Accomplishments & Performance REPORT

WIND ENERGY PROGRAM: Q3 FISCAL YEAR 2019

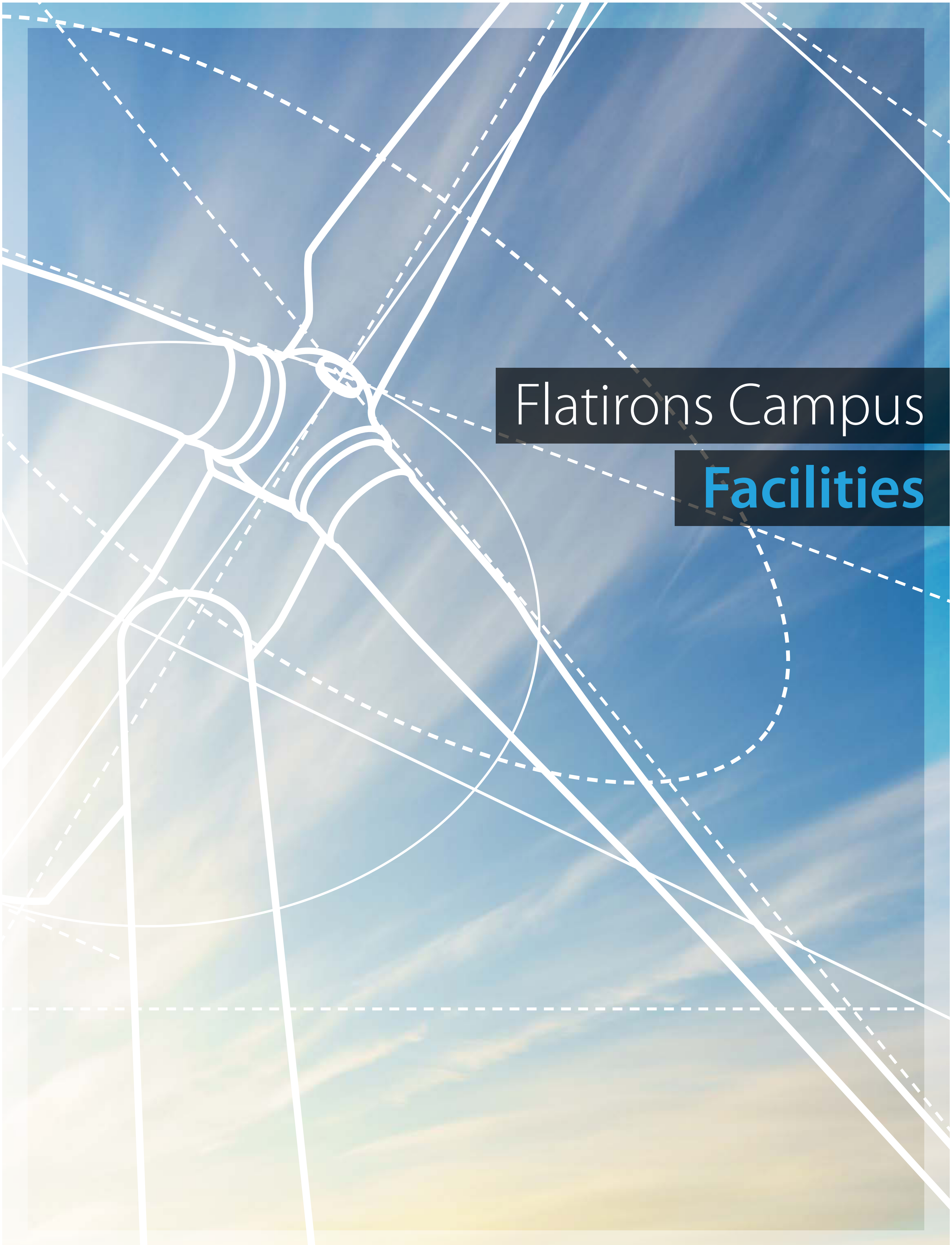
NREL
Transforming ENERGY

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.

Offering 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.

This report provides an overview of the many achievements NREL delivered on behalf of DOE's Wind Energy Technologies Office (WETO) and other partners during the third quarter of Fiscal Year 2019 (Q3 FY 2019).

TABLE OF CONTENTS



Flatirons Campus Facilities

Enhanced Characterization and Capabilities for Wind Research Testing

As part of its ongoing work to maintain facilities and expertise at the Flatirons Campus, NREL completed operational modal characterization of the DOE 1.5 turbine to reflect drivetrain modifications. Additional instrumentation was installed to enhance power hardware-in-the-loop (PHIL) capabilities and new protection strategies for PHIL test configurations were developed and validated.

DOE's 1.5-MW wind turbine at the Flatirons Campus. *Photo by Dennis Schroeder, NREL*

Significance and Impact

The characterization of the DOE 1.5 turbine will enable development of updated structural dynamics models for reliability and wake modeling research. New PHIL 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.

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WBS: 1.1.0.401

Electrical Configuration Planning at the Flatirons Campus

NREL continued to make progress on the 3-MW load bank and second controllable grid interface (CGI-2) electrical configuration specifications, approval, and procurement. New guidance from DOE GO and Xcel Energy on the Flatiron Campus' electrical configuration is under review to understand its impact on CGI-2 electrical design.

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.

The DOE GO and Xcel Energy guidance for 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.

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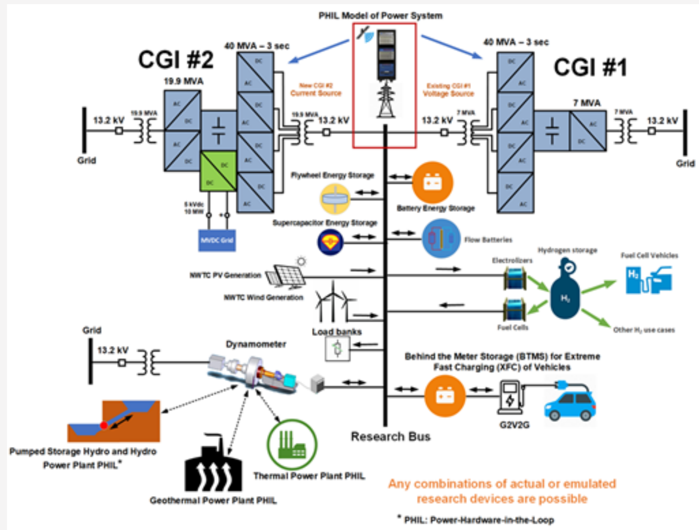


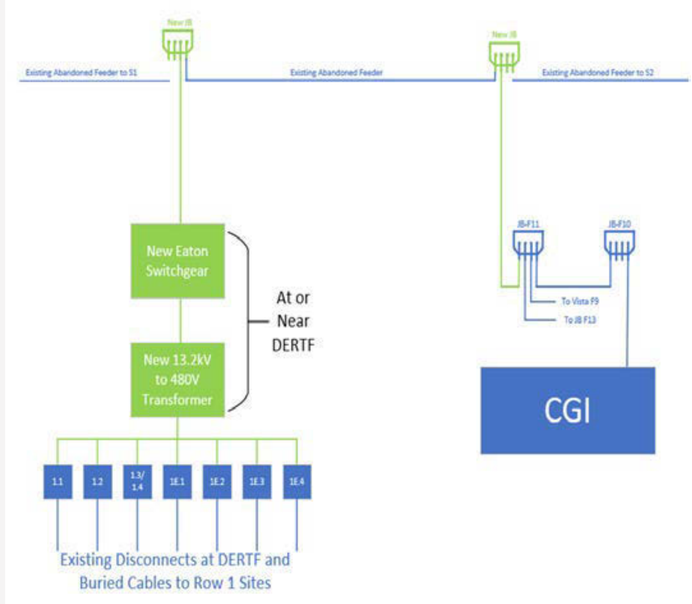
Graphic of the future Flatirons Campus controllable grid interface research system that includes both controllable grid interfaces. *Credit: Vahan Gevorgian, NREL*

Distributed Wind-Specific Research and Development

Enhancing the MIRACL of Distributed Wind

The Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project improves the integration of distributed wind (DW) into microgrids and other DW networks. Activities in Q3 FY 2019 included hosting team and advisory board meetings to obtain project feedback.

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



Schematic drawing (green new and blue existing) shows planned connection of the small wind (Row 1) sites to the controllable grid Interfaces. *Credit: Robert Preus, NREL*

Significance and Impact

The MIRACL project now has an initial advisory board and a clear idea of what other industry representation should be added. The current members have been briefed and they provided direct feedback on work, informational outreach, and testing infrastructure needs from the wider industry perspective. 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 DW 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 DW on a utility distribution system.

Interconnecting the existing Row-1 DW test sites to the CGI will allow the DW 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.

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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 helps distributed wind systems become more cost-competitive and overcome barriers to market entry.

As part of this project, NREL conducted a design review and technically advised Pecos Wind Power in the design of an 85-kW, Class IV, low-cost wind turbine. The Final Production Prototype Design Plan is a major accomplishment. NREL also provided technical monitoring and support to companies including Bergey Windpower, Windurance, Eocycle, RockConcrete, Intergrid, NPS, and Sonsight, Inc.

Significance and Impact

The 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.

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Tools Assessing Performance Workshop Gathers Experts To Address Challenges of Distributed Wind Resource Assessment

The Tools Assessing Performance project aims to address the challenges of resource assessment in distributed wind by improving resource characterization capabilities and estimate precision. In Q3 FY 2019, NREL hosted a workshop to discuss preliminary analysis and priorities with participants from the Pacific Northwest National Laboratory, Argonne National Laboratory, Los Alamos National Laboratory, DOE, and industry. The Tools Assessing Performance team plans 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, boosting consumer and investor confidence and opening the door to low-cost financing.

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Reducing Risks on Remote Military Bases Through the Use of Wind Energy

Wind energy has the potential to offset the use of diesel fuel to supply power to remote military installations, but existing wind turbines do not currently meet the needs of military applications. In Q3 FY 2019, Sandia National Laboratory submitted a report on the Modeling and Simulation Scenario for a specific army forward operating base configuration with input from NREL.

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.

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

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WBS: 1.2.4.401

New Model To Reduce Levelized Cost of Energy of Distributed Wind Applications

NREL is aiming to reduce technical, economic, and market barriers that have limited utilization of distributed wind. In Q3 FY 2019, NREL conducted work on the forthcoming balance of station model for distributed wind applications. Recent efforts have focused on MW-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 levelized cost of energy impacts of different foundation and installation strategies and solutions. NREL also supported development, implementation, and reporting for an ongoing U.S. Standards assessment. Both projects were quarterly accomplishments.

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 MW scale, single turbine installations of 4-MW class turbines could lead to 20+% levelized cost of energy reductions relative to 1-MW class single turbine installations.

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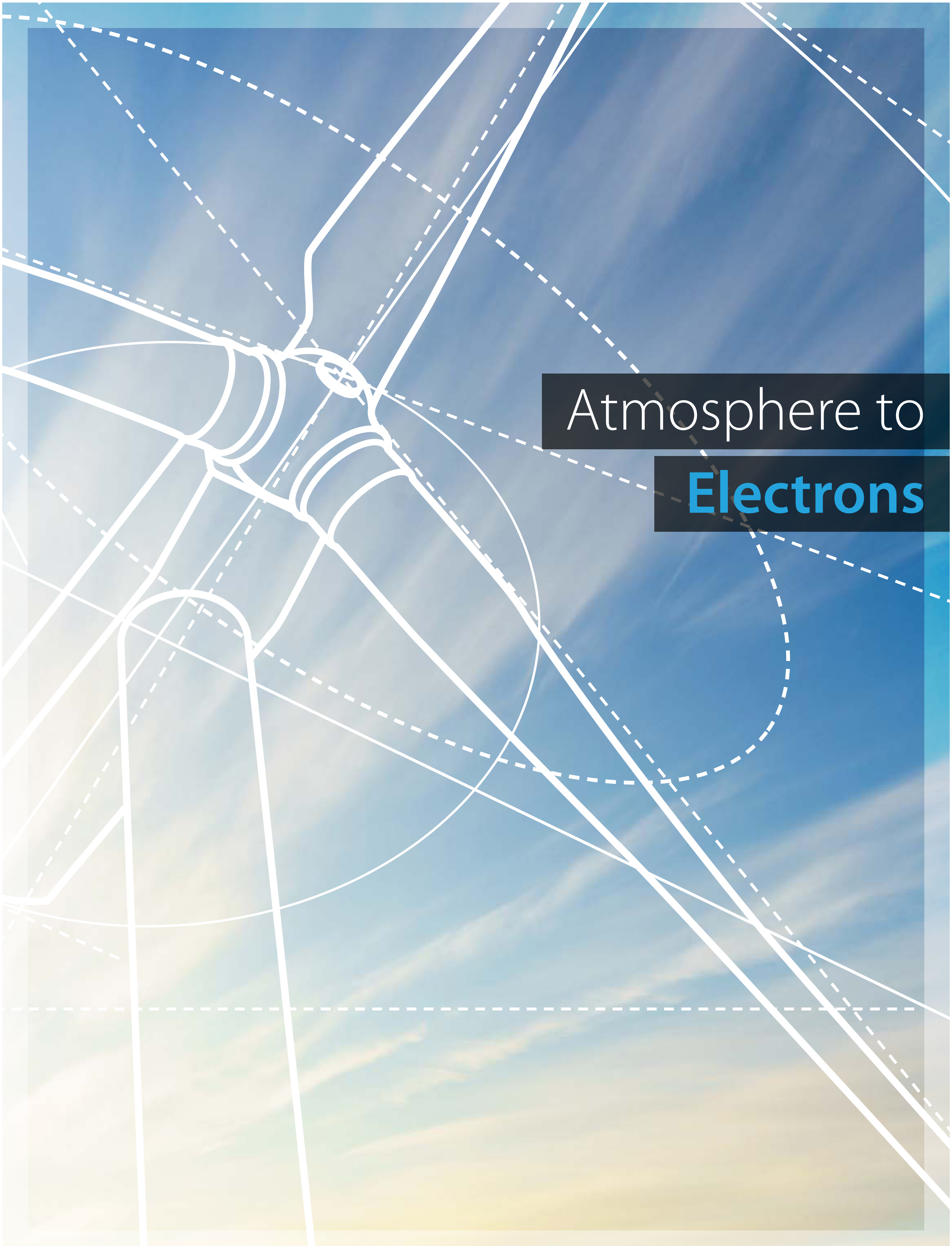
Atmosphere to **Electrons**



