Sandia National Laboratories

SANDIA WIND ENERGY PROGRAM

FY23 ACCOMPLISHMENTS

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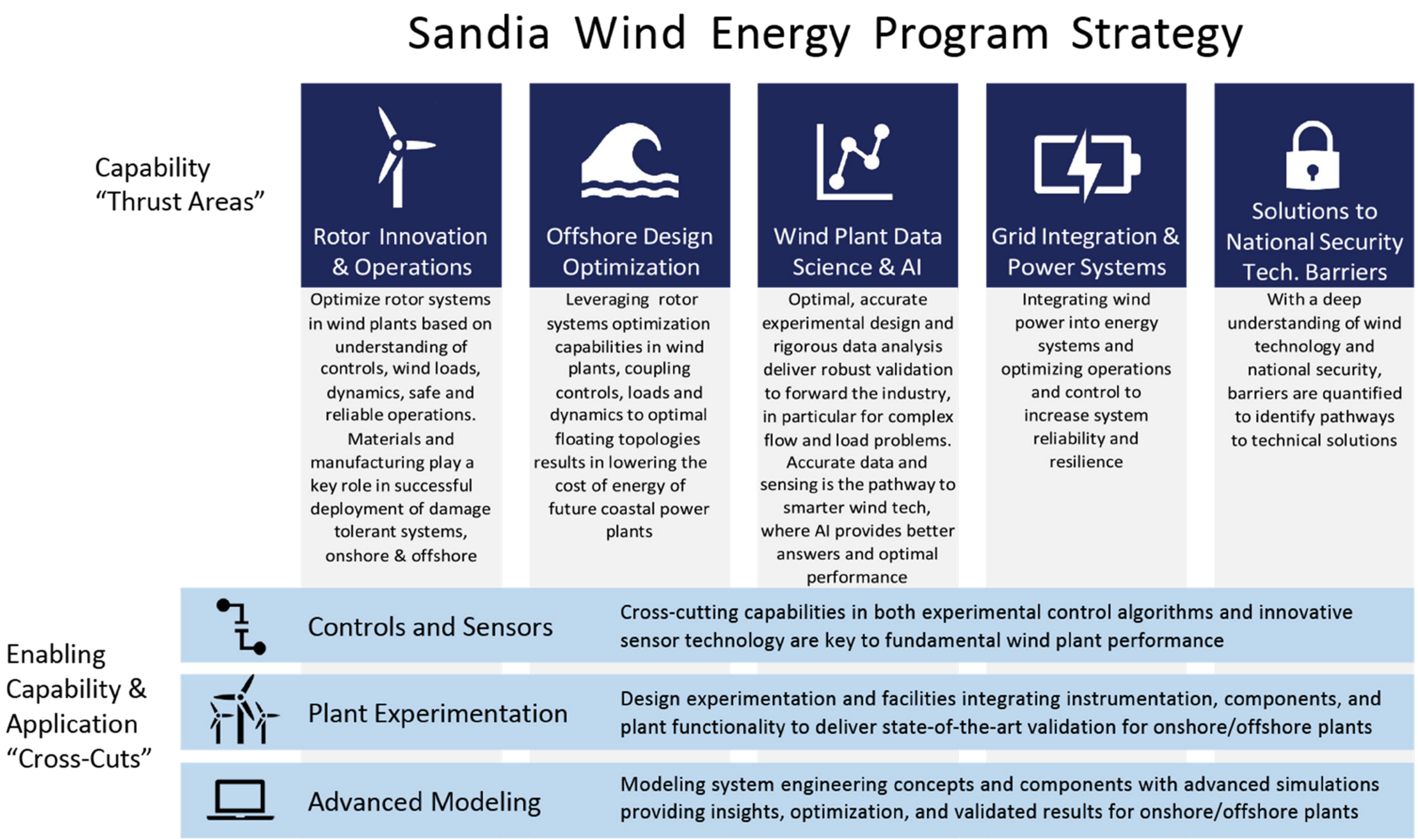
INTRODUCTION

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 2023 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), the Sandia Laboratory Directed Research and Development (LDRD) program, and private industry. 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

