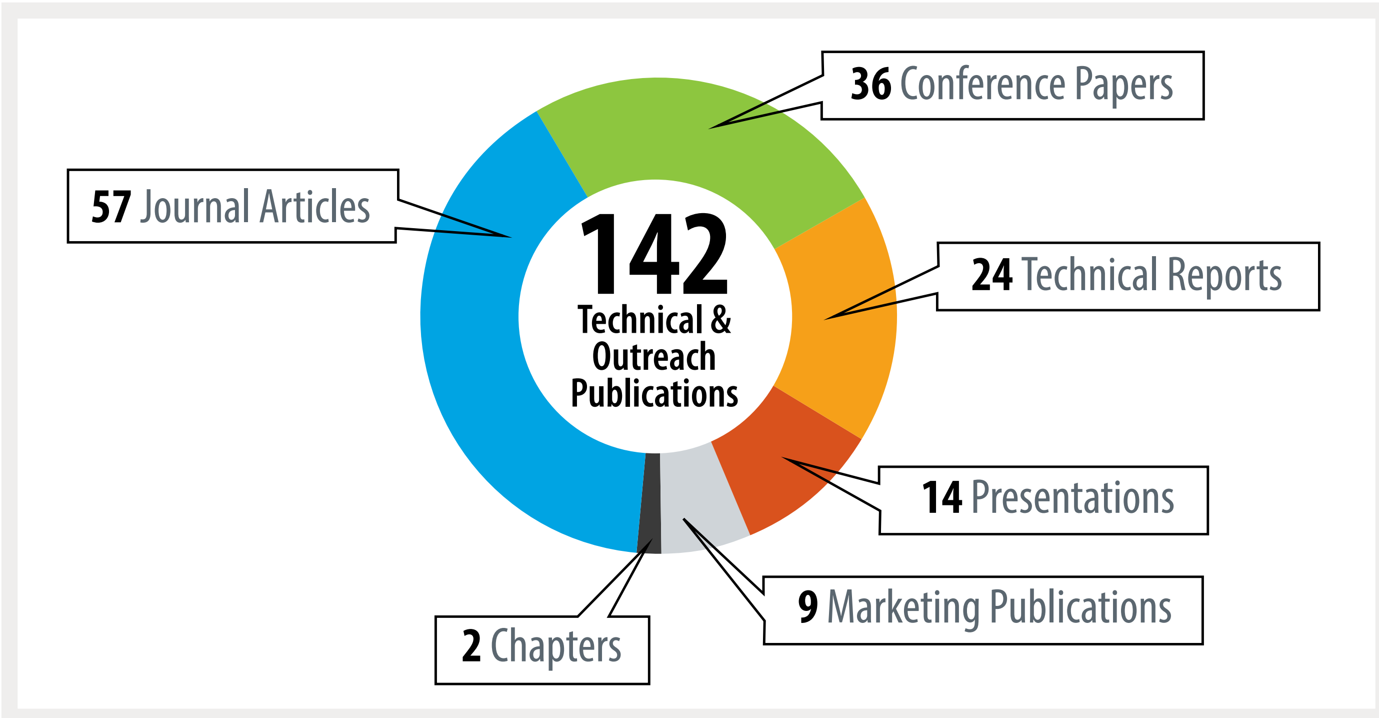
- Achieve an improved understanding of the wind resource and flow in the region of the atmosphere where wind power plants operate.
- Address the structural and system dynamics of the largest rotating machines in the world.
- Design and operate wind power plants to support and foster grid reliability and resiliency.

These wind research grand challenges build on each other in much the same way as the accomplishments highlighted in this report—and having a better understanding of these challenges of can inform the direction of both existing and future AOPs. Among these new projects are initiatives like Atmosphere to Electrons to Grid (A2e2g), which will examine the cost and performance of entire wind plants for opportunities to significantly reduce the levelized cost of wind energy while incorporating A2e advances for wind plant optimization.