NREL Researcher Paul Fleming gives a presentation on FLORIS at the 2019 Wind Energy Science Conference. *Photo by Tony Martinez, NREL*

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

NREL researchers presented their research at the 2019 Wind Energy Science Conference (WESC) in Cork, Ireland. WESC provides a forum for international collaboration and multidisciplinary discussion of wind energy topics and is the most significant scientific and technical conference on wind energy research in the world. Ten NREL researchers presented at the event, covering topics related to wind resources and turbulence and wakes as well as turbine technology and aeroelasticity. Advances from NREL in wake steering, fluid dynamics, and control generated enthusiasm from this international audience because of the potential to improve wind power plant performance.

Significance and Impact

NREL continues to track as an international leader in advanced flow control science. Researchers Tony Martinez, Paul Fleming, and Jennifer King shared their latest research on the curled wake model, FLORIS, and consensus-based optimization respectively, advancing the field's ability to optimize energy output through new wind farm control strategies. Shreyas Anathan presented on the recent results of blade-resolved computer simulations produced by NREL that now reflect how wind turbine blades bend and deform as they would in reality, providing a more accurate picture of how wind turbines interact with the atmosphere. And, Matthew Churchfield presented research that examines how gravity waves interact with wind turbines and surrounding terrain at a wind farm, further demonstrating NREL's expertise in model development and validation.

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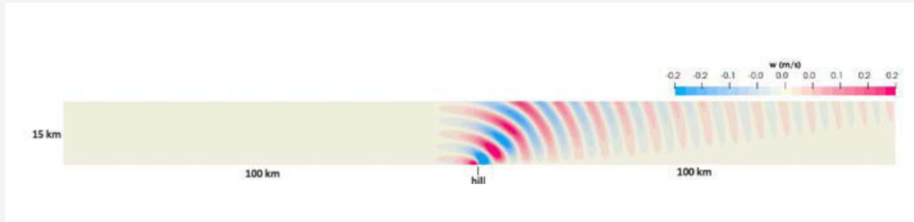
NREL Mesoscale-Microscale Researchers Improve Their Ability To Simulate Flows with Atmospheric Gravity Waves

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.



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

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.

The NREL talk, Treatment of Atmospheric Gravity Waves in Wind-Energy Large-Eddy Simulations, presented at the 2019 Wind Energy Science Conference in Cork, Ireland, highlighted this progress. A figure from this talk is shown above that illustrates atmospheric gravity waves caused by flow over a small hill.

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.

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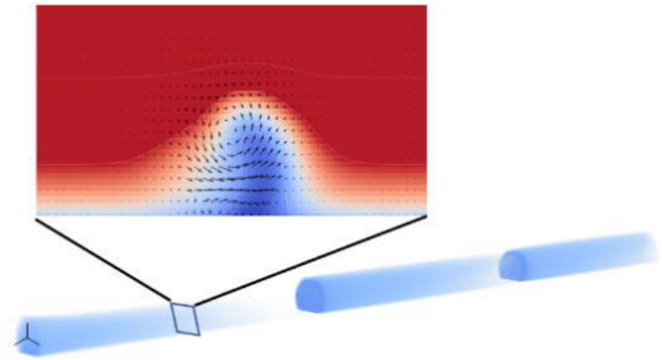
NREL Releases Enhanced Controls-Oriented Wind Farm Modeling Tool

NREL's wind plant controls optimization software framework, FLOw Redirection and Induction in Steady State (FLORIS), was updated to improve usability and accuracy. The release also features additional representation of flow physics that incorporates new advances in the understanding of wake steering aerodynamics pertaining to advanced wind farm control strategies based on field testing. This improvement is derived from the curled wake model, which was originally proposed by NREL researcher Tony Martínez in *Wind Energy Science* and is further described and compared with other models in a publication by Christopher Bay.



This 3D illustration shows a FLORIS simulation of three turbines generated using the new 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*

Significance and Impact

The curled wake model can simulate critical behaviors to more precisely capture the value of wind farm controls. FLORIS is made available as an open-source software platform providing transparent methods-sharing across the wind industry. Improvements to the FLORIS framework enhance the software's usability by including integrated tools such as wake-steering optimization, flow visualizations, simulation comparisons, and annual energy production calculations.

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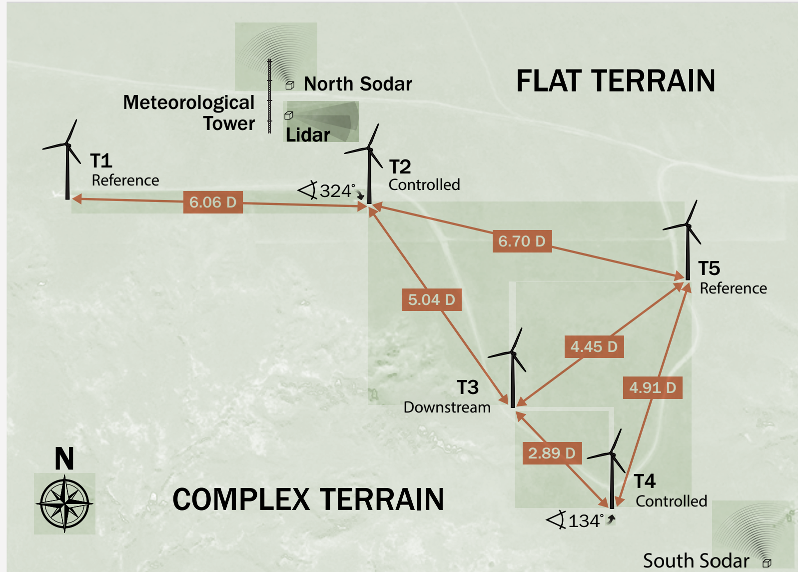
Wind Plant Control Field Trials Validate Efficacy of Wake Steering

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 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*.



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*

Significance and Impact

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.

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NREL Gets Turbines To Talk

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 supervisory control and data acquisition are communicated with nearby turbines and allow turbines 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.

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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 50700*

Results of Blade-Resolved Computer Simulations Reflect How Wind Turbine Blades Bend and Deform

NREL researcher Ganesh Vijayakumar implemented flexible blade modeling capability into high-fidelity modeling simulations that capture how wind turbine blades bend and deform as they would in real life. NREL researcher Shreyas Ananthan 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.

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Understanding Wind Lidar Data Errors Impacting Wake Measurement Predictions

Wind lidar devices provide only line-of-sight (LOS) measurements, and retrieval of horizontal wind speed from the LOS measurements of a single lidar in the wind turbine wake could introduce errors as a result of the assumptions used in the retrieval process. In the paper, "Evaluation of Wind Speed Retrieval from Continuous-Wave Lidar Measurements of a Wind Turbine Wake Using Virtual Lidar Techniques," NREL researchers estimate errors associated with the retrieval processes and provide guidelines for best practices by generating International Energy Agency (IEA) Wind Task 31 Scaled Wind Farm Technology (SWiFT) benchmark measurement data from a large-eddy simulation tool. The virtual lidar samples are obtained by sampling the flow field with a model of the Technical University of Denmark SpinnerLidar, which provides an idea and overview of the errors associated with lidar data used for the IEA Wind Task 31 SWiFT benchmark.

The faster wake recovery and mixing in the wake create a larger variation of wind speed in the sample volume. The lidar overestimates the wind speed in the near wake and underestimates the wind speed in the far wake. The location of the transition from an overestimation to an underestimation of wind speed in the wake is dependent on the wake recovery rate. For both cases, projection error in the wake decreases with downstream distances and an error resulting from the volume averaging increases with downstream distances, which impact wake measurement predictions at wind power plants.

Significance and Impact

This research helps quantify errors associated with both real lidar data and post-processing of the lidar data, providing researchers a better understanding of wake measurement data. This work ultimately creates a better numerical model validation platform for future research.

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NREL Provides Detailed Wind Turbine Blade Cost Model to Industry

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 the cycle time; and the costs related to direct labor, overhead, buildings, tooling, equipment, maintenance, and capital. The model is implemented within the Wind Plant Integrated System Design and Engineering Model (WISDEM®), a multidisciplinary analysis and optimization design framework developed at NREL. The model 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 aim at optimizing the design of the blades and the manufacturing processes, ultimately reducing blade and wind turbine costs.

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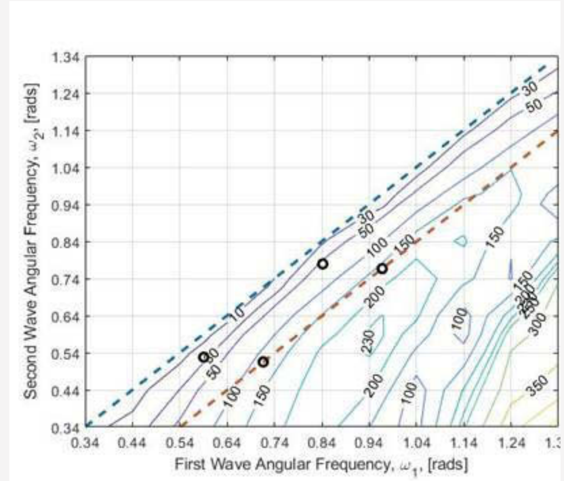
Offshore-Specific Research and Development

Bichromatic Wave Cases Provide Three-Way Validation among Simulations and Measurements



Second-order pitch wave-exciting moment qtf magnitude for assembly 1, with average panel size of 1 m. The black circles indicate the bichromatic wave pairs chosen. *Credit: Amy Robertson, NREL*

As part of the IEA Wind Task 30 Offshore Code Comparison Collaboration, Continuation, with Correlation and unCertainty (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 OpenFAST simulations, higher-fidelity computational fluid dynamics (CFD) simulations, and experimental measurements. Previous validation work has shown the need for more dedicated load cases that match the capabilities of CFD tools.

A study performed by Nathan Tom and visiting professional Manuela Bohm (from Leibniz Universität Hannover) 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 CFD tools compared to a full irregular wave spectrum, and thus provide a means for the three-way validation with engineering tools and experimental data. These load cases will be implemented in the component-level hydrodynamic validation campaign to be performed in summer 2019. An abstract was submitted summarizing the findings for presentation at the International Offshore Wind Technical Conference in November 2019.

Significance and Impact

Although state-of-the-art tools capture many of the dynamics and loads of the complex floating wind turbine, research has shown persistent differences between the simulated loads and motion of a floating semisubmersible and measurements. The largest differences are associated with the low-frequency response at the semisubmersible's pitch-and-surge natural frequencies. Within the OC6 project, participants are seeking to try to better understand the reason for this under-prediction through additional testing and comparison to higher-fidelity CFD modeling tools. The newly developed bichromatic wave cases will provide a means to study this issue effectively within the higher-fidelity tools.

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Researchers Validate OpenFAST/FAST.Farm Using SWiFT Data

As part of the IEA Wind Task 31 Phase III (WakeBench) project, which focuses on validation of wind farm flow models through an international verification and validation collaborative, NREL submitted updated and additional load-case simulations using OpenFAST/FAST.Farm models of the V27 turbine at the Scaled Wind Farm Technology (SWiFT) wind farm. The team discussed the results and related topics at the Task 31 meeting held in conjunction with the Wake Conference 2019 in Sweden.