1.1 News Releases

Wind Energy Technologies Office, "Rotating Laser on Texas Wind Turbine to Improve Accuracy of Wind Industry Simulation Tools," WETO Press Release, Oct. 20, 2023, https://www.energy.gov/eere/wind/articles/rotating-laser-texas-wind-turbine-improve-accuracy-wind-industry-simulation

1.2 News Articles

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Kelly Sullivan, and Christopher Kelley. "Spinner lidar will improve accuracy, prediction of wind turbine data," California Communicator, June 30, 2023. https://prod-ng.sandia.gov/8000/2023/06/27/sandia-researchers-install-spinner-lidar-to-improve-accuracy-prediction-of-wind-turbine-data/

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1.3 Blogposts

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1.4 Social Media

X (formerly known as Twitter)

Kelly Sullivan. (@SandiaEnergy), "Check out @eeregov's new Floating Offshore Wind Shot and how Sandia's research can help further these goals," Twitter, Oct. 4, 2022. https://twitter.com/SandiaEnergy/status/1577652813336903680?cxt=HHwWgIC83f-3-eQrAAAA

Kelly Sullivan. (@SandiaEnergy), "Back in business. Sandia's Scaled Wind Farm Technology facility is the first @ eeregov user facility in the U.S. to offer multiple wind turbines to measure turbine performance in a wind farm environment." Twitter, Dec. 15, 2022, 09:52 a.m. https://twitter.com/SandiaEnergy/status/1603432773456478210?cxt=HHwWhIC-sZbnxMAsAAAA

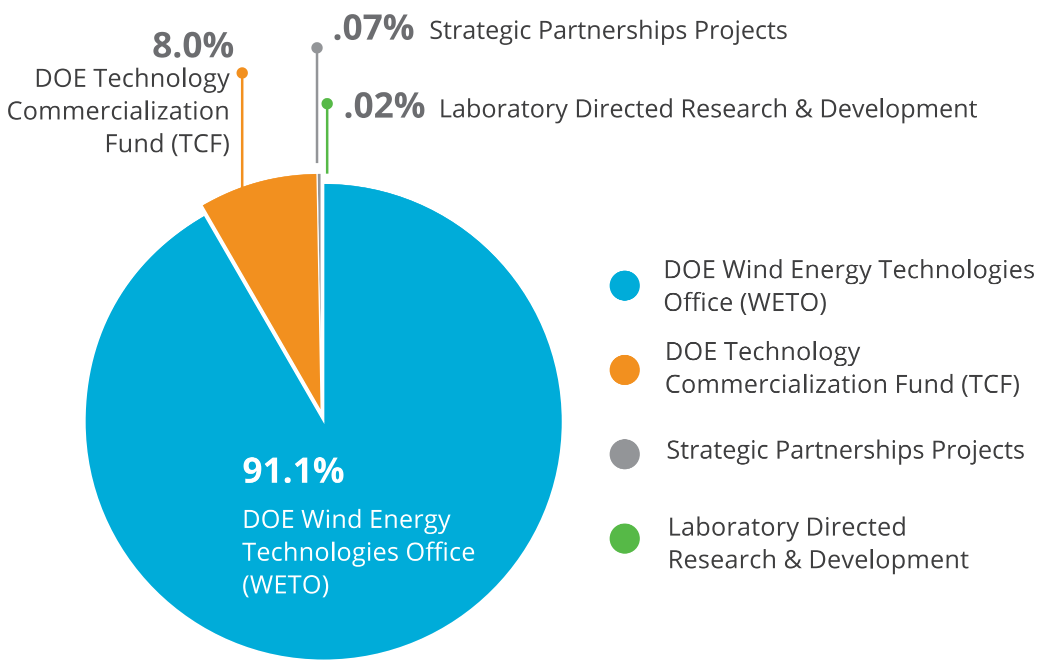
Kelly Sullivan. (@SandiaEnergy), "#YearInReview : A Sandia team created new software that helps design innovative floating wind turbines," Twitter Dec. 30, 2022, 12:27 p.m. https://twitter.com/SandiaEnergy/status/1608907533049110528?cxt=HHwWgIC9_Y-4_tMsAAAA

Kelly Sullivan. (@SandiaEnergy), "A record-breaking 190 wind energy industry experts, wind farm owners & operators, manufacturers, & researchers from around the world met at the Sandia Blade Workshop, hosted by @ ENERGY's @SandiaEnergy. Catch a recap of their activities here: https://bit.ly/Catch_The_Wind" Twitter, Jan. 6, 2023, 1:50 p.m.

