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Sandia National Laboratories

SANDIA WIND ENERGY PROGRAM

FY21 ACCOMPLISHMENTS

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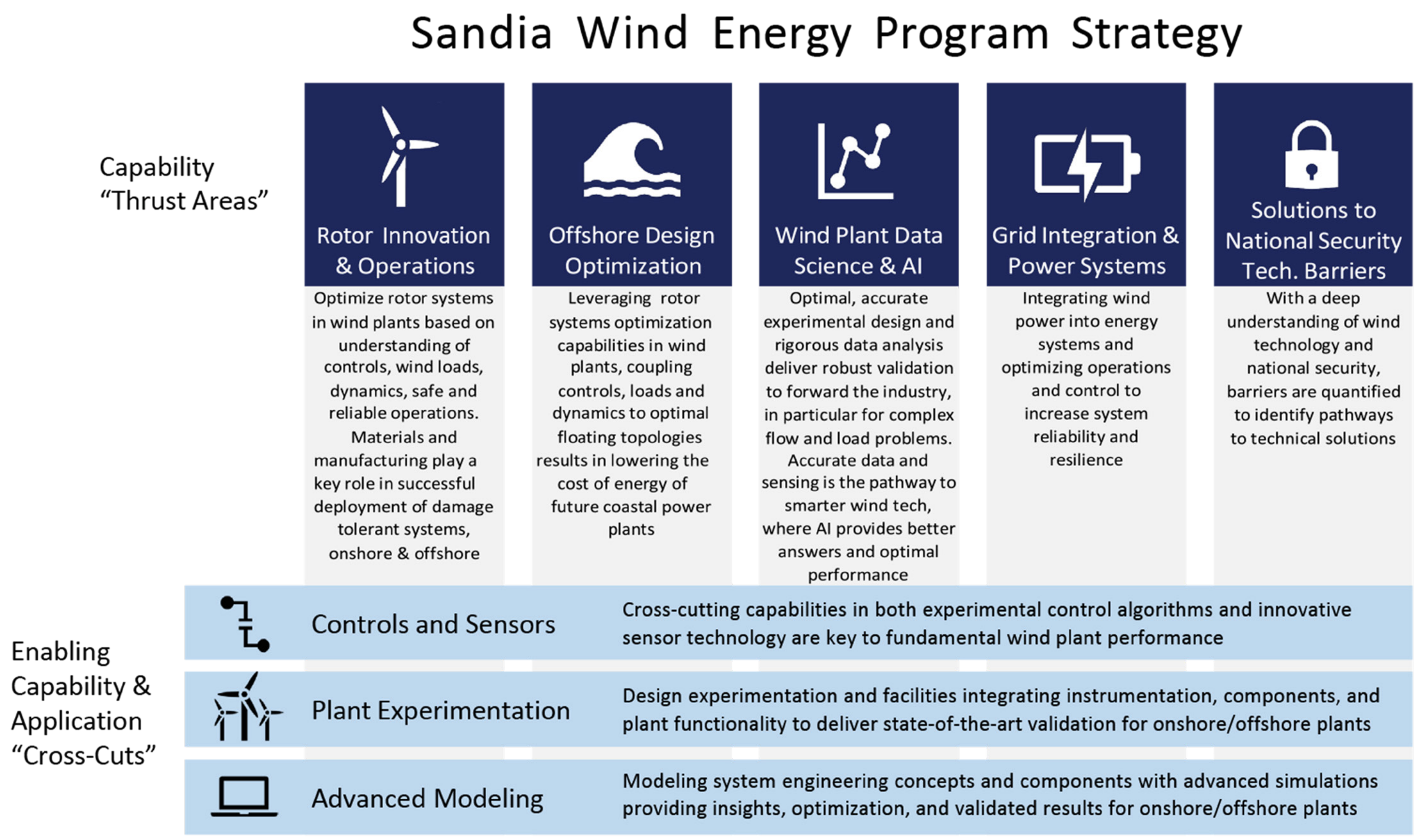
INTRODUCTION

Sandia's research and innovation in wind energy science enables a future that accelerates the global deployment and adoption of clean, renewable energy systems

This report summarizes Fiscal Year 2021 accomplishments from Sandia National Laboratories Wind Energy Program. The portfolio consists of funding provided by the DOE EERE Wind Energy Technologies Office (WETO), Advanced Research Projects Agency-Energy (ARPA-E), DOE Small Business Innovation Research (SBIR), and the Sandia Laboratory Directed Research and Development (LDRD) program. These accomplishments were made possible through capabilities investments by WETO, internal Sandia investment, and partnerships between Sandia and other national laboratories, universities, and research institutions around the world.

Sandia's Wind Energy Program is primarily built around core capabilities as expressed in the strategic plan thrust areas, with 29 staff members leading and supporting R&D at the time of this report. Staff from other departments support the program by leveraging Sandia's unique capabilities in other disciplines.

The Wind Energy Program currently structures research in five Capability Thrust Areas and three Enabling Capability and Application Cross-Cuts. The figure below illustrates the current Program strategy, developed in 2019.



Capability "Thrust Areas" and "Cross-Cuts"

CONTENTS

1. HIGHLIGHTS

1. HIGHLIGHTS

1.1. News Articles

Image credit: Randy Montoya

1.1.1. Carbon fiber optimized for wind turbine blades could bring cost, performance benefits

https://newsreleases.sandia.gov/carbon_fiber

ALBUQUERQUE, N.M. — A new carbon fiber material could bring cost and performance benefits to the wind industry if developed commercially, according to a study led by researchers at Sandia National Laboratories.

Wind blades containing carbon fiber weigh 25% less than ones made from traditional fiberglass materials. That means carbon fiber blades could be longer than fiberglass ones and, therefore, capture more energy in locations with low wind. A switch to carbon fiber could also extend blade lifetime because carbon fiber materials have a high fatigue resistance, said Brandon Ennis, a wind energy researcher at Sandia Labs and the principal investigator for the project.

Image credit: Brett Latter

1.1.2. New tool at Sandia brings some West Texas wind to the Duke City — virtually

https://newsreleases.sandia.gov/turbine_emulator

ALBUQUERQUE, N.M. — Researchers at Sandia National Laboratories have a new tool that allows them to study wind power and see whether it can be efficiently used to provide power to people living in remote and rural places or even off the grid, through distributed energy.

A new, custom-built wind turbine emulator has been installed at Sandia's Distributed Energy Technologies Laboratory. The emulator, which mimics actual wind turbines at Sandia's Scaled Wind Farm Technology Site near Lubbock Texas, will be used to study how wind farms behave under multiple weather conditions and load demands, and if they can be efficiently used as a source of distributed energy for consumers who live near the farms, according to Brian Naughton, a researcher with Sandia's Wind Energy Technologies program.

1.2. WETO R&D Newsletter Articles

1.2.1. Spring 2021 Edition: Webinar Series Improves Understanding of Offshore Wind Turbine-Radar Interference

As U.S. offshore wind energy project installations increase, so does the importance of understanding the challenges these projects present for government agencies and industries that use sensitive radar systems off U.S. coasts. Research indicates that wind turbines located within the line of sight of radar systems can cause interference, potentially resulting in poor performance of these radar systems. This degradation can present conflicts with radar missions related to air traffic control, weather forecasting, homeland security, and national defense.

Although there are currently only 42 megawatts of offshore wind energy installed off U.S. coasts, the market is primed to grow. To accommodate this growth, it is important that stakeholders understand the potential risk that wind turbines pose to radar systems before a problem arises.

To improve stakeholders' understanding of offshore wind turbine-radar interference, DOE, and Sandia National Laboratories (Sandia) held a series of webinars for the offshore wind industry, federal agencies, and radar experts.

The webinars were designed to build relationships among stakeholders, reveal government and industry perspectives on potential impacts of offshore wind on radar missions, and identify ways the federal government and industry can work together to mitigate these issues.

To learn more, visit https://www.energy.gov/eere/wind/articles/webinar-series-improves-understanding-offshore-wind-turbine-radar-interference.

1.2.2. Fall 2021 Edition: DOE Commissions Open-Source Wind Turbine for Wake Control Research

Wakes—turbulent and complex air flows behind wind turbine rotors—cause wind to slow down through wind power plants, resulting in energy losses. Wakes also represent physical evidence of the power each wind turbine extracts from the air.

Wake dynamics can be simulated and studied with the new DOE computational fluid dynamics (CFD) code Nalu-Wind, which is part of the ExaWind tool suite. The challenge is that these codes require experimental data to validate the accuracy of their predictions. However, commercial wind turbine performance and experimental data are proprietary and not readily available for validation of new computational codes, especially for wake data.

The National Rotor Testbed (NRT), an open-source wind turbine designed at Sandia National Laboratories (Sandia) to study wind turbine wakes, solves this challenge by providing all design documentation to facilitate CFD code validation and collaboration among DOE laboratory researchers and academic research partners.

To learn more, visit https://www.energy.gov/eere/wind/articles/doe-commissions-open-source-wind-turbine-wake-control-research.

1.3. Sandia News/Blog Posts

1.3.1. WETO supports reclamation of retired wind blade turbines

The Wind Energy Technologies Office is supporting an effort by the University of Tennessee, Knoxville researchers and partners at Carbon Rivers to develop a novel method of reclaiming fiberglass from retired wind turbine blades. To learn more about how this effort, and how work through Sandia National Laboratories' Blade Reliability Initiative is helping to close the loop on a circular economy for wind turbine components, read No Time To Waste: A Circular Economy Strategy for Wind Energy.

To learn more, visit: https://energy.sandia.gov/weto-supports-reclamation-of-retired-wind-blade-turbines.