The project team also presented on the ISDA-MV project at the 2019 Wind Energy Program Peer Review meeting and gave an invited presentation titled "Engineering Design Competence and Modeling to Advance Wind Energy Technology" at DOE headquarters.

Significance and Impact

The IEA Wind Task 31 SWiFT benchmark supports the validation of high-fidelity and engineering models of wake dynamics and wind turbine loads within wind farms to enhance the design and operation of wind plants with higher efficiencies, improved reliability, and lower cost of energy.

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

In Q3 FY 2019, NREL executed the cooperative research and development agreement among NREL, Stiesdal LLC (Denmark), and Magellan Wind (U.S. partner) to collaborate within this Technology Commercialization Fund project. The team continued the development of detailed implementation plans for computing floating substructure flexibility and member-level loads within OpenFAST, including detailed planning of changes to the structural (SubDyn) and hydrodynamic (HydroDyn) modules.

Significance and Impact

This project aims to enable the design and optimization of floating substructures for offshore wind turbines—including the next-generation floating wind technologies that show promise to be streamlined, flexible, and cost-effective—by upgrading, validating, and demonstrating improvements to OpenFAST. This effort is part of a larger initiative at NREL to develop an open-source, multifidelity systems analysis capability for floating offshore wind turbine analysis and optimization that captures the relevant physics and costs that drive designs and trade-offs.

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NREL Takes New Approaches for Offshore Floating Wind Systems

NREL researchers are developing an innovative offshore floating wind system using new ideas and design approaches that will lower the levelized cost of energy. In Q3 FY 2019, NREL finalized the cooperative research and development agreement with Equinor as well as an update on the model test matrix. The nondisclosure agreement with Texas A&M has been prepared and the team began discussions of technical specifications of the model test.

Significance and Impact

The model test campaign will help assess the suitability of the numerical models for new design features and will generate test data that characterizes the actual behavior of the new substructure design.

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Advanced Components, Reliability, and Manufacturing

Report Investigates Drivers for White-Etching Crack Failure Modes in Wind Turbine Gearbox High-Speed-Shaft Bearings

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. 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.

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Workers swap out a wind turbine gearbox. *Photo by Dennis Schroeder, NREL 49409*

Wind turbine blades wind their way by train through Denver. *Photo by Dennis Schroeder, NREL 20894*

New Study Explores Future of Low-Specific-Power Wind Turbine Technology

The emergence and prevalence of low-specific-power wind turbine technology in many markets around the world during the past decade is indicative of the rapid pace of technological advancement within the wind industry. In relatively capacity-constrained markets, lower specific power has been the most direct way to boost MWh and revenue per invested dollar, supporting large reductions in the levelized cost of energy. In "Opportunities for and Challenges to Further Reductions in 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 U.S. 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. Relevant follow-on work could entail estimating the actual cost differences between lower and higher specific-power technology, the value of specific innovations that could affect specific power, and the potential trade-offs between turbines optimized for capacity- or land-constrained markets versus unconstrained turbines optimized to minimize the levelized cost of energy.

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Standards Support and International Engagement

NREL Provides Wind Standards Leadership at Meetings in South Africa, Europe, and the United States

In Q3 FY 2019, NREL participated in the following wind standards development activities and meetings:

- Presented at DOE WETO Peer Review on Standards Development Project. Alexandria, VA, May 2, Jeroen van Dam
- Chaired Annual IEC TC 88 meeting, including preparation meeting with secretary and technical officer, May 5–7, Pretoria, South Africa, Jeroen van Dam
- Participated in annual IECRE WE-OMC meeting, May 8–10, Pretoria, South Africa
- Organized and participated in PT 101 meeting, June 12–13, Copenhagen, Denmark, as well as follow-up conference calls, Jeroen van Dam
- Organized and led American Wind Energy Association offshore wind standards meeting, New York, April 8, Walt Musial, Jason Jonkman, Caroline Draxl
- Represented the IEA Wind ExCo at REWP #75, April 3–4, Paris, France, Brian Smith
- Participated in IEC TC 88 PT 5 (rotor blades) meeting, June 17–20, Copenhagen, Denmark, Derek Berry
- Participated in IEC TC 88 MT 23 (blade testing) meeting, June 12–14, Copenhagen, Denmark, Scott Hughes
- Participated in IEC TC 88 JWG 1 (gearboxes) meeting, June 17–19, Stockholm, Sweden, Jon Keller
- Participated in IEC TC 88 WG 15 (resource assessment) meeting, May 6–9, Seattle, Jason Fields
- Participated remotely in IEC TC 88 PT 11-2 (noise at receptor location) meeting, Arlinda Huskey
- Finalized U.S. Chapter for the 2018 IEA Wind TCP Annual Report, Carol Laurie
- Participated in IEA High-level Workshop on Offshore Wind Energy Outlook, May 13, Paris, Philipp Beiter.

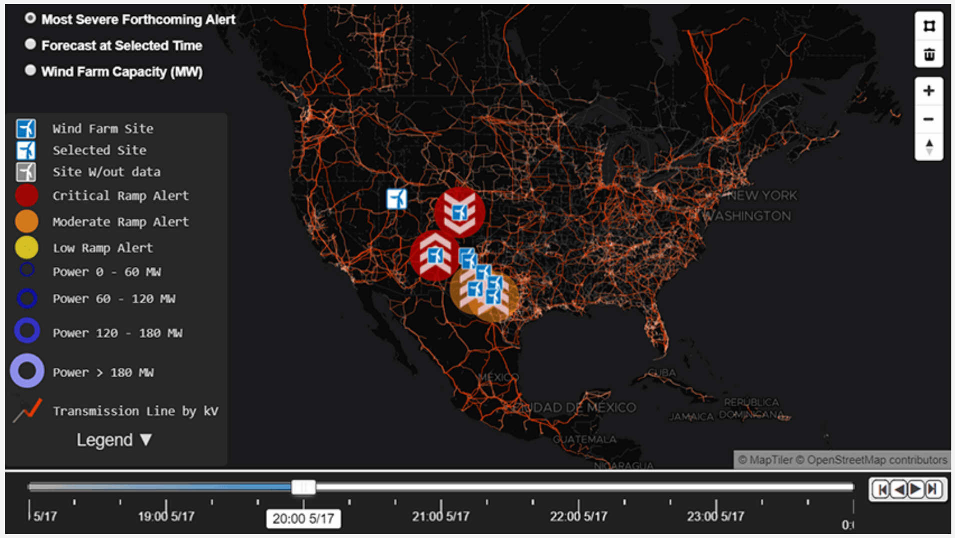
Significance and Impact

NREL makes major contributions to wind standards at the international and national levels and has a particular focus on standards that have a large impact on the market and those with links to the DOE wind program. Standards assure minimum levels of safety, remove market barriers, and provide high-quality, reproducible test methods.

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

Grid Integration

WindView Provides a Real-Time Look at Wind Data



WindView tool showing the most severe forthcoming alerts on the map of the United States.
Credit: Bri-Mathias Hodge, NREL

The project to release the WindView open-source software reached completion in Q2 FY 2019, but efforts to build awareness and expand use of the tool continued in Q3 FY 2019. In addition to presenting the project at the 2019 Wind Energy Program Peer Review, a story will be published in the WETO fall Wind R&D Newsletter, and another has been published on the NREL website. The Council for Scientific and Industrial Research in South Africa is working with NREL to install WindView. DOE's Solar Energy Technologies Office plans to rework WindView to provide comparable resource forecasting for solar energy. A beta version and tutorial are available on the NREL website.

Significance and Impact

WindView provides electric grid operators with visual forecasting tools that display real-time probabilistic wind power forecasts. Widespread use will allow system operators to make control decisions based on the data provided by the software. Adapting the tool for use with solar energy provides further forecasting benefits for grid managers.

Point of Contact: Bri-Mathias Hodge, *Bri-Mathias.Hodge@nrel.gov*
WBS: 3.1.0.410

Research Helps Improve Understanding of the Impact of Zero-Marginal Cost Resources

In a collaboration with Argonne National Laboratory and the Electric Power Research Institute, NREL is working to understand the impact of wind and other zero-marginal cost resources on resource adequacy and revenue sufficiency under a wide range of market design options and revenue sources. In Q3 FY 2019, the team presented the project at the 2019 Wind Energy Program Peer Review. The team also completed a draft publication titled, "Impacts of Price Formation Efforts Considering High Renewable Penetration Levels and System Resource Adequacy Targets." Robin Hytowitz of the Electric Power Research Institute presented the findings from this report at the Federal Energy Regulatory Commission Technical Conference on Resilience.

Significance and Impact

This project is providing insights into key drivers of wholesale electricity energy and ancillary service prices, including resource adequacy level, operating reserve treatment, and price formation rules. Other aspects of the project are enabling a greater understanding of capacity market rules and investor behavior. The presentations and publication completed in Q3 FY 2019 allow the team to receive technical feedback and disseminate findings.

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

Research Promotes Understanding of the Impact of Renewable Energy Integration Across North America

The North American Renewable Integration Study is a collaboration between the United States, Canada, and Mexico to study the impacts of renewable integration in North American power systems. In Q3 FY 2019, the team refined the analysis of grid operations in several of the scenarios that were designed previously, exercising the newly created North American Renewable Integration Study data sets in several models.

Significance and Impact

The study will help power system planning entities, electricity system operators, government energy agencies, legislators, and regulators to better understand the implications of integrating large amounts of renewable resources into the power system. It will also aid in understanding the impact of cooperation between nations and between grid operators.

Point of Contact: Greg Brinkman, *Greg.Brinkman@nrel.gov*
WBS: 3.1.0.409

Researchers Work To Reduce Wind Power Costs through Active Power Controls

Work on this project focuses on developing and testing 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. In Q3 FY 2019, the team modeled use cases for a fast frequency response provision by wind-storage systems for a multi-area power grid. The use cases included fast frequency response of the power system to large contingencies and demonstrated the ability of fast frequency response to quickly restore the system frequency to pre-fault levels. The team also completed a report on a large wind 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.

Point of Contact: Vahan Gevorgian, *Vahan.Gevorgian@nrel.gov*
WBS: 3.1.0.413

Discussions Build Awareness of Cybersecurity Needs on Wind Farms

Cybersecurity on wind farms is increasingly important as the share of electricity generated by wind power in the United States grows. To evaluate the threat of cyberattacks and discuss approaches to model, detect, and mitigate these attacks, NREL hosted a workshop titled, "Assessing the Impact of Cybersecurity on the Nation's Wind Farms." The workshop highlighted cyberattacks that have already happened, ways to address vulnerabilities, and relevance from an investor perspective.

To build awareness and identify priorities, NREL and Idaho National Laboratory also facilitated a Cybersecurity Panel Session at AWEA WINDPOWER 2019. Panelists and participants discussed cyber and physical threats to wind farms, as well as best practices and priorities for future research and development and industry-led solutions.

Significance and Impact

Cyberattacks on wind farms present a threat to U.S. energy stability and security, but industry and investor awareness is lacking. Results from the panel and workshop will inform WETO's Wind Cybersecurity Roadmap to prioritize future cybersecurity research and development efforts, as well as cybersecurity standards for the International Electrotechnical Commission Technical Committee 88.

