NREL
NATIONAL RENEWABLE ENERGY LABORATORY

2017 Publications Demonstrate Advancements in Wind Energy Research

In 2017, wind energy experts at the National Renewable Energy Laboratory (NREL) made significant strides to advance wind energy. Many of these achievements were presented in articles published in scientific and engineering journals and technical reports that detailed research accomplishments in new and progressing wind energy technologies. During fiscal year 2017, NREL wind energy thought leaders shared knowledge and insights through 45 journal articles and 25 technical reports, benefiting academic and national-lab research communities; industry stakeholders; and local, state, and federal decision makers. Such publications serve as important outreach, informing the public of how NREL wind research, analysis, and deployment activities complement advanced energy growth in the United States and around the world. The publications also illustrate some of the noteworthy outcomes of U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) and Laboratory Directed Research and Development funding, as well as funding and facilities leveraged through strategic partnerships and other collaborations.

Summaries of a selection of 2017 NREL wind energy journal articles and technical reports are listed in this document. Browse through a complete list of wind publications at ***NREL's publications database*** (*http://bit.ly/2B91uiO*).

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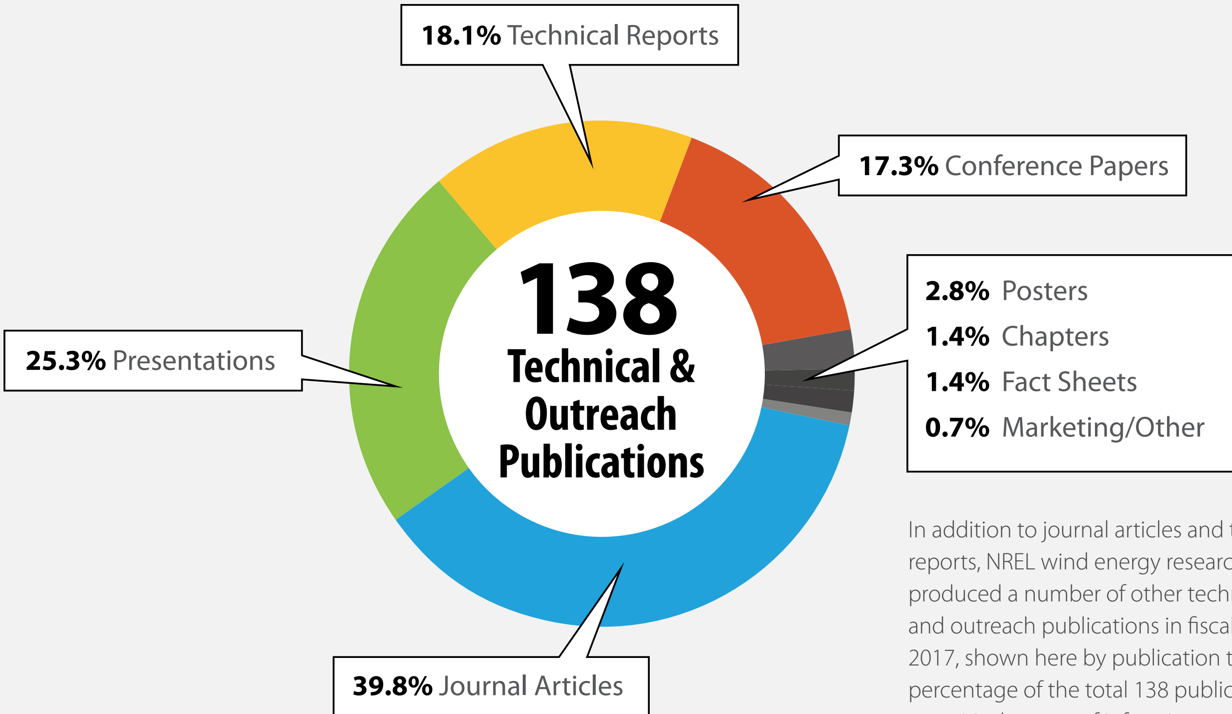

In addition to journal articles and technical reports, NREL wind energy researchers produced a number of other technical and outreach publications in fiscal year 2017, shown here by publication type and percentage of the total 138 publications. All are critical means of informing stakeholder groups and the public about wind energy.