Image credit: Brandon Ennis, Sandia

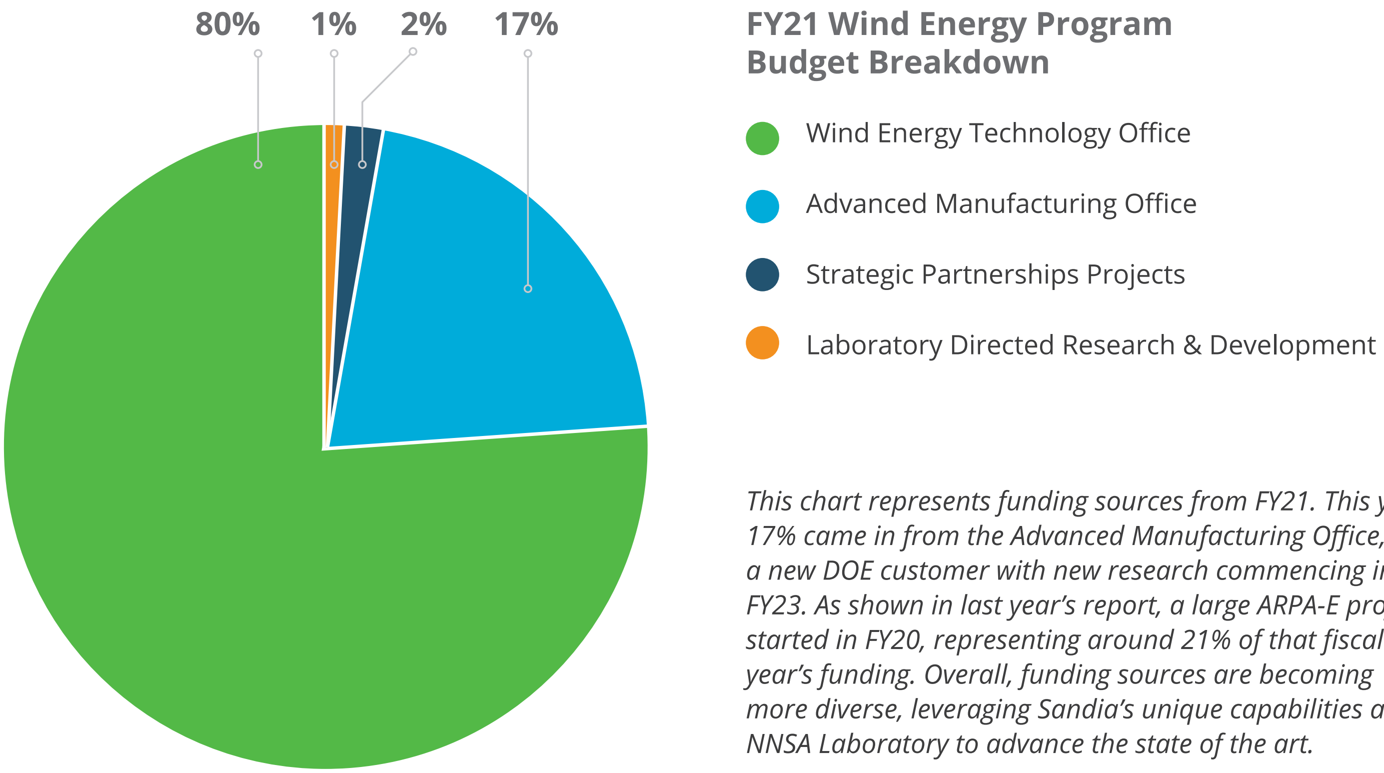
1.3.2. Webinar Series Improves Understanding of Offshore Wind Turbine-Radar Interference

To better understand the potential impacts of wind turbine radar interference, the Wind Turbine Radar-Interference Mitigation, or WTRIM, Working Group, led by Sandia National Laboratories' researcher Ben Karlson, hosted a series of six webinars for the offshore wind industry, federal agencies, and radar experts. Research indicates that offshore wind turbines can interfere with radar systems like those used for air traffic control, weather forecasting, and homeland security. Learn more in the Spring 2021 Wind R&D newsletter: Webinar Series Improves Understanding of Offshore Wind Turbine-Radar Interference.

To learn more, visit: https://energy.sandia.gov/webinar-series-improves-understanding-of-offshore-wind-turbine-radar-interference.

Image credit: Suzanne Tegen, NREL

1.4. Funding



This chart represents funding sources from FY21. This year, 17% came in from the Advanced Manufacturing Office, a new DOE customer with new research commencing in FY23. As shown in last year's report, a large ARPA-E project started in FY20, representing around 21% of that fiscal year's funding. Overall, funding sources are becoming more diverse, leveraging Sandia's unique capabilities as an NNSA Laboratory to advance the state of the art.

2. SWIFT FACILITY

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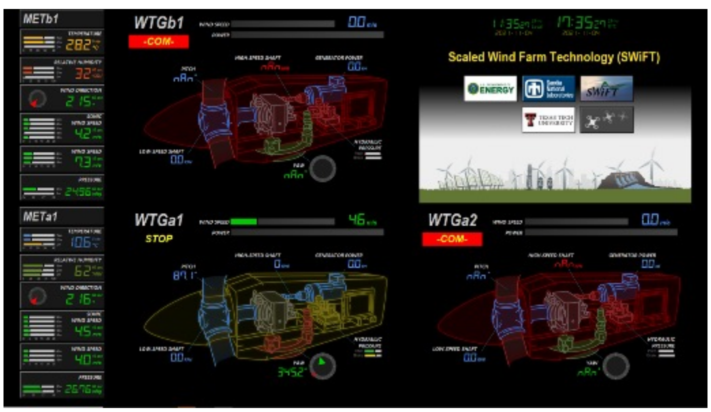
The Scaled Wind Farm Technology (SWiFT) team commenced with final commissioning of the National Rotor Testbed (NRT) Rotor on SWiFT Turbine A1. The team was able to do this with all COVID safety protocols in place. The team operated the turbine for the first time with the NRT rotor and was able to send power to the grid during the first two phases of commissioning.

Focusing on the continual improvement of site assets and infrastructure to meet the current and future needs of wind energy research, Sandia staff worked with several subject matter experts (SMEs) in the fields of meteorological (MET) tower electrical grounding and instrumentation to develop a plan for updates to the site's two MET towers. This will significantly improve data delivery reliability from the METs, as well as making the system more robust with regard to lightning strikes and other environmental stressors on the hardware.



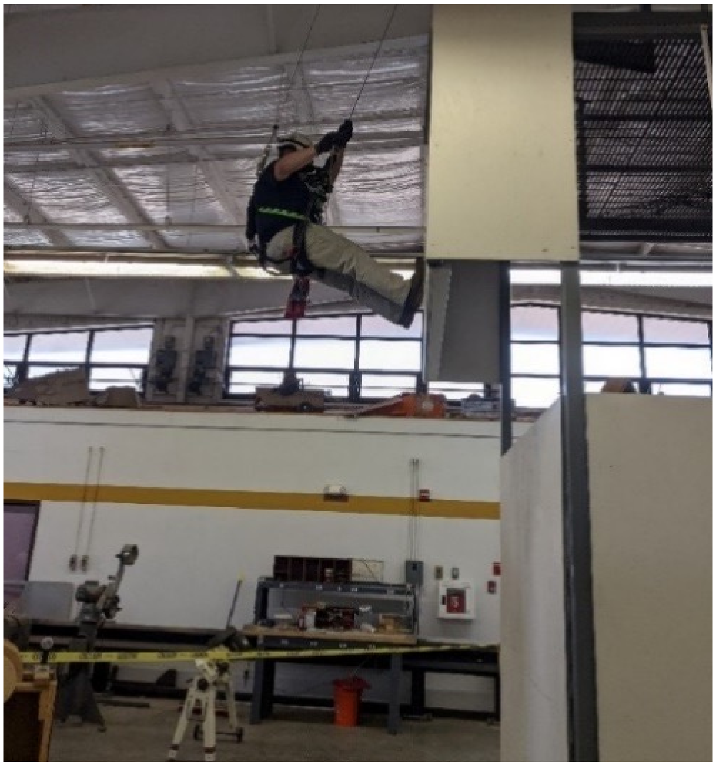
SCADA operational dashboard showing turbine and met tower operational parameters. Image credit: Jonathan Berg

Working towards remote operation of the SWiFT turbines, the SWiFT Supervisory Control and Data Acquisition (SCADA) capability was enabled. This provides the site and staff in Albuquerque, New Mexico, to visualize different turbine operational states, sensor messages and overall health of the turbine systems real-time, giving operators greater fidelity and faster access to critical turbine systems operation data in an intuitive format.

New switchgear with enhanced safety features to allow for safe switching to support experiments where SWiFT turbines are providing power to the TTU GLEAMM microgrid. Image credit: Brandon Davis

Continuing Sandia's strong partnerships with Texas Tech University (TTU) and Group NIRE, the power and communications intertie between the SWiFT Facility and the nearby TTU Global Laboratory for Energy Asset Management and Manufacturing (GLEAMM) facility was completed. The installation of a switchgear purchased and provided by Sandia now will allow the SWiFT wind turbines and the GLEAMM microgrid assets to operate together either in a grid-connected configuration or to disconnect from the grid and operate in an islanded mode.

Sandia also entered into a new partnership with the South Plains College (SPC) Industrial Manufacturing and Engineering Technology (IMET) program. Its specialty area is renewable energy and wind technician training. Sandia provided an opportunity for a graduating student to work with the site team over the summer term, which provided the student real-world experience in wind turbine operations and maintenance.



Sandia staff participating in rescue training on the purpose-built rescue tower at South Plains College. Image credit: Rami Katrib

The partnership with SPC has also led to Sandia SWiFT personnel now using SPC's climb tower in Building 6 on the Reese Technology Center, providing SWiFT climbers with a purpose-built training platform to conduct annual climb rescue training recertification, and testing of new rescue techniques.

The Sandia Field Office (SFO) representative for the SWiFT Facility visited the site to gain an understanding of site operations, safety, and overall improvements and challenges the site has experienced since the last SFO visit in 2017. The SFO representative safely climbed Turbine A2 for an overview of turbine systems.

For more information on SWiFT Facility and research capabilities, visit https://energy.sandia.gov/programs/renewable-energy/wind-power/swift-facilities.

3. ROTOR INNOVATION & OPERATIONS

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3.1. Rotor Wake

The Rotor Wake project focuses on targeted data acquisition and analysis to address pressing validation needs and answer crosscutting science questions that have emerged with recent advances in wind energy science and technology. Through the design and execution of field experiments, this project produces high-quality, high-fidelity, and low-uncertainty data sets that address the validation needs of wind turbine and wind plant simulation tools across fidelity levels. Fiscal year 2021 efforts were focused on experiments for validation including the National Rotor Testbed (NRT) and the Rotor Aerodynamics, Aeroleastics, and Wakes (RAAW).

3.1.1. RAAW

RAAW experimental turbine, approximately 3 MW, near Reese Technology Center to be site of new validation experiment. The CRADA has formally been executed between Sandia, NREL, and GE. Image credit: Chris Kelley

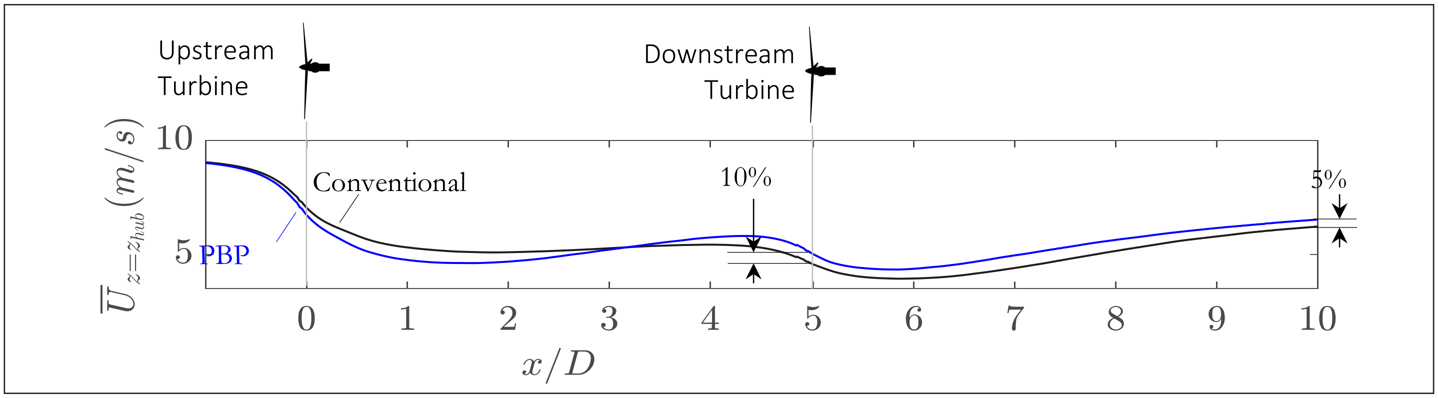
The RAAW experiment is a collaboration with NREL and General Electric (GE) under a recently executed Cooperative Research and Development Agreement (CRADA) to conduct a highly instrumented wind turbine experiment that will be used for validating DOE wind turbine simulation codes. This partnership allows the national laboratories to conduct an experiment on a 2.8 MW prototype wind turbine and bring their own expertise in wind turbine instrumentation to fully characterize the inflow, turbine loads, and wake all in one dataset. This dataset will be used to validate a range of DOE and GE wind turbine simulation codes, from engineering to high fidelity models.