Point of Contact: Jon White, *Jonathan.White@nrel.gov*
WBS: 3.1.0.416

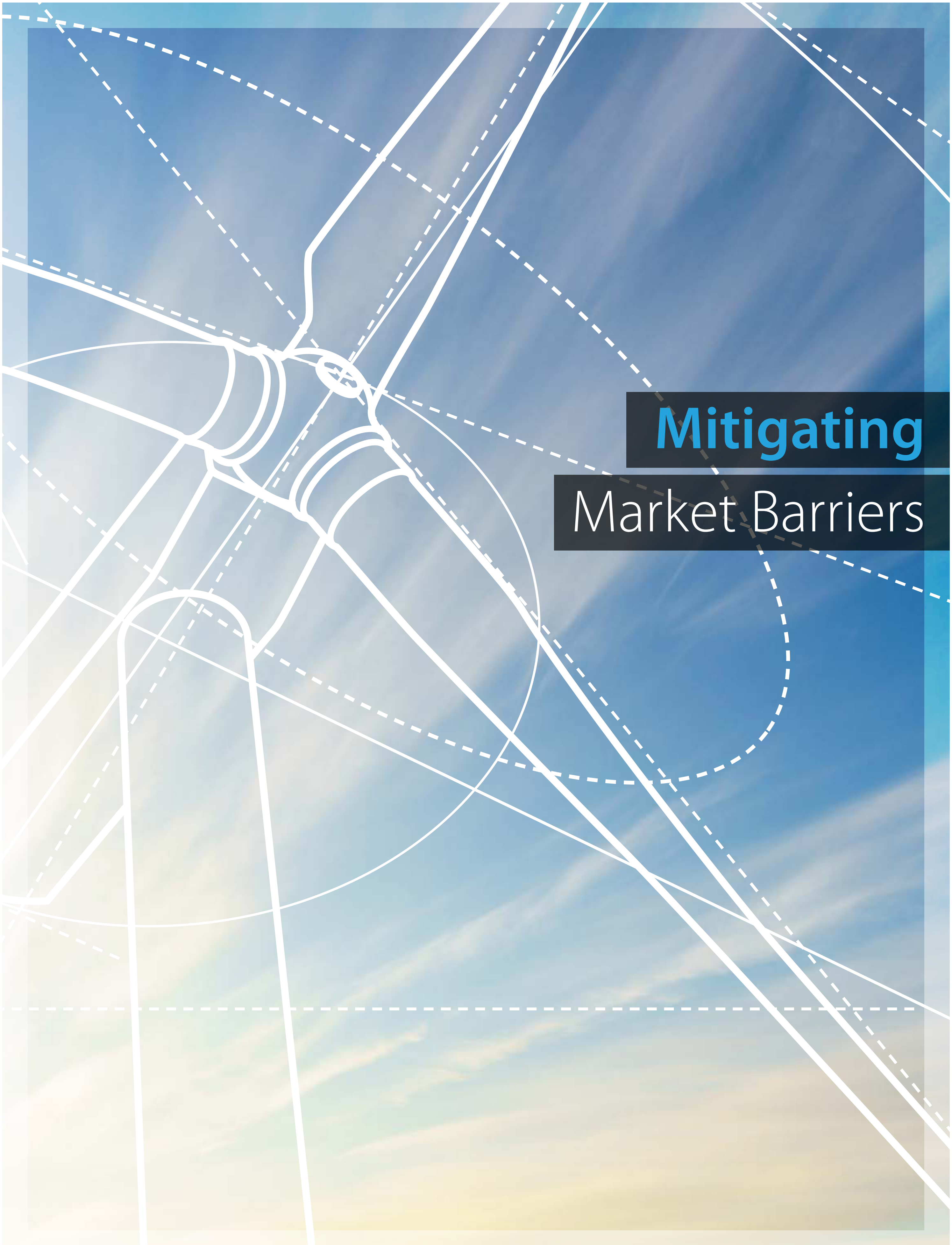
New Models Improve Wind's Contribution to Grid Resilience

The North American Energy Resilience Model (NAERM) provides models and data to mitigate the negative impacts of extreme events and accelerate wind's contribution to grid reliability and resilience. In Q3 FY 2019, the team successfully implemented modeling methods, such as extended component outages, on the Reliability Test System Grid Modernization Lab Consortium and designed and initiated a Resilience Operational Model within the NAERM system. Researchers also created use cases to assess wind's impact on reliability and resilience.

Significance and Impact

This work supports the NAERM mission to build a rigorous and quantitative assessment, prediction, and improvement of national-scale energy planning and real-time situational awareness capabilities.

Point of Contact: Jessica Lau, *Jessica.Lau@nrel.gov*
WBS: 5.1.0.412



Mitigating Market Barriers

Brazilian free-tailed bats emerging from a colony in central Texas. These bats represent some of the wildlife these impact minimization efforts aim to protect.
Photo by Cris Hein, NREL

Global Collaboration To Reduce Wind Wildlife Impacts

The Working Together to Resolve Environmental Effects of Wind Energy (WREN, also known as Task 34, established by the IEA Wind Committee) effort focuses on the development and characterization of mitigation technologies that detect and deter birds and bats and reduce fatalities at wind energy facilities. On behalf of WREN, NREL researchers attended the spring meeting in Inverness, Scotland. They mapped out the informational webinars and deliverables for the next year and developed a strawman proposal for phase 3 of the project, which begins in October 2020.

Significance and Impact

NREL's leadership in WREN places the lab at the forefront of global conversations about wind and wildlife interactions and the environmental effects of wind energy.

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WBS: 3.3.0.401

Photo by Werner Slocum, NREL

ThermalTracker Software Detects and Deters Wildlife

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. The ThermalTracker software uses thermal cameras to track flight paths of wildlife to help further develop detection technology and prevent wildlife interactions with wind turbines. NREL has been working with Pacific Northwest National Laboratory to validate the software in the presence of wind turbines. In Q3 FY 2019, the first two runs of the software were completed at the Flatirons Campus in a range of weather conditions, including snow.

Significance and Impact

Field validation of the ThermalTracker software at the Flatirons Campus allows 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 and deterrence of wildlife and could also prove useful in offshore wind energy facilities.

Point of Contact: Bethany Straw, *Bethany.Straw@nrel.gov*
WBS: 3.3.0.406

WINDExchange Information Sources Updated

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.

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

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 becomes 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.

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WBS: 3.4.0.401

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*

And the Winner Is . . .

Pennsylvania State University! Collegiate Wind Competition 2019 Technical Challenge organizers from NREL have brought another successful year to a close. 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 competition.

NREL has already started preparing for the 2020 Collegiate Wind Competition, taking place at the AWEA WINDPOWER Conference in Denver, June 1–4, 2020.

Significance and Impact

DOE's Collegiate Wind Competition prepares participating college and university students to enter the wind energy workforce by providing them 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.

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WBS: 3.4.0.402

NREL Works To Resolve Workforce Gaps at AWEA WINDPOWER

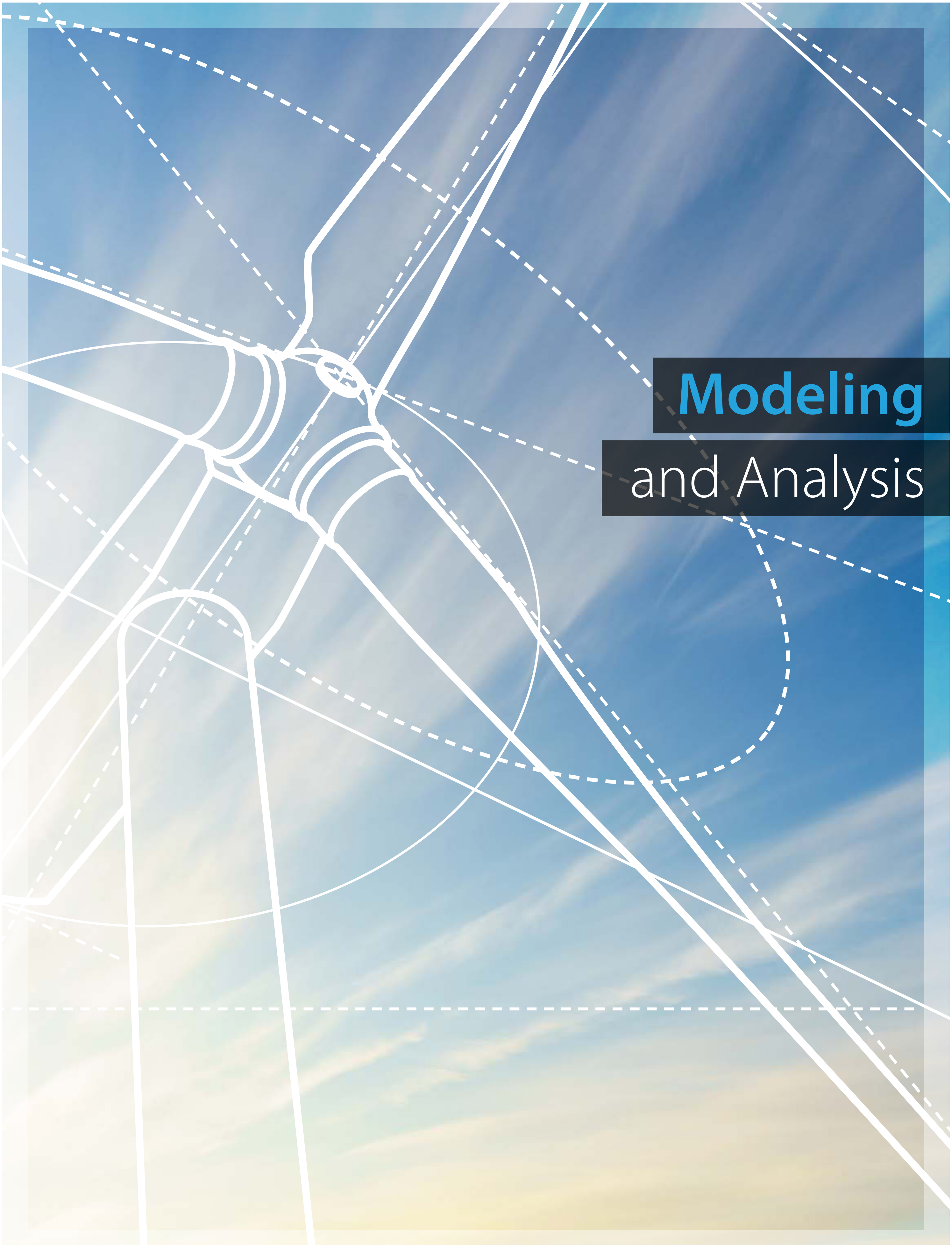
To help bridge the disconnect between academia and industry, NREL partnered with AWEA to hold the first Workforce Pavilion at the AWEA WINDPOWER Conference in May. This pavilion was created to leverage AWEA's interest in the future wind energy workforce. It brought together students, professors, and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

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*

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.

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



Modeling and Analysis

Wind Technology Trends Illuminate the Electric Sector of the Future

NREL wind researchers focus 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. This analysis presents a sweeping view of the market context for wind energy by looking at the frontier of technology and costs and putting this information into a historical context. Efforts to maintain transparency and replicability, including with open-source models and publicly available data, are incorporated in and among the array of tasks and subtasks.

In Q3 FY 2019, the project team completed the identification, collection, and analysis of relevant offshore wind market data and trends at a domestic and global scale covering the period from January–December 2018. A draft of the peer-reviewed *2018 Offshore Wind Technologies Market Report* was submitted to DOE at the end of June.

NREL's Offshore Wind Technologies Market Reports, published biennially, provide key market, technology, and cost trend information for the global offshore wind industry.

Significance and Impact

The *2018 Offshore Wind Technologies Market Report* provides stakeholders with quantitative information about the offshore wind market, technology, and cost trends in the United States and worldwide. This information can inform assessments of the acceptance, viability, and impact of offshore wind technology innovation. Analysis of trends can also play a critical role in informing the future direction of technology change, understanding opportunities for future gains in offshore wind industry efficiency, and, ultimately, lowering the cost of energy.

Point of Contact: Walt Musial, *Walter.Musial@nrel.gov*
WBS: 4.1.0.401

Higher hub heights make it possible to cost-effectively tap wind resources beyond the reach of today's typical turbines. *Photo by Lee Jay Fingersh, NREL 54225*

Increasing Wind Turbine Tower Heights: Opportunities and Challenges

Another Q3 FY 2019 accomplishment was publication of a new study, *Increasing Wind Turbine Tower Heights: Opportunities and Challenges*, in which researchers examine opportunities for increasing the height of wind turbine hubs—where the turbine drivetrain and rotors attach—and the conditions and locations in which taller towers would have the most impact.

Significance and Impact

Ongoing NREL research like this will help guide future wind energy development to reduce the cost of wind energy and increase its contribution to the electrical grid. The report assesses how increased hub heights could impact key indicators of wind energy viability across the nation by looking at wind speed, capacity factor, and levelized cost of electricity, as well as incremental costs that could be incurred with increases in turbine hub height. NREL's analysis indicated that there are many areas that could warrant the pursuit of technology enabling higher hub heights. Growing hub heights to 110 meters in the three modeled conceptual turbine classes ranging from 3 MW to 5 MW led to capacity factor increases from 35% to 45% in many locations, with continued capacity factor improvement with hub heights of 140 m. Hub heights of 110 m to 140 m could also offer levelized cost of electricity advantages relative to today's shorter turbines, especially in locations where wind shear is relatively strong, such as the eastern United States.

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

Outreach activities, which include NREL and WETO newsletter articles, program news stories for nrel.gov, videos, social media, and more help raise awareness of the work conducted by NREL researchers and its impact. *Photo by Dennis Schroeder, NREL 50697*

Outreach Informs Public Sector Investment in Wind Technology

This project provides analytic support for WETO requests to meet ongoing and emerging knowledge needs that arise from DOE executive leadership, Congress, senior management at DOE's Office of Energy Efficiency and Renewable Energy, the WETO office director, and others. In FY 2019, this project includes a dedicated task to support communications and dissemination of wind power techno-economic and strategic analysis.

In Q3 FY 2019, outreach activities included those conducted on behalf of the *Increasing Wind Turbine Tower Heights: Opportunities and Challenges* technical report. Articles about the report ran in the WETO spring Wind R&D Newsletter and the NREL wind newsletter as well as on the NREL website. This outreach generated an interview with the *Oklahoma Journal Record* in early Q4 FY 2019. Also in Q3 FY 2019, outreach activities were conducted on behalf of OpenOA, which is a new open-source software tool that provides a generalized framework for working with wind plant operational data. The outreach for OpenOA included articles featured on the NREL intranet, the NREL website, and in the NREL wind newsletter. A 60-second video was created to encourage developers to add data to the codebase. Social media was also used on behalf of both projects.