Facebook

Kelly Sullivan, and Sandia National Labs. "Sandia researchers installed a spinner lidar on a GE wind turbine in Lubbock, Texas. The device enables pulses of laser light to measure approaching turbulent wind and will improve simulations of turbine blade performance," July 14, 2023, 9:18 a.m., https://www.facebook.com/SandiaLabs/

1.5 Funding



This chart represents funding sources from FY2023

2. SWIFT FACILITY

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In Fiscal Year 2023, the A1 Turbine was utilized to complete the NRT Project runtime and data gathering (See Section 3.1). Wind turbine A2 Commissioning continued with Phase I completed and most of Phase II completed during this period with one remaining step to be completed in Fiscal Year 2024. The team also began Commissioning with the B1 Turbine with the goal of completing this process in Fiscal Year 2024. The meteorological towers remained fully operational for most of Fiscal Year 2023, due to improvements with the grounding system.

Continuous Improvement efforts also occurred throughout the year which included updating electrical diagrams and drawings with NFP70E inspections. The SWiFT team also hosted the bi-annual Sandia corporate subject matter experts meeting that included performing an emergency training simulation, with participation from the local Lubbock Fire Department, to rescue a life size dummy from the A2 Turbine nacelle.

Fiscal Year 2023 delivered a major change in direction for the SWiFT facility that included a funding transition to a user facility model where Sandia is actively seeking non-DOE sponsored customers to use SWiFT for their R&D needs. The team has already secured funding partnerships from many different companies and expects to expand experimental activities at SWiFT in support of the wind industry.

High angle rescue training with rescue manikin being lowered from a turbine. (Photo by Nick Johnson)

3. ROTOR INNOVATION & OPERATIONS

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3.1 Rotor Wake

During Fiscal Year 2023, the Rotor Wake project accomplished major milestones in wind turbine field testing, instrumentation deployment, model development, and validation. The Rotor Wake project included two tasks: The Rotor Aerodynamics, Aeroelastics, and Wake (RAAW) experiment and the National Rotor Testbed (NRT).

Rotor Aerodynamics, Aeroelastics, and Wake

The Rotor Wake team at Sandia successfully purchased and deployed a one-of-a-kind spinner lidar on the hub of the GE 2.8 MW turbine in Lubbock, Texas. The instrument operated for 6 months, collecting data on the temporal and spatial fluctuations of inflow velocity that the rotor experiences. The team made progress on understanding the benefits of data informed simulations using the spinner lidar to improve the accuracy of aeroelastic model predictions of turbine performance and loads. For example, using the spinner lidar wind field to drive wind simulations showed significant reduction of error compared to driving the simulation with the meteorological tower wind speed measurements.

Spinner Lidar installed on the hub of the GE 2.8 MW turbine in Lubbock, Texas and collecting inflow data for the RAAW experiment. (Photo by Tommy Herges)

Optimized aerodynamic instrumentation was developed and designed for the Rotor Wake project. An improvement over best practices for airfoil pressure measurements was found. For less than 5% error of lift measurements, the number of pressure ports and number of pressure transducers was reduced from 30 to 18, a cost savings of up to 40%. This capability is significant to reduce the cost of high-Reynolds number airfoil testing for future offshore wind turbines. The optimized pressure measurements were not deployed in RAAW but will be flown in the DOE funded Big Adaptive Rotor (BAR) project.