Sandia provided design and uncertainty quantification expertise to major instrument systems in development for the RAAW experiment. The Sandia Photometrics Calculator was used to evaluate the resolution of a new photogrammetry system that will be used to measure blade deflection and twist during the experiment, a key data set to validating the performance of flexible wind turbine blades. The tool is also being used for camera placement to find the optimal stereo angle to reduce measurement uncertainty for varying wind directions. Sandia also analyzed CFD simulation data to evaluate the Danish Technical University SpinnerLidar for high spatial resolution inflow measurements upstream of the GE turbine. The analysis showed this to be an ideal instrument to use as a detailed inflow measurement of the entire rotor disc because it correlates inflow turbulence to local blade loads. The team plans to procure a SpinnerLidar for deployment in Fiscal Year 2022.

3.2. National Rotor Testbed

The NRT experiment has completed all commissioning tests necessary to produce power and operate. The NRT commissioning progress was featured in the Fall 2021 Wind R&D Newsletter. Data analysis has been performed including the quantification of the coefficients of thermal expansions for all the NRT blade strain gages. This allows researchers to calculate the distribution of aerodynamic bending forces along the blade spans, and to show that the NRT produces the scaled wake of a MW-scale wind turbine.

Simulations of the NRT were also performed this year regarding wake control strategies. Active wake mixing was simulated in the DOE code Nalu-Wind, where NRT blades were harmonically pitched at an optimal frequency to mix the wake more rapidly with the freestream. The wake mixing effect was enhanced even in turbulent conditions, showing promise to increase wind plant performance and reduce array losses.



Results of active wake mixing simulation showing 6% power increase (10% velocity increase) of waked turbine 5D downstream, simulated in NALU with 6% turbulence intensity. Image credit: Brown et al., "Towards Periodic Blade Pitching to Increase Deep Array Power in Wind Plants," Wind Energy Science Conference 2021.

3.3. Blade Durability and Damage Tolerance

The Blade Durability and Damage Tolerance project develops tools and experimental data sets to improve the reliability of wind blades. The work is divided into six tasks: remote inspection methods, effects of defects and repairs, blade life value modeling, lightning effects on carbon fiber, leading edge erosion, and damage accumulation monitoring.

ARROW[(e)] system being tested on wind blade. Image credit: Dennis Roach

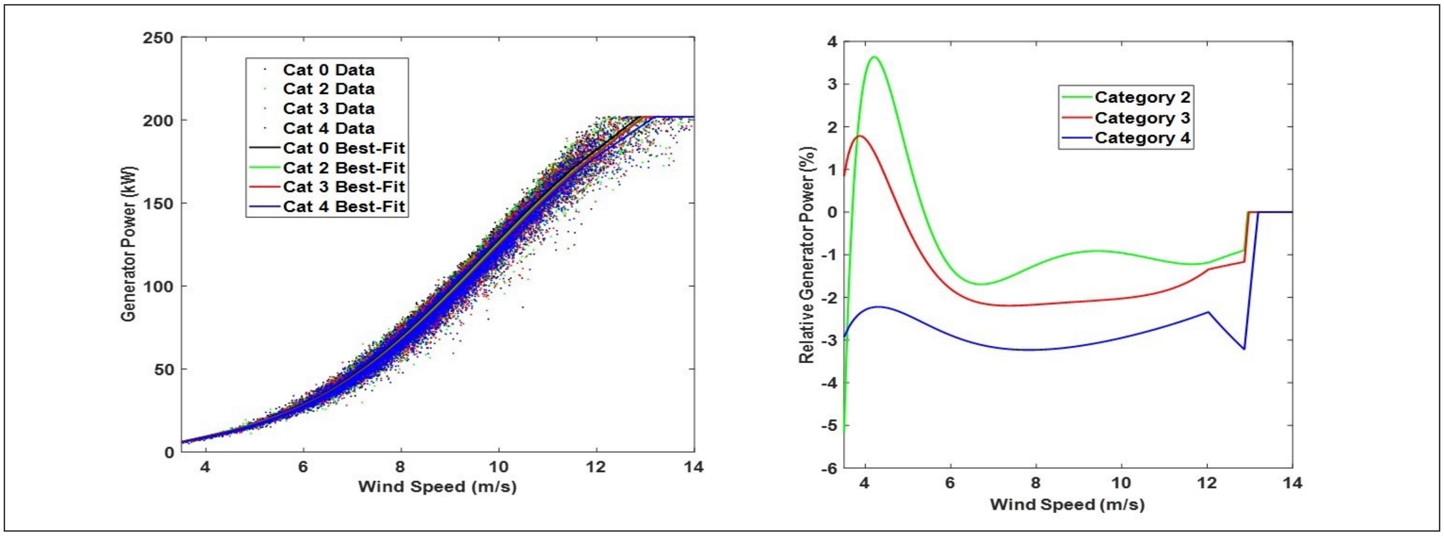
The Remote Inspection task completed controls integration, the addition of a marking system, and user documentation for the Assessment Robot or Resilient Optimized Wind Energy (ARROW[(e)]) Non Destructive Inspection (NDI) robotic crawler system. The ARROW[(e)] system employs advanced inspection technology to find damage on blades to evaluate optimal repair strategies. Two years of work on this system resulted in a $1M award from the DOE Technology Commercialization Fund in Fiscal Year 2021 with matching cost share from an industrial partner to commercialize this system for deployment on wind systems.

The team completed a report entitled "Alternative Damage Tolerant Materials for Wind Turbine Blades: An Overview." This document summarizes opportunities for a different design approach to wind blade structures and materials. This subject was presented virtually at the 2021 Wind Energy Science Conference. Additionally, significant testing and analysis of a solvent that improved wind blade repairs was completed, demonstrating improved strength and reliability. The results of this work will be published as part of a doctoral thesis.

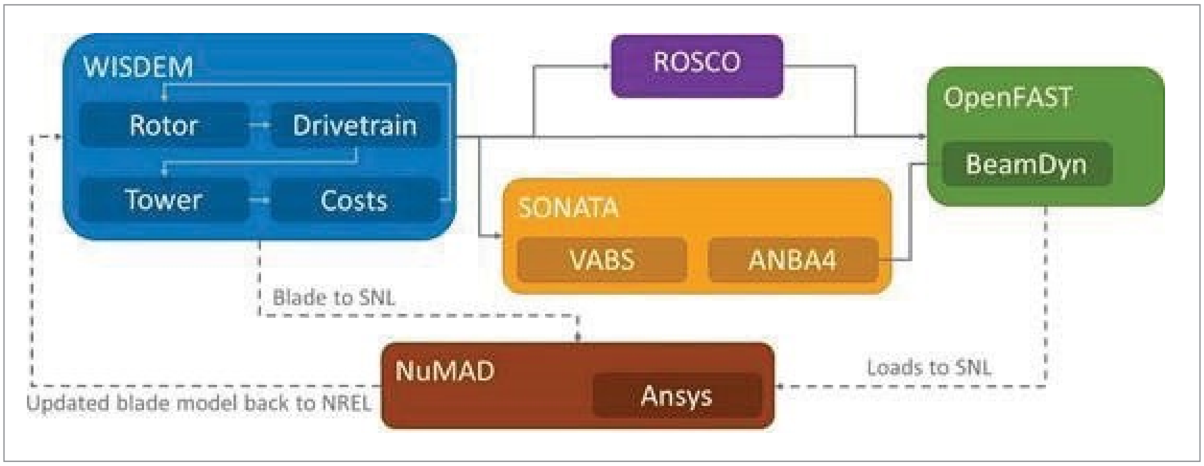
The Blade Life Value Model task sponsored participation in IEA Wind Task 43: Digitalization, to connect DOE-funded work with international research efforts. As part of this international effort, Sandia developed a novel leading edge erosion predictive model that connects field inspection data to validated physics models.

The Leading Edge Erosion task played a major role in initiating IEA Task 46: Erosion of blades. As part of this effort, Sandia is leading two of the four task areas: Climatic Conditions Affecting Erosion and Operations under Erosion. In addition to the IEA work, an initial analysis of a partner wind farm was completed and presented at AIAA SciTech and the 2021 Wind Energy Science Conference.

The Damage Accumulation Monitoring task developed a wind blade load estimation algorithm using state estimation and Kalman filtering. After evaluation, the Sandia team transitioned to an artificial neural network system to estimate damage equivalent loads, which was trained with both FAST simulation data and field data from the SWiFT site.



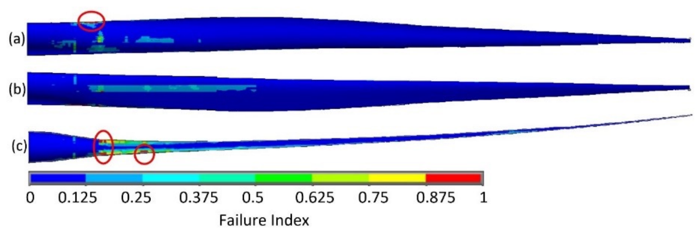
Probabilistic simulations of performance degradation from leading edge erosion. Image credits: David Maniaci



Integrated Rotor Design Tools. Image Credit: Pietro Bortolotti, National Renewable Energy Laboratory

3.4. Big Adaptive Rotor (BAR)

The Big Adaptive Rotor (BAR) project is led by Sandia with partners National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), and Lawrence Berkeley National Laboratory (LBNL). The objective of this project is to identify the needed science and technology required to build the next generation of high energy capture rotors. Phase I of the project was completed in Fiscal Year 2021, with the publication of a final report documenting the results of design studies on five reference models. The development of these models was the result of a collaboration between Sandia and NREL that combined the NREL WISDEM code for system optimization with the Sandia NuMAD code for detailed blade structural optimization. Through development of these models, the team was able to identify several validation needs for the wind industry going forward, developing a multi-year Phase II project plan for DOE. In addition to the final report, two journal articles were authored and co-authored by Sandia covering the design and optimization of highly flexible, rail transportable blades. Additionally, three presentations were given at the 2021 Wind Energy Science Conference on the topics of uncertainties in composite laminate strength predictions, design of a bi-wing blade with partial-span pitch control, and modeling of active flow control devices.

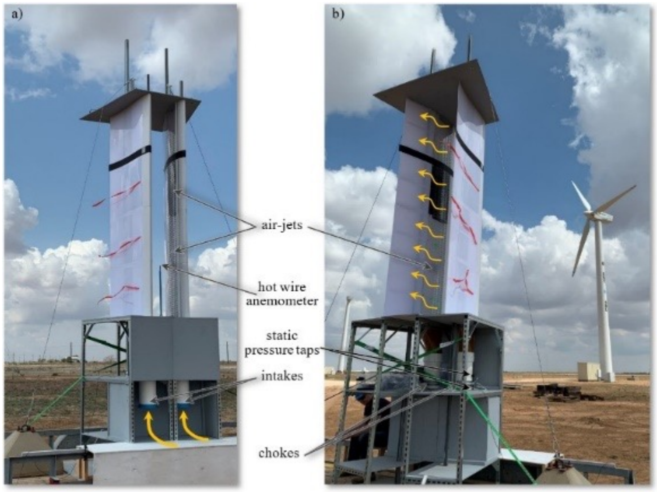


Failure analysis of BAR highly flexible downwind blade with optimized carbon fiber. Image credit: Ernesto Camarena

Finally, through a collaboration between Sandia and ORNL, a novel, heavy-tow carbon fiber material was developed, characterized, and analyzed in the design of the BAR blade designs. The material was found to provide exceptional properties for the anticipated cost.

3.5. AeroMINE [Sandia LDRD]

A pilot-scale (3 m tall) AeroMINE was built and tested at SWiFT in September 2020 and April 2021 as part of an LDRD-funded project. Major outcomes included the proof-of-concept at scale, and demonstration of negligible dependence to more than 30 degrees off-axis wind direction in low wind conditions. These findings were presented at the 2021 Wind Energy Science Conference. A year-round intern researched the optimal internal turbine design. She presented her work at the 2020 APS Division of Fluid Dynamics annual conference and published findings in the 2021 AIAA Propulsion and Energy Forum proceedings. She has since joined Sandia as a postdoc to work on HydroMINE optimization through an ARPA-E funded project. An Academic Alliance partnership with the University of Illinois, Urbana-Champaign was initiated with Professor Andres Goza's group.



Pilot-scale testing AeroMINE at SWiFT shown from front and behind. Image credit: Sandia, B.C. Houchens

A patent was awarded on the optimization of AeroMINE (US 11,047,360 B1) and AeroMINE won an R&D100 award in the Mechanical/Materials category.

Arctic and Alaska engagement was furthered through exploration of the potential of AeroMINE as an alternative generation source for reducing diesel fuel to power remote DOE/DoD outposts. This includes potential icing testing on the North Slope and exploring potential collaboration with remote communities in Alaska under existing DOE funded activities.

4. OFFSHORE DESIGN OPTIMIZATION

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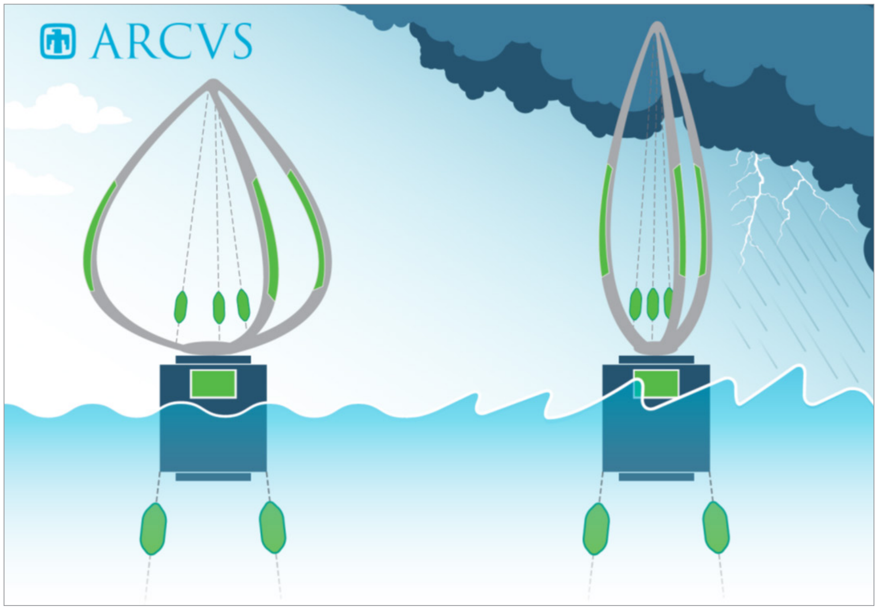
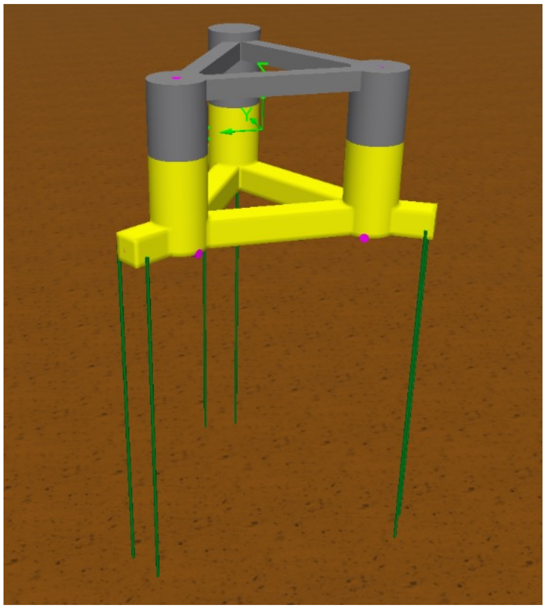
4.1. ARCUS Vertical-Axis Floating Offshore Wind Turbine Design and Optimization

The ARCUS project team has made substantial progress in developing the simulation and design capabilities for advanced control co-design of floating offshore wind turbines, funded by the Advanced Research Projects Agency-Energy (ARPA-E). The project team performed a detailed scaling analysis to reveal the sensitivities of the system levelized cost of energy (LCOE) with the turbine size.

Project partner FPS Engineering & Technology completed detailed design studies to identify an optimal architecture for the project's tension-leg platform (TLP). A three-column TLP has been found to result in the lowest cost platform that enables quayside integration of the turbine, considering tow-out stability of the Vertical Axis Wind Turbine (VAWT)-TLP system. As part of the scaling analysis, FPS designed platforms for three turbine sizes with 1x, 2x, and 4x rotor swept areas. The platform paired with the largest rotor was found to also have the lowest mass and cost, making this size the optimal point for LCOE minimization within the study sizes. Mass (and cost) relationships of the three-column TLP have been determined through a minimum scantling design process, and these relationships will be used to identify the dimensions of the platform that result in the lowest cost through numerical optimization of five dimensional variables. Work has begun to integrate Sandia's Rapid Optimization Library (ROL) into the Julia programming language to enable this extensive optimization package to be used for floating offshore wind, with methods identified using this subsystem test case.





The ARCUS vertical-axis wind turbine will be designed concurrently with a three-column tension-leg platform, identified as the optimal platform architecture. Image credit: Left, Brandon Ennis; Right, FPS Engineering & Technology

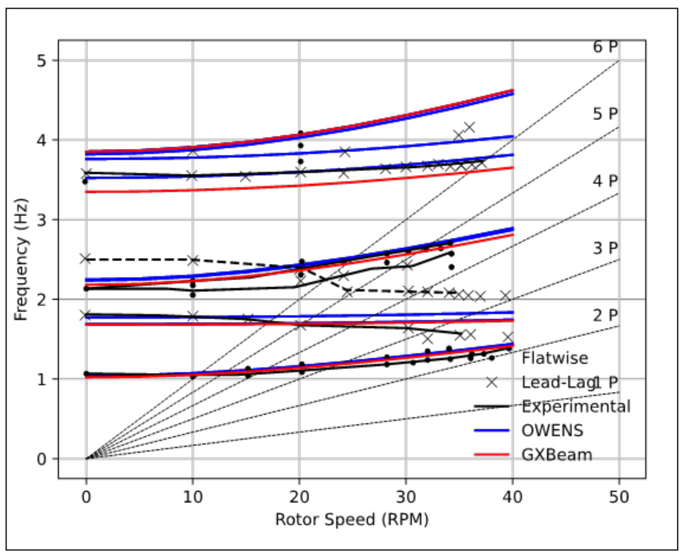
The ARCUS vertical-axis wind turbine will be designed concurrently with a three-column tension-leg platform, identified as the optimal platform architecture.

The analysis tools required for simulating a VAWT are greatly limited and there is no publicly available tool with the coupled, multi-physics models necessary for the accurate design of a floating VAWT. The Offshore Wind Energy Simulator (OWENS) design tool developed by Sandia is an aero-hydro-servo-elastic analysis tool that enables the design and concurrent system optimization of the ARCUS floating VAWT. This development has progressed to include the coupled physics of topside and bottom-side forcing and the simulation of representative turbulent wind conditions.

A comprehensive validation plan is being executed which includes comparison of OWENS predictions to known analytical solutions, experimental data, and to validated tools. The structural model in OWENS has been validated using a simple cantilevered beam for static and rotational test cases and compared to a higher fidelity tool. The aero-elastic performance of OWENS is being compared to experimental data from the legacy Sandia 34m VAWT testbed, found in technical reports through a rigorous review. OpenFAST modules HydroDyn and MoorDyn have been coupled to OWENS, in partnership with NREL, and a representative test case is being used to compare predicted platform forces and hydro-elastic motions to OpenFAST results. A pre-processor has been developed which generates the mesh of a platform, applies the boundary element method to the mesh to calculate its hydrodynamic coefficients, and combines these coefficients with a user-defined wave model and mooring forces to calculate the total forces acting on the platform.

Experimental data from the legacy Sandia 34m VAWT testbed are being used as part of the validation plan of the OWENS aero-hydro-servo-elastic design tool.

The design and optimization capabilities, as well as the detailed system models, will be used to perform full system, control co-design of the ARCUS floating VAWT to achieve the ATLANTIS program LCOE target of less than $75/MWh with trusted analysis predictions. The project team will begin performing design studies of the novel ARCUS rotor and developing advanced optimization approaches to move towards the full system design optimization of the ARCUS rotor, floating platform, and control methods.

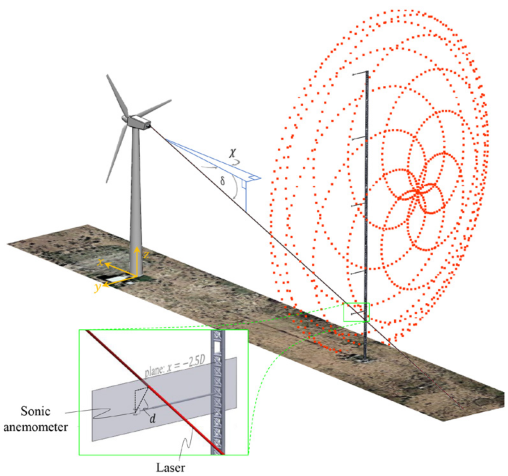


Experimental data from the legacy Sandia 34m VAWT testbed are being used as part of the validation plan of the OWENS aero-hydro-servo-elastic design tool. Image credit: Top, Sandia National Laboratories; Bottom, Kevin Moore

5. WIND PLANT DATA SCIENCE & ARTIFICIAL INTELLIGENCE

5. WIND PLANT DATA SCIENCE AND ARTIFICIAL INTELLIGENCE

5.1. Verification & Validation/ Uncertainty Quantification



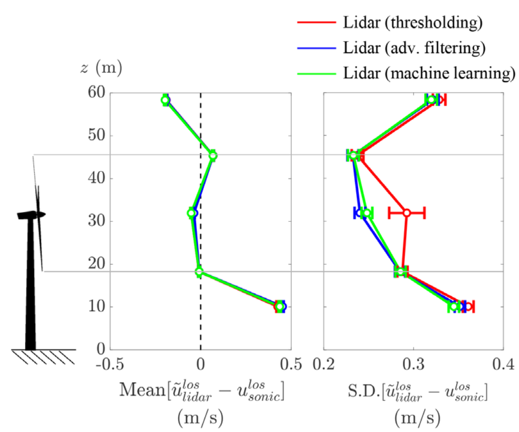
Rendering of SWiFT A1 turbine and met tower A1 used for the lidar uncertainty quantification study. Image credit: Kenneth Brown

The Verification, Validation, and Uncertainty Quantification (V&V/UQ) project ensures that the predictive capability of the suite of computational models being developed across the Atmosphere to Electrons (A2e) program is established through formal verification, validation, and uncertainty quantification processes. Multi-million dollar decisions are made using computational models for wind energy applications; this project establishes the processes to build trust in these models. It is accomplishing this goal by coordinating validation activities across A2e, developing and applying formal V&V/UQ processes, and ensuring that any V&V gaps are addressed.

Uncertainty Quantification (UQ) is critical for quantitative model validation focused on enabling predictive numerical simulations in research studies and advanced engineering design, as it codifies the assimilation of observational data; the characterization of errors, uncertainties, and model inadequacies; and forward predictions with confidence for untested / untestable regimes.

In Fiscal Year 2021, a wake validation journal paper was published, which covers a completed validation study of Nalu-Wind, part of the ExaWind code suite, for wake deficit strength and deflection under neutral inflow conditions using experimental data from the SWiFT facility. Several papers were presented at the 2021 AIAA SciTech conference, including the topics of offshore ABL simulations, multilevel-multifidelity uncertainty quantification with Nalu-Wind, and Optimization Under Uncertainty (OUU) with WindSE. Additionally, a session on wind energy uncertainty analysis was organized for the conference. The use of state-of-the-art algorithms for the large-scale, multilevel-multifidelity forward uncertainty quantification propagation of Nalu-Wind and efficient low-fidelity auxiliary models were also explored in 2021.

An enhanced forward UQ workflow was developed by integrating wake analysis capabilities into the multifidelity UQ methods for high fidelity models. The work was presented at the 2021 Wind Energy Science Conference, along with several other papers on actuator model verification, higher-order methodology for lidar based validation, and the effect of refined mesh lead-in length on modeling rotor quantities in an atmospheric boundary layer.



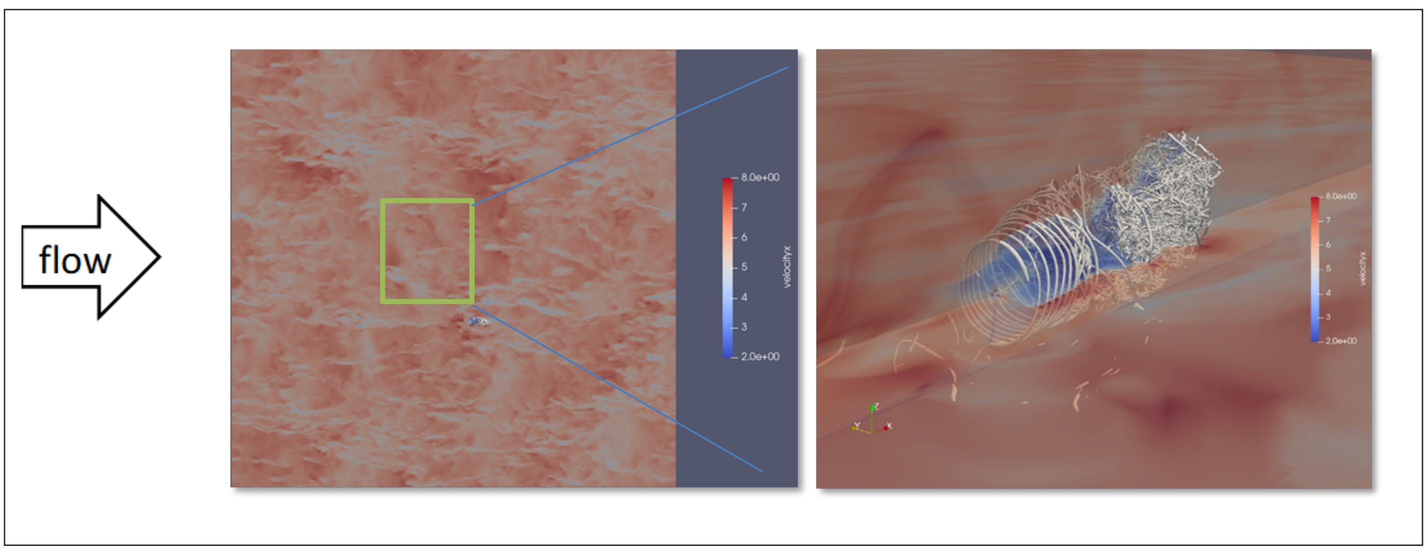
Aggregate results for the lidar uncertainty quantification study from inflow cases for (left) mean error and (right) root-mean-square error plotted versus height off the ground with the dimensions of a V27 turbine.learning techniques increase to 0.3 to 0.5 m/s for waked cases. Image credit: Kenneth Brown

Additionally, two methods for the high-fidelity processing of nacelle-mounted lidar data have been developed and compared to a conventional method, with the goal of estimating the uncertainty for use in validation studies and experiment design. The first method (termed Advanced Filtering) has been previously applied, and a novel method leveraging machine learning for reduced uncertainty has been developed to explore relative performance for challenging lidar data analysis scenarios. The work describes the first-time development of a machine learning approach to process noisy, contaminated lidar data, and results are generally better than the reference quality assurance/ quality control thresholding algorithm. A manuscript is being developed, with plans to submit to a journal for publication in Fiscal Year 2022.

5.2. High Fidelity Modeling (HFM)

The joint Sandia-NREL High-Fidelity Modeling (HFM) project is funded out of the DOE Wind Energy Technologies Office's A2e program and is closely affiliated with the ECP-funded ExaWind project. HFM is focused on developing, verifying, and validating the models, numerical algorithms, and software engineering embodied in the Nalu-Wind, AMR-Wind and OpenFAST codes that are necessary for predictive offshore and land-based wind farm simulations.

To date, HFM has implemented and validated state-of-the art models for wind turbine simulations, including turbulence models for blade-resolved simulations, fluid-structure interactions, complex terrain, and advanced actuator lines. During Fiscal Year 2021, HFM established a baseline hybrid-RANS/LES capability appropriate for both land-based and offshore blade-resolved simulations, implemented a new stress-type boundary condition in Nalu-Wind, and evaluated the performance of the immersed boundary capability for wall-modeled large-eddy simulations in complex terrain. HFM also demonstrated the capability of the hybrid AMR-Wind/ Nalu-Wind code suite to simulate a single, utility-scale wind turbine geometry immersed in atmospheric boundary layer turbulence. An initial validation using IEA Task 29 NM80 turbine measurements was also performed, with more work to be done in Fiscal Year 2022.

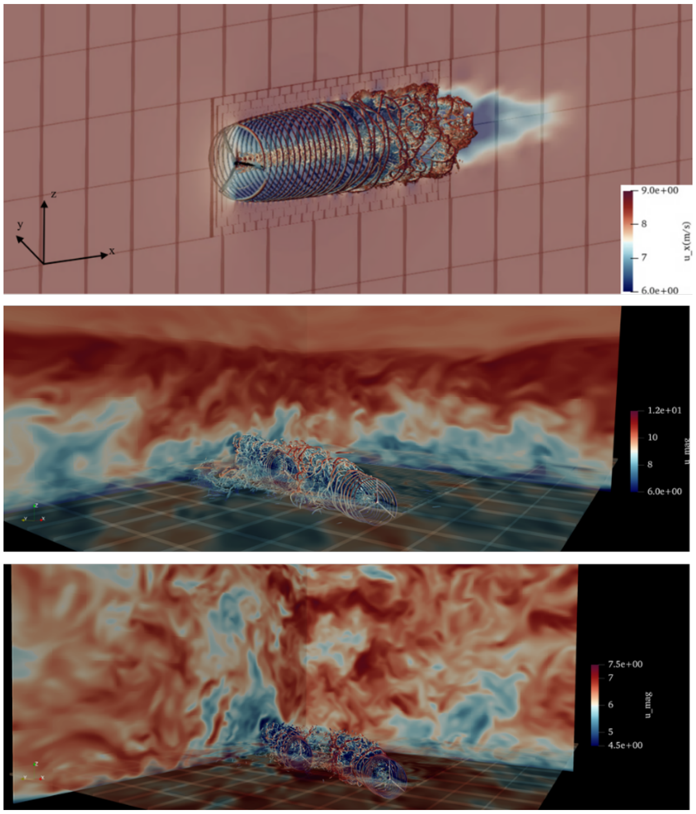


Contour slice: Instantaneous velocity in flow direction Isosurface: Q (an indicator of vortical structures).
Image credit: Ganesh Vijayakumar, National Renewable Energy Laboratory

5.3. ExaWind

The multi-institutional (NREL, Sandia, ORNL, University of Texas at Austin) ExaWind project is part of DOE's Exascale Computing Project (ECP) and aims to create a computational fluid and structural dynamics platform for exascale predictive simulations of wind farms. The ExaWind project is closely affiliated with the HFM project that is funded by the DOE Wind Energy Technologies Office's A2e program.

During Fiscal Year 2021, ExaWind's marquee accomplishment was a blade-resolved simulation of two turbines in uniform flow using the hybrid AMR-Wind/Nalu-Wind solver, which sets the early stage for ExaWind's wind farm challenge problem, which ECP has targeted for completion in Fiscal Year 2023. Many improvements were made to the Trilinos and hyper linear-system solvers during Fiscal Year 2021 with performance evaluated on CPU and GPU based systems, including OLCF Summit, NREL Eagle, and Spock, the Frontier precursor. The new Active Model Split (AMS) turbulence model was improved, and a turbulent flow transition model was added.