Journal Articles

"Full-Scale Field Test of Wake Steering"

Paul Fleming, Jennifer Annoni, Andrew Scholbrock, Eliot Quon, Scott Dana, Scott Schreck, et al.

Wake steering as a form of wind farm control has been studied in simulations as well as in wind tunnels and scaled test facilities. In this study, a field test of wake steering was performed on a full-scale turbine. The yaw controller of the turbine was set to track different yaw misalignment set points while a nacelle-mounted lidar scanned the wake downwind. The lidar measurements, combined with turbine data and measurements of the inflow, were then compared to the predictions of a wind farm control-oriented model of wakes. The results indicate that wake steering can positively impact wind farm annual energy production and further validate the use of wind farm modeling to optimize power. *Journal of Physics: Conference Series*. ***https://doi.org/10.1088/1742-6596/854/1/012013***

"Downwind Pre-Aligned Rotors for Extreme-Scale Wind Turbines"

Patrick Moriarty et al.

Wind systems are increasing in size and power as they strive to move closer to utility-scale production. Extreme-scale wind systems—those with power levels of 10–20 megawatts (MW)—are particularly suited to offshore locations because of the beneficial conditions for large turbines found there. Large turbines, however, pose a wide array of challenges, making structural design difficult. One of the most significant design challenges associated with extreme-scale systems is limiting rotor blade mass, which provides the structural integrity required to resist the imposed blade loads. The authors propose a new downwind prealigned rotor (DPAR) concept that uses a rigid coned rotor at the hub based on force alignment principles. This study represents the first comprehensive analysis of the DPAR concept for an extreme-scale turbine (13 MW in this case), comparing the concept with a conventional, well-accepted design.

The proposed solution was found to achieve the same power production as the conventional rotor in simulations, providing impetus for further research. *Wind Energy*. ***https://doi.org/10.1002/we.2092***

"An Error Reduction Algorithm to Improve Lidar Turbulence Estimates for Wind Energy"

Jennifer Newman et al.

Lidars are currently being considered as a replacement for meteorological towers for wind resource assessment and power performance testing because they can be more easily deployed at different locations and can collect wind speed measurements at heights spanning the entire turbine rotor disk. However, lidars measure different values of turbulence intensity (TI) than a cup or sonic anemometer, and uncertainty about estimates is a major barrier to the adoption of lidars. In this work, a lidar turbulence error reduction model—Lidar Turbulence Error Reduction Algorithm (L-TERRA)—was developed and tested on data from two different sites. The study found that the difference between TI measured by a cup or sonic anemometer and TI measured by a vertically profiling lidar can be reduced using appropriate physical models of the lidar measurement. Also, performance of L-TERRA improves substantially when different model configurations are used for different stability conditions. Improved TI estimates can be used for wake characterization, site monitoring, and resource assessment, among other functions. *Wind Energy Science*. ***https://doi.org/10.5194/wes-2-77-2017***

"Optimal Smoothing Length Scale for Actuator Line Models of Wind Turbine Blades Based on Gaussian Body Force Distribution"

Matt Churchfield, Luis Martinez, et al.

In this work, researchers determined an optimal body force to represent wind turbine blades when performing simulations of flow past a wind turbine. The primary finding is that by using this optimal body force, simulations can be run that reproduce an accurate representation of the wind turbine blades. Using this optimal body force to represent a more realistic blade allows for more realistic tip vortices to be reproduced. The impact, particularly for researchers performing simulations of flow through wind turbines, is that they can now use the optimal body force to represent the wind turbine blades more realistically. As a broader impact goal, this type of simulation can be used to better understand the flow past wind farms and to test different wind farm control strategies. *Wind Energy*. ***https://doi.org/10.1002/we.2081***

"A Data-Driven Multi-Model Methodology with Deep Feature Selection for Short-Term Wind Forecasting"

Bri-Mathias Hodge et al.