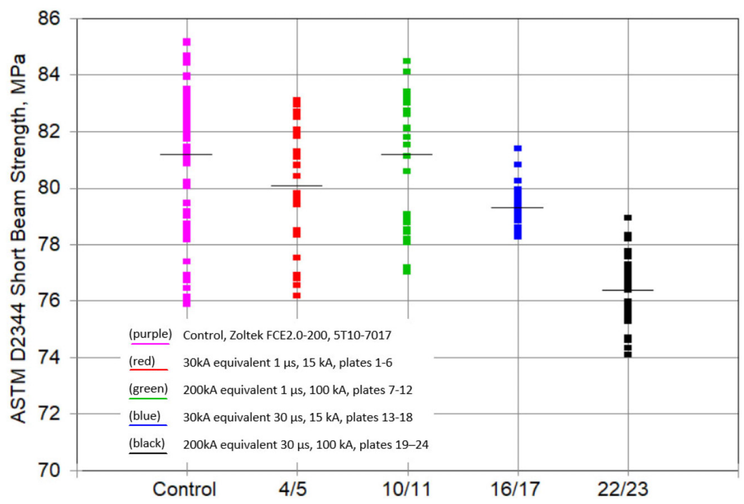
National Rotor Testbed

The National Rotor Testbed (NRT) is now in its designed state: to create the same scaled wake as a GE 1.5sle. This means the NRT and SWiFT are a research platform relevant for full-scale wake and turbine interaction experiments. Technical work completed this year included deploying NRT controller changes for scaled wake operation. The NRT collective blade pitch was reduced from its initial deployment setting. This ensured the measured NRT tower thrust coefficient and blade bending moment coefficients matched the design of the GE full-scale turbine based on NRT measurements. The final torque constant was also deployed to the NRT controller. This engineering change made the NRT spin at the same tip-speed-ratio as the GE full-scale turbine.

3.2 Blade Durability and Damage Tolerance

The Sandia-led Blade Durability and Damage Tolerance project seeks to improve the reliability of wind turbine blades through research into structural design and manufacturing, as well as environmental causes of early failure. In Fiscal Year 2023 the project focused on five subject areas: Robotic Inspection, Damage Tolerant Materials and Repairs, O&M Optimization, Lightning, and Erosion.

The Robotic Inspection Task completed a technoeconomic analysis for using crawlers and drones to perform inspections of wind blades. The analysis showed the potential for significant reductions in lifetime maintenance costs by using these robots to conduct faster, higher fidelity inspections.



Impact of lighting current amplitude on carbon composite matrix properties. (Graphic by Michelle Williams)

In the area of Damage Tolerant Materials and Repairs, the team performed an analysis of the use of composite doublers to increase reliability and reduce the cost of major structural repairs of wind blades. The results of this first analysis were used to develop an experimental plan to validate the findings. This work is done in partnership with Montana State University.

In O&M Optimization, the team completed the development of a novel leading edge erosion prediction model that links images of blade erosion to a well-validated physics model. Once validated with field data, this model will allow wind plant owners to better plan for maintenance activities. Additionally, a crack growth model was also added that predicts the growth of trailing edge separations, another common failure mode in blades.

The lightning task completed simulated lighting testing of wind blade carbon fiber samples at Sandia and mechanical testing at Montana State University. The results showed the potential for damage to the materials that is not currently detectable by inspection systems. The team is now preparing to do additional testing on stacked plates and with multiple strikes.

Finally, the leading edge erosion task worked extensively with IEA Task 46: Erosion, managing two of the work packages on Atmospheric Effects and Operations. The results of this work were studies on the impact of water droplet size on erosion and an analysis of erosion classification ratings.