Isocontours of Q-criterion with velocity visualized in the wake for NREL 5-MW turbine(s) operating under uniform inflow wind speed of 8 m/s. Image credit: Ashesh Sharma, National Renewable Energy Laboratory

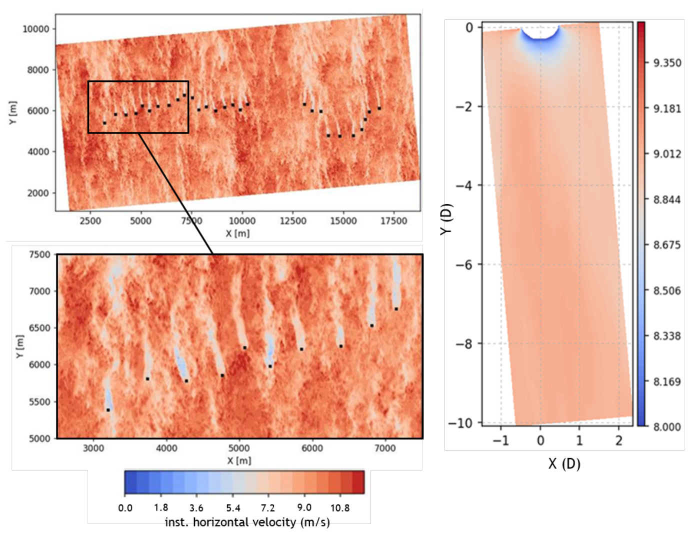
5.4. AWAKEN

The American WAKE experimeNt, or AWAKEN, is a landmark international wake observation and validation campaign occurring in north central Oklahoma. The AWAKEN project will provide the validation data to improve our understanding on the interaction between the atmosphere and wind plants. Specifically, improving the available validation data in the areas of momentum transport between the atmosphere and wind plant, turbulence development within the plant, upstream wind plant blockage, wind plant wakes and their effects on downstream plants, and control strategies to improve wind plant performance. This year, as part of the AWAKEN project, Sandia focused on design for the experiment and instrumentation layout, and along with the team, had an initial site visit. Sandia also led the creation of the Wind Energy Instrumentation Development Roadmap (published in Fiscal Year 2022) and performed high-fidelity Nalu-Wind simulations to look at the effect of wind plant blockage for field campaign planning.

A major accomplishment this year toward the successful execution of the AWAKEN field test was working with the team to develop the experimental plan and instrumentation layout for the start of the experiment in mid- Fiscal Year 2022. The team participated in a site visit to evaluate the wind farm layout and terrain to determine good locations for instrumentation in the vicinity of the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site.

The Wind Energy Instrumentation Development Roadmap provides recommendations for instrumentation development to narrow the gap between the current fidelity of measurements and the higher-fidelity simulations that are currently possible. The gap that exists between measurements and simulations creates a hurdle for validating and assessing the quality of the wind plant numerical models. The roadmap is a powerful resource for determining instrumentation that can capture the important phenomena at the necessary resolution for both the science goals and validation needs of wind energy field campaigns and where gaps in instrumentation exist. A recommendation on instrumentation for development was provided and the framework developed through this process can be applied to future field test design, such as offshore wind energy campaigns. The report will be published in early Fiscal Year 2022. An overview of the development framework was presented at the 2021 AIAA SciTech conference.

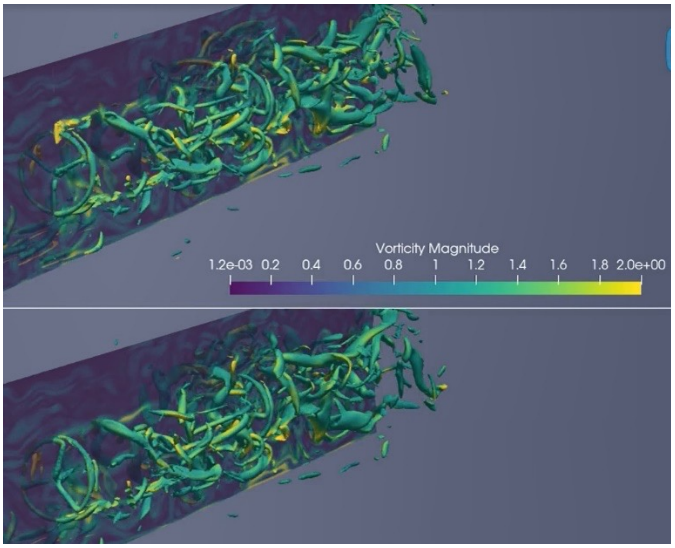
High-fidelity Nalu-Wind simulations focusing on wind plant blockage were run of a wind plant near the ARM SGP site. The simulations used an unstable atmospheric stratification, matching common atmospheric conditions to what occurs at the ARM SGP site. The figure below shows an instantaneous snapshot of the horizontal velocity field through the wind plant in addition to the average effect of blockage on the horizontal wind speed near the wind turbines. These results will be used to determine how well the planned instruments can capture wind plant blockage. Additional simulations using stable atmospheric stratification and an additional wind plant in the region will further help the planning and data analysis in the coming year.



Nalu-Wind simulations of 28 wind turbines in the western part of the study area with an unstable atmospheric stratification matching similar atmospheric conditions to what occurs in the region. The top left shows an instantaneous snapshot of all 28 wind turbines with a zoomed in view on the bottom left. The image on the right shows the averaged effect of wind turbine blockage on the horizontal velocity for all 28 wind turbines. Image credit: Lawrence Cheung

5.5. SPIRE [Sandia LDRD]

Sandia National Laboratories provides competitive funding through its Lab Directed Research and Development program, or LDRD. Among these opportunities is the Exploratory Express award intended for short studies to de-risk new ideas that have not previously been researched. In Fiscal Year 2021, an Exploratory Express was awarded to a staff member in the wind department to evaluate the technical basis of a nacelle mounted spire for accelerated wind turbine wake decay that may result in increased wind farm power density.



Snapshot of isosurfaces of Q criterion colored by vorticity magnitude. Top: Large cylinder (yellow part at top of rotor plane). A tip vortex can be seen passing unperturbed through the spire. Bottom: Baseline case. Image credit: Daniel Houck

It is well known that wind turbine wakes are characterized by helical tip vortices that are highly stable at first and act as a shield against mixing with the ambient flow and thereby delay wake recovery. These vortices will naturally breakdown, usually due to destructive interference with one another. The idea behind the spire was fairly simple: place an obstruction in the flow forcing the tip vortices from their usual paths and closer to each other to begin their destructive interference sooner in the wake. Accelerated wind turbine wake decay allows for increases in the power density of wind farms and can increase the lifetimes of the turbines.

The project team used the SNL-developed code, Nalu-Wind, to perform five high-fidelity simulations of four possible spires and a baseline. To address the large parameter space, two spire cross-sections were simulated: a circle and a thin symmetric airfoil, and two characteristic sizes for each. The size differences also changed how close behind the rotor they were positioned and analyzed their wakes and the power production of a downstream turbine.

The results showed essentially no effect on the wake of the upstream turbine with the spire or the power of a downstream turbine for any of the four spire designs. In particular, these simulations suggest that mesh resolution can have a large effect on the propagation of tip vortices and higher resolution is likely necessary. Next steps include a provisional patent filing and seeking additional opportunities for further research on this concept.

A conceptual illustration of a possible spire design. Image credit: Nathaniel deVelder

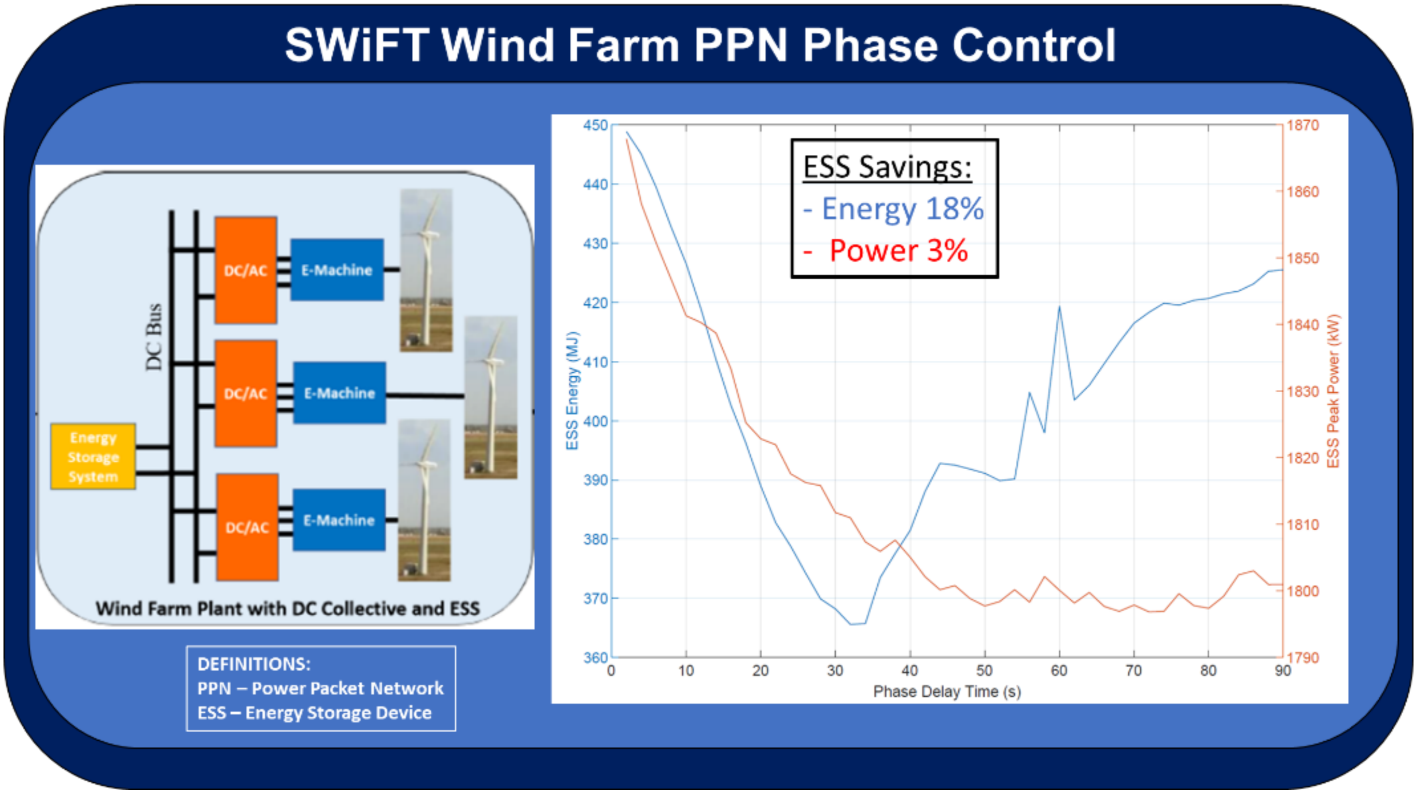
6. GRID INTEGRATION & POWER SYSTEMS

6. GRID INTEGRATION & POWER SYSTEMS

6.1. Wind Farm Controls

The technical approach for this project develops representative reduced order models (ROM's) that capture the critical coupled dynamics of wind turbine/wind farm mechanical-electrical systems and develops an advanced nonlinear control and agents/informatics architecture that seamlessly integrates and harmonizes Energy Storage Systems (ESS). The nonlinear control design encompasses a distributed/decentralized approach that identifies where and how much ESS is required to operate efficiently. The mechanical-electrical wind turbine coupled models concentrated on Type IV generator systems as part of a DC or AC collective interface for the wind farm into the electric power grid.

In Fiscal Year 2021, Power Packet Network (PPN) phase control designs improved our system metrics. Novel PPN phase controls showed: increased pay-off for ESS savings in both reductions in energy and power requirements (Figure below), identified power electronic (N-2) component reductions, and efficient increases in wind farm power quality. The DC collective case is based on a calibrated ROM from the SWiFT Facility. Realistic wind inputs were generated with Sandia's high fidelity Nalu-Wind and NREL's FAST farm codes for all three wind turbines. The final stage of the project will concentrate on offshore wind applications under realistic conditions. Our results will help guide the wind community regarding wind farm controls that increase performance and grid resiliency.