As wind power increasingly expands in the advanced energy domain, improving the accuracy of wind power forecasting is becoming ever more important to ensure continued economic and reliable power system operations. This article explains how a data-driven multi-model wind forecasting methodology was developed with a two-layer ensemble machine-learning technique. A deep feature selection framework was also developed to determine the most suitable inputs to the first-layer machine-learning models; then, a blending algorithm was applied in the second layer to create an ensemble of the forecasts produced by first-layer models and generate both deterministic and probabilistic forecasts. This two-layer model seeks to utilize the statistically different characteristics of each machine-learning algorithm. After comparing machine-learning algorithms in both layers, the methodology was compared to several benchmarks. The results show that the developed multi-model framework with the deep feature selection framework improved the forecasting accuracy by up to 30%. *Applied Energy*. ***https://doi.org/10.1016/j.apenergy.2017.01.043***

"Field Test of Wake Steering at an Offshore Wind Farm"

Paul Fleming, Jennifer Annoni, et al.

A field test of wake-steering control, conducted collaboratively by NREL and smart-energy management company and turbine manufacturer Envision Energy, involved an array of turbines within an operating commercial offshore wind farm in China. The normal yaw controller was modified to implement wake steering according to a yaw control strategy. The strategy was designed using NREL wind farm models, including a computational fluid dynamics model, Simulator fOr Wind Farm Applications, for understanding wake dynamics and an engineering model, FLOw Redirection and Induction in Steady State, for yaw control optimization. Results indicated that, within the certainty afforded by the data, the wake-steering controller was successful in increasing power capture by amounts similar to those predicted from the models. *Wind Energy Science*. ***https://doi.org/10.5194/wes-2-229-2017***

"Monitoring of Wind Turbine Gearbox Condition through Oil and Wear Debris Analysis: A Full-Scale Testing Perspective"

Shuangwen Sheng

Premature turbine subsystem/component failures remain a challenge for the wind industry, especially for turbines rated above 1 MW. Gearboxes are a focal point for improving reliability and availability, factors that condition monitoring (CM) can help improve, leading to reduced turbine operation and maintenance costs and, subsequently, lower cost of energy for wind power. This article helps to address the lack of published information on the advantages and limitations of each CM technique. First-hand oil and wear debris analysis results are reported that were obtained through tests based on full-scale wind turbine gearboxes rated at 750 kW. The investigated CM techniques included real-time oil condition and wear debris monitoring, both inline and online sensors, and offline oil-sample and wear-debris analysis, in both onsite and offsite laboratories. The reported results and observations help increase wind industry awareness of the benefits and limitations of oil and debris analysis technologies. *Tribology Transactions*. ***https://doi.org/10.1080/10402004.2015.1055621***

"Validating Precision Estimates in Horizontal Wind Measurements from a Doppler Lidar"

Julie Lundquist et al.

In this study, the accuracy of wind speed and direction precision estimates produced by a Doppler lidar wind retrieval algorithm were assessed. The algorithm, based on the velocity azimuth-display (VAD) technique, estimated the wind speed and direction measurement precision using standard error propagation techniques, assuming the input data to be contaminated by random, zero-mean, errors. Several wind retrieval trials were conducted using different precision-estimation schemes. The resulting wind speed and direction precision estimates were compared to differences in wind speed and direction between the VAD algorithm and sonic anemometer measurements taken on a nearby 300-meter tower. All trials produced qualitatively similar wind fields with negligible bias but substantially different wind speed and direction precision fields. The most accurate wind speed and direction precisions were obtained when the radial velocity precision was determined by direct calculation of radial velocity standard deviation along each pointing direction and range gate of the plan-position-indicator scan. *Atmospheric Measurement Techniques*. ***https://doi.org/10.5194/amt-10-1229-2017***

"Development of Performance Specifications for Hybrid Modeling of Floating Wind Turbines in Wave Basin Tests"

Jason Jonkman, et al.