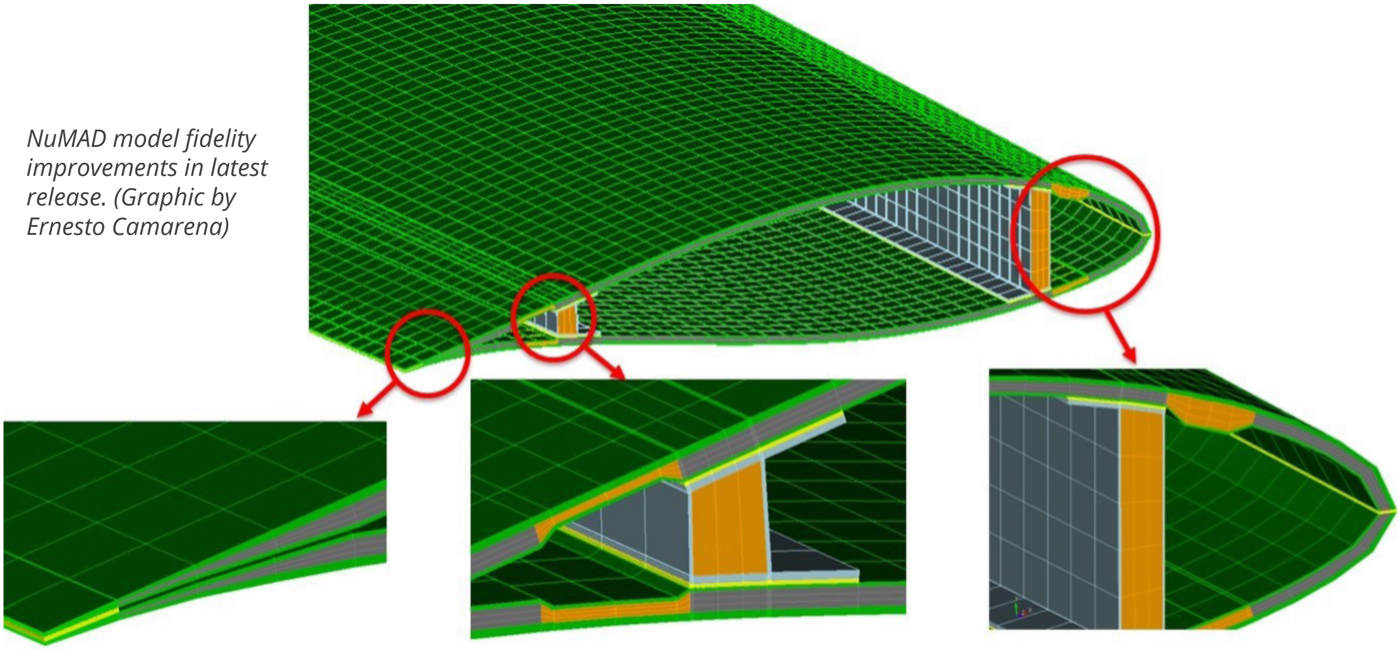
3.3 Big Adaptive Rotor (BAR)

The Big Adaptive Rotor (BAR) project is an NREL/Sandia research program focused on identifying and reducing uncertainties in the design of the next generation of wind turbine blades. In the current phase of the project, the Sandia and NREL teams are conducting research into noise and loads on downwind turbines, the impact of distributed aerodynamic controls, methods to quantify and improve blade damping, reducing uncertainties in composite material properties, and increasing the speed and fidelity of aero-structural blade analyses.

This year, the Sandia team completed a technoeconomic analysis of distributed aerodynamic controls. These devices can react much more quickly to gusts, reducing loads on wind blades and the rest of the system. While these devices have been studied before, the Sandia team, along with partner Rose-Hulman Institute of Technology, analyzed a different method for controlling the devices to offer a more practical implementation. The technoeconomic analysis was the first of its kind to quantify the lifetime cost and benefit of these systems and showed that they produced a moderate decrease in cost of energy.

The Sandia team also released a new version of the NuMAD blade modeling code. The latest version is decoupled from commercial software, allowing researchers at Sandia and elsewhere to use a multitude of different finite element codes and run many more simulations than the previous versions. The new release also produces much more accurate models of blades, including details like interfaces and bondlines.