Significance and Impact

Disseminating information about the research and analysis conducted by NREL on behalf of DOE helps to raise awareness of and support for the work among a variety of stakeholders, including Congress, industry, universities, employees, and the general public.

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WBS: 4.1.0.402

Research Guides Long-Term Technology Design To Increase Variety and Quantity of Grid Services

This project includes multiple tasks designed to improve underlying wind energy models and data for national-scale long-term planning; evaluate the technical system needs of the future energy system as well as 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.

In Q3 FY 2019, NREL researchers developed a new methodology to quantify the cost targets needed for electricity generation technologies to achieve certain penetration levels in the energy market. In *Applied Energy*, the researchers presented the methodology and initial estimates of competitive cost targets for offshore wind energy—referred to as the "required costs" or the levelized cost of energy needed to achieve a specific annual generation level.

Significance and Impact

After analyzing 168 scenarios for the future U.S. power sector, researchers found that offshore wind would need to attain a required cost range between $39/MWh) and $77/MWh to achieve 1% grid penetration, about 12 GW, by 2050.

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WBS: 4.1.0.405

NREL researchers developed a new methodology to quantify the technology cost targets needed for electricity generation technologies to achieve certain penetration levels in the energy market. *Photo by Dennis Schroeder, NREL 40460*

NREL researchers implemented a wind plant energy-loss and uncertainty framework in the System Advisor Model. *Photo by Deb Lastowka, NREL 54462*

Wind Plant Performance Models To Increase Certainty for Investors and Owners

The Performance Risk, Uncertainty, and Finance (PRUF) multiyear project works to improve understanding of financial risks and uncertainties in wind plant investment decisions to improve wind plant energy production and operational cost estimation methods and reduce uncertainties about 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 the levelized cost of energy.

In Q3 FY 2019, NREL researchers implemented a wind plant energy-loss and uncertainty framework in the System Advisor Model (SAM), which will include an IEC 61400-15 compliant loss and uncertainty model that allows for further analysis and valuation of wind plant performance improvements.

Significance and Impact

SAM model improvements in loss and uncertainty categories and the additional mathematical mode for combining uncertainties allow for better fidelity of modeling about wind plant performance and technology improvements. This will enable improved scenario modeling for DOE wind modeling and analysis tasks and represents a first open-source implementation of the IEC framework.

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WBS: 4.1.0.406-1

Analyses Build Understanding of Wind Energy Potential To Maximize New Opportunities

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. Core research tasks under this project in FY19 address 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.

In Q3 FY 2019, researchers examined how cost-based exclusions and wildlife mitigation scenarios will change the addressable gigawatts of wind capacity (such as available land). The team also designed an offshore wind supply curve model in reV to increase flexibility in modeling assumptions and potential for assessing pathways for technology innovations.

NREL researchers examined how cost-based exclusions and wildlife mitigation scenarios will change wind capacity through factors such as available land. *Photo by Werner Slocum, NREL 56759*

Significance and Impact

The cost-based exclusions and wildlife mitigation analyses will help inform baseline scenarios for next-generation exclusions. The offshore supply curve model in reV will increase flexibility in modeling assumptions and the potential for assessing pathways for technology innovations.

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WBS: 4.1.0.407

Programmatic Support

Strategic Communications Amplify the Wind Energy Technology Office Mission

NREL's core communications 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 for U.S. wind energy.

NREL's communications team leveraged a variety of tactics and channels to engage with stakeholders in Q3 FY 2019, including adding the peer review report pages to the WETO website, creating several web articles, and adding dozens of events and opportunities to ensure the most accurate and up-to-date program information is presented on the website. The team also coded and disseminated breaking news emails; audited priority web pages; collected subject matter expert opinion on improving site animations; managed the process and finalized the content for WETO's Spring Wind R&D Newsletter and the U.S. chapter for the IEA Wind TCP [Technical Collaboration Programme] 2018 Annual Report.

The DOE Collegiate Wind Competition team from California State University Maritime Academy stands in front of the tunnel as they assess their model wind turbine. *Photo by Werner Slocum*

The communications team also completed a quarterly 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 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 helps amplify 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 also ensures all communications materials pull together all message points into one cohesive whole to ensure the message is not disjointed or confusing, while adhering to brand standards and previous communications messaging language, as appropriate.

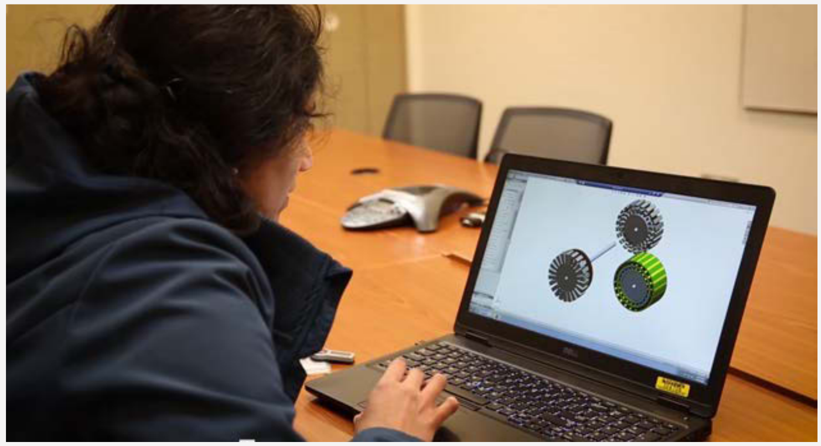
Additionally, the communications project is cross-cutting among all NREL FY 2019 Wind Program agreements, and the team is working toward becoming the central communications interface between NREL and WETO, further enforcing message continuity and EERE brand standards. Consistent, clear communication between the program office and NREL ensures the lab is aligned with the WETO mission and is disseminating the most relevant wind messaging to stakeholders.

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

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.



Latha Sethuraman, MADE3D Team, NREL. *Photo by Deb Lastowka, NREL*

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 identified 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.

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WBS: 5.1.0.405

Hands-On Support Broadens Wind Research Impact

NREL's extensive portfolio of 52 active WETO-funded projects necessitates strategic, hands-on management from NREL's Wind Program leadership team. This team provides program management and operations support to effectively plan, integrate, implement, control, and report NREL's activities to execute program projects on time and within budget, ultimately supporting WETO, other labs, and partners.

In Q3 FY 2019, NREL's Wind Program leadership team achieved several objectives. Primary among these were leading NREL's participation in the WETO Project Peer Review, held April 30–May 2 in Alexandria, Virginia. This involved coordinating presentations of 20 NREL researchers, which documented results of 27 projects that represented $70,079,995 of combined FY 2017 and FY 2018 project budget, and engaging with national laboratory and industry participants. Another highlight of Q3 FY 2019 was the AWEA WINDPOWER conference, for which members of the NREL Wind Program leadership team oversaw NREL's research presentations, posters, and panel participation. NREL also hosted the Workforce Pavilion and supported the WETO booth.

During Q3 FY 2019, NREL added 10 projects to its portfolio, including seven projects from the FY 2019 WETO Lab Call in the areas of research and development and grid integration. NREL's Wind Leadership team also created and delivered to WETO the NREL Q2 FY 2019 Accomplishments Report; submitted the Q2 FY 2019 NREL Wind Program Status Report; and provided WETO with regular newsletters communicating NREL wind research progress, accomplishments, and travel.

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 research and development, 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.

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

NREL Presents 2 Years of Project Impacts at Recent Peer Review, Helps Build Wind's Momentum at Wind Energy Conference

The WETO Project Peer Review, held April 30–May 2 in Alexandria, Virginia, showcased NREL research conducted on behalf of WETO during fiscal years 2017 and 2018. The Project Peer Review gives subject matter experts from the wind industry, academia, and federal agencies the opportunity to provide feedback on projects funded by WETO. Every 2 years, all programs within DOE's Office of Energy Efficiency and Renewable Energy, as well as 80%–90% of its funded active project portfolio, are required to undertake rigorous, objective peer reviews.

As part of this effort, 20 NREL researchers presented results from 27 projects that represented $70,079,995 of combined FY 2017 and FY 2018 project budgets. NREL's Alex Lemke, senior advisor, external affairs, provided leadership for the WETO event through external affairs and stakeholder engagement, project management, communications, financial planning, and overall event execution and facilitation.

Assistant Secretary in the Office of Energy Efficiency and Renewable Energy Daniel R. Simmons addresses the audience during the Wind Energy Technologies Office Project Peer Review held in late April. *Photo by Alex Lemke, NREL*

Additionally, industry audiences at May's AWEA WINDPOWER conference in Houston learned about the impacts of NREL's wind research through two channels—the spring edition of WETO's Wind R&D Newsletter, written and produced by NREL's Communications and Public Affairs team, and onsite networking and presentations coordinated by Lemke.

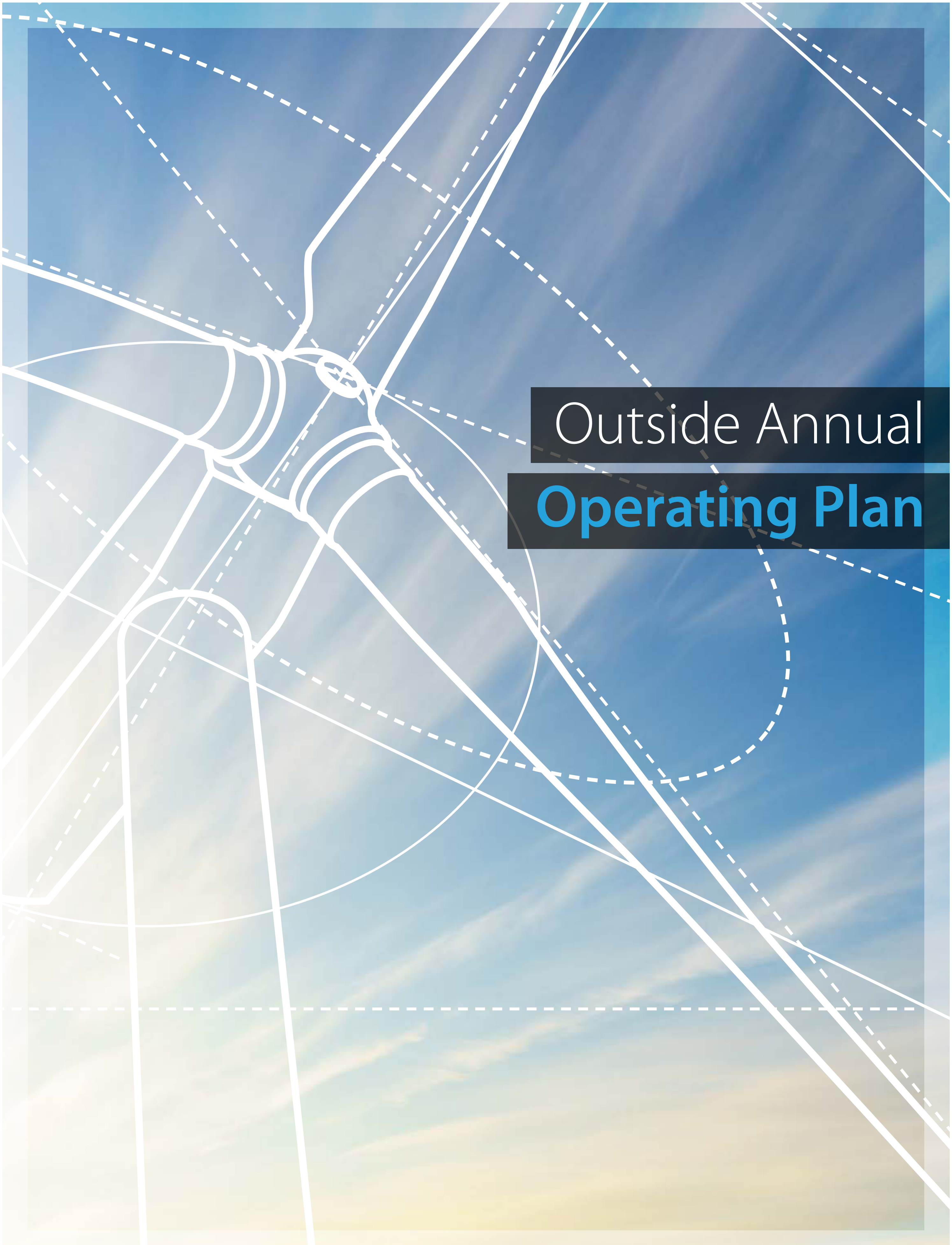
Significance and Impact

The purpose of the peer review is to evaluate projects funded by DOE based on their contribution to the mission and goals of the office, track progress made against stated objectives, and assess the office's overall management and performance. By highlighting the combined efforts from government agencies, national laboratories, industry, and academia, the Project Peer Review process is an important step in working toward the highest level of accountability and upholding a shared commitment to act as responsible stewards of taxpayer dollars.

At WINDPOWER, providing presentation support through meeting coordination, event logistics, and collateral support helped amplify NREL's recent work while allowing researchers to provide scientifically based resources on wind energy directly to stakeholders and decision makers.

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

Outside Annual
Operating Plan



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*

Meet the Flatirons Campus, Home of the National Wind Technology Center

The National Wind Technology Center (NWTC) campus has been renamed the Flatirons Campus. With its strong reputation and name recognition, the research center is alive and well. The only difference is that it is now housed at the Flatirons Campus.

Officially declared in a letter sent by DOE to NREL on March 26, the new name recognizes that the site has accommodated research beyond wind—such as grid integration, water power, energy storage, solar photovoltaics, and advanced manufacturing—for several years.

"The transition from the NWTC to the Flatirons Campus is more than just a name change. It signifies an expansion toward becoming the world's only multimegawatt-scale research facility dedicated to advancing a comprehensive range of renewable energy technologies and systems and their integration onto the electricity grid," said Johney Green, associate laboratory director, Mechanical & Thermal Engineering Sciences. "The 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."

Like NREL's South Table Mountain Campus, the NREL Flatirons Campus references the site's location rather than a specific program or function.

Point of Contact: Carol Laurie, *Carol.Laurie@nrel.gov*

Defining a Grand Vision for Wind Energy Technology

Realizing wind energy's full potential will require a new way of thinking about how wind turbines and power plants are designed, controlled, and operated, according to a new IEA Wind report led by former NWTC researcher Katherine Dykes and current researchers Paul Veers and Eric Lantz.

The Results of *IEA Wind TCP Workshop on a Grand Vision for Wind Energy Technology* report presents the outcomes of a meeting of more than 70 international experts who recognized the need for continued innovation in wind energy to enable the full potential for wind power in the future electricity system. They examined:

- The current challenges to continued large-scale deployment of wind energy
- The opportunities for innovation to address those challenges
- The necessary research and development to realize those innovations.

"This workshop considered each objective separately and then sought to harmonize across objectives to create an integrated grand vision for wind energy," said NREL Chief Wind Engineer Paul Veers. "Researchers identified that if wind energy can overcome challenges, such as characterizing the unknown dynamics of the atmosphere and its interaction with the turbine at the scale of the next generation of these gigantic machines, wind energy has the potential to form the foundation of the world's future electricity system."

A new International Energy Agency Wind Technology Collaboration Programme report, led by NREL researchers, sets out an integrated grand vision for wind energy to form the foundation of the future electricity system. *Photo by Deb Lastowka, NREL 54459*

The report documents the overall findings of these experts and highlights trends in science and technology that are expected to enable wind energy research and development. For instance, future wind power plants will have to consider trade-offs in design and operation between levelized cost of energy and system value. Depending on the architecture and makeup of the grid, the relative importance of each objective will change.

Veers said he anticipates that the grand vision report will influence the direction of wind research and development as well as the integration of research in the countries represented by the report's authors.

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

Musial Nominated for Floating Wind Power Player of the Year Award

NREL's offshore wind energy research program lead Walt Musial was one of four international offshore wind movers and shakers nominated for the second annual Floating Wind Power Player of the Year award, which recognizes a pioneer, innovator, or influencer in the fast-emerging offshore wind sector.

"It's an honor to be nominated for this award and be recognized internationally as a leader in floating offshore wind," Musial said. "When we first proposed floating platforms for offshore wind turbines, it was considered a fringe idea. Now, floating wind has the potential to deliver more energy to the United States than fixed-bottom offshore wind."

Musial leads NREL's offshore wind energy research program, which he launched in 2003. In 2018, he was selected to serve as the technical director for the National Offshore Wind Research and Development Consortium, a $41 million, industry-led research and development consortium funded jointly by the New York State Energy Research and Development Authority and DOE. As early as 2004, Musial made the case for building cost-competitive "deepwater wind turbines" to diversify the U.S. electric energy supply. He has written more than 100 publications and holds two patents.

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

Walt Musial, NREL's offshore wind energy research lead, contended recently for an international offshore wind energy award. *Photo by Dennis Schroeder, NREL*

Publications

Journal Articles

The Importance of Atmospheric Turbulence and Stability in Machine-Learning Models of Wind Farm Power Production

Mike Optis and Jordan Perr-Sauer

Machine learning is frequently applied in the wind energy industry to build statistical models of wind farm power production using atmospheric data as input. In the field of wind power forecasting, in particular, there has been substantial research into finding the best-performing learning algorithms that improve model predictions. Overlooked in the literature, however, is the influence of atmospheric turbulence and stability measurements in improving model predictions. It has been well-established through observations and physical models that these effects can have considerable influence on wind farm power production, yet consideration of these effects in statistical models is almost entirely absent from the literature. In this work, we examine the impact of atmospheric turbulence and stability inputs on statistical model predictions of wind farm power output. Hourly observations from a wind farm in very complex terrain in the Pacific Northwest of the United States are used. Five common learning algorithms and nine atmospheric variables are considered, five of which represent some measure of turbulence or stability. Here, we find a considerable improvement in hourly power predictions when some measure of turbulence or stability is included in the model. In particular, turbulent kinetic energy was found to be the most important variable apart from wind speed and more important than wind direction, pressure, and temperature. By contrast, the choice of learning algorithm is shown to be relatively less important in improving predictions. Based on this work, we recommend that turbulence and stability variables become standard inputs into statistical models of wind farm power production.

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

Paul Fleming, Jennifer King, Katherine Dykes, Eric Simley, Jason Roadman, Andrew Scholbrock, Patrick Murphy, Julie K. 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

Wake steering is a form of wind farm control in which turbines use yaw offsets to affect wakes to yield an increase in total energy production. In this first phase of a study of wake steering at a commercial wind farm, two turbines implement a schedule of offsets. Results exploring the observed performance of wake steering are presented and some first lessons learned. 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 production of the combined upstream–downstream turbine pair. Finally, the influence of atmospheric stability on the results is explored.

U.S. East Coast Lidar Measurements Show Offshore Wind Turbines Will Encounter Very Low Atmospheric Turbulence

Nicola Bodini, Julie K. Lundquist, and Anthony Kirincich

The rapid growth of offshore wind energy requires accurate modeling of the wind resource, which can be depleted by wind farm wakes. Turbulence dissipation rate (ε) governs the accuracy of model predictions of hub-height wind speed and the development and erosion of wakes. Here we assess the variability of turbulence kinetic energy and ε using 13 months of observations from a profiling lidar deployed on a platform off the Massachusetts coast. Offshore, ε is 2 orders of magnitude smaller than onshore, with a subtle diurnal cycle. Wind direction influences the annual cycle of turbulence, with larger values in winter when the wind flows from the land, and smaller values in summer, when the wind flows from open ocean. Because of the weak turbulence, wind plant wakes will be stronger and persist farther downwind in summer.

Unlocking the Full Potential of Wake Steering: Implementation and Assessment of a Controls-Oriented Model

Christopher J. Bay, Jennifer King, Paul Fleming, Rafael Mudafort, and Luis A. Martínez-Tossas

In this work, a controls-oriented wake model is modified and compared to an analytical Gaussian wake model and high-fidelity simulation data. This model, called the curled wake model, captures a wake phenomenon that occurs behind yawed turbines, modeled as a collection of vortices shed from the rotor plane. Through turbine simulations, these vortices are shown to have a significant impact on the prediction of wake steering's performance. Also, optimizations using the model are performed and produce results consistent with recent published research. Results indicate that wind farm controllers designed and analyzed with the curled wake model produce wake steering controllers that can realize larger gains in power production than previously estimated. Overall, the results support the concept of secondary steering, or a yawed turbine's ability to deflect the wake of a downstream turbine, and suggest that future turbine wake studies and yaw optimizations should include the curled wake phenomenon.

New High-Order Spectral Difference Method for Simulating Viscous Flows on Unstructured Grids with Mixed-Element Meshes

Mao Li, Zihua Qiu, Chunlei Liang, Michael Sprague, Min Xu, and Charles A. Garrisa

In the present study, a spectral difference (SD) method is developed for viscous flows on meshes with a mixture of triangular and quadrilateral elements. The standard SD method for triangular elements, which employs Lagrangian interpolating functions for fluxes, is not stable when the designed accuracy of spatial discretization is third order or higher. Unlike the standard SD method, the method examined here uses vector interpolating functions in the Raviart-Thomas (RT) spaces to construct continuous flux functions on reference elements. The spectral-difference Raviart-Thomas (SDRT) method was originally proposed by Balan et al. and implemented on triangular-element meshes for invisid flow only. Our present results demonstrated that the SDRT method is stable and high-order accurate in two dimensions for a number of test problems by using triangular-, quadrilateral-, and mixed-element meshes for both inviscid and viscous flows. A stability analysis is also performed for mixed elements. Furthermore, we found our current SDRT scheme is stable for fourth-order accurate spatial discretizations. However, a stable fifth-order SDRT scheme remains to be identified.

Setting Cost Targets for Zero-Emission Electricity Generation Technologies

Trieu Mai, Wesley Cole, and Andrew Reimers

Clean energy deployment scenarios typically assume a diverse mix of low-emission generation. However, because of historically low natural gas prices and cost reductions for onshore wind and photovoltaic technologies, recent new capacity deployment, especially in the United States, has come largely from these three generation sources. Here, we quantify competitive cost targets for three less-common zero-emission generation technologies—nuclear, concentrating solar, and offshore wind—under a range of future conditions. We determine the cost targets based on the technologies' system value, such that technology value equals or exceeds its cost. Using a capacity expansion model that develops system-wide, economically optimal generation scenarios of the United States power sector, we find that nuclear, concentrating solar, and offshore wind would need to attain levelized cost ranges of \$53–\$84/MWh, \$65–\$91/MWh, and \$39–\$77/MWh, respectively, to achieve 1% additional grid penetration. We refer to this metric as the "required cost," which is a technology's levelized cost of energy needed to achieve a specific penetration level. Higher penetrations lead to lower required costs as lower-cost generation is displaced. We estimate that to reach 10% penetration, the required cost for nuclear declines to \$45–\$76/MWh. Because of resource variability and increased transmission needs for concentrating solar power and offshore wind, even lower costs are needed to reach higher penetrations: required cost ranges to achieve 10% penetration are estimated to be \$30–\$56/MWh and \$18–\$40/MWh for these two technologies respectively. Our analysis informs research and development priorities and the design of policies supporting clean technologies.

Do Wind Turbines Pose Roll Hazards to Light Aircraft?

Jessica M. Tomaszewski, Julie K. Lundquist, Matthew J. Churchfield, and Patrick J. Moriarty

Wind energy accounted for 5.6% of all electricity generation in the United States in 2016. Much of this development has occurred in rural locations, where open spaces favorable for harnessing wind also serve general aviation airports. As such, nearly 40% of all U.S. wind turbines exist within 10 km of a small airport. Wind turbines generate electricity by extracting momentum from the atmosphere, creating downwind wakes characterized by wind-speed deficits and increased turbulence. Recently, the concern that turbine wakes pose hazards for small aircraft has been used to limit wind-farm development. Herein, we assess roll hazards to small aircraft using large-eddy simulations of a utility-scale turbine wake. Wind-generated lift forces and subsequent rolling moments are calculated for hypothetical aircraft transecting the wake in various orientations. Stably and neutrally stratified cases are explored, with the stable case presenting a possible worst-case scenario as a result of longer-persisting wakes permitted by lower ambient turbulence. In both cases, only 0.001% of rolling moments experienced by hypothetical aircraft during down-wake and cross-wake transects lead to an increased risk of rolling.

An Anomaly Detection Framework for Dynamic Systems Using a Bayesian Hierarchical Framework

Ramin Moghaddass and Shuangwen Sheng

Complex systems are susceptible to many types of anomalies, faults, and abnormal behavior caused by a variety of off-nominal conditions that may ultimately result in major failures or catastrophic events. Early and accurate detection of these anomalies using system inputs and outputs collected from sensors and smart devices has become a challenging problem and an active area of research in many application domains. In this article, we present a new Bayesian hierarchical framework that models the relationship between system inputs (sensor measurements) and outputs (response variables) without imposing strong distributional/parametric assumptions while using only a subset of training samples and sensor attributes. Then, an optimal cost-sensitive anomaly detection framework is proposed to determine whether a sample is an anomalous one taking into consideration the trade-off between misclassification errors and detection rates. The model can be used for both supervised and unsupervised settings depending on the availability of data regarding the behavior of the system under anomaly conditions. The unsupervised model is particularly useful when it is prohibitive to identify in advance the anomalies that a system may present and where no data are available regarding the behavior of the system under anomaly conditions. A Bayesian hierarchical setting is used to structure the proposed framework and help with accommodating uncertainty, imposing interpretability, and controlling the sparsity and complexity of the proposed anomaly detection framework. A Markov chain Monte Carlo algorithm is also developed for model training using past data. Furthermore, the numerical experiments conducted using a simulated data set and a wind turbine data set demonstrate the successful application of the proposed work for system response modeling and anomaly detection.

The Second Wind Forecast Improvement Project: Observational Field Campaign

James M. Wilczak, Mark Stoelinga, Larry K. Berg, Justin Sharp, Caroline Draxl, Katherine McCaffrey, Robert M. Banta, Laura Bianco, Irina Djalalova, Julie K. Lundquist, Paytsar Muradyan, Aditya Choukulkar, Laura Leo, Timothy Bonin, Yelena Pichugina, Richard Eckman, Charles N. Long, Kathleen Lantz, Rochelle P. Worsnop, Jim Bickford, Nicola Bodini, Duli Chand, Andrew Clifton, Joel Cline, David R. Cook, Harinda J.S. Fernando, Katja Friedrich, Raghavendra Krishnamurthy, Melinda Marquis, Jim McCaa, Joseph B. Olson, Sebastian Otarola-Bustos, George Scott, William J. Shaw, Sonia Wharton, and Allen B. White

The science of wind energy forecasting has taken a leap forward with the unique meteorological observations gathered in complex terrain during the Second Wind Forecast Improvement Project (WFIP2). WFIP2 is a DOE and National Oceanic and Atmospheric Administration funded program, with private-sector and university partners, which aims to improve the accuracy of numerical weather prediction model forecasts of wind speed in complex terrain for wind energy applications. A core component of WFIP2 was an 18-month field campaign that took place in the U.S. Pacific Northwest between October 2015 and March 2017. A large suite of instrumentation was deployed in a series of telescoping arrays, ranging from 500 km across to a densely instrumented 2 x 2 km area similar in size to a high-resolution numerical weather prediction model grid cell. Observations from these instruments are being used to improve our understanding of the meteorological phenomena that affect wind energy production in complex terrain, and to evaluate and improve model physical parameterization schemes. We present several brief case studies using these observations to describe phenomena that are routinely difficult to forecast, including wintertime cold pools, diurnally driven gap flows, and mountain waves/wakes. Observing system and data product improvements developed during WFIP2 are also described.

Adjustable and Distributionally Robust Chance-Constrained Economic Dispatch Considering Wind Power Uncertainty

Xin Fang, Bri-Mathias Hodge, Fangxing Li, Ershun Du, and Chongqing Kang

This paper proposes an adjustable and distributionally robust chance-constrained (ADRCC) optimal power flow (OPF) model for economic dispatch considering wind power forecasting uncertainty. The proposed ADRCC-OPF model is distributionally robust because the uncertainties of the wind power forecasting are represented only by their first- and second-order moments instead of a specific distribution assumption. The proposed model is adjustable because it is formulated as a second-order cone programming model with an adjustable coefficient. This coefficient can control the robustness of the chance constraints, which may be set up for the Gaussian distribution, symmetrically distributional robustness, or distributionally robust cases considering wind forecasting uncertainty. The conservativeness of the ADRCC-OPF model is analyzed and compared with the actual distribution data of wind forecasting error. The system operators can choose an appropriate adjustable coefficient to trade off between the economics and system security.

The Second Wind Forecast Improvement Project (WFIP2): General Overview

William J. Shaw, Larry K. Berg, Joel Cline, Caroline Draxl, Irina Djalalova, Eric P. Grimit, Julie K. Lundquist, Melinda Marquis, Jim McCaa, Joseph B. Olson, Chitra Sivaraman, Justin Sharp, and James M. Wilczak

WFIP2, a multi-institutional, multiscale modeling and observational study in complex terrain, advances understanding of boundary-layer physics and improves forecasts for wind energy applications. In 2015, DOE initiated a 4-year study, WFIP2, to improve the representation of boundary-layer physics and related processes in mesoscale models for better treatment of scales applicable to wind and wind power forecasts. This goal challenges numerical weather prediction models in complex terrain in large part because of the inherent assumptions underlying their boundary-layer parameterizations. The WFIP2 effort involved the wind industry, universities, the National Oceanographic and Atmospheric Administration, and DOE's national laboratories in an integrated observational and modeling study. Observations spanned 18 months to assure a full annual cycle of continuously recorded observations from remote-sensing and in situ measurement systems. The study area comprised the Columbia Basin of eastern Washington and Oregon, containing more than 6 GW of installed wind capacity. Nests of observational systems captured important atmospheric scales from mesoscale to numerical weather prediction subgrid scale. Model improvements targeted NOAA's High-Resolution Rapid Refresh (HRRR) model to facilitate transfer of improvements to National Weather Service operational forecast models, and these modifications have already yielded quantitative improvements for the short-term operational forecasts. This paper describes the general WFIP2 scope and objectives, the particular scientific challenges of improving wind forecasts in complex terrain, early successes of the project, and an integrated approach to archiving observations and model output. It provides an introduction for a set of more detailed Bulletin of the American Meteorological Society (BAMS) papers addressing WFIP2 observational science, modeling challenges and solutions, incorporation of forecasting uncertainty into decision support tools for the wind industry, and advances in coupling improved mesoscale to microscale models that can represent interactions between wind plants and the atmosphere.

OpenOA: An Open-Source Code Base for Operational Analysis of Wind Power Plants

Mike Optis, Jordan Perr-Sauer, Caleb Philips, Anna E. Craig, Joseph C. Y. Lee, Travis Kemper, Shuangwen Sheng, Eric Simley, Lindy Williams, Monte Lunacek, John Meissner, and M. Jason Fields

As global wind capacity continues to grow, the need for accurate operational analyses of a rapidly growing fleet of wind power plants has increased proportionally. The wind energy industry at present, however, is not ideally positioned to address this need. First, there is a lack of best practices and limited published standards for performing operational analyses. Second, operational data and methods are typically proprietary and not shared among the wind energy community. Consequently, there is considerable duplication of effort in developing methods as well as uncertainty in the calculated metrics. To address these problems, NREL has publicly released OpenOA, an open-source code base for performing operational analyses on wind plant data. The intent of OpenOA is to provide a framework in which best practices can be developed, refined, and disseminated. Ultimately, such collaboration is expected to lead to a working example (i.e., reference implementation) of methods from which a published standard may develop. This article provides an overview of OpenOA, highlighting its release as a public repository, modular software architecture, current functionality, and planned functionality in subsequent releases. It is our goal for OpenOA to evolve into an indispensable tool for performing operational analyses that is used and supported by a large community of wind energy experts.

Spatial and Temporal Variability of Turbulence Dissipation Rate in Complex Terrain

Nicola Bodini, Julie K. Lundquist, Raghavendra Krishnamurthy, Mikhail Pekour, Larry K. Berg, and Aditya Choukulkar

To improve parameterizations of the turbulence dissipation rate (ε) in numerical weather prediction models, the temporal and spatial variability of ε must be assessed. In this study, we explore influences on the variability of ε at various scales in the Columbia River Gorge during the WFIP2 field experiment between 2015 and 2017. We calculate ε from five sonic anemometers all deployed in a ~4 km2 area as well as from two scanning Doppler lidars and four profiling Doppler lidars located in a ~300 km2 region. We retrieve ε from the sonic anemometers using the second-order structure function method, from the scanning lidars with the azimuth structure function approach, and from the profiling lidars with a novel technique using the variance of the line-of-sight velocity. The turbulence dissipation rate shows large spatial variability, even at the microscale, especially during nighttime stable conditions. Orographic features have a strong impact on the variability of ε, with the correlation between ε at different stations being highly influenced by terrain. ε shows larger values in sites located downwind of complex orographic structures or in wind farm wakes. A clear diurnal cycle in ε is found, with daytime convective conditions determining values of more than an order of magnitude higher than nighttime stable conditions. ε also shows a distinct seasonal cycle, with differences of more than an order of magnitude between average ε values in summer and winter.

Evaluation of the Impact of Horizontal Grid Spacing in Terra Incognita on Coupled Mesoscale-Microscale Simulations Using the Weather Research and Forecasting Framework

Raj K. Rai, Larry K. Berg, Branko Kosović and Sue Ellen Haupt, Jeffrey D. Mirocha, Brandon L. Ennis, and Caroline Draxl

Coupled mesoscale-microscale simulations are required to provide time-varying weather-dependent inflow and forcing for large-eddy simulations under general flow conditions. Such coupling necessarily spans a wide range of spatial scales (i.e., ~10 m to ~10 km). Herein, we use simulations that involve multiple nested domains with horizontal grid spacings in the terra incognita (i.e., ≤km) that may affect simulated conditions in both the outer and inner domains. We examine the impact on simulated wind speed and turbulence associated with forcing provided by a terrain with grid spacing in the terra incognita. We perform a suite of simulations that use combinations of varying horizontal grid spacings and turbulence parameterization/modeling using the Weather Research and Forecasting Model using a combination of planetary boundary layer and large-eddy simulation subgrid-scale models. The results are analyzed in terms of spectral energy, turbulence kinetic energy, and proper orthogonal decomposition energy. The results show that the output from the microscale domain depends on the type of turbulence model (e.g., planetary boundary layer or large-eddy simulation subgrid-scale) used for a given horizontal grid spacing but is independent of the horizontal grid spacing and turbulence modeling of the parent domain. Simulation using a single domain produced less proper orthogonal decomposition energy in the first few modes compared to a coupled simulation (one-way nesting) for similar horizontal grid spacing, which highlights that coupled simulations are required to accurately pass the mesoscale features into the microscale domain.

Load Response of a Floating Wind Turbine to Turbulent Atmospheric Flow

Paula Doubrawaa, Matthew J. Churchfield, Marte Godvik, and Senu Sirnivasa

The two turbulence-generation models [Kaimal Spectrum Exponential Coherence (KSEC) and Mann] specified in the international standard for wind turbine design assume neutral atmospheric conditions and are based on statistical and spectral methods. Mainly because of the lack of physics, the flow fields simulated with these models ultimately differ in their underlying structure, especially in terms of the spatial coherence of longitudinal velocity perturbations. Although this may not be critical for smaller wind turbine rotors, it becomes important when rotor sizes increase. Furthermore, it might be especially important in the context of floating technologies as they are more sensitive to large turbulent coherent structures. Previous work found that these differences between KSEC and Mann can propagate to loads predictions and thereby affect the design space of the entire wind turbine system. It is therefore crucial to determine in which ways these two models are underperforming. Up until now, validation of these models had only been done in the vertical direction because it is extremely difficult to obtain atmospheric turbulence measurements separated laterally and sampled at heights relevant to wind energy. In this work, we address the lack of measurements by using high-fidelity, high-resolution simulation data as a reference. We perform hour-long, large-eddy simulations of turbulent velocity fields that are stability-dependent and contain three-dimensional coherent structures. These flow fields are then used to investigate which stochastic model is a better predictor of loads on a realistic spar-system floating offshore wind turbine, and to quantify how the assumption of neutral stratification propagates to short-term load estimates. Both stochastic turbulence models are found to overpredict fatigue loading in high-wind scenarios (in some cases, by more than 25%) and underpredict it when the wind speed is low (by as much as 20%). The KSEC model matches the high-fidelity flow fields more closely than Mann at high wind speeds, and the opposite is true at low wind speeds. Finally, turbine loading is found to be sensitive to atmospheric stability even when the turbulence intensity remains fairly constant. This sensitivity is most pronounced at low wind speeds, when fatigue load estimates on the spar system can differ by 40%.

[Fleetwide Data-Enabled Reliability Improvement of Wind Turbines]

Timothy Verstraeten, Ann Nowé, Jonathan Keller, Yi Guo, Shuangwen Sheng, and Jan Helsen

Wind farms are an indispensable driver toward renewable and nonpolluting energy resources. However, as ideal sites are limited, placement in remote and challenging locations results in higher logistics costs and lower average wind speeds. Therefore, it is critical to increase the reliability of the turbines to reduce maintenance costs. Robust implementation requires a thorough understanding of the loads subject to the turbine's control. Yet, such dynamically changing multidimensional loads are uncommon with other machinery, and generally under-researched. Therefore, a multitiered approach is proposed to investigate the load spectrum occurring in wind farms. Our approach relies on both fundamental research using controllable test rigs, as well as analyses of real-world loading conditions in high-frequency supervisory control and data acquisition data. A method is introduced to detect operational zones in wind farm data and link them with load distributions. Additionally, although focused research further investigates the load spectrum, a method is proposed that continuously optimizes the farm's control protocols without the need to fully understand the loads that occur. A case of gearbox failure is investigated based on a vast body of past experiments and suspect loads are identified. Starting from this evidence on the causes and effects of dynamic loads, the potential of our methods is shown by analyzing real-world farm loading conditions on a steady-state case of wake and developing a preventive row-based control protocol for a case of cascading emergency brakes induced by a storm.

Technical Reports

FAST Model Calibration and Validation of the OC5-DeepCwind Floating Offshore Wind System Against Wave Tank Test Data

Fabian Wendt, Amy Robertson, and Jason Jonkman

During the Offshore Code Comparison Collaboration, Continued, with Correlation (OC5) project, which focused on the validation of numerical methods through comparison against tank test data, the authors created a numerical FAST model of the 1:50-scale DeepCwind semisubmersible system that was tested at the Maritime Research Institute Netherlands ocean basin in 2013. The OC5 project revealed a general underprediction of loads and motions by the participating numerical models. This paper discusses several model calibration studies that were conducted to identify potential model parameter adjustments that help to improve the agreement between the numerical simulations and the experimental test data. These calibration studies cover wind-field-specific parameters (coherence, turbulence), and hydrodynamic and aerodynamic modeling approaches, as well as rotor model (blade-pitch and blade-mass imbalances) and tower model (structural tower damping coefficient) adjustments. These calibration studies were conducted based on relatively simple calibration load cases (wave only/wind only). The agreement between the final FAST model and experimental measurements is then assessed based on more complex combined wind and wave validation cases. The analysis presented in this paper does not claim to be an exhaustive parameter identification study but is aimed at describing the qualitative impact of different model parameters on the system response. This work should help to provide guidance for future systematic parameter identification and uncertainty quantification efforts.

IEA Wind TCP Task 37: Systems Engineering in Wind Energy - WP2.1 Reference Wind Turbines

Pietro Bortolotti, Helena Canet Tarr´es, Katherine Dykes, Karl Merz, Latha Sethuraman, David Verelst, and Frederik Zahle

This report describes two wind turbine models developed within the second work package of IEA Wind Task 37 on Wind Energy Systems Engineering: Integrated RD&D. The wind turbine models aim at acting as references for future research projects on wind energy, representing a modern land-based wind turbine and a next generation offshore wind turbine. The land-based design is a class IIIA geared configuration with a rated electrical power of 3.4 MW, a rotor diameter of 130 m, and a hub height of 110 m. The offshore design is a class IA configuration with a rated electrical power of 10.0 MW, a rotor diameter of 198 m, and a hub height of 119 m. The offshore turbine adopts a direct-drive generator.

A Detailed Wind Turbine Blade Cost Model

Pietro Bortolotti, Derek Berry, Robynne Murray, Evan Gaertner, Dale Jenne, Rick Damiani, Garrett Barter, and Katherine Dykes

This technical report describes a detailed blade cost model for wind turbine blades in the range of 30 to 100 m in length. The model estimates the bill of materials, the number of labor hours and the cycle time as well as the costs related to direct labor, overhead, buildings, tooling, equipment, maintenance, and capital. The model applies to multimegawatt wind turbine blades manufactured via vacuum-assisted resin transfer molding, which is the most commonly adopted manufacturing method for modern wind turbine blades. The model is implemented both in a large Excel file and in Python. The latter is freely available in the repository of the Wind-Plant Integrated System Design and Engineering Model (WISDEM™; github.com/WISDEM). WISDEM is a multidisciplinary analysis and optimization design framework developed at NREL. This blade cost model represents a valuable tool to run design optimization studies for wind turbines. In this report, the model is first presented with its approach and assumptions and then computes the costs of three blades, namely the 33 m Wind Partnership for Advanced Component Technologies (WindPACT) study blade, the 63 m IEA Wind Task 37 land-based reference wind turbine blade, and the 100 m SNL-100-03 blade developed at Sandia National Laboratories.

IEA Wind TCP Task 26: Wind Technology, Cost, and Performance Trends in Denmark, Germany, Ireland, Norway, Sweden, the European Union, and the United States: 2008–2016

Alberto Dalla Riva, János Hethey, Silke Lüers, Anna-Kathrin Wallasch, Knud Rehfeldt, Aidan Duffy, David Edward Weir, Maria Stenkvist, Andreas Uihlein, Tyler Stehly, Eric Lantz, and Ryan Wiser

The IEA Wind TCP Task 26—The Cost of Wind Energy represents an international collaboration dedicated to exploring the past, present, and future cost of wind energy. The entities currently represented by participating organizations in IEA Wind TCP Task 26 included in this report are Denmark, Germany, Ireland, Norway, Sweden, the European Union, and the United States. This report discusses trends from 2008 through 2016 that affected the cost of land-based wind energy in each country. The cost of wind energy during this period is compared with the market value of wind energy in the respective electricity market for each country. This report builds from previous analysis conducted since the inception of Task 26 in 2009. Schwabe et al. (2011) explored differences in the cost of wind energy in 2008 among countries participating in Task 26 at that time. Vitina et al. (2015) presented turbine- and project-level trends in the wind industry from 2008 to 2012, including wind project size, turbine size, specific power and hub height, project performance, investment costs, operation and maintenance costs, and project financing. These inputs are used to calculate the levelized cost of energy, a widely recognized metric for understanding how technology performance, capital investment, operations, and financing impact the life cycle cost of building and operating a wind project. Both prior reports—as well as this report—used this metric to estimate the cost of wind energy.

Increasing Wind Turbine Tower Heights: Opportunities and Challenges

Eric Lantz, Owen Roberts, Jake Nunemaker, Edgar DeMeo, Katherine Dykes, and George Scott

This report has two primary objectives. First, it seeks to inform the opportunities and potential associated with increasing wind turbine hub heights. It also explores the conditions and locations where taller towers offer the most significant potential to increase wind technology performance and reduce costs. The second objective is to examine the status of tall tower technology as a key subcomponent of wind power advancement.

Wind Energy Instrumentation Atlas

Julie K. Lundquist, Andrew Clifton, Scott Dana, Arlinda Huskey, Patrick Moriarty, Jeroen van Dam, and Tommy Herges

This report is intended to serve as a reference for experimental study planners that describes the capability, accuracy, and resolution of existing and developing measurement technologies to observe the level of interest in wind plant model validation. Such systems can be broken into two major categories—those that measure the flow field and surrounding atmosphere around and within a wind plant and those that measure the turbine response within the wind plant. The A2e validation team will use this catalogue of instrument capability in conjunction with the validation plan, to choose the optimal set of instruments to be deployed, inform instrument placement and operation, and estimate the types of validation that may be gathered through new field campaigns. Where existing instrumentation is deficient, this document will help highlight areas in which instrumentation development is required to meet validation objectives. Further, A2e technology development funding may be required.

Distributed Wind Resource Assessment Framework: Functional Requirements and Metrics for Performance and Reliability Modeling

Heidi Tinnesand and Latha Sethuraman

The focus of the distributed wind resource assessment performance framework is to first clarify the key parameters that define the wind resource for any distributed wind turbine project and then describe the loss and uncertainty factors associated with long-term performance of wind turbine projects. Next it will identify and define the key parameters required to analyze the operational performance of a project. This framework could then be the foundation for understanding the predictability of the power and revenue from a project. Improving the predictability and reliability of wind power generation and operations will reduce costs and potentially establish a framework to attract new capital to the distributed wind industry sector. This report is the first part of a research effort to investigate the impact that improved resource assessment and energy estimation for distributed wind can have on consumer confidence, cost of capital, cost of ownership and operations, perception of financial risk, and levelized cost of energy.

Uptower Investigation of Main and High-Speed-Shaft Bearing Reliability

Jonathan Keller, Yi Guo, and Latha Sethuraman

This purpose of this report is to summarize the investigation of the operational conditions conducive to premature main bearing wear and gearbox bearing axial cracking failures in wind turbines. The report fully describes the series of operations conducted and measurements gathered from commissioning of the instrumented drivetrain in January 2017 through the end of the wind season in May 2018.

California Time-of-Use Transition: Effects on Distributed Wind and Solar Economic Potential

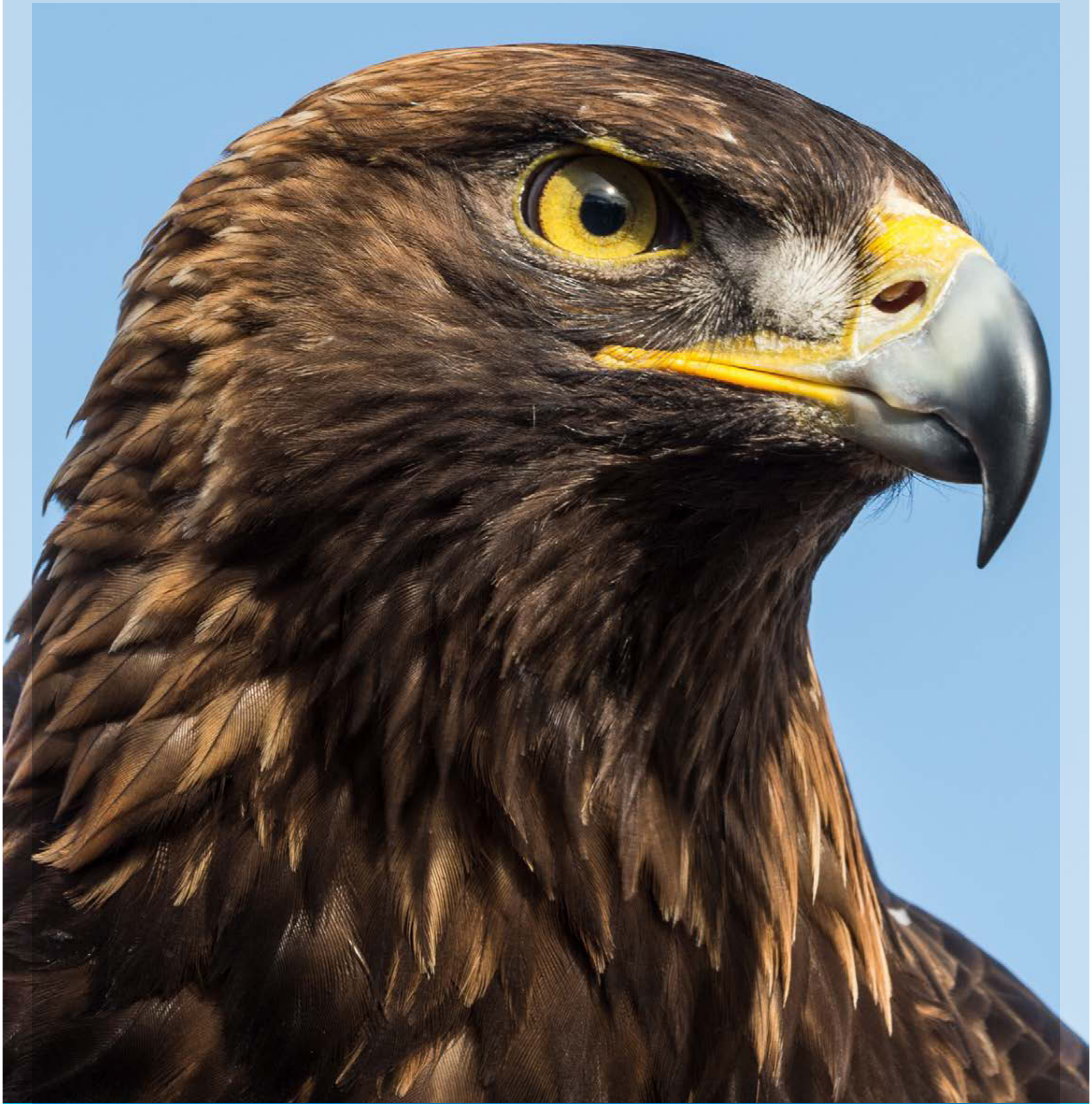
Ashwin Ramdas, Kevin McCabe, Paritosh Das, and Benjamin Sigrin

Time-of-use retail energy rates price electricity differently by the time of day, thereby communicating to consumers the costs of supplying electricity throughout the day. This study evaluates the impact of the pending enactment of the California time-of-use mandate on the economic attractiveness of behind-the-meter distributed wind and solar systems. The authors also identify cost improvements needed for a robust (i.e., 1-GW) distributed wind market and the counties and sectors with substantial wind and solar economic potential.

Investigation of Roller Sliding in Wind Turbine Gearbox High-Speed-Shaft Bearings

David Vaes, Yi Guo, Pietro Tesini, and Jonathan Keller

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 is attributed to so-called white-etching cracks. These cracks tend to propagate to spalls or lead to a complete splitting of the inner ring. This mode of failure can occur at 5%–20% of the predicted design life and has been observed in many other industries, bearing locations, bearing types, bearing parts, and steel types. In a collaborative project, Flender Corporation, SKF, and NREL have instrumented a commercial drivetrain, installed it in a wind turbine, and operated the turbine for more than a year. The gearbox was specifically instrumented to measure high-speed bearing loads, sliding, and the lubricant environment. In this report, these measurements are used to validate two different modeling approaches for bearing sliding—one analytical dynamic model and one multibody model. Once validated, these models can be used to evaluate the roller slip losses or cumulative frictional energy that are considered potential driving factors for wind turbine gearbox bearing failures by white-etching cracks.



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