This paper demonstrates the development of performance specifications for a system that couples a wave basin experiment with a wind turbine simulation. Two different points for the hybrid coupling were considered: the tower-base interface and the aero-rotor.

Analyzing simulations of three floating wind turbine designs across seven load cases revealed the motion and force requirements of the coupling system. By simulating errors in the hybrid coupling system, the sensitivity of the floating wind turbine response to coupling quality was quantified. The sensitivity results were used to determine tolerances for motion tracking errors, force actuation errors, bandwidth limitations, and latency in the hybrid coupling system. Results showed that sensitivities vary significantly between support structure designs and that coupling at the aero-rotor interface has less stringent requirements than those for coupling at the tower base. The methods and results presented can inform design of future hybrid coupling systems and enhance understanding of how test results are affected by hybrid coupling quality. *Journal of Ocean Engineering and Marine Energy.* ***https://doi.org/10.1007/s40722-017-0089-3***

"Gusts and Shear Within Hurricane Eyewalls can Exceed Offshore Wind Turbine Design Standards"

Julie Lundquist, Rick Damiani, Walt Musial, et al.

Offshore wind energy development is underway in the United States, with proposed sites located in hurricane-prone regions. Turbine design criteria outlined by the International Electrotechnical Commission do not encompass the extreme wind speeds and directional shifts of hurricanes stronger than category 2. We examine a hurricane's turbulent eyewall using large-eddy simulations with Cloud Model 1. Gusts and mean wind speeds near the eyewall of a category 5 hurricane exceed the current Class I turbine design threshold of 50 m s^{-1} mean wind and 70 m s^{-1} gusts. Largest gust factors occur at the eye-eyewall interface. Further, shifts in wind direction suggest that turbines must rotate or yaw faster than current practice. Although current design standards omit mention of wind direction change across the rotor layer, large values (15°–50°) suggest that veer should be considered. *Geophysical Research Letters.* ***https://DOI.org/10.1002/2017GL073537***

Technical Reports

"Enabling the SMART Wind Power Plant of the Future Through Science-Based Innovation"

Katherine Dykes, Maureen Hand, Tyler Stehly, Paul Veers, Mike Robinson, Eric Lantz, et al.

An essential element of future wind technology is a move toward highly optimized and integrated plant design and operations that focus on the design and development of the entire wind power plant rather than individual wind turbines. The collection of intelligent and novel technologies that comprise this next-generation technology can be characterized as "System Management of Atmospheric Resource through Technology," or SMART strategies. In this report, a land-based future SMART wind power plant that incorporates this collection of innovations was analyzed to understand the potential impact on levelized cost of energy. The realization of the SMART wind power plant is projected to result in an unsubsidized cost of energy of $23/megawatt-hour and below—a reduction of 50% or more from current cost levels by 2030. This research indicates that technology innovation will provide the bridge from the wind power plant of today to the SMART wind power plant of the future, resulting in cost-competitive wind energy nationwide. NREL/TP-5000-68123. ***https://www.nrel.gov/docs/fy17osti/68123.pdf***

"Outlooks for Wind Power in the United States: Drivers and Trends under a 2016 Policy Environment"

Trieu Mai, Eric Lantz, Jonathan Ho, Tyler Stehly, and Donna Heimiller

Wind is one of the fastest-growing electricity sources in the United States, but the pace of U.S. wind power deployment is affected by wide-ranging market, technology, and policy conditions that make its future uncertain. In this report, researchers analyze multiple scenarios in several time frames that can help inform future energy sector decision making. Rather than presenting predictions or forecasts, the report identifies drivers and trends that influence future wind deployment. For example, competition with natural gas, declining solar costs, and slow or negative growth in electricity consumption could limit the use of wind power over the next few decades, whereas reductions in wind prices or increases in the cost of natural gas could spur the expansion of wind installations. Despite the uncertainties, the results of this analysis suggest that wind power can continue to play a significant role in the U.S. electricity system, especially if a robust research and development effort focuses on reducing the cost of wind energy. NREL/TP-6A20-67058. ***https://www.nrel.gov/docs/fy17osti/67058.pdf***