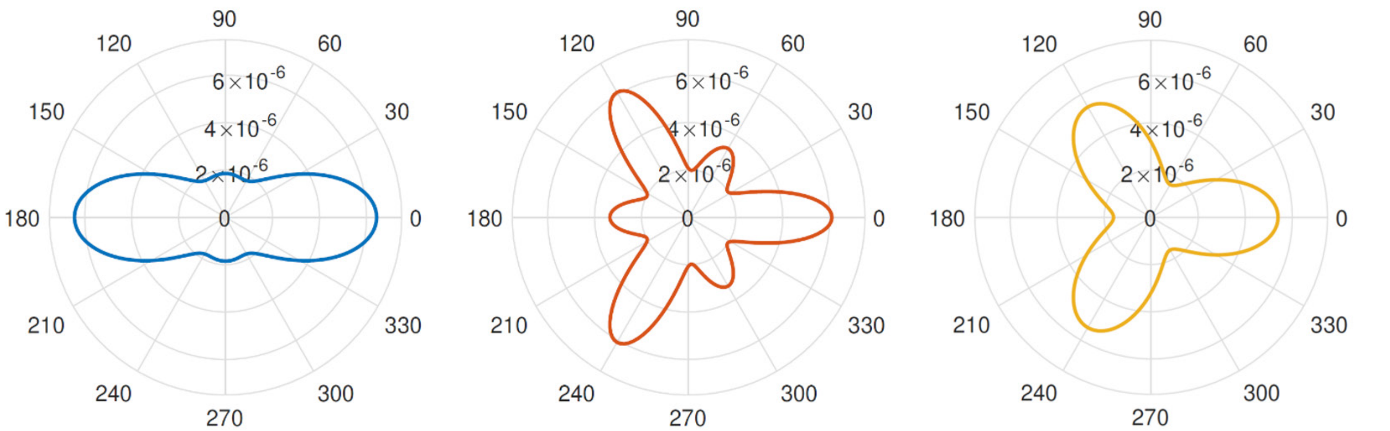
NuMAD model fidelity improvements in latest release. (Graphic by Ernesto Camarena)



3.4 Carbon Fiber Material Design for Targeted Performance Enhancement

For cost-driven industries, such as with the wind energy and automotive industries, the cost of commercial carbon fiber materials is often prohibitive for their usage compared to alternatives. The improved mechanical properties of carbon fiber are often negated by the lower cost of glass fiber reinforced polymers in many wind turbine blade designs.

The Carbon Fiber Material Design project, in partnership with Oak Ridge National Laboratory and Montana State University, is working to assess the impact of carbon fiber geometry on composite compressive strength and cost. Early project work developed an analytical approach to optimize fiber geometries for use in carbon fiber reinforced polymers to increase the compressive strength per unit cost. Robust optimal shapes were identified, shown in the figure below, that outperform circular fibers due to increases in area moment of inertia and perimeter, as well as decreases in carbon fiber processing costs.

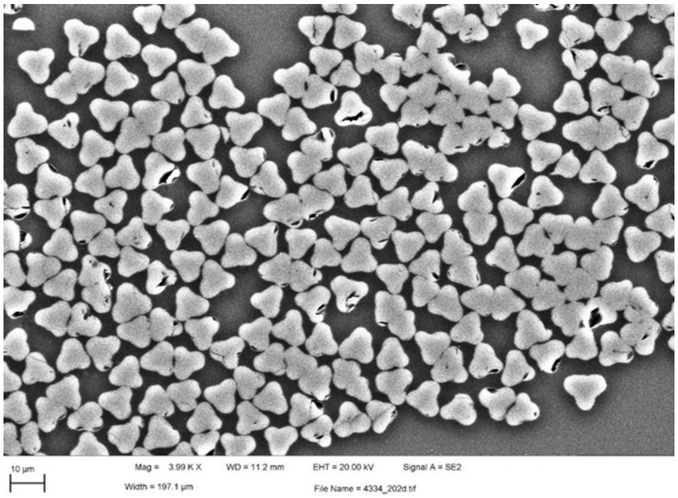


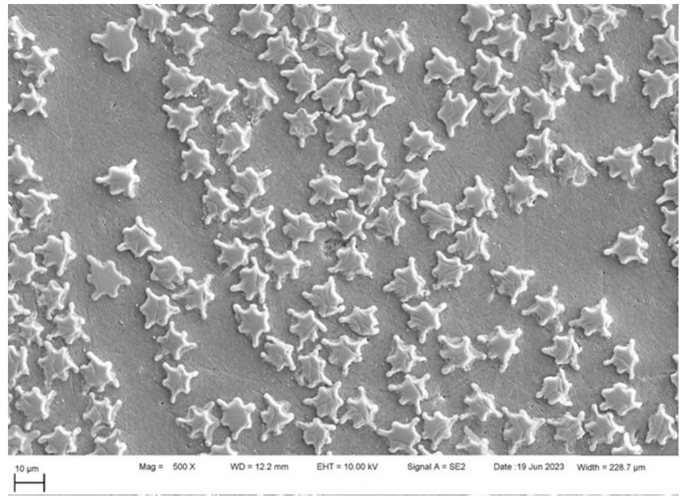
(a) Four lobe (b) Six Lobe (c) Three Lobe