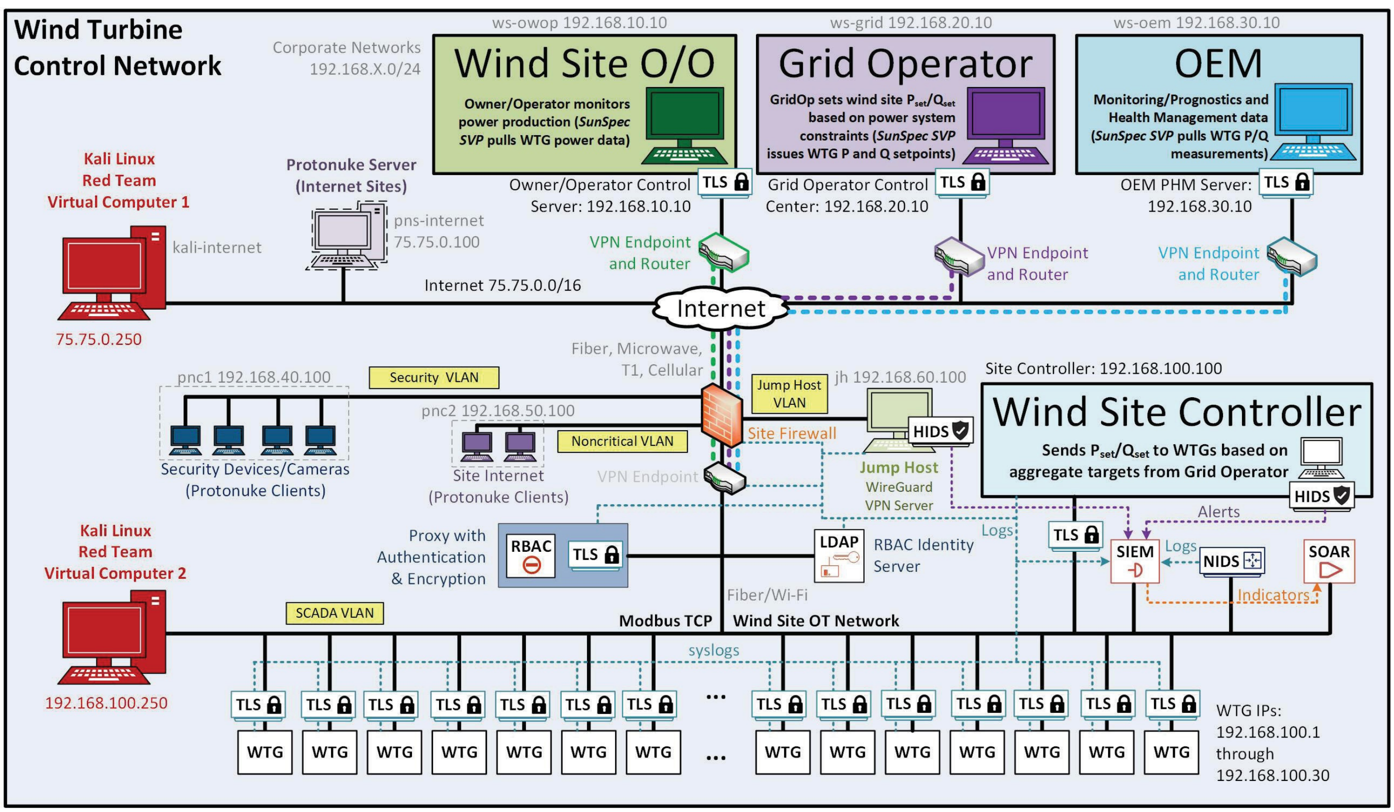
SWiFT wind farm PPN phase control performance results and ESS savings. Image credit: David Wilson

6.2. Cyber Hardening

Large-scale deployment of wind energy is transforming today's power grid through sophisticated grid-support functionality and utility-to-turbine communications. These enhanced control features provide grid operators with new capabilities, but they also expand the power system attack surface significantly. Turbine vendors, plant operators, and utilities lack clarity on what security upgrades are necessary or most effective. In Fiscal Year 2021, Sandia and Idaho National Laboratory (INL) constructed wind networks with multiple hardening technologies that will increase cyber-resilience performance and maintainability in wind-specific applications. This network was built using the SCEPTRE co-simulation platform and represented the Electric Reliability Council of Texas (ERCOT) transmission power system, 30 wind turbine controllers, and wind site networking equipment. The cyber hardening features included:

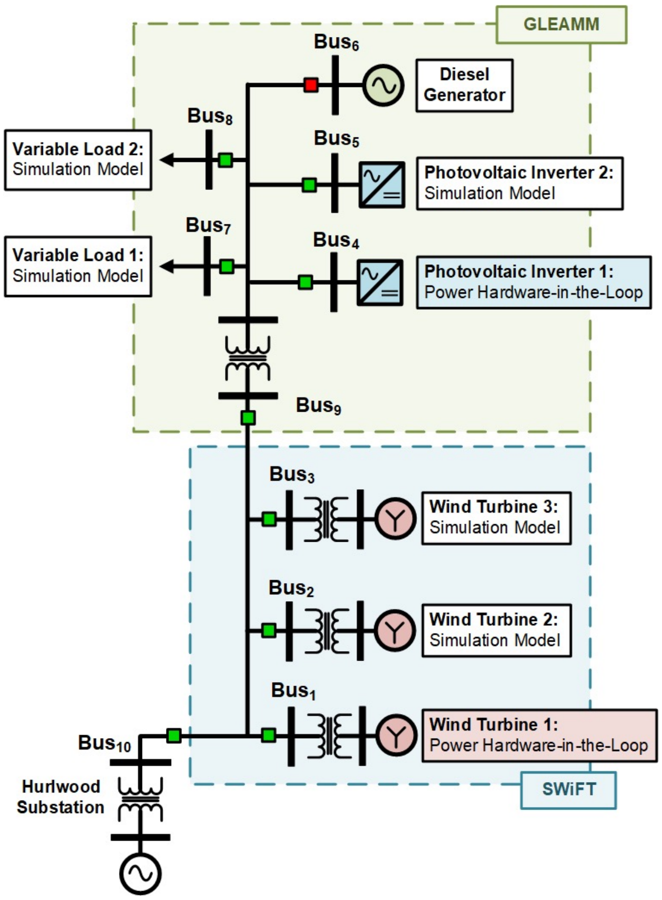
- Operational Technology (OT) encryption
- Role-based access control (RBAC)
- Security Information and Event Management (SIEM) systems
- Network-based Intrusion Detection Systems (NIDSs)
- Host-based Intrusion Detection Systems (HIDSs)
- Security Orchestration, Automation, and Response (SOAR) technologies

The network environment with the hardening features is shown in the figure below. The final phase of the project will conduct automated adversary-based assessments of the network with different security features to quantify the security improvement from each hardening element against a set of realistic cyberattacks. Results from the project are regularly shared with the wind industry to advise stakeholders of potential cybersecurity improvements to wind systems.

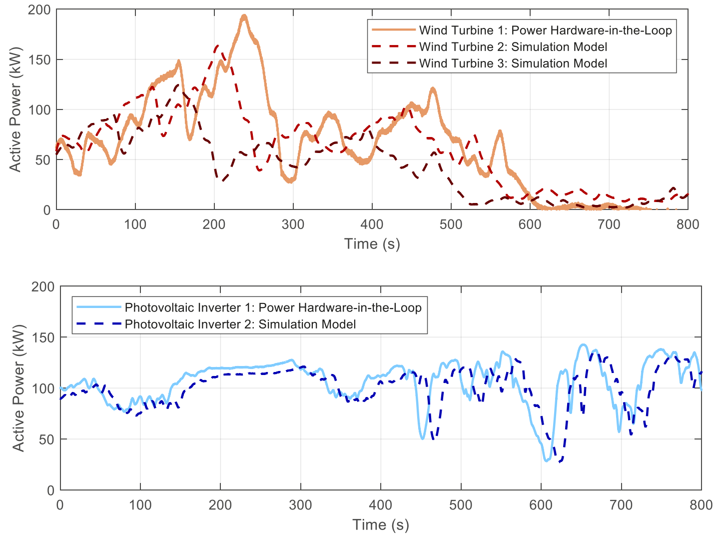


Wind site cybersecurity hardening features built into the networking simulation environment. Image credit: Jay Johnson

6.3. Microgrids, Infrastructure Resilience and Advanced Controls Launchpad (MIRACL)



SWiFT/GLEAMM One-Line Diagram. Image credit: Rachid Darbali



Power Hardware-in-the-Loop results for the active power from the simulated and hardware wind turbines and photovoltaic inverters. Image credit: Rachid Darbali

In Fiscal Year 2021, Sandia delivered a key capability to facilitate the broader research goals of the multi-lab Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project. A real-time power system simulation model was successfully built and demonstrated representing the SWiFT facility interconnected with the nearby Texas Tech University (TTU) Global Laboratory for Energy Asset Management and Manufacturing (GLEAMM) microgrid assets and the local electrical cooperative distribution system. The modeled distributed energy resource (DER) assets include the SWiFT wind turbines and the TTU GLEAMM photovoltaic (PV) inverters.

The Sandia team integrated the SWiFT wind turbine emulator hardware on the developed SWiFT real-time simulation model to support Power Hardware-in-the-Loop distributed power system analysis at the Sandia Distributed Energy Technology Laboratory (DETL). The experimental configuration consisted of the wind turbine emulator and two simulated wind turbines to represent the full SWiFT site. The hardware emulators for the wind turbine and PV inverters are a fraction of the power that the field systems produce, so the power generated in the laboratory experiment is scaled up by the relevant factor in the real-time simulation software. In addition, two 3-phase dynamic load simulation models (labelled "Variable Load 1" and "Variable Load 2") are used to emulate the programmable 500 kW variable AC load banks located in the GLEAMM microgrid.

The Power Hardware-in-the-Loop platform enables programmable resource profiles for both the wind and PV emulators. Wind speed data collected from the SWiFT site was used to create the wind speed profiles used for the wind turbine emulator and the wind turbine simulation models. An irradiance profile is programmed into the PV emulator, which serves as the DC input of the PV inverter. This irradiance profile is also used for the PV inverter simulation model.

These results demonstrate that the real-time simulation model is stable and that the Power Hardware-in-the-Loop wind turbine emulator platform is able to successfully generate active power. Moreover, both the wind turbine emulator and the commercial PV inverter do so by using wind speed and irradiance profiles, respectively.

While this demonstrates the ability to replicate the performance of the SWiFT site, in general the capability can represent almost any distributed power system with a mix of Distributed Energy Resources (DERs).

7. SOLUTIONS TO NATIONAL SECURITY TECHNOLOGY BARRIERS

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7.1. Defense and Disaster Deployable Turbine (D3T)

The Defense and Disaster Deployable Turbine (D3T) project team released two major reports this year to facilitate the development of deployable wind turbine systems for defense and disaster response applications. The first report builds on and extends the modeling and simulation work from last year to consider the performance of deployable wind systems operating in a hybrid wind-solar-diesel microgrid modeled after a forward operating base. The second report is a culmination of three years of stakeholder interviews, technical analysis, and literature research to develop design guidelines for a deployable wind system. Both documents are summarized below.

7.1.1. Deployable wind-hybrid power systems for defense and disaster response applications

This report presents an analysis of the performance of deployable energy systems comprised of wind energy systems integrated with diesel generators, photovoltaic systems, and battery storage to meet the load requirements of a representative U.S. Army forward operating base. The analysis is conducted using HOMER, a microgrid analysis software that can search through a wide range of parameters to design and optimize microgrid power systems. The search parameters include the system architecture, the wind and solar resources, and the availability of diesel fuel. The results of the analysis measure the relative performance of the different systems and environments in terms of the overall transportation cost to deploy the system and the ability to provide resilience in terms of meeting mission critical loads. Among other findings, the key takeaways are that hybrid wind-solar deployable systems with optimally sized battery storage can provide significant resilience benefits to remote sites as measured by reduced diesel consumption and maintaining critical loads even without access to any fuel for diesel generators.

7.1.2. Design Guidelines for Deployable Wind Turbines for Military Operational Energy Applications

This document aims to provide guidance on the design and operation of deployable wind systems that provide maximum value to missions in defense and disaster relief. Common characteristics of these missions are shorter planning and execution time horizons and a global scope of potential locations. Compared to conventional wind turbine applications, defense and disaster response applications place a premium on rapid shipping and installation, short-duration operation (days to months), and quick teardown upon mission completion. Furthermore, defense and disaster response applications are less concerned with cost of energy than conventional wind turbine applications. These factors impart design drivers that depart from the features found in conventional distributed wind turbines, thus necessitating unique design guidance. The supporting information for this guidance comes from available relevant references, technical analyses, and input from industry and military stakeholders. This document is not intended to be a comprehensive, prescriptive design specification. This document is intended to serve as a written record of an ongoing discussion of stakeholders about the best currently available design guidance for deployable wind turbines to help facilitate the effective development and acquisition of technology solutions to support mission success.

Rendering of various deployable wind and solar power concepts at a forward operating base. Image credit: Besiki Kazaishvili, National Renewable Energy Laboratory

7.2. Radar Interference Mitigation

NORAD FTE aircraft. Image credit: Major Karla West, Civic Air Patrol

In 2012, Sandia and MIT Lincoln Laboratory (MIT LL) conducted an Interagency Field Test & Evaluation (IFT&E) at a Common Air Route Surveillance Radar (CARSR) in the southwest area of Minnesota that confirmed the adverse impacts that wind turbines have on radar systems when they are located in the line-of-sight of the radar systems. At that time, 459 wind turbines existed in the test area. Currently there are 1,226 wind turbines visible to this CARSR. Over the last 10 years, an average of 3,800 wind turbines were built each year in the U.S. with 2020 seeing a record 6,944 wind turbines built, bringing the total number of wind turbines in the continental United States to 67,814 by the end of 2020. At the request of the North American Radar Aerospace Defense (NORAD) Command, Sandia supported a similar Field Test & Evaluation (FT&E) of radar systems in the presence of wind turbines, specifically an upgrade to the CARSR.

NORAD FTE team. Image credit: Major Karla West, Civic Air Patrol

Given the nation's aggressive renewable energy goals, wind farm development is forecasted to continue to increase and place more stress on the air surveillance system across the country. It is imperative to ascertain the effectiveness of potential wind turbine radar interference mitigation technologies to allow continued wind energy deployment while maintaining air surveillance for national safety and security. The wind development industry is aware of this challenge and pursuant to 10 U.S.C. section 183a, wind farm developers can voluntarily contribute funds to offset the cost of measures undertaken by the Department of Defense (DOD) to mitigate the adverse impacts of their projects on military operations and readiness, or to conduct studies of potential measures to mitigate such impacts. As part of the interagency Wind Turbine Radar Interference Mitigation (WTRIM) Working Group's strategy to address this challenge, Sandia and MIT LL organized and conducted this latest FT&E in August and September 2021. The goal was to repeat the 2012 IFT&E to ensure that similar data was collected that can be compared to the 2012 pre-radar upgrade data.

View from aircraft. Image credit: Major Karla West, Civic Air Patrol

The week-long FT&E consisted of seven different types of aircraft flying above wind turbines in the test area at various altitudes and speeds. A total of 65 sorties were flown totaling 185.6 hours between the airframes. Wind farm owners in the area provided subsets of the wind turbine SCADA data, which included the wind turbines' yaw direction and rotor rpm for the final analysis. The team is currently analyzing the test data and expects to report back to NORAD, the DOD, and the DOE in early Fiscal Year 2022.

8. WIND INDUSTRY STANDARDS DEVELOPMENT

8. WIND INDUSTRY STANDARDS DEVELOPMENT

8.1. IEC 61400-5 blade design standard

After working with an international team to complete the IEC 61400-5 blade design standard in Fiscal Year 2020, a Sandia staff member was nominated to lead the -5 standard update in Fiscal year 2021. As blade designs and materials are changing, this presents a unique opportunity to lead worldwide experts in a new standards effort that addresses new designs and materials.

8.2. IEA Wind Task 43

The Blade Life Value Model task as described above in Section 3.3 sponsored participation in IEA Wind Task 43: Digitalization, to connect DOE-funded work with international research efforts. As part of this international effort, Sandia developed a novel leading edge erosion predictive model that connects field inspection data to validated physics models.

8.3. IEA Wind Task 46

Sandia's past and current work in leading edge erosion played a major role initiating IEA Task 46: Erosion of blades. As part of this effort, Sandia is leading two of the four task areas: Climatic Conditions Affecting Erosion, and Operations under Erosion.

9. INTELLECTUAL PROPERTY

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9.1. Patents Awarded

Houchens, B.C., M.L. Blaylock, D.V. Marian, D.C. Maniaci, and C.H. Westergaard. Methods, systems, and devices to optimize a fluid harvester. US Patent 11,047,360 B1, issued June 28, 2021.

9.2. Provisional Patents Filed

Ennis, B. Thrust-Optimized Blade Design for Offshore Wind Turbines. US Provisional Patent 63/237,384, filed Aug. 26, 2021.

9.3. Invention Disclosures

Kelley, C.K., Additive Manufactured System Integrated Tip for Wind Turbine Blades. Invention Disclosure, (SD# 15551). 2020.

Wilson, D.G., W.W. Weaver, and R.D. Robinett III. PPN phase control with DC collective for onshore/offshore wind farms. Invention Disclosure, (SD# 15895). Sept. 8, 2021.

Wilson, D.G., W.W. Weaver, and R.D. Robinett III. PPN phase control with AC collective for onshore/offshore wind farms. Invention Disclosure, (SD# 15894). Sept. 13, 2021.

9.4. Software Copyright

Johnson, Jay. Commercial copyright assertion, Secure Wind Plant phenix Topologies v.1.0.0 - Open Source Software under the GPL 3.0 license. SCR#:2650.0.

Paquette, Joshua, Brandon Ennis, Chris Kelley, Evan Anderson, Ernesto Camarena, Kelley Reuhl, Ryan Clarke. Commercial copyright assertion, Numerical Manufacturing and Design (NuMAD) Tool for Wind Tubine Blades v3.0. https://github.com/sandialabs/NuMAD. SCR#1540.

10. PUBLICATIONS

10. PUBLICATIONS

10.1. Journal Articles

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Bortolotti, P., N. Johnson, N. Abbas, E. Anderson, E. Camarena, J. Paquette, “Land-based wind turbines with flexible rail transportable blades – Part I: Conceptual design and aeroservoelastic performance,” *Wind Energy Science,* (2022): https://doi.org/10.5194/wes-6-1277-2021.

Camarena, E., E. Anderson, J. Paquette, P. Bortolotti, R. Feil, and N. Johnson, “Land-based wind turbines with flexible rail transportable blades – Part II: 3D FEM design optimization of the rotor blades,” *Wind Energy Science,* (2022): https://doi.org/10.5194/wes-7-19-2022.

Camarena, E., R. J. Clarke, and B. L. Ennis, “Development of a compressive failure model for carbon fibercomposites and associated uncertainties,” *Composites Science and Technology*, vol. 211, (2021): https://doi.org/10.1016/j.compscitech.2021.108855.

Ennis, B.L., H.S. Perez and R.E. Norris, “Identification of the Optimal Carbon Fiber Shape for Cost-Specific Compressive Performance,” *Materials Today Communications*, (forthcoming).

Houck, D.R., “Wake Management Techniques for Wind Turbines,” *Wind Energy*, (2021): https://doi.org/10.1002/we.2668.

Hsieh, A.S, K.A. Brown, N.B. deVelder, T.G. Herges, R.C. Knaus, P.J. Sakievich, L.C. Cheung, B.C. Houchens, M.L. Blaylock, and D.C. Maniaci, “High-fidelity wind farm simulation methodology with experimental validation,“ *Journal of Wind Engineering and Industrial Aerodynamics,* 218 (Nov. 2021): 104754. https://doi.org/10.1016/j.jweia.2021.104754.

Moore, K.R., and B.L. Ennis, “Vertical-Axis Wind Turbine Steady and Unsteady Aerodynamics for Curved Deforming Blades.” *AIAA Journal.* (Aug. 2021): https://doi.org/10.2514/1.J060476.

10.2. Conference Papers and Proceedings

Anderson, E., “Investigation of Spatial Smoothing Techniques Applied to Design Variables in Structural Optimization Problems.” Wind Energy Science Conference 2021, Hannover, Germany (Virtual Event), May 25-28, 2021.

Blaylock, M., L.A. Martinez-Tossas, P. Sakievich, B. Houchens, A. Hsieh, D. Maniaci, and M. Churchfield. “Comparison of Actuator Line Model and a Filtered Lifting Line Correction Implemented in Nalu Wind Large Eddy Simulations of the Atmospheric Boundary Layer.” Wind Energy Science Conference 2021, Hannover, Germany (Virtual Event), May 25-28, 2021.

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Cheung, L., M. J. Brazell, A. Hsieh, S. Ananthan, G. Vijayakumar and N. deVelder. “Computation and comparison of the stable Northeastern US marine boundary layer.” AIAA Scitech 2021 Forum (Virtual Event), Nashville, TN, USA, Jan. 11-15, 2021. https://arc.aiaa.org/doi/10.2514/6.2021-0454.

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Hsieh, A.S., D.C. Maniaci, G. Geraci. “Multifidelity Uncertainty Quantification of Wind Turbine Interaction Using Enhanced Nalu-Wind Actuator Simulations.” AIAA Scitech 2021 Forum (Virtual Event), Nashville, TN, USA, Jan. 11-15, 2021.

Hsieh, A., D. Maniaci, G. Geraci, D. T. Seidl, T. Herges, K. Brown, and J. Cutler. “Application of Multilevel-Multifidelity Uncertainty Quantification Towards Multi-turbine Interaction and Wake Characterization.” Wind Energy Science Conference 2021, Hannover, Germany (Virtual Event), May 25-28, 2021.

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Mertz, B., J. Paquette, N., Johnson. “Low-Fidelity Modeling of Active Flow Control Devices for Wind Turbine Applications.” Wind Energy Science Conference 2021, Hannover, Germany (Virtual Event), May 25-28, 2021.

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10.4. Partnerships

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