"An Assessment of the Economic Potential of Offshore Wind in the United States from 2015 to 2030"

Philipp Beiter, Walter Musial, Levi Kilcher, Michael Maness, and Aaron Smith

Development of offshore wind installations depends in part on accurate assessments of the economic potential at specific sites. This report documents the variation in the economic potential of more than 7,000 U.S. coastal locations by comparing, over the expected lifetime of a wind plant at a specific site, the cost of generating a unit of electricity with a metric that captures the value of the wind technology to the larger electrical system. The difference between the two, or "net value," can help stakeholders gain an initial understanding of the economic potential of a new offshore wind project at a particular site. This information is useful during energy development and energy portfolio planning and can help federal and state agencies and planning commissions make early strategic decisions about offshore wind development in the United States. NREL/TP-6A20-67675. ***https://www.nrel.gov/docs/fy17osti/67675.pdf***

"2016 Offshore Wind Technologies Market Report"

Walter Musial, Philipp Beiter, Paul Schwabe, Tian Tian, Tyler Stehly, Amy Robertson, Vahan Gevorgian, et al.

The United States marked a milestone in December 2016 with the commissioning of its first commercial offshore wind project, off the coast of Rhode Island, and there are other indicators that the U.S. offshore wind industry is poised for dynamic growth. In this report, researchers provide wind industry stakeholders with information and analysis on offshore wind market, technology, and cost trends in the United States and worldwide. They note that confidence in the emerging U.S. offshore wind market has been boosted by declining offshore wind costs globally; continued supply chain development; supportive state policies and the presence of well-capitalized and experienced offshore wind developers. An indication of that confidence is that the U.S. offshore wind project development pipeline includes more than 20 projects totaling 24,135 MW of potential installed capacity. DOE/GO-102017-5031. ***https://energy.gov/eere/wind/downloads/2016-offshore-wind-technologies-market-report***

"2016 State of Wind Development in the United States by Region"

Ruth Baranowski, Frank Oteri, Ian Baring-Gould, and Suzanne Tegen

Public acceptance can be key to the development of new wind installations, and regional stakeholders in the United States face unique local challenges. To address those challenges, in 2014, DOE's Wind Energy Technologies Office established six Regional Resource Centers to provide local stakeholders with unbiased, credible wind energy information. DOE's WINDExchange initiative (managed by NREL) supports states not covered by one of the regional organizations and also provides additional information to the regional centers. This report includes updates for each region and state on renewable portfolio standards, workforce development, and manufacturing and economic development as well as individual states' progress on installed wind capacity, ongoing policy developments, planned projects, and transmission progress reports. To date, these outreach efforts have resulted in contacts with more than 2.5 million people. NREL/TP-5000-67624. ***https://www.nrel.gov/docs/fy17osti/67624.pdf***

"Timescales of Energy Storage Needed for Reducing Renewable Energy Curtailment"

Paul Denholm and Trieu Mai

As the amount of solar and wind energy integrated into power grids increases, the incidence of reductions in the power production from these installations (curtailments) can also increase. During curtailments, which are often caused by transmission constraints, the output of the system is substantially reduced compared with what it could be producing given the available solar or wind resource. These events can negatively affect the value and cost-competitiveness of the project, and, as energy storage prices decline, interest in using storage to reduce curtailments and provide other grid support functions is growing. This report analyzes the storage duration required to cost-effectively reduce curtailment in grid scenarios with high penetrations of renewables and examines the value of different storage durations. The findings suggest that—at wind and solar penetrations up to 55%—at least half the potential avoided-curtailment benefits are realized with 8 hours of storage and the first 4 hours provide the largest benefit. NREL/TP-6A20-68960. ***https://www.nrel.gov/docs/fy17osti/68960.pdf***

"Reducing Wind Curtailment through Transmission Expansion in a Wind Vision Future"

Jennie Jorgenson, Trieu Mai, and Greg Brinkman

DOE's 2015 *Wind Vision* study analyzed an aggressive scenario in which wind power provides 35% of total U.S. electricity consumption in 2050. This report builds on this research by using a higher-fidelity modeling framework to investigate the operational feasibility of a similar high-wind future in the western United States. The analysis identifies no reliability issues in high-wind scenarios, but finds that transmission expansion to avoid reductions in power production (curtailments) due to transmissions constraints is likely to be critical. The findings indicate that wind curtailment could be reduced by approximately 50% by adding 10.5 gigawatts of new transmission, and that this avoided wind curtailment could lower annual production costs and reduce carbon dioxide emissions substantially. NREL/TP-6A20-67240. ***https://www.nrel.gov/docs/fy17osti/67240.pdf***

"Potential Offshore Wind Energy Areas in California: An Assessment of Locations, Technology, and Costs"

Walter Musial, Philipp Beiter, Suzanne Tegen, and Aaron Smith

The California coastline has technical offshore wind resource potential of 112 gigawatts, which corresponds to 392 terawatt-hours/year of potential energy production, about 1.5 times the state's electric energy consumption based on 2014 Energy Information Administration figures. This report identifies six California offshore wind areas that researchers use as reference sites to estimate the cost of floating offshore wind technology as well as the energy production potential at those locations. The authors also detail the limitations of this study, including, for example, that the modeled cost trajectory depends in part on continued global investments in offshore wind technology innovation and the emergence of a robust domestic and Californian supply chain similar to recent supply chain developments in Europe. In the relatively deep waters off the California coast, wind development will also be somewhat dependent on the development of floating (as opposed to fixed-bottom) wind technology, which is still an emerging technology but is advancing toward commercialization in both Europe and Asia. NREL/TP-5000-67414. ***https://www.nrel.gov/docs/fy17osti/67414.pdf***

"The Distributed Wind Cost Taxonomy"

Tony Jimenez, Robert Preus, Suzanne Tegen, and Ian Baring-Gould

Distributed wind systems serve local electricity loads ranging in scale from residential to industrial, and—although wind power is one of the fastest-growing sources of new electricity generation in the United States—factors including reduced incentives, low electricity prices, and competition from other renewable technologies have led to a contraction in the distributed wind market. Recent modeling from NREL identified the reduction of installed costs as a way to increase the competitiveness of distributed wind. Toward that end, this report describes the development of a peer-reviewed classification system or taxonomy to help stakeholders understand distributed wind costs in enough detail to guide decision-making. The value of creating a standard method or tool to analyze installed and operational costs is that a common understanding of cost details can help identify high-value cost-reduction opportunities, which could in turn help accelerate the deployment of distributed wind installations. Based on preliminary data, the Distributed Wind Cost Taxonomy has proven to be flexible and comprehensive enough to cover, categorize, and compare diverse, distributed wind turbine project costs. NREL/TP-5000-67992. ***https://www.nrel.gov/docs/fy17osti/67992.pdf***

"2015 Cost of Wind Energy Review"

Christopher Mone, Maureen Hand, Donna Heimiller, and Jonathan Ho, et al.

Maintaining an up-to-date understanding of wind energy cost trends and drivers is important because it provides insight into current costs as well as a basis for understanding the considerable variability in generation costs at both land-based and offshore wind facilities. This report—the fifth annual installment in the series—investigates the cost of land-based and offshore wind energy using empirically-derived and modeled data that represent 2015 market conditions. The authors identify the factors that influence the cost of wind-generated electricity and consider a range of specific variables that affect cost and performance and that might help explain the substantial difference in cost from one installation to another. The report further finds that both land-based and offshore wind costs continue to decrease, and the researchers estimate the relative contributions of various drivers of this decline in wind turbine prices since 2010. NREL/TP-6A20-66861. ***https://www.nrel.gov/docs/fy17osti/66861.pdf***

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NREL/BR-5000-70680 • January 2018