Identified optimal carbon fiber geometries based on analytical modeling and constant cross section area. (Graphic by Brandon Ennis)

A micromechanical failure model was developed and validated for prediction of composite compressive failure through simulation of fibers, resin, and the fiber-resin interface. This modeling tool has been used for numerical prediction of the identified fiber geometries, predicting 6 to10% improvements in composite compressive strength for the three and six lobe fibers, respectively. A 10% reduction in the fiber alignment standard deviation increases the compressive strength improvements to 10 to 14% for the three and six lobe fibers (Camarena, 2023).

Representative three lobe and six lobe carbon fiber material systems have been produced at Oak Ridge National Laboratory as shown in the next figure. These research materials were developed to gain insights into precursor manufacturing distinctions in addition to assessing the shape translation and mechanical performance of the fibers through the various processing stages, from precursor production to carbon fiber conversion. The project work will continue towards identifying the optimal carbon fiber design specifications by increasing the design space beyond carbon fiber shape to also include the cross-sectional area and the carbon fiber tow (strand grouping) properties. Detailed cost models have been developed to estimate the cost implications of the design parameters and numerical tools will be used to assess the compressive performance of the variable geometries to identify carbon fiber pathways that offer greater advantage for the wind industry.





Three lobe carbon fiber	Six lobe carbon fiber

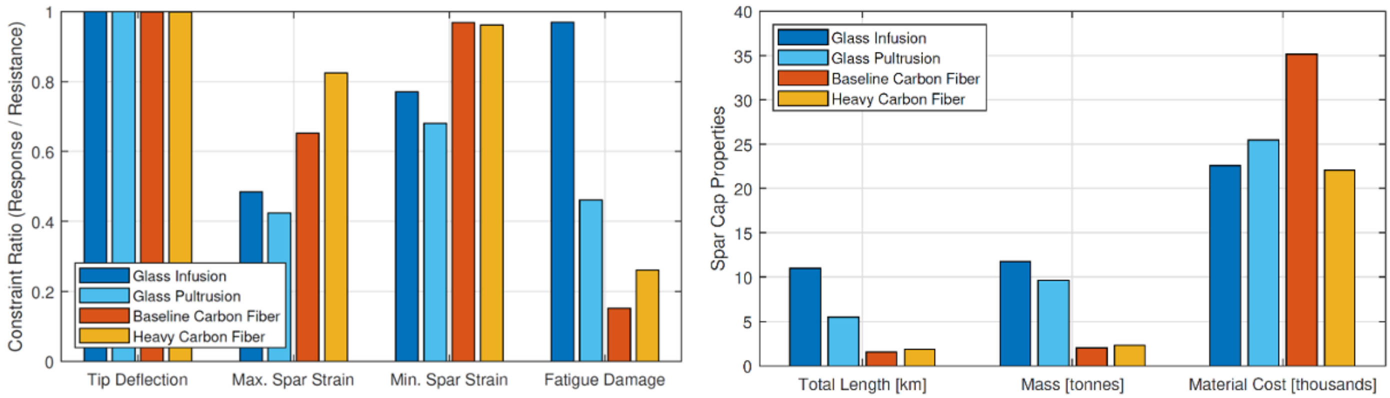
Research carbon fiber systems manufactured at ORNL to represent more optimal, noncircular geometries. (Photo by Bob Norris, ORNL)

3.5 Optimized Carbon Fiber Composites in Wind Turbine Blade Design

Increases in wind turbine blade length produce an exponential increase in energy capture (related to blade length squared) and also result in increases in the capacity factor, which is another comparative metric for energy systems. However, as blade lengths increase, the challenge of controlling blade mass becomes even more critical to enabling the associated levelized cost of energy reductions. Stiffer and stronger reinforcement fibers can help to resolve the challenges of meeting the loading demands while limiting the increase in weight, but these materials are substantially more expensive than the traditional E-glass fiber systems.

This project identified opportunities to bring further reductions in the mass and cost of modern wind turbine blades while enabling continued increases in blade length through the use of alternative material systems and composite manufacturing processes. Pathways were identified to improve the performance of carbon fiber in wind blades, while also reducing the levelized cost of energy. The use of alternative material systems, such as heavy-tow textile carbon fiber systems, can outperform existing materials in the spar cap and reduce the blade cost and weight when used in the edgewise reinforcement. The use of heavy-tow textile carbon fiber material systems can reduce the blade mass by 30-31% when used in the spar cap and by up to 7% when used in edgewise reinforcement.

A pultrusion cost model was developed to enable a material cost comparison that includes an accurate estimate of the intermediate manufacturing step of pultrusion for the carbon fiber composite. Material cost reductions were revealed for the heavy-tow textile carbon fiber compared to infused E-glass and commercial carbon fiber material systems, as seen in the figure below. The pultrusion cost model was also used to assess the opportunity for using pultruded fiberglass in wind blades, studying conventional E-glass fiber reinforcement. When using pultruded fiberglass as the spar cap material for two design classifications, the blade weight was reduced by 6% and 9% compared to infused fiberglass. However, due to the relatively large share of the pultrusion manufacturing cost compared to fiber cost, the spar cap material cost increased by 12% and 7%. When considering the system benefits of reduced blade mass and potentially lower blade manufacturing costs for pultruded composites, there may be opportunity for pultruded E-glass in wind blade spar caps. Additional studies are recommended to compare high-modulus glass fibers in pultruded composite form where the additional pultrusion manufacturing cost may be offset more effectively by the increased mechanical properties.

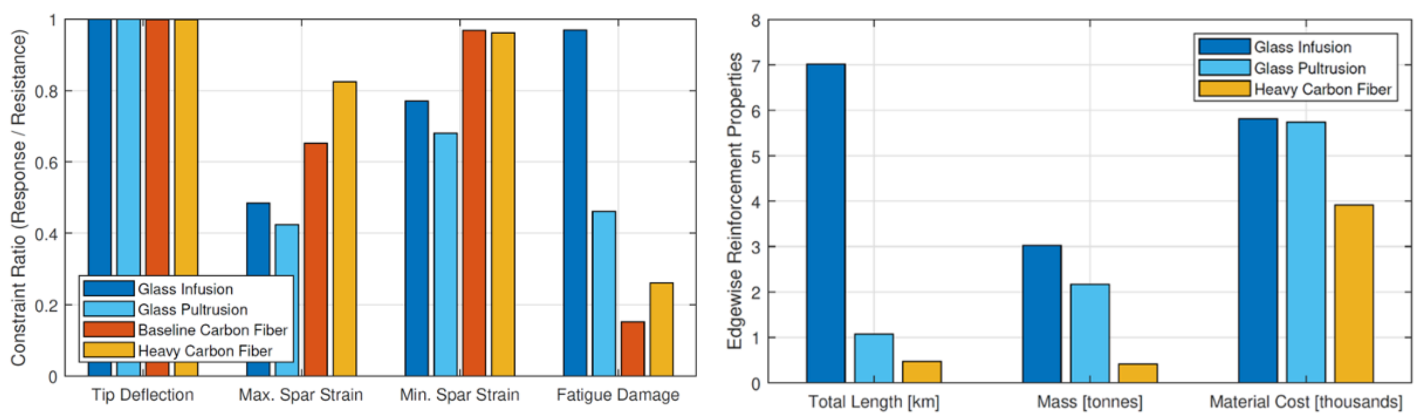


(a) Optimal spar cap design constraint performance

(b) Optimal spar cap properties

Spar cap optimization for a low wind resource site (IEC Class 3a) using four study materials. (Graphic by Brandon Ennis) [Ennis et al., