Sandia National Laboratories

SANDIA WIND ENERGY PROGRAM

FY22 ACCOMPLISHMENTS

Geoffrey T. Klise - Wind Energy Computational Sciences
Nick A. Johnson - Wind Energy Design & Experimentation

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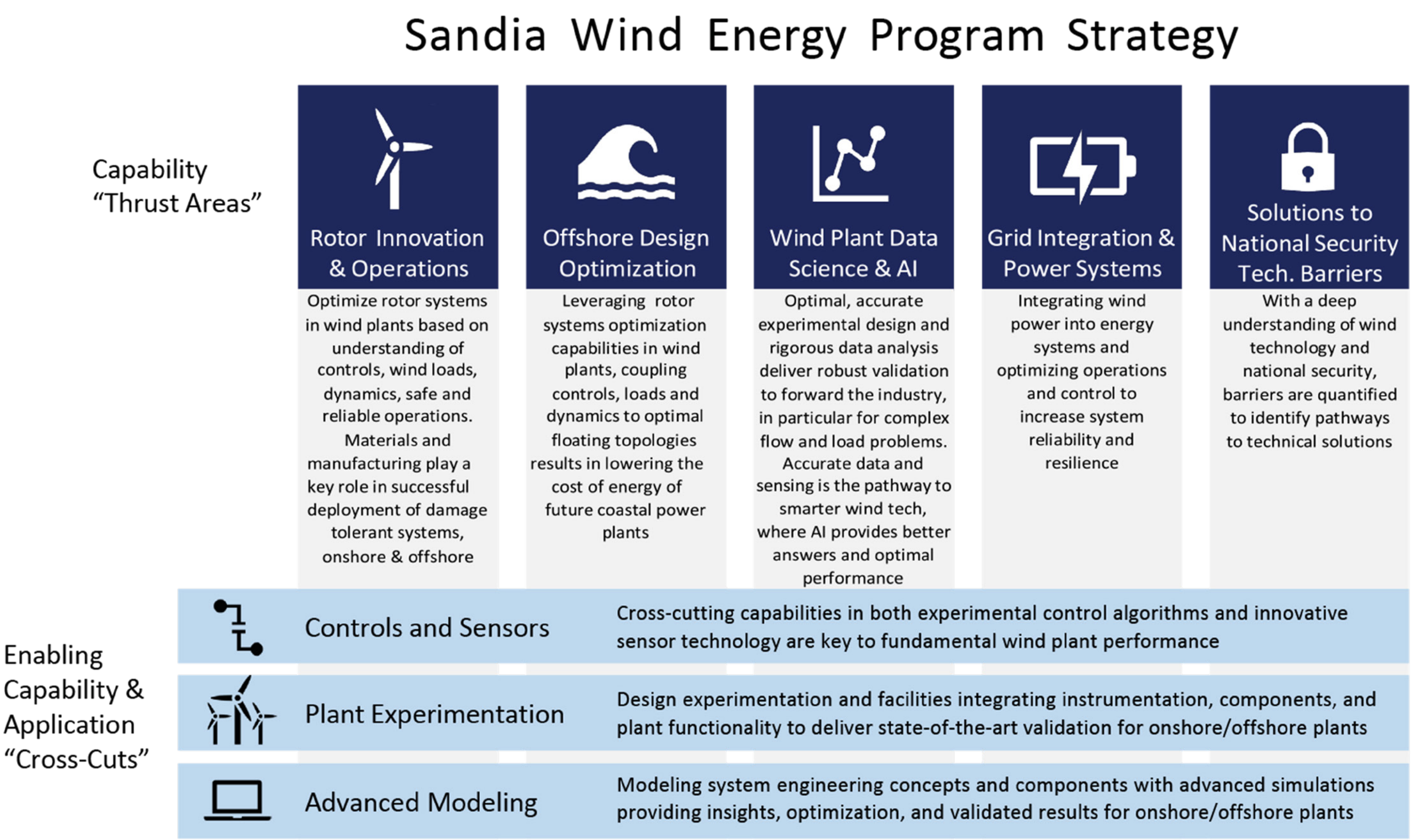
INTRODUCTION

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 2022 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), Advanced Manufacturing Office (AMO), 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 in the Wind Energy Design and Experimentation department and the Wind Energy Computational Sciences department leading and supporting R&D at the time of this report. Staff from other departments at Sandia 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.



Capability "Thrust Areas" and "Cross-Cuts"

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1. HIGHLIGHTS

1. HIGHLIGHTS

1.1 Sandia Blade Workshop

After a four-year hiatus, the Sandia Blade Workshop returned to Albuquerque, NM, Oct. 17-20, 2022. The workshop is a key venue for wind energy stakeholders, bringing together wind industry experts, wind farm owners and operators, manufacturers, and researchers from across the world. This year's conference drew record-breaking attendance with over 190 participants and 43 presenters and panelists, including Sarah Cottrell Propst, Cabinet Secretary of the New Mexico Energy, Minerals and Natural Resources Department. Over sixty percent of the attendees and presenters were from the wind industry.

Sandia National Laboratories' Wind Energy Technologies Program hosts the blade workshop every two years to engage the wind energy industry by examining the main energy capture component of the wind turbine: the blades. Together, workshop attendees identified engineering and scientific issues in wind energy; discussed research technology pathways towards better wind turbines with a focus on blades; and facilitated interaction between the different stakeholders.

The blade workshop continues to be useful in identifying and addressing these communication breakdowns between different stakeholders within the wind industry.

The next workshop will explore important topic areas further: blade lightning risks, reliability, recycling, and offshore developments as emerging topic areas of high importance to the industry. The presentations are archived publicly on the Sandia Wind Energy Workshops webpage.

Save the Date! (Twitter)

Sandia's 2022 Blade Workshop registration is now open! (Twitter)

The Path to 100% Carbon-Free Electricity in New Mexico panel and organizers. From Left to right: Michelle Williams, Chris Kelley, Nicholas Phillips, Stan Atcitty, Charlie Hanley, Secretary Cottrell Propst, and Stephen. Gomez. (Photo by Brett Latter)

1.2 News Releases

Back to the drawing board: Reinventing offshore wind turbines

Brandon Ennis, Sandia National Laboratories' offshore wind technical lead, had a radically new idea for offshore wind turbines: instead of a tall, unwieldy tower with blades at the top, he imagined a towerless turbine with blades pulled taut like a bow.

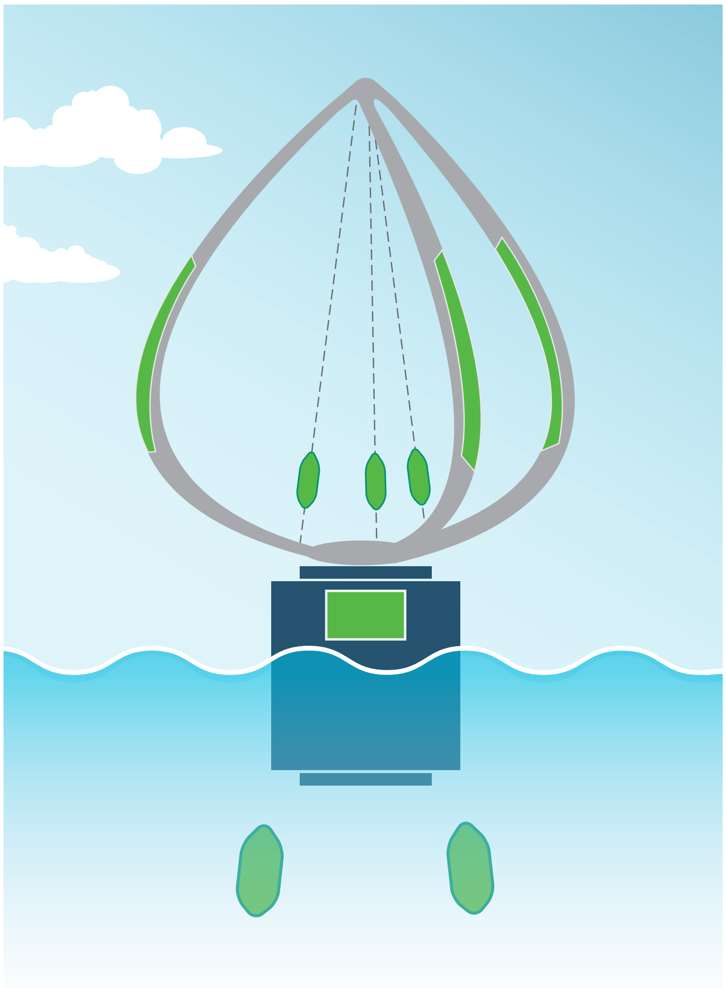
This design would allow the massive generator that creates electricity from spinning blades to be placed closer to the water, instead of on the top of a tower 500 feet above. This makes the turbine less top-heavy and reduces the size and cost of the floating platform needed to keep it afloat. Sandia filed a patent application for the design in 2020.

Reinventing offshore wind turbines (Lab News)

Back to the drawing board: Reinventing offshore wind turbines (blogpost)

Sandia engineers are designing an innovative vertical-axis wind turbine (Facebook)

Rethinking wind turbines (Instagram)



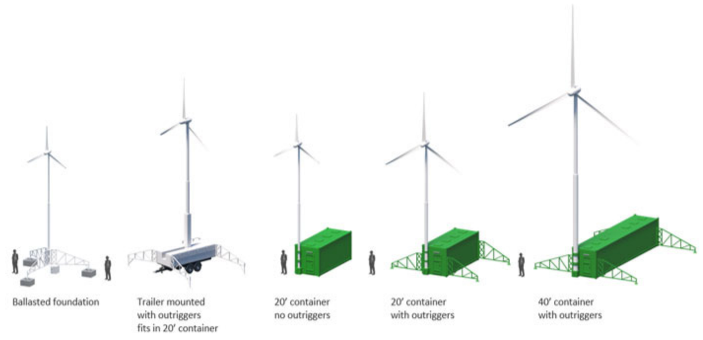
Sandia National Laboratories' innovative design for offshore wind: no heavy tower, instead wind blades pulled taut with guy wires. (Illustration by Brent Haglund)

1.3 News Articles

New guidelines for wind energy systems (Lab News)

Sandia researchers have devised a new set of design guidelines and procurement specifications that help the wind energy industry and the U.S. military develop and evaluate rapidly deployable wind energy systems for use in defense and disaster-response applications.

The Defense and Disaster Deployable Turbine, or D3T, project was funded by DOE's Wind Energy Technologies Office to assess the potential market for deployable wind systems, define the design guidelines for these systems and facilitate engagement between the wind energy industry and the military.



Deployable wind turbine general design concepts from the new guidelines for wind energy systems, drafted by Sandia researchers. (Rendering by Besiki Kazaishvili, National Renewable Energy Laboratory)

Sandia researchers wrap up D3T project, develop guidelines (Blogpost)

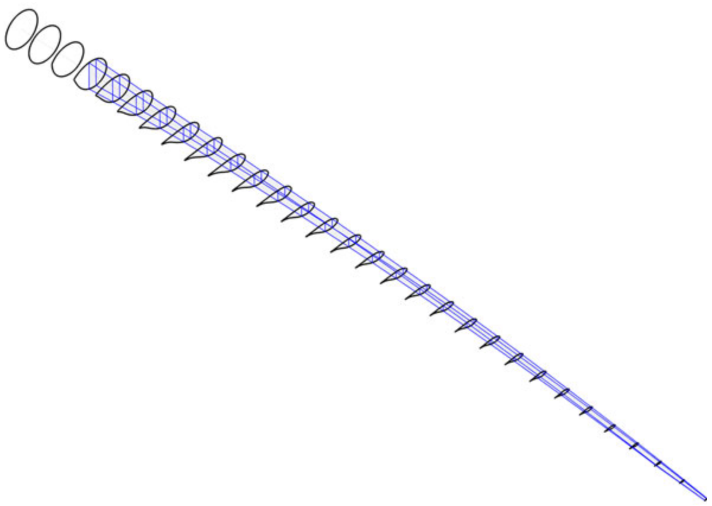
Virtual D3T Workshop (Twitter)

Bridging the Gap (Twitter)

Sandia researchers update software tool for wind turbine blades (Lab News)

Researchers from Sandia's wind energy program have released a new version of the software tool Numerical Manufacturing and Design, or NuMAD, for the structural design and modeling of wind turbine blades.

NuMAD version 3.0, which was funded by DOE's Wind Energy Technologies Office, is an object-oriented, open-source software program written in the MATLAB programming language that simplifies the process of creating a 3D model of a wind turbine blade. The tool manages all blade information, including aerodynamic properties, material properties and material placement. Blade data can be modified by a structural optimizer in NuMAD, or it can be used to run other tools in a stand-alone mode.



NuMAD produces blade geometry visualizations, like the one pictured here. (Graphic by Ernesto Camarena)

Sandia researchers update NuMAD software tool, foster new GitHub community (blogpost)

NuMAD Software Update (Twitter)

1.4 Blogposts

Registration is now open for the 2022 Sandia Blade Workshop

Sandia to host Deployable Wind Power for Defense and Disaster Response Workshop on June 17th

Sandia's Wind Energy Program releases its FY21 Accomplishments Report

Sandia researcher contributes to Wind report published by National Academy of Sciences

Save the Date — 2022 Sandia Blade Workshop: Oct. 17-20, Albuquerque, NM

DOE's WETO commissions the National Rotor Testbed

1.5 Social Media

FY22 Accomplishments Report (Twitter)

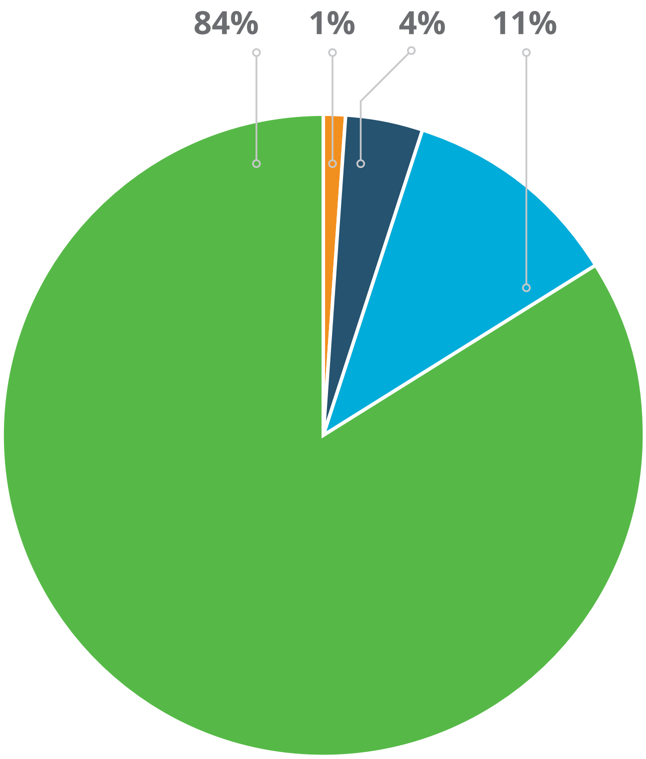
Sandia Report featured in National Academies of Science (Twitter)

Carbon fiber for wind turbine blades could bring cost, performance benefits (Twitter)

Congratulations to WEC-Sim and AEROMINE (Twitter)

Collaboration Opportunity (Twitter)

1.6 Funding



FY22 Wind Energy Program Budget Breakdown

- Wind Energy Technologies Office
- Advanced Research Projects Agency - Energy
- Advanced Manufacturing Office
- Laboratory Directed Research & Development

This chart represents funding sources from FY22. Wind Energy Technology Office funding was the highest percentage of research projects, with a higher percentage than previous years.

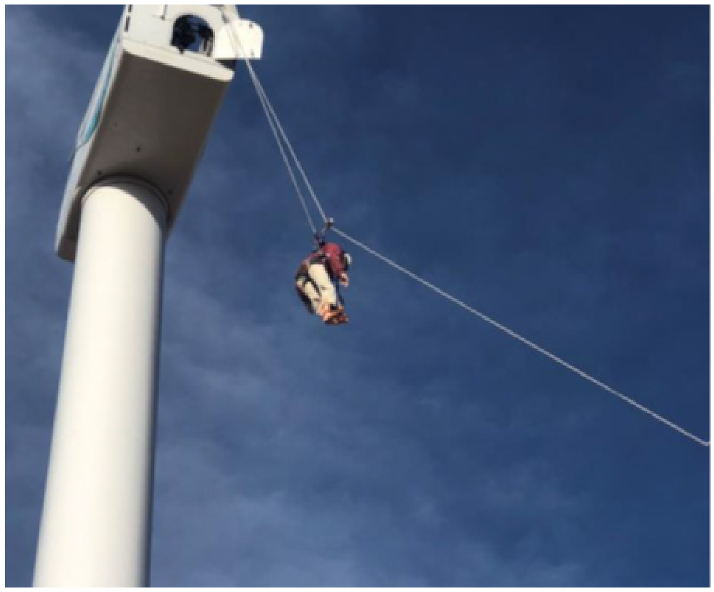
2. SWIFT FACILITY

2. SWIFT FACILITY

Fiscal Year 2022 was a busy year for the Scaled Wind Farm Technology (SWiFT) Facility. Authorization was obtained from the Center 08900 Director to begin normal operations on the A1 Turbine, which allows for operational data collection for the National Rotor Testbed (NRT) project. This was the first experimental data collected from one of the turbines since 2018. As a continuously improving and agile-run project, troubleshooting of technical issues, site operations and maintenance, turbine operation, and project support all benefitted from a number of safety-related events. The 3rd Annual Multidisciplinary subject matter expert (SME) team visit to SWiFT Facility brought a number of Sandia safety engineering staff members to the site, including electrical safety, emergency preparedness, fall protection and lifting safety, and industrial hygiene. The team engaged with SWiFT site staff on a number of topics over two days, solidifying the importance of regular engagement across organizations.

Texas Tech University wind turbine technician Miguel Hernandez operates NRT Turbine A1 from the control building. The turbine can be viewed from the window. (Photo by Tim Riley)

The SWiFT site team also partnered with Sandia emergency response (SMEs) in developing and executing an emergency drill scenario, in which a rescue mannequin was used to simulate an incapacitated person inside the nacelle of the A2 turbine. Personnel developed the techniques for moving and manipulating the mannequin using the nacelle in Building 350 in consultation with a Tech Safety Lines climb rescue professional. The scenario validated the procedures developed as the mannequin was extracted and lowered to the ground out of the back of the nacelle. Another notable accomplishment was the completion of a safety and orientation video for the SWiFT Facility, developed in collaboration with Sandia's Creative Services team.



Emergency rescue drill using a rescue mannequin, shown being lowered to the ground out of the back of the Turbine A2 nacelle. (Photo by Johnny Luevano)

On the A2 Turbine, the site team completed pre-rotor commissioning root insert pull tests on the V27 blades, followed by a safely executed rotor installation. Turbine final commissioning then began and will be completed in early FY23. SWiFT project staff also supported both the AWAKEN and RAAW projects, with the Test Engineer and Engineering Technologist both traveling to NREL to assist with fabrication of data acquisition (DAQ) boxes.

Looking ahead to future capabilities, controls SMEs conducted testing at Sandia's Distributed Energy Technologies Laboratory (DETL) to develop a simulation model of the GLEAMM (Global Energy Asset Management and Manufacturing) microgrid and SWiFT Facilities, with plans to possibly use the models to simulate experiments that could be conducted at the field test site in Lubbock. This is occurring in parallel with the ongoing work by the TTU, Group NIRE, and Sandia team to integrate and commission the interconnected GLEAMM and SWiFT Facilities.

For infrastructure development and investments, Sandia, TTU, and the Reese Technology Center all worked closely to initiate the procurement of a steel ballistic canopy for the South Plains Association of Governments (SPAG) firing range, which is adjacent to the SWiFT Facility. This effort had a high level of engagement and support from Sandia senior management as well as the DOE Sandia Field Office (SFO). Sandia leadership also approved the purchase of a self-contained, green restroom to replace the Portalet at the SWiFT Control Building. Additionally, a storage building on the west side of the Reese Technology Center airfield was approved for lease by Sandia's Facility Capital Planning & Acquisition team to be used for storage of SWiFT equipment and spares.

Emergency rescue drill using a rescue mannequin, shown being lowered to the ground out of the back of the Turbine A2 nacelle. (Photo by Tim Riley)

Lastly, a Sandia staff member continues to support outreach through participation on the Advisory Board for South Plains College's Industrial Manufacturing and Engineering Technology (IMET) program. A part of IMET is devoted to the training of wind turbine technicians, which Sandia and the SWiFT project support through a summer internship available to the IMET students.

3. ROTOR INNOVATION & OPERATIONS

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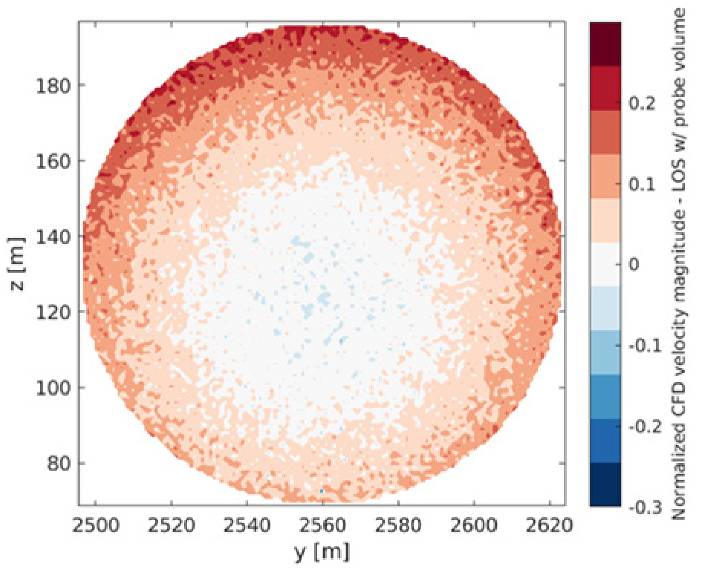
3.1 Rotor Wake

During fiscal year 2022, the Rotor Wake project accomplished major milestones in wind turbine field testing, instrumentation development, model development, and validation. The Rotor Wake project team at Sandia operated and collected data for the National Rotor Testbed (NRT) and started field deployments of instruments for the Rotor Aerodynamics, Aeroelastics, and Wake (RAAW) experiment, working with the National Renewable Energy Laboratory (NREL) and commercial partner GE.



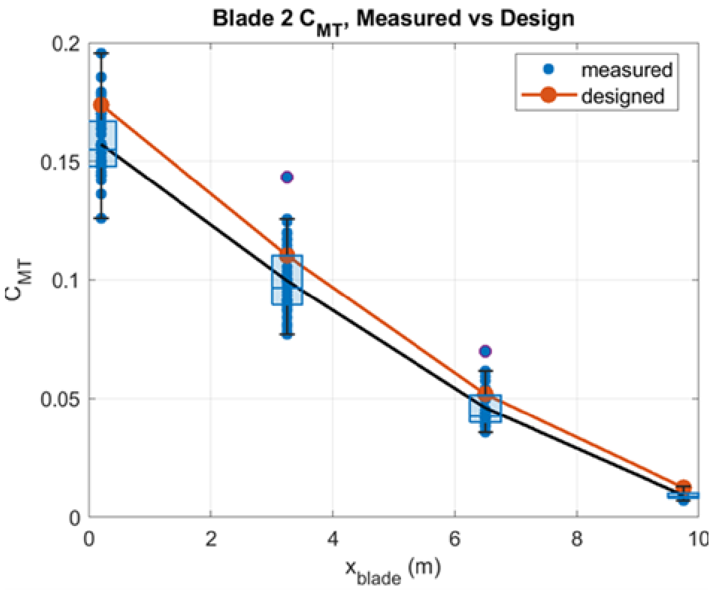
DTU SpinnerLidar inflow uncertainty estimated with virtual instrument implemented in ExaWind computational fluid dynamics simulations for the average wind conditions of the RAAW experiment. The measurement error does not exceed ±0.3 m/s based on these simulations. (Graphic by Dan Houck)

3.1.1 National Rotor Testbed

The NRT was operated for over 160 hours, and with over 50 hours of time correlated blade strain measurements, showed that the NRT is operating close to the scaled wake design intended with the turbine. This year the team implemented the full calculation of aerodynamic bending moments across the span of the NRT blades to show the scaled wake design. This important aerodynamic loading was found from blade strain measurements during power production of the NRT in a process that removed the effects of strain due to sensor drift, temperature changes, centripetal acceleration, and flap/edge crosstalk. This data shows how the NRT produces a wake and is relevant to Megawatt scale wind turbine and wake research.

3.1.2 Rotor Aerodynamics, Aeroelastics, and Wake

Within the RAAW experiment, the team prepared instrumentation leveraging collaborations with the Technical University of Denmark (DTU) and Texas Tech University (TTU). Work focused on preparing and designing the integration of various inflow measurements, including the DTU SpinnerLidar, DTU aerodynamic pressure belts, and the TTU Spidar.



140 hours of NRT experimental data showing the average aerodynamic flap bending moment coefficient on blade 2 at 4 different span locations. The NRT collective pitch should be adjusted approximately 1.3° towards feather to match the designed, scaled wake. (Graphic by Tommy Herges)

3.2 Blade Durability and Damage Tolerance

Wind blade maintenance and replacement is a significant portion of the O&M costs of running a wind plant. Improving the reliability of blades is quite challenging as the sources of damage include manufacturing quality, lightning, and erosion. The Sandia Wind Blade Durability and Damage Tolerance project is addressing these challenges through targeted research in damage inspection technology, damage tolerant material and structures, repair methods, lightning physics, and erosion modeling.

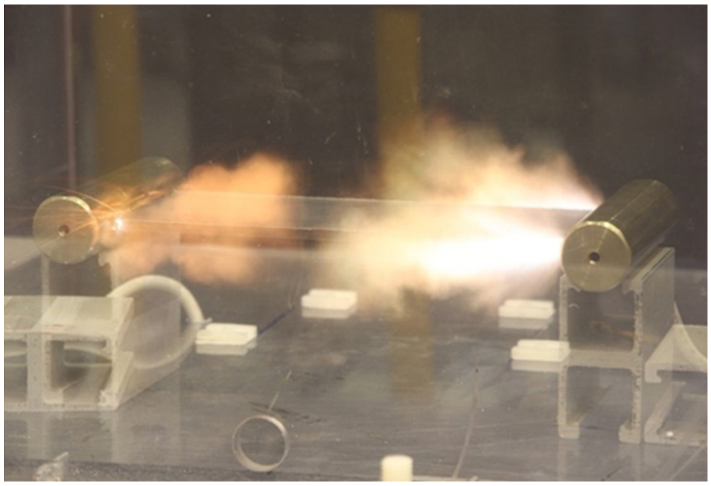
Sandia recently worked with the wind blade service industry to commercialize the ARROWe non-destructive inspection (NDI) crawler robot. This technology allows an operator to conduct a detailed, 3D inspection of a potential damage site on a blade quickly and safely. The results can be used to make an accurate determination of the severity of damage and how to repair it.

Sandia ARROWe NDI crawler robot. (Photo by Randy Montoya)

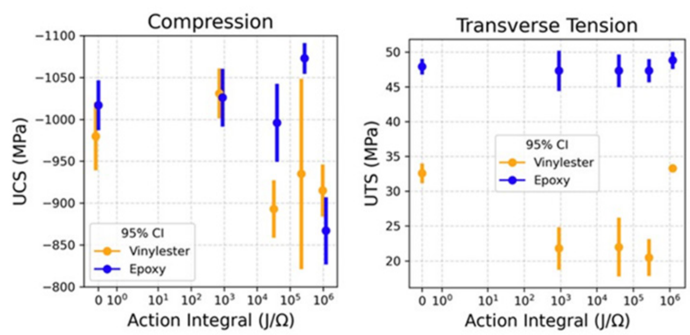
Sandia has also been working with partner Montana State University on developing better and more reliable processes for blade repairs, finding that the use of solvents can significantly increase repair durability.

Sandia has also been studying the environmental factors of lightning and erosion. The team conducted testing of lightning current impacts on carbon fiber blade materials to determine the structural impact of a potential lightning strike. Additionally, the team worked with New Mexico Tech University to develop a proposed lighting monitoring array that could be deployed to take vital measurements of the physics of wind blade lightning strikes.

Finally, Sandia worked with a wind plant owner to analyze data from eroded and repaired turbines to quantify the real-world performance impacts of erosion. The results of this research were presented and reviewed by over 80 members of the wind blade industry at a meeting of the Blade Reliability Collaborative hosted in conjunction with the 2022 Sandia Wind Blade Workshop.



Lightning testing of carbon fiber composites. (Photo by Ray Martinez)



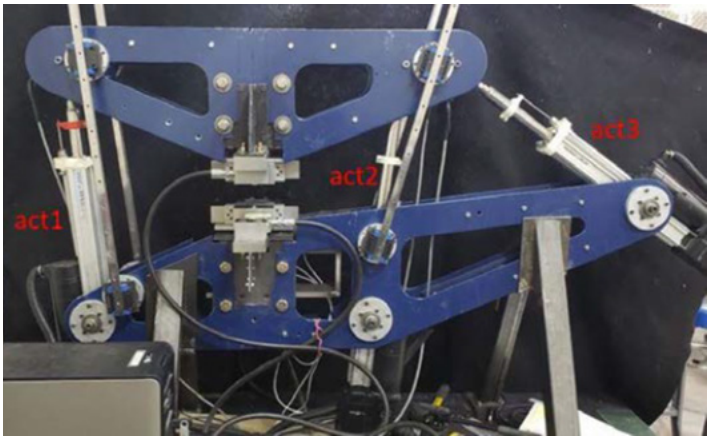
Results of mechanical testing showing some strength degradation due to simulated lighting strikes. (Graphic by Tommy Herges)

3.3 Big Adaptive Rotor (BAR)

The Big Adaptive Rotor project entered its second phase, focusing on further technoeconomic analysis of design innovations and addressing modeling gaps identified in Phase I. Sandia completed an initial technoeconomic analysis of distributed aerodynamic controls that would potentially allow for large wind turbine rotors to react much faster to gust loads. This in turn has the potential to allow for higher energy production through more aggressive controller settings and larger rotor sizes for a given machine. While this topic has been studied for well over a decade, a more thorough look at the economics of such systems was conducted. The Sandia team developed a cost model for several variants of a potential system and explored the tradeoffs between the size and duty cycle of the actuators and the life-cycle cost. Further and more detailed analysis is under way and the results will be the subject of a journal publication in the next year.

Sandia is also making significant upgrades to the NuMAD code which allows for quick generation of a wind blade finite element model (FEM) for structural analysis. The code was migrated to GitHub over the past year to allow for faster and better documented changes, as well as fostering a user community to make further improvements. The Sandia team is currently working on adding adhesive joints, more detailed representation of the composite structure with brick elements, and direct generation of the FEM mesh which allows the code to work with any commercial or academic finite element code.

Finally, the team started working with Montana State University to address knowledge gaps in wind turbine blade materials that may affect future designs. As part of continual updating of the DOE/SNL/MSU composite materials database, the largest public database of its kind in the world, the team will be adding results of the strength of multi-axial composites under combined loading and fatigue resistance of materials under combined load cycles. Additionally, the team is conducting analysis on adding structural damping to blades to reduce potential instabilities in operation and will be performing a validation test for some of the identified innovations.



Montana State In-plane loader test frame for multi-axial material testing. multi-directional fatigue testing (Photo courtesy of Montana State University)

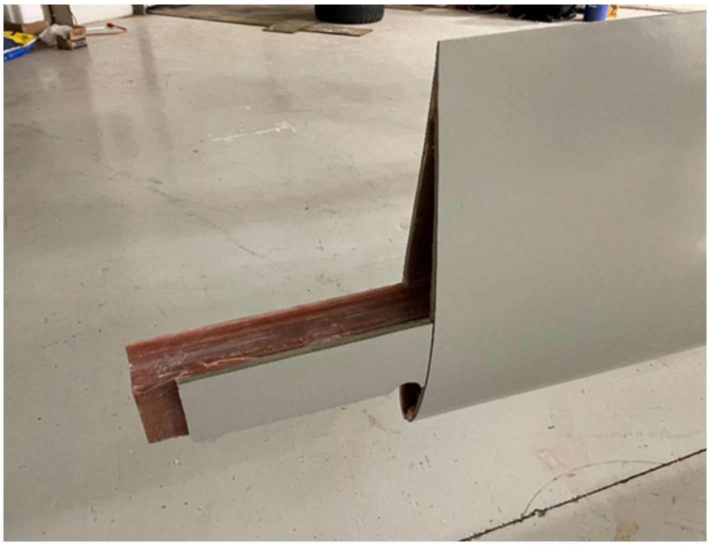
Montana State In-plane loader test frame for multi-directional fatigue testing. (Photo courtesy of Montana State University)

3.4 AMSIT

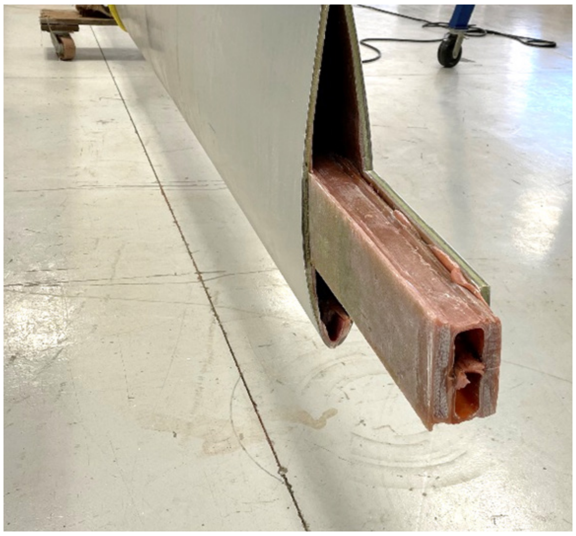
The additive-manufactured, system integrated tip (AMSIT) project demonstrates the ability of additive manufacturing (AM) to enable the integration of advanced wind turbine blade tip technologies that reduce wind energy levelized cost of electricity. Additive manufacturing enables the use of new materials and designs that can better withstand lightening strikes and erosion, and additive manufacturing also enables advances in aerodynamics and aeroacoustics not possible with traditional blade manufacturing methods. Finally, AM allows for segmented blades with customized tips, reducing transportation costs and tailoring blade designs to specific wind conditions.

AMSIT is integrating an array of blade technologies into a novel blade tip design. The team is a collaboration between Sandia, Wetzel Wind and Stratasys.

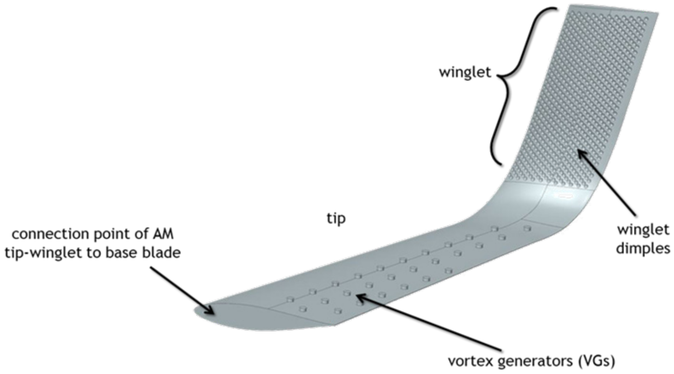
In FY22, the team completed the initial design considering improved aerodynamics, erosion resistance and integrated lightning protection as well as an initial cost model to estimate levelized cost of energy reduction. The team filed a provisional patent and had a conference abstract accepted to AIAA SciTech (Maniaci et al., 2023).



V27 blade tip cut for AMSIT project data gathering. (Photo by Brent Houchens)



Cut wind turbine blade at SWiFT to determine tip attachment strategies. (Photo by Brent Houchens)



AMSIT aerodynamic design with winglet and surface features. (Rendering courtesy of Jim Payant, Wetzel Wind)

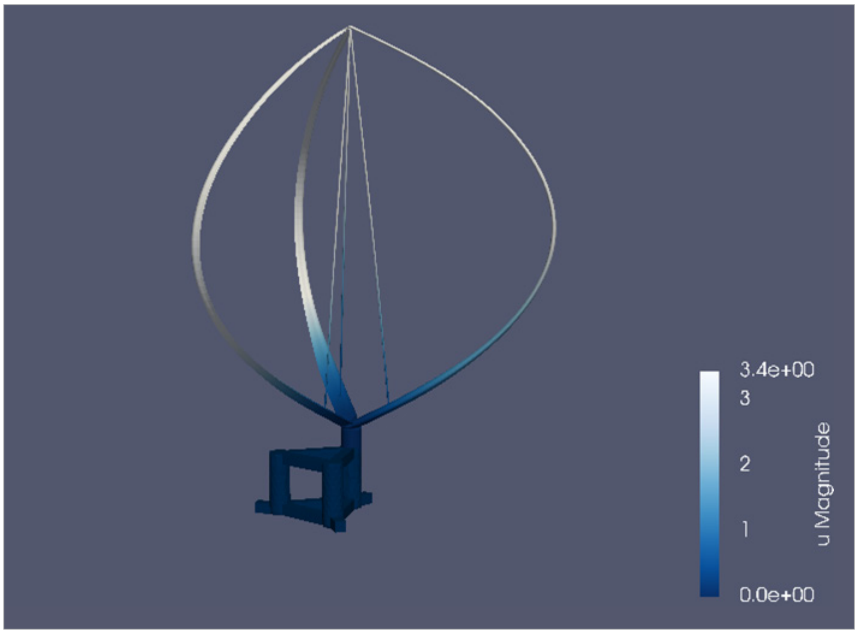
4. OFFSHORE DESIGN OPTIMIZATION

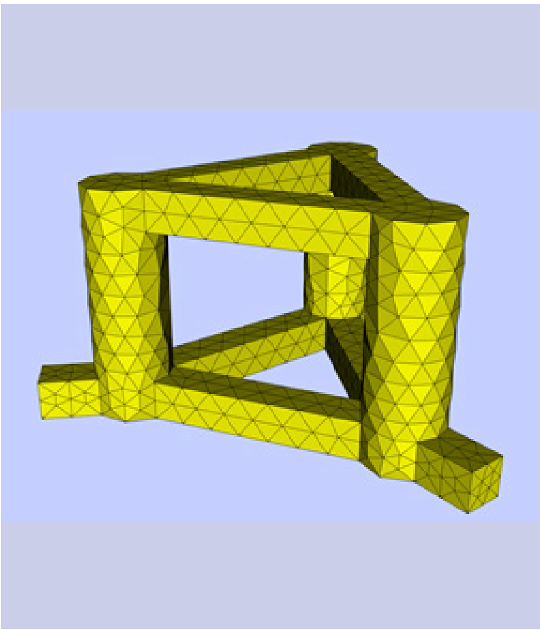
4. OFFSHORE DESIGN OPTIMIZATION

4.1 ARCUS Vertical-Axis Wind Turbine Design and Optimization

The ARCUS team continued to develop the capabilities necessary for design and optimization of floating vertical-axis wind turbines (VAWTs) using control co-design optimization approaches, funded by the Advanced Research Projects Agency – Energy (ARPA-e). The project team completed the development of simulation software for analysis of the ARCUS turbine and tension-leg platform (TLP) system to capture the coupled dynamics present for floating offshore wind turbines for analysis of the critical operational and preservice load cases specified by governing design standards. Simulation capabilities have been added that include the following:

- Hydrostatic stability checks and preservice constraint evaluation for the system to satisfy quayside integration and system tow-out requirements for platform design and analysis
- Design of the ARCUS rotor with pre-stress effects from assembling the rotor using manufactured straight blades that are bent into the Darrieus rotor shape
- Aero-hydro-servo-elastic simulation of VAWTs with fully coupled dynamics and non-linear elastic solutions using stochastic wind and wave forcing
- Simulation in the pseudo-spectral time domain with an elastic rotor coupled to hydrodynamic forcing and platform dynamics for identification of numerical optimal control pathways
- Optimization using Sandia's Rapid Optimization Library to minimize the levelized cost of energy based on detailed mass and cost equations developed for the major cost components





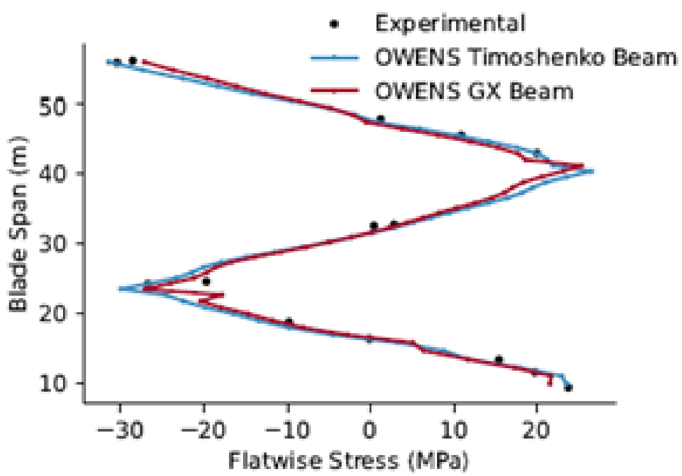
The simulation capabilities developed within the project are used to optimize the design of the ARCUS VAWT and floating platform to exploit the complicated system cost and performance tradeoffs.
(Graphic left: Kevin Moore; right: Michael Devin)

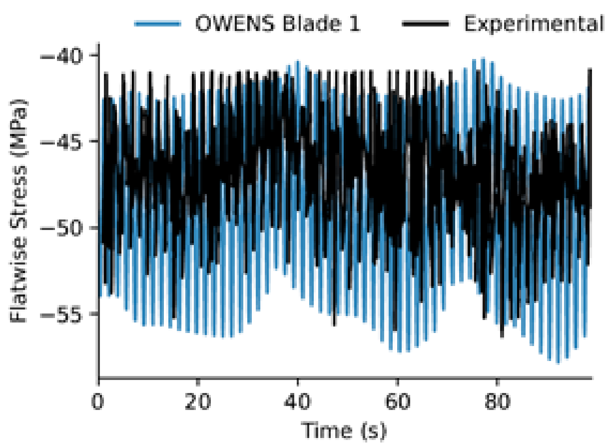
The successful design optimization of the ARCUS-TLP system relies on the accuracy of numerical predictions for stochastic simulations. Significant efforts were undertaken to validate the Offshore Wind Energy Simulator (OWENS) toolset using a hierarchical approach that increases simulation complexity from cases with analytical solutions to coupled multi-physics analyses.

This validation roadmap was followed to assess the accuracy of the elastic and hydrodynamic predictions, followed by validation of the aeroelastic and hydroelastic predictions. Aeroelastic validation was accomplished by comparing to legacy data from the land-based Sandia 34-meter VAWT with representative cases including gravitational forcing, centrifugal forcing, and dynamic operation. Hydroelastic verification was accomplished with a code-code comparison to OpenFAST results when simulating a flexible tower on a floating platform with hydrodynamic and applied tower-top forcing. The validation exercises provide confidence in the numerical predictions of the OWENS toolset and show good agreement to have certainty in the optimized system results.

Detailed design studies have been performed for the ARCUS turbine and the tension-leg platform hull and tendons. The towerless ARCUS rotor was compared to an early version of a traditional towered Darrieus rotor and resulted in greater than 50% mass reduction, revealing the benefits of this patented VAWT design. Project partner FPS Engineering and Technology completed a detailed minimum scantling design of the platform with volumetric mass relationships defined for the eleven characteristic regions within the hull. The mass relationships developed from the baseline hull design enables geometric optimization of the three-column TLP hull for levelized cost of energy minimization, resulting in mass and cost savings for the system.

Additional design studies were performed to assess the connection between the turbine and platform, where bearings transfer the turbine loads into the platform hull. The potential challenge of this load transfer is understood for floating VAWTs and studied in detail to quantify the impact of the radial bearing forces on the platform hull. Two scenarios were studied with a drivetrain located above the platform freeboard, and with the drivetrain integrated within the platform primary column. It was identified that the existing column material required for the minimum scantling design required only minor modifications to withstand the bearing loads with an integrated drivetrain within the column, which saves system mass while also reducing the overall center of gravity for the turbine components.



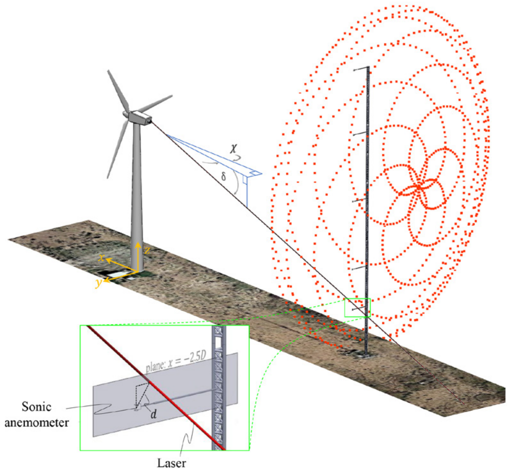


The multi-physics OWENS toolset predictions have been validated for various fundamental simulation approaches, including comparison to data from the legacy Sandia 34-meter VAWT. (Graphics by Kevin Moore)

5. WIND PLANT DATA & ARTIFICIAL INTELLIGENCE

5. WIND PLANT DATA AND ARTIFICIAL INTELLIGENCE

5.1 Verification & Validation/ Uncertainty Quantification

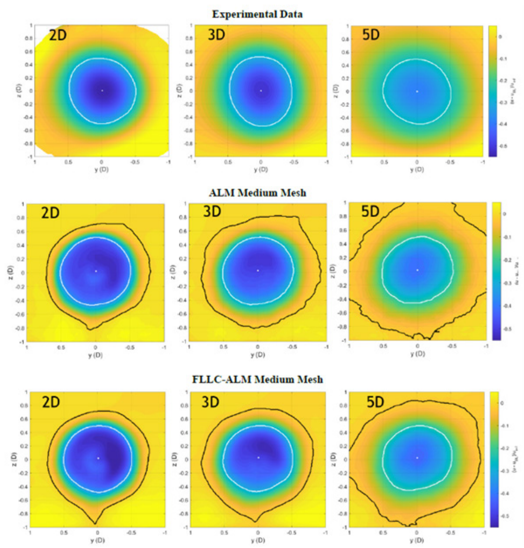


Rendering of SWiFT A1 turbine and met tower A1 used for the lidar uncertainty quantification study. (Graphic by Kenneth Brown)

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-billion dollar decisions are made using computational models for wind energy applications; this project establishes the processes to build trust in these models. It is accomplishes 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.

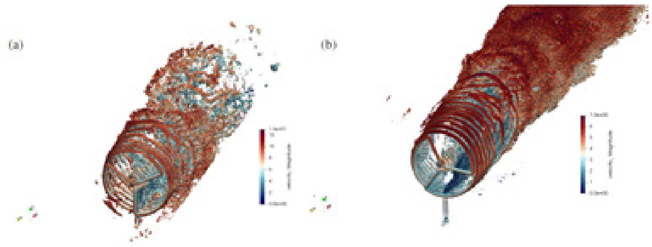
To ensure that such gaps are addressed by future validation campaigns, an offshore computational model validation planning activity was completed by a multi-lab team from the A2e program. This group identified key physical phenomena that must be accurately modeled and validated to support offshore wind system design and analysis, and the work will continue in FY23 by gathering input from a broad group of wind stakeholders from across the wind industry.

One area of work in the V&V/UQ project is the testing of novel modeling capabilities for complex system simulation, such as the filtered lifting-line correction (FLLC) actuator line and actuator disc models from the High Fidelity Modeling project. Results from testing of these models indicated that the FLLC model allows for coarser mesh resolutions with more accurate power predictions than the prior state of the art actuator models and compared well to wake validation data, as shown in the image below.



Experimental data of mean wake from lidar measurements (Top) is the same dataset used to compare to the Nalu-Wind simulations actuator line method (ALM) and ε/D = 0.035 (Middle) and the FLLC-ALM using the medium mesh (Bottom), all in the meandering frame of reference for a neutral atmospheric benchmark. The white line shows the wake defined with the same area as the rotor and the black line shows the wake defined using the converged thrust method. (Graphic by Tommy Herges and Myra Blaylock)

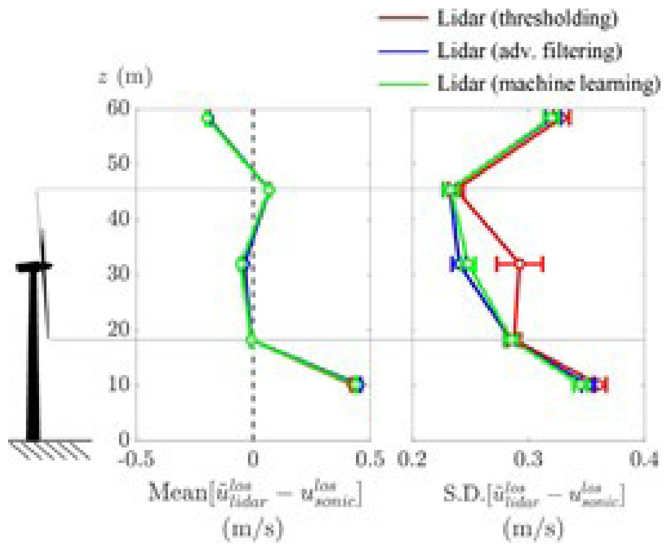
The V&V/UQ project also has performed complex system validation of ExaWind code suite capabilities for high priority applications, such as wake modeling. A paper on the validation of the Nalu-Wind for wake physics under a range of atmospheric boundary layer (ABL) conditions compared wake measurements from the SWiFT wake steering experiment to model simulation results for a range of inflow stability states as shown in the image to follow.



Tip vortex visualizations of q-criteria highlighted by velocity magnitude for the (a) neutral atmospheric boundary layer (ABL) simulation and (b) stable ABL simulation.
(Graphic by Lawrence Cheung)

The V&V/UQ project has also completed work on advanced data analysis methods, some of which resulted in a publication on high-fidelity processing for nacelle-mounted lidar leveraging machine learning for reduced uncertainty [Brown 2022]. The work describes the first-time development of a machine learning approach to processing noisy, contaminated lidar data, and results are expected to be as good or better than a reference quality assurance/quality control algorithm. This project also supported work using machine learning to develop advanced control methods while a turbine is waked, which was presented at the Torque 2022 conference [Farrell 2022] and resulted in the filing of a technical advance. Work was also completed on the demonstration of model predictions for a two-turbine system with turbine-turbine interaction for power and loads, showing how wake validation studies impact wake steering analysis.

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. Work has progressed on the automation of a multi-level, multi-fidelity uncertainty quantification methods, namely in the inclusion of the high-fidelity ExaWind code suite and in the application of the Multi-level Monte Carlo (MLMC) Optimization Under Uncertainty approach [Menhorn 2022].



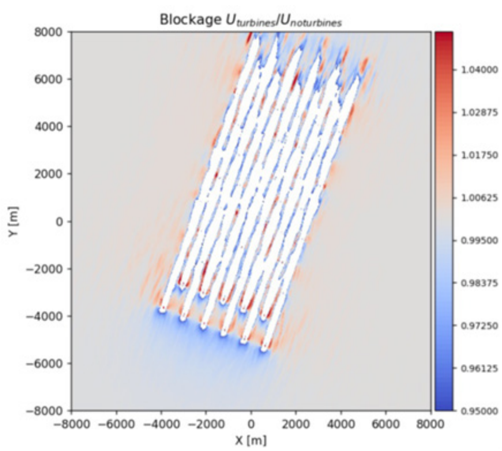
(Graphic by Ken Brown and Tommy Herges)

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, fluid-controls interactions, complex terrain, ocean waves, and advanced actuator lines.

During Fiscal Year 2022, HFM performed highly resolved actuator line two-turbine simulations and quantified the influence of different turbulence length scales on the aerodynamic and structural dynamic response of the rotor. Wake evolution and downstream turbine interactions were investigated. HFM also implemented a fluid-controls co-simulation framework and used it to perform a multi-billion cell, 50-turbine wind-plant blockage simulation on the GPU-based Summit supercomputer. In Fiscal Year 2023, HFM will implement more realistic models for towers, nacelles, gravity-wave damping, and a coupled AMR-Wind/ Nalu-Wind approach for efficient simulation of air/water two-phase flows.

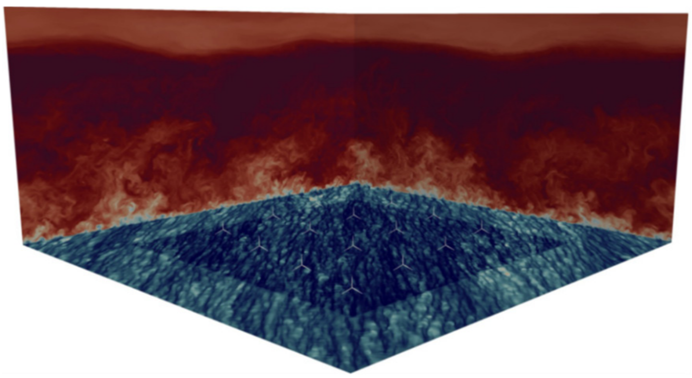


Blockage effects on a large wind farm. Note that data is clipped beyond color scale bounds. Blockage can be seen in blue, and wind acceleration in red. (Graphic by Lawrence Cheung)

5.3 ExaWind

The multi-institutional (NREL, Sandia, ORNL, University of Texas at Austin) ExaWind project is part of the U.S. Department of Energy'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 2022, ExaWind demonstrated and benchmarked a 22-billion grid-point blade-resolved simulation of 15 turbines on the Summit GPU-based supercomputer. ExaWind has made significant advances in preparing its software for the AMD GPUs found on Frontier, the world's first exascale supercomputer at ORNL. The underlying Trilinos and hypre solver stacks used by ExaWind have likewise been improved and prepared for Frontier. Overall, ExaWind is on track to succeed with its ECP Challenge Problem on Frontier early in Fiscal Year 2023. ExaWind will continue to improve computational performance, accuracy, and utility of blade-resolved simulations of whole wind farms.

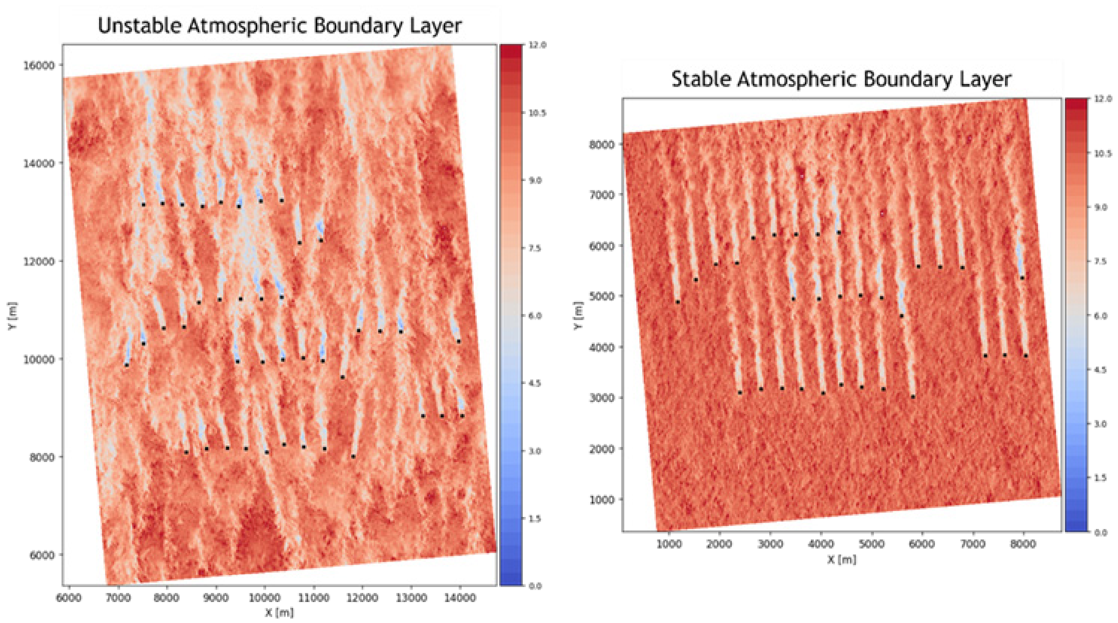


ExaWind's hybrid Nalu-Wind / AMR-Wind solver blade-resolved simulation of 15 turbines, run primarily on GPUs. (Graphic by Paul Crozier)

5.4 AWAKEN

This year the American WAKE experimeNt (AWAKEN) project, led by NREL, completed the experimental design, the land lease agreements, and started site construction and instrument deployment. Sandia performed high-fidelity ExaWind simulations using Nalu-wind to look at the effects of atmospheric stability on wind turbine wakes and wind plant blockage. AWAKEN is an ongoing international wake observation and validation campaign occurring in north central Oklahoma to provide validation data for improved understanding on the interaction between wind plants and the atmosphere. Specifically, investigating the momentum transport between the atmosphere and wind plant, upstream wind plant blockage, turbulence development within the plant, wind plant wakes and interaction between plants, and control strategies to improve wind plant performance. Sandia technologists also contributed to the construction of the wind turbine instrumentation data acquisition system, with installation occurring in FY23 following the completion of the multiparty CRADA.

Sandia performed high-fidelity large Eddy Simulations (LES) studies of the eastern portion of the King Plains Wind Project under stable and unstable atmospheric conditions using Nalu-Wind coupled with OpenFAST actuator disk models representing the wind turbine. The atmospheric inflow states match the median unstable and stable conditions of the region measured by the ARM Central Facility. Each atmospheric condition was simulated both with and without turbines to precisely quantify the blockage and wake effects of the turbines. The figure below shows an instantaneous snapshot of the both the unstable and stable horizontal wind speed at hub height. The unstable case simulates the easternmost 41 turbines of King Plains while the stable case only simulates 31 turbines due to the required higher resolution of the stable case and the constraints on computational resources. The simulations show the presence of wind plant blockage at similar magnitude for both atmospheric conditions and show the persistence of wind turbine wakes under the stable condition. Additional simulations involving multiple wind plants in FY23 will quantify the effects of wind plant wakes across the region.



Nalu-Wind simulations of the eastern portion of King Plains in north-central Oklahoma under both unstable and stable atmospheric boundary layer conditions. (Graphics by Lawrence Cheung)

5.5 Active Wake Mixing (Sandia LDRD)

Sandia's LDRD program is funding a nascent wind farm control technology called active wake mixing. This technology addresses an emerging focus area of both wind developers and OEMs: to improve wind farm power production by reducing wake effects. The technique centers on the upstream turbines in a wind farm, which apply certain blade pitching and/or rotor speed fluctuations to excite instabilities in the wake flow and promote faster wake recovery. A unique Sandia approach borrows a page from the jet-flow fluid-dynamics community to potentially provide increases in wind farm power for a small cost to wind farm lifetime.

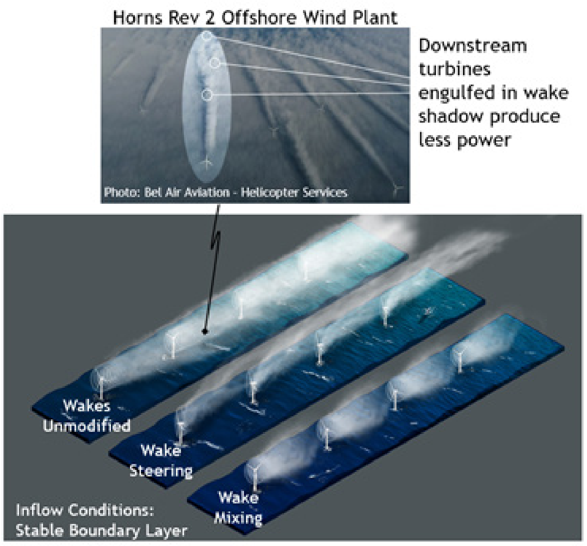
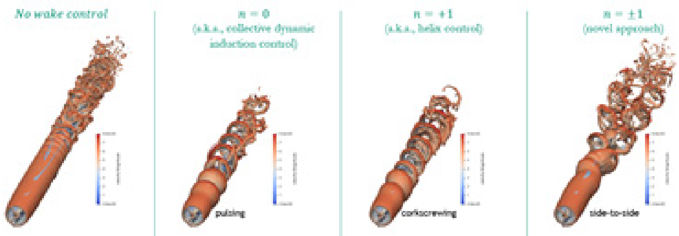


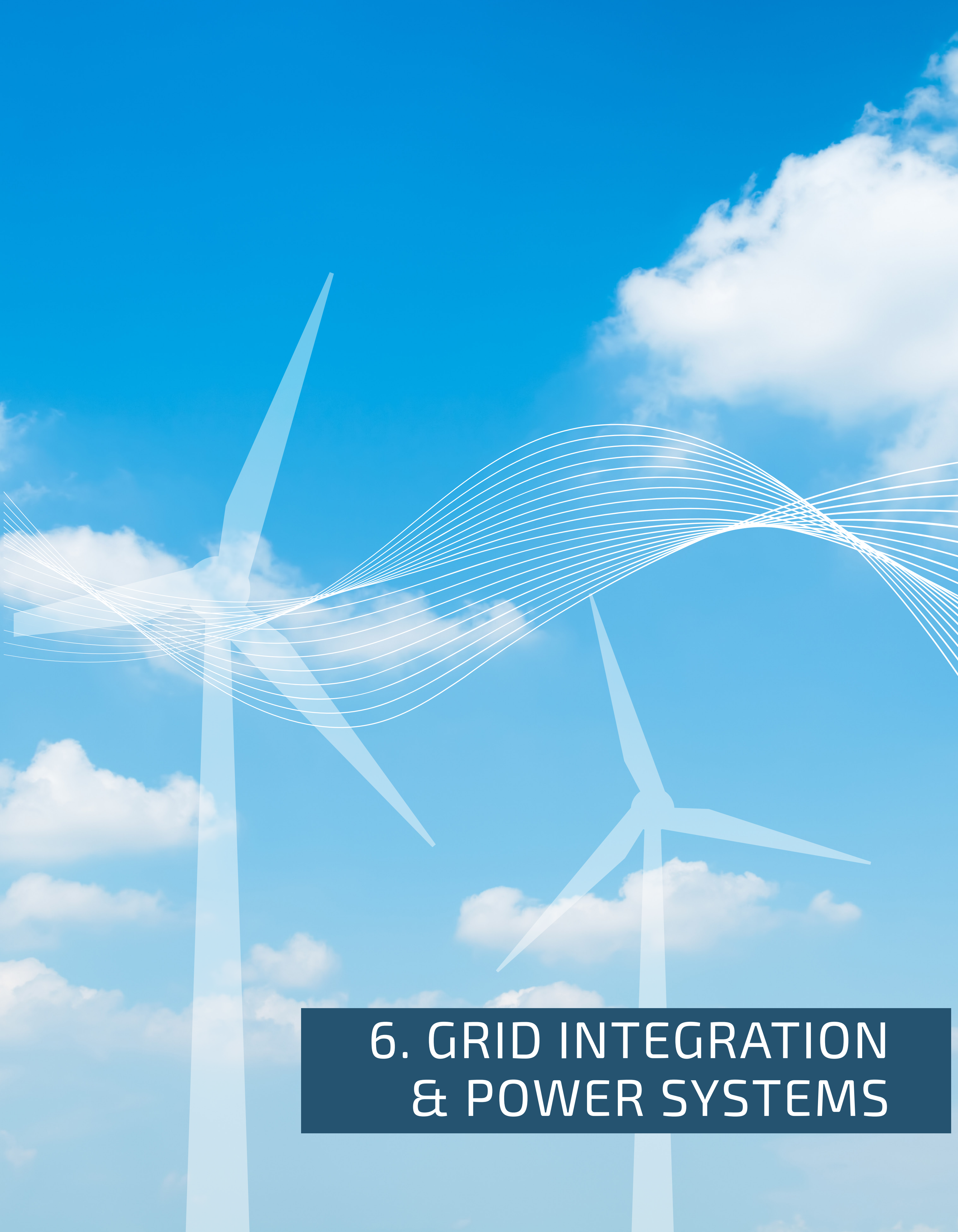
Illustration of wake effects, as well as two strategies to mitigate wake effects: wake steering and wake mixing. The Sandia team pursued and developed a novel approach to wake mixing, which may be particularly effective for the prevailing stable atmospheric boundary layers found in offshore environments. (Graphic by Eric Lundin/Ken Brown/Dan Houck)

Trials of the new technology are performed in a high-fidelity fluid simulation environment using Nalu-Wind, a large eddy simulation solver, coupled to a turbine model in OpenFAST. The figure below shows simulation results for the case of an idealized atmospheric inflow compared with three different wake mixing approaches. Whereas previous studies imposed an axisymmetric (2nd pane) or single-helical (3rd pane) disturbance to the flow, the Sandia team applied a double-helical disturbance, which may provide more separation of flow structures in the far wake and therefore more power available for turbines deeper in the wind farm.

This work is being continued in Fiscal Year 2023 with newly awarded funding from WETO that includes teaming with NREL to demonstrate and quantify the potential of wake mixing technologies in the offshore environment.



Comparison of wake mixing strategies. Simulations are performed in the large-eddy simulation solver Nalu-Wind with coupling to an OpenFAST turbine model designed to perform similarly to a GE2.8-127 machine. The flow structures shown are vorticity isosurfaces, which are colored by axial velocity magnitude. Inflow conditions are idealized to aid in visualization of the structures. (Graphic by Lawrence Cheung)



6. GRID INTEGRATION & POWER SYSTEMS

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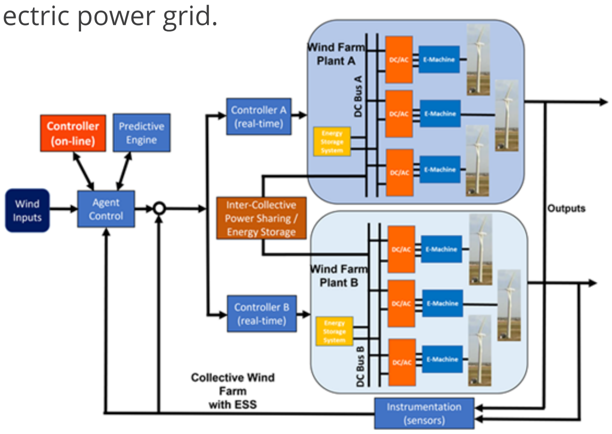
6.1 Wind Farm Controls

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).

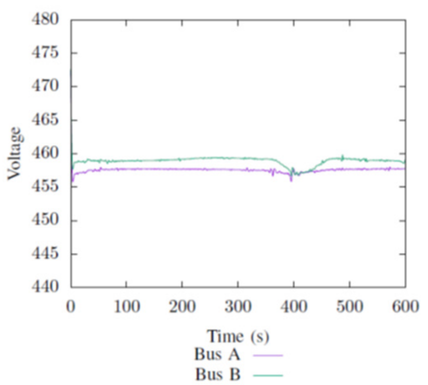
The nonlinear control design encompasses a distributed/decentralized approach that identifies where and how much ESS is required to operate efficiently. The mechanical-electrical wind turbine coupled models concentrated on Type IV generator systems as part of a DC or AC collective interface for the wind farm into the electric power grid.



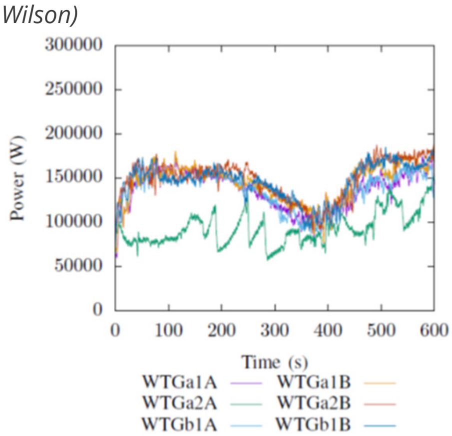
Overview of the nested control architecture used to operate the collective of wind turbines. (Graphic by Dave Wilson)

In Fiscal Year 2022, a new supervisory optimal control system based on PPN (power packet networks) implicit phase coordination of a collective of wind turbines was completed. This demonstrated efficient use of ESS with increased performance. This analysis focused on an optimal control algorithm that coordinates a small collective of wind turbines. The algorithm consisted of a ROM of the wind turbine collective, a discretization of the resulting state equations using a collocation method, and an optimization formulation that guides the collective's behavior. In order to validate this algorithm, the team investigated a scenario where two separate three-turbine collectives are connected via a transmission line. Realistic wind inputs were generated with Sandia's high fidelity Nalu-Wind and NREL's FAST.Farm codes for all three wind turbines for each collective. Combined with energy storage, each collective delivers a constant amount of power to the grid while simultaneously coordinating their performance to bound any excessive fluctuations in the voltage.

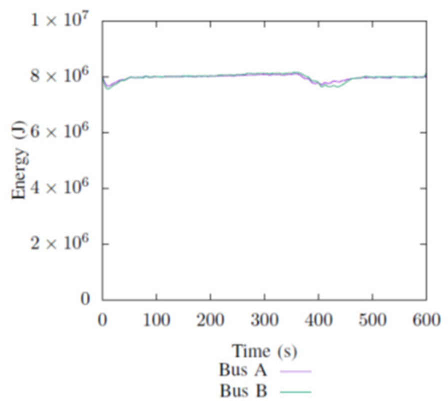
This scenario suggests that a collective of wind turbines, combined with energy storage, can be coordinated to provide grid power with consistent voltage to the grid through rapidly changing wind conditions. Our results will help guide the wind community regarding wind farm controls that increase performance and grid resiliency.



DC bus voltage: Note that while bus voltage varies slightly, it remains close to desired 460 V. This indicates that the control successfully coordinated the turbines and storage to support constant bus voltages. (Graphic by Dave Wilson)



Power transmitted to DC bus. Wind turbine Ga2A generates less power than the other turbines since it lies in the wake of WTGa1A. (Graphic by Dave Wilson)

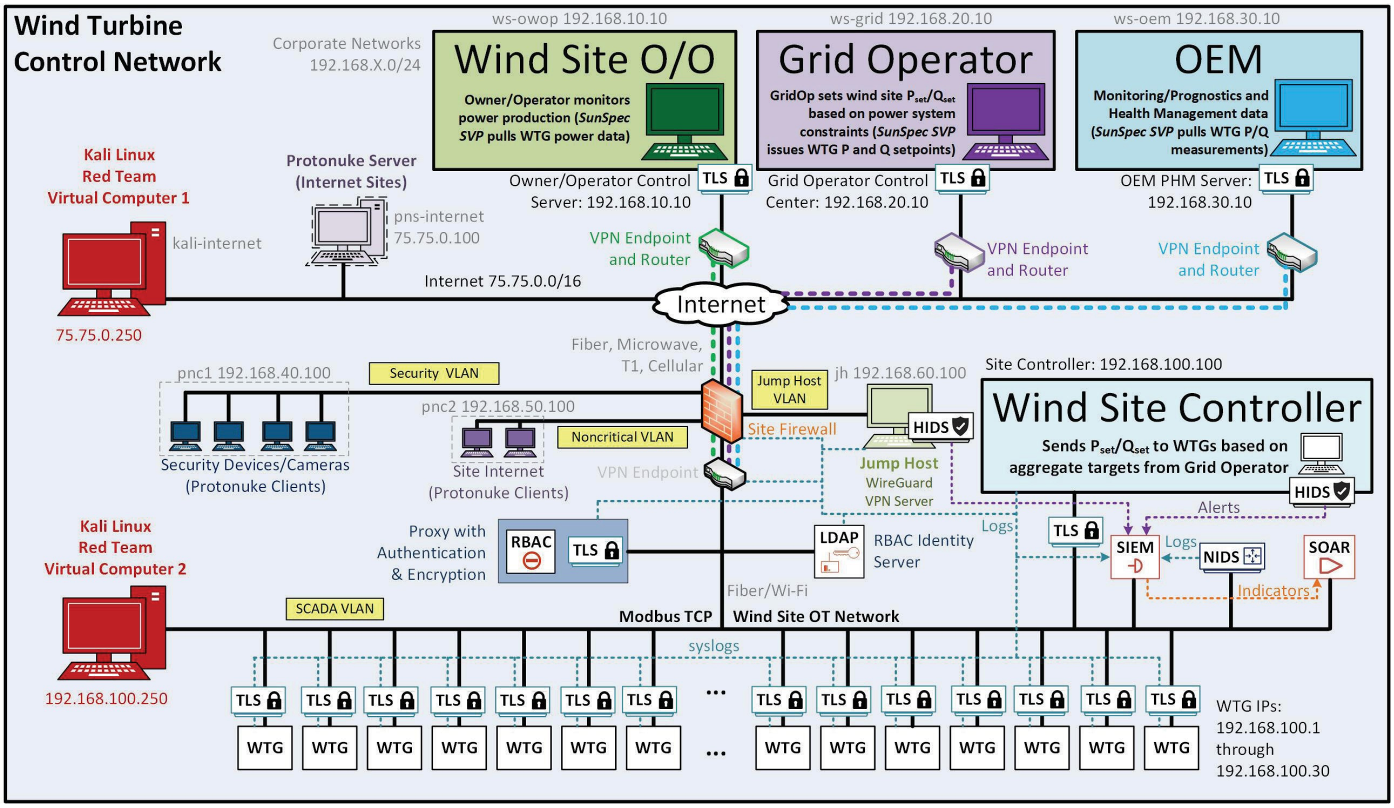


Energy in the explicit storage device. This is coordinated with the amount of energy stored in the momentum of the turbines. This also demonstrates the ability of optimal controls to assist with sizing parameters for specific types of ESS. (Graphic by Dave Wilson)

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 2022, 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:

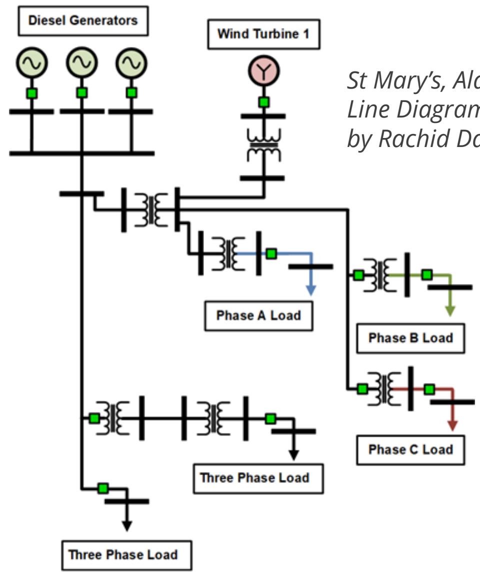
- Operational Technology (OT) encryption
- Role-based access control (RBAC)
- Security Information and Event Management (SIEM) system
- Network-based Intrusion Detection System (NIDS)
- Host-based Intrusion Detection System (HIDS)
- Security Orchestration, Automation, and Response (SOAR) technology



Wind site cybersecurity hardening features built into the networking simulation environment. (Graphic by Jay Johnson)

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

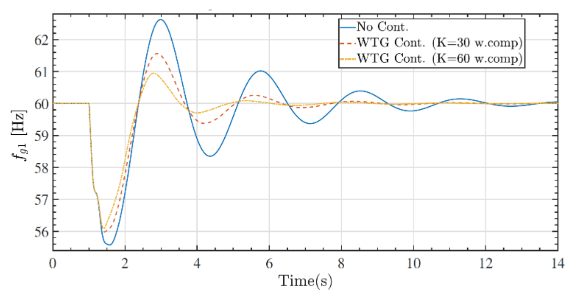
In Fiscal Year 2022, Sandia developed control strategies for grid support functions for the broader research goals of the multi-lab Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project. Through these efforts, the Sandia team developed advanced controls for distributed wind with the objective of enabling grid support for voltage and frequency regulation. These controls were tested using two use cases: St. Mary's Alaska and the SWiFT facility in Lubbock, Texas.



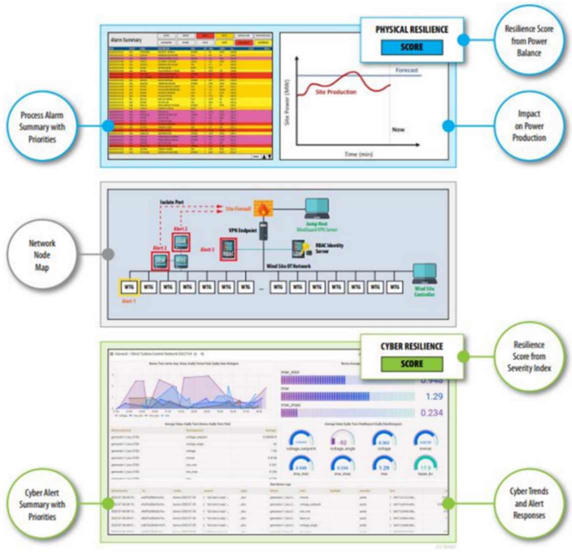
St Mary's, Alaska One-Line Diagram. (Graphic by Rachid Darbali)

The advanced control for frequency regulation was tested in a simulation model of a wind turbine generator (900 kVA) connected to a simulation model representing St. Mary's, Alaska. The St. Mary's power system consists of three diesel generators a wind turbine generator and a variety of single and three phase loads representing critical infrastructure in the community such as hospitals, airports, etc. The one-line diagram for the St. Mary's simulation model is shown below.

The simulation results for the system frequency are shown in the figure below.



Frequency measurements for the wind turbine generators operating with no control and with two different advanced controls. (Graphic by Rachid Darbali)

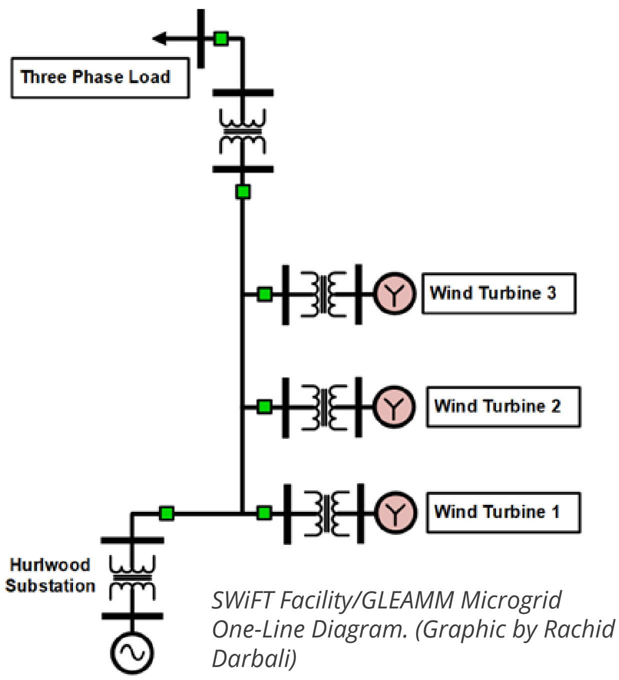


Design of a cyber-physical dashboard for wind sites. (Graphic courtesy of Craig Rieger, Idaho National Laboratory)

Simulation results demonstrated that using the advance frequency control to curtail active power from a distributed wind turbine during a loss of diesel generation could help mitigate underfrequency events (Wilches-Bernal, 2022). A variety of compensators were tested to compare the performance of this advanced frequency control. The control strategy presented in this work allows the wind turbine generator to mitigate the effect of severe loss of generation disturbances for this type of microgrid.

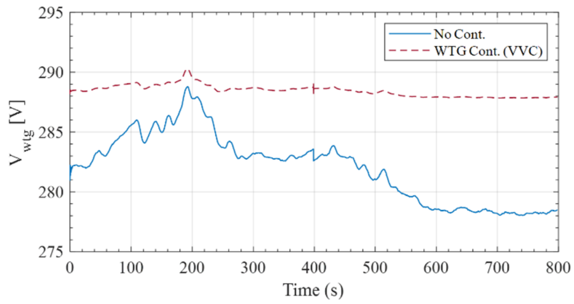
The advanced control for voltage regulation was tested using a simulation model of the SWiFT facility, consisting of the three Sandia wind turbines and a varying load located at the GLEAMM microgrid. This effort also included developing a wind turbine simulation model that represented the SWiFT wind turbines and validating the developed models using field data collected from the SWiFT facility (North-Piegan III, 2022). Results from these simulations illustrate when creating a voltage drop at the GLEAMM microgrid, the SWiFT wind turbines are able to regulate voltage in an acceptable range (Ojetola, 2023). Additional voltage regulation simulations were performed utilizing traditional Volt-VAR Curve controls (commonly used in photovoltaic inverters) (Darbali, 2022).

The one-line diagram for the SWiFT Facility/GLEAMM Microgrid simulation model is shown below.



SWiFT Facility/GLEAMM Microgrid One-Line Diagram. (Graphic by Rachid Darbali)

Voltage variations in the system are produced by both the GLEAMM microgrid varying load and variable power generated by the SWiFT wind turbine generators. Simulation results utilizing a Volt-VAR Curve control demonstrated that at varying wind speed conditions, implementing an autonomous control regulates the voltage at the point of interconnection. The simulation results for the voltage measurements of a single SWiFT wind turbine generator are shown in the figure below.



Voltage measured at the wind turbine generators point of interconnection operating with no control and with Volt-Var Curve control. (Graphic by Rachid Darbali)

These advanced controls for frequency and voltage will be tested utilizing the wind turbine emulator located in Sandia's Distributed Energy Technology Laboratory (DETL) in a Power Hardware-in-the-Loop platform (Berg, 2022). These experiments will help identify communication challenges that might exist when deploying these controls in actual power converters.

7. SOLUTIONS TO NATIONAL SECURITY TECHNOLOGY BARRIERS

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7.1 Defense and Disaster Deployable Turbine (D3T)

In its final year, the Defense and Disaster Deployable Turbine (D3T) team, including representatives from Sandia, NREL, INL and University of Dayton Research Institute completed analysis and focused on disseminating results. These efforts included news releases, publishing two SAND reports, a conference abstract, conference poster and journal proceeding, and hosting a virtual workshop for stakeholders.

Eleven companies presented their technology to an audience of over 90 attendees at the Deployable Wind Power for Defense and Disaster Response Workshop. Two keynotes highlighting use-cases for defense and disaster relief were presented by representatives from DoD and a nonprofit, respectively.

https://energy.sandia.gov/defense-and-disaster-deployable-turbine/

Rendering of a potential military or humanitarian base utilizing wind and solar as complements to diesel generation (Graphic courtesy of NREL)

Deployable Wind Power for Defense and Disaster Response Workshop

On June 17, 2022, the multi-lab, U.S. Department of Energy (DOE) funded Defense and Disaster Deployable Turbine (D3T) project team held a virtual workshop with stakeholders from defense and disaster response communities and technology developers to discuss the needs for demonstrating and deploying wind-hybrid deployable energy systems.

Approximately 90 stakeholders participated in the workshop. The D3T team presented an overview of the current research and 11 solution providers presented lightning round talks giving overviews of their technology. Two keynotes were given by representatives from disaster response and defense perspectives. Discussion was facilitated by a poll with questions that allowed real-time response from the audience.

7.2 Radar Interference Mitigation

7.2.1 Wind Turbine Generator Impacts to Marine Vessel Radar

Sandia National Laboratories was a co-author in the report published by the National Academies of Sciences, Engineering, and Medicine which, at the request from the Bureau of Ocean Energy Management, sought to identify and characterize the impacts of wind turbines on marine vessel radar systems as the offshore wind industry is set to expand rapidly across the U.S. Outer Continental Shelf over the next few decades. Because of the size and materials that make up wind turbines, they can have a large electromagnetic reflectivity and can interfere with radar systems in their vicinity. In addition, the rotation of the blades of the wind turbines can cause large Doppler-shifted reflections that can saturate radar Doppler bins and obfuscate moving targets such as smaller vessels.

The report concludes that offshore wind turbines can have a significant radar reflectivity and will lead to complications with marine navigation, but that there are opportunities to ameliorate these impacts. The report recommends that the Bureau of Ocean Energy Management and other relevant agencies implement practicable guidelines and options to help mitigate some of these impacts such as enhanced mariner training, requiring vessels to utilize radar reflectors, the deployment of reference buoys, and to continue to fill in the knowledge gaps of the impacts of offshore wind turbines on marine vessel radar through data collection and modeling and analysis when these offshore wind turbines are deployed.

The report is available on the National Academies of Sciences, Engineering, and Medicine website at https://www.nationalacademies.org/our-work/wind-turbine-generator-impacts-to-marine-vessel-radar.

7.2.2 Congressional Report: Update on the Efforts of the Wind Turbine Radar Interference Mitigation Working Group

This U.S. Department of Energy report responds to language set forth in the House Committee on Appropriations report 116-449, which accompanied the Energy and Water Development and Related Agencies Appropriations Bill (2021). Sandia National Laboratories was a lead author on this report to Congress that addresses the:

- status of testing, certification and deployment of mitigation options by radar type and department or agency;
- remaining steps and timelines before mitigation options currently being developed or tested could be available for deployment;
- identification of resource gaps to achieve deployment of mitigation options currently being tested;
- identification of mitigation options that are not currently being considered due to resource constraints but may be promising with additional resources and prioritization; and
- mitigation options that have been dismissed along with an explanation of why the option is not considered viable.

The federal interagency Wind Turbine Radar Interference Mitigation (WTRIM) working group was established by a consortium of federal agencies including the U.S. Department of Energy, the U.S. Department of Defense, the Federal Aviation Administration, the National Oceanic and Atmospheric Administration, and the Bureau of Ocean Energy Management to address the impacts of wind turbines on civilian and national defense radar system operations. Each agency participates voluntarily in the WTRIM working group and receives its own appropriations, direction, and funding from Congress.

At the time of publishing of this document, the report was undergoing internal review at the U.S. DOE.

8. WIND ENERGY STANDARDS AND COLLABORATION TASKS

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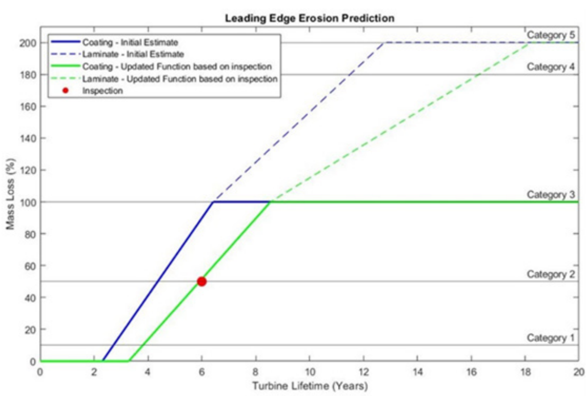
8.1 IEC 61400-5 blade design standard

Sandia organized and led the 61400-MT5 group to address conflicts with IECRE (the International Electrotechnical Commission (IEC) System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications) and address unclear language in Edition 1 of the 61400-5 blade design standard. The group has grown to over 30 members from 11 countries. A draft amendment to Ed. 1 has been developed and is currently in the process of being approved for publication. The group has also begun planning for development of Ed. 2 of the standard. Finally, a meeting of U.S. experts to collect feedback on the standards work was hosted in conjunction with the 2022 Sandia Wind Blade Workshop.

8.2 IEA Task 43: Digitalization

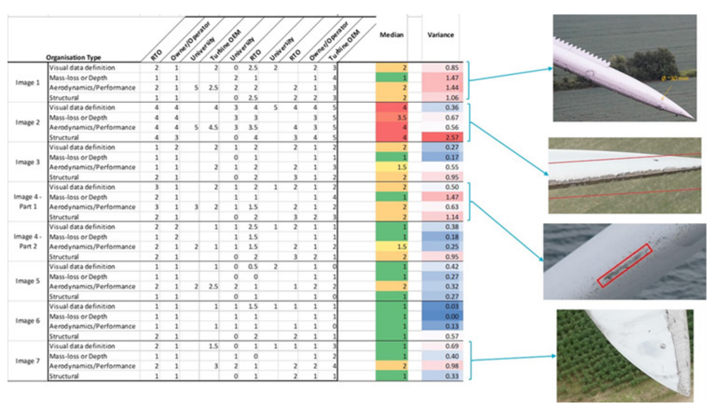
Sandia contributed this IEA Wind task by working with Aalborg University to develop a probabilistic model for leading edge erosion prediction. The model combines an accepted physics-based model for erosion with data from blade inspection images. Sandia is currently working on obtaining extensive data sets of wind plant performance and erosion inspection images to validate the model. Once complete, the code will be made available to wind plant owners to help improve maintenance planning.



Theoretical prediction of initial and updated blade erosion projection from sample data set. (Graphic by Josh Paquette)

8.3 IEA Wind Task 46: Erosion of Blades

Wind turbine blade leading edge erosion causes degradation in the power production of wind farms due to the summed performance loss of individual turbines. This performance deficit is caused by the structural erosion of the blade leading edge, which causes degradation in the blade aerodynamics. To address these issues, Sandia supports the leadership of IEA Task 46 on the Leading-Edge Erosion of Wind Turbine Blades, leading work package 3 on Wind Turbine Operations with Erosion. This work package is focused on understanding wind turbine performance under varying levels of leading-edge erosion, including the effect of leading-edge erosion surface roughness on rotor blade aerodynamics. In Fiscal Year 2022, the work package group that Sandia leads developed a standard erosion classification system, which will enable greater research collaboration across the wind industry and will facilitate more efficient decisionmaking and reporting between wind turbine owners and repair companies. A report on leading-edge erosion classification was developed based on input from the participating members from the wind turbine industry and research communities. This report brings together several other classification systems from across the wind community into a single framework, which will be adopted by the other Task 46 work packages.



Erosion classification study results showing wide disagreement among experts. (Graphic by Josh Paquette)

9. INTELLECTUAL PROPERTY

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