As we look forward to FY 2020, NREL will continue to influence the direction of wind research and development by tackling wind energy science's grand challenges.

# Publications

# 2019 Publications Demonstrate Advancements in Wind Energy Research



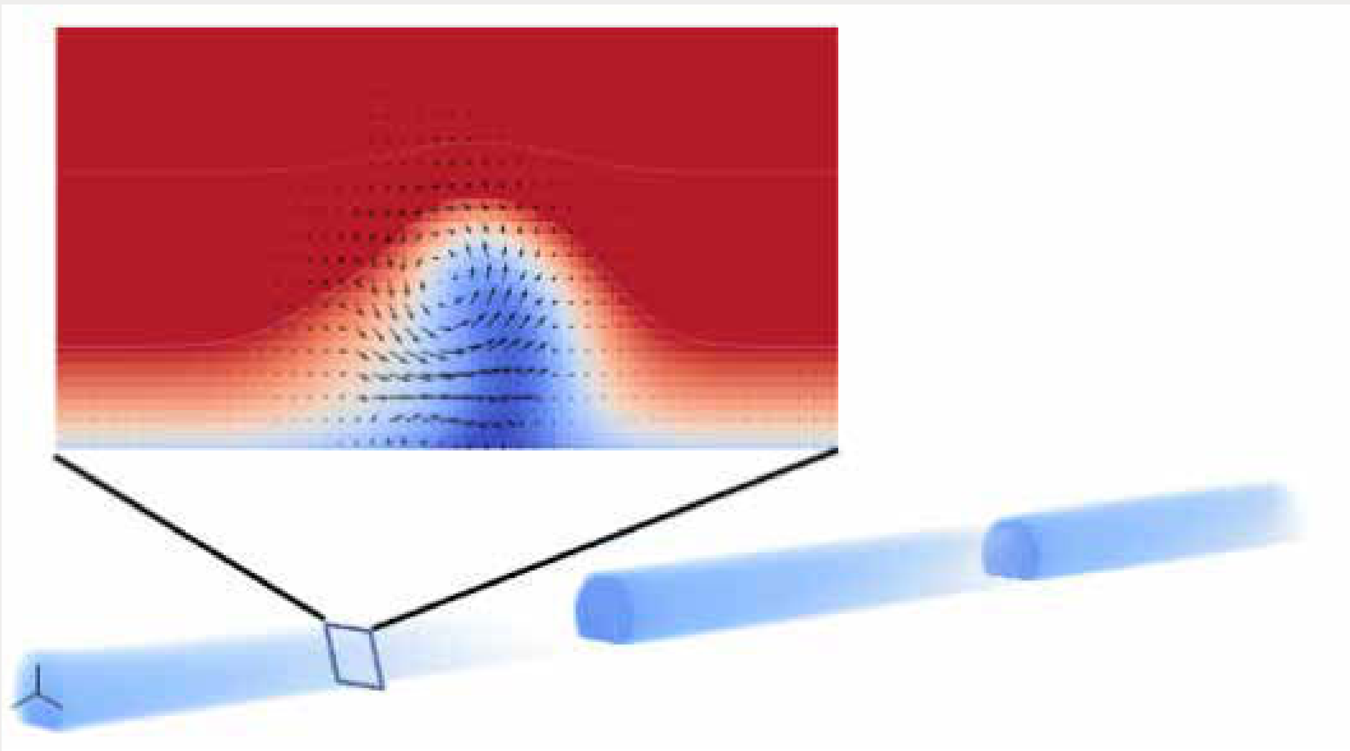

To inform the wind industry and the public about advancements in wind energy, NREL's Wind Energy Program staff produced over 140 publications in FY 2019. These ranged from articles published in peer-reviewed journals to technical reports and outreach publications that shared the latest research and technology findings.

# The Top Five Wind Publications for FY 2019

The top five wind publications, presented in no-particular order, provide a cross-sectional look at wind research across the wind program portfolio.

# The Aerodynamics of the Curled Wake: A Simplified Model in View of Flow Control

Authored by **Luis A. Martínez-Tossas**, **Jennifer King**, **Paul Fleming**, and **Matthew Churchfield**. Published in *Wind Energy Science*



Waking to a new model. This 3D illustration shows a FLORIS simulation of three turbines generated using the curl wake model. Shown above the three turbine wakes is a single-plane visualization featuring the in-plane vortex flows leading to the curled shape of the wake. *Illustration by Paul Fleming, NREL*

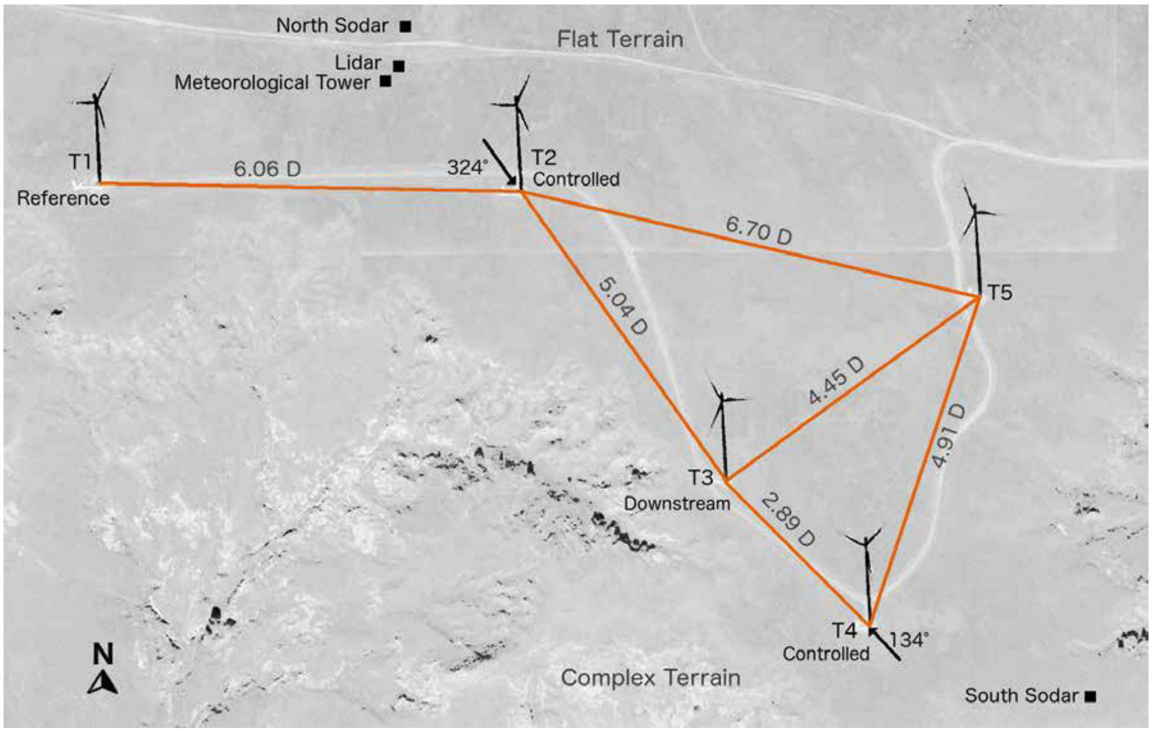
When a wind turbine is yawed, the shape of the wake changes and a curled wake profile is generated. The curled wake has drawn a lot of interest because of its aerodynamic complexity and applicability to wind farm controls. The main mechanism for the creation of the curled wake has been identified in the literature as a collection of vortices that are shed from the rotor plane when the turbine is yawed. Based on the literature, researchers documented a new vortex-based wake modeling theory and published their findings in the journal *Wind Energy Science*. The vortex behaviors were incorporated into the open-source FLORIS tool. The methods can be used for designing wake-steering controllers.

## Significance and impact:

Advanced flow control science develops the technical capabilities and methods for smart power plants, where the activities of wind turbines are coordinated by a central wind farm controller. The ability to use information from turbines and adjust in real time can substantially improve performance, optimize energy capture, and minimize loads of existing and new wind farms. This research unlocks new potential for wake steering not previously captured in any engineering wake model. FLORIS has also been updated to include terrain that can be used on many land-based wind farm applications based on the development of the curled wake model. Researchers also developed a method to include uncertainty in their wind farm controller designs, which accounts for variability in the wind and allows for the maximum amount of power capture in the face of uncertainty from the wind.

# Initial Results from a Field Campaign of Wake Steering Applied at a Commercial Wind Farm – Part 1

Authored by **Paul Fleming**, **Jennifer King**, Katherine Dykes, **Eric Simley**, **Jason Roadman**, **Andrew Scholbrock**, **Patrick Murphy**, **Julie Lundquist**, **Patrick Moriarty**, **Katherine Fleming**, **Jeroen van Dam**, **Christopher Bay**, **Rafael Mudafort**, Hector Lopez, Jason Skopek, Michael Scott, Brady Ryan, Charles Guernsey, and Dan Brake. Published in *Wind Energy Science*.




Making connections for impact. NREL measured the impact of steering individual turbine wakes away from downstream turbines at NextEra Energy Resource's Peetz Table Wind Energy Center. *Figure by Katherine Fleming, NREL*

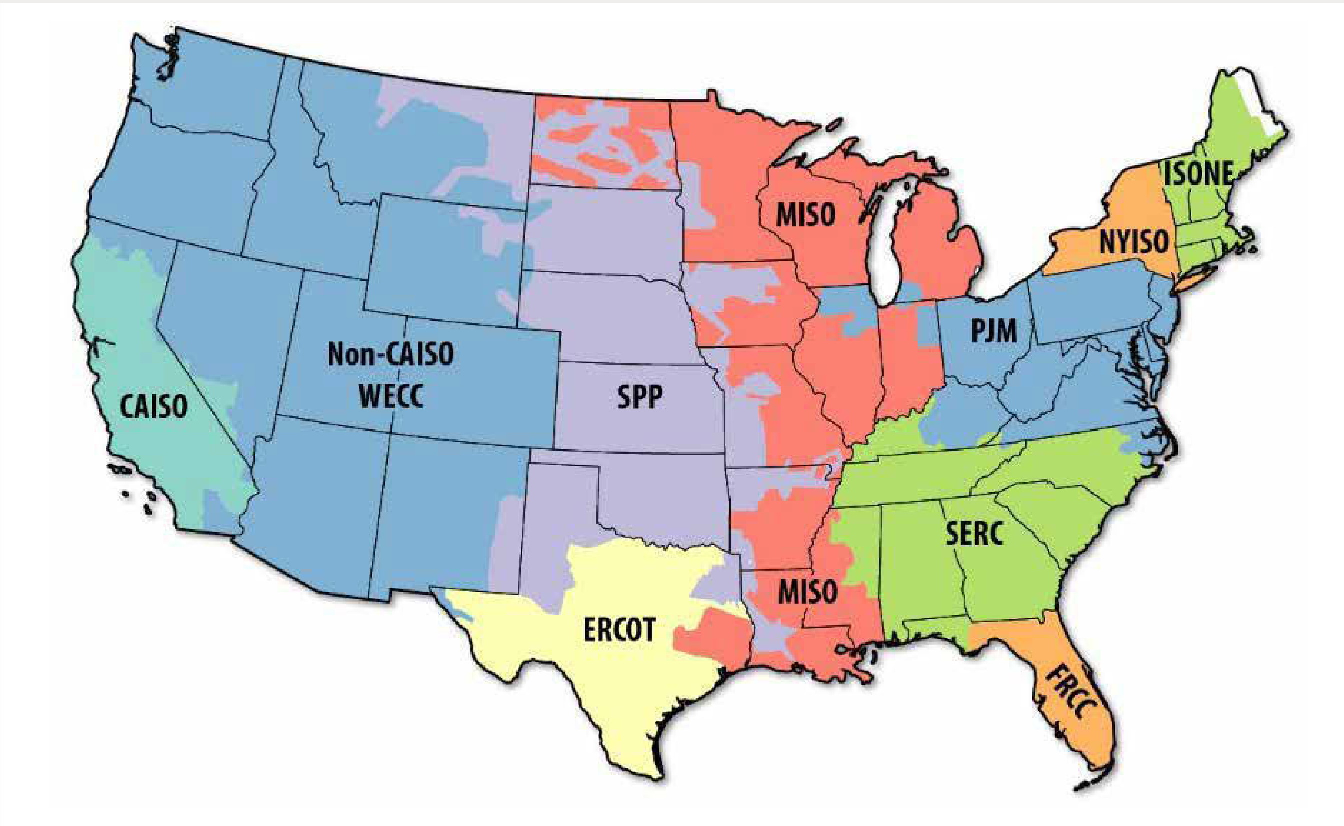
Written in collaboration with NextEra Energy and the Department of Atmospheric and Oceanic Sciences at the University of Colorado, Boulder, NREL researchers measured the impact of wake steering on a subsection of a commercial wind plant. The field trials were consistent with simulated predictions, which suggest that annual energy production gains of 1%–2% are achievable for existing facilities implementing wind-power-plant-level controls. NREL and NextEra deployed a range of sensing equipment for the field trial—including a ground-based lidar, meteorological tower, and two sodars—which allowed researchers to quantify the atmospheric inflow during the test and investigate the effect of different conditions on performance. Campaign findings are published in Wind Energy Science.

## Significance of the publication:

Initial results from the first phase of a field campaign evaluating wake steering at a commercial wind farm showed that for two closely spaced turbines, an approximate 14% increase in energy was measured on the downstream turbine over a 10° sector with a 4% increase in energy when accounting for losses of the upstream turbine. Efficiency improvements like these could account for increases in annual profits at wind farms by $1 million or more, depending on plant size and design. Given that a 2% gain at a typical 300-MW wind plant could represent $1 million per year in additional profits, there is widespread interest in implementing optimized controls.

# An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind

Authored by **Paul Denholm**, **Yinong Sun**, and **Trieu Mai**. NREL technical report.




Kaleidoscope of study. A map of the regions studied in "An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind."
*Map courtesy of NREL*

Many of the services needed by the grid to maintain reliable and stable operation can be provided by wind power plants, but there are challenges from wind's intrinsic variability and dispersion that pose unique challenges relative to conventional power plants. For example, longer-duration but slower-operating reserve services are among the least technically demanding and lower-cost services for conventional generators to provide but are less suitable for wind. As the provision of many reserve products would require precurtailment, the opportunity cost to provide reserves becomes a more significant issue for wind than thermal generators. These costs highlight that the technical considerations need to be weighed with the economic factors for providing grid services. Further, the need for and value of energy and capacity exceed those of operating reserves and other essential reliability services.

## Significance of the publication:

This research helps improve underlying wind energy models and data for national-scale, long-term planning; evaluate the technical system needs of the future energy system and how wind technology—including future turbine and plant design—can economically service those needs; and assess how the services provided by offshore and land-based wind technologies are valued under prevailing market rules and contractual arrangements. By assessing the potential impacts of achieving specific technology targets, informing a better understanding of the value proposition of wind technology, and guiding long-term wind technology design, this work could help increase the grid value of wind or enable wind to provide a greater variety and quantity of grid services.

# Recycling Glass Fiber Thermoplastic Composites from Wind Turbine Blades

Dylan Cousins, Yasuhito Suzuki, **Robynne Murray**, Joseph Samaniuk, Aaron Stebner. Published in the *Journal of Cleaner Production*

Green blade for green enterprise. NREL researchers are currently validating a 13-m thermoplastic composite wind blade at the Structural Technology Laboratory. A report comparing the structures of a thermoplastic composite wind turbine blade and a thermoset composite wind turbine blade will be published soon. *Photo by Dave Snowberg, NREL*

Composite parts used to produce wind turbine parts have high embedded energy, meaning a great deal of energy is necessary to make the part throughout the product's life cycle from cradle (extraction) to grave (deconstruction and/or decomposition). Because of this high embedded energy, recovery of composite parts could have significant economic benefit and cost savings for the industry.

In "Recycling Glass Fiber Thermoplastic Composites from Wind Turbine Blades," researchers determine the feasibility of recycling wind turbine blade composites that are fabricated with glass-fiber- reinforced Elium thermoplastic resin. Study experiments are conducted to tabulate important material properties that are relevant to recycling, including thermal degradation, grinding, and dissolution of the polymer matrix to recover the constituent materials.

## Significance and impact:

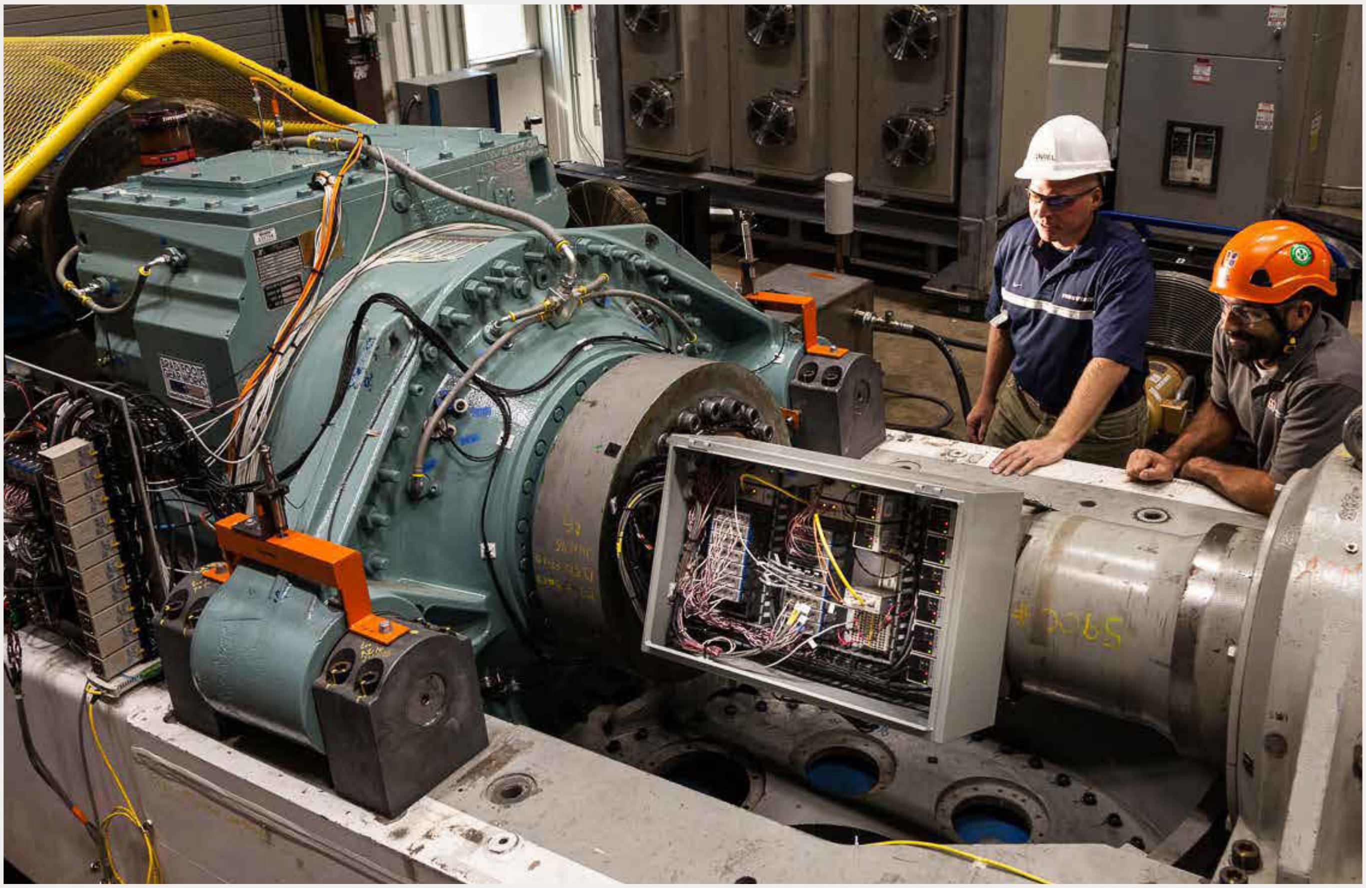
Advancements in wind energy have helped lower the LCOE, thereby helping this green technology rapidly advance. However, disposal of the materials used to create the world's largest rotating machines can be a challenging process, one that requires developing new materials and methods to dispose of raw materials. Thermoplastic resin systems have long been discussed for use in large-scale composite parts, but largely have gone unused by the energy industry; however, that could change based on the findings of this research.

Economic analysis shows that recycling thermoplastic–glass fiber composites via dissolution into their constituent parts is commercially feasible under certain conditions. Based on the analysis, recovery of constituent materials from a thermoplastic composite part can be economically feasible when displacing virgin materials in the supply chain.

Study authors go on to further explore the manufacturing process for specific parts of a thermoplastic wind blade in a separate research article published in *Applied Composite Materials*. In that article, the team noted that significant improvements in energy savings can be achieved by recycling retired materials and using thermal welding practices. In addition, thermoplastic materials have a room-temperature cure and require no postcure steps, which is a huge improvement over traditional epoxy thermoset materials that require expensive heated molds and an energy- and time-intensive postcure oven procedure.

# Comparison of Planetary Bearing Load-Sharing Characteristics in Wind Turbine Gearboxes

Authored by **Jonathan Keller**, **Yi Guo**, Zhiwei Zhang, and Doug Lucas. Published in *Wind Energy Science*.



Planetary movements. Gearbox Reliability Collaborative gearbox in the 2.5-MW dynamometer. *Photo by Mark McDade, NREL*

In coordination with researchers at Argonne National Laboratory, NREL addressed the lack of drivetrain component failure models in design standards. In the paper, "Comparison of Planetary Bearing Load-Sharing Characteristics in Wind Turbine Gearboxes," researchers examined the planetary load-sharing behavior and fatigue life of different wind turbine gearboxes when subjected to rotor moments. The article compares two planetary bearing designs: one using cylindrical roller bearings with clearance and the other using preloaded tapered roller bearing to support both the carrier and planet gears. The gearbox with preloaded tapered roller bearings showed significant improvement in planet load bearing compared to the gearbox with cylindrical roller bearings.

## Significance and impact:

The new gearbox design demonstrated improved planetary load-sharing characteristics in the presence of rotor pitch and yaw moments, resulting in a predicted gearbox lifetime that is 3.5 times greater than the previous, conventional design. Knowing the different failure modes in turbine gearboxes helps increase wind turbine reliability, reduce operation and maintenance costs, and increase turbine availability and energy capture, all of which help reduce LCOE for wind power plants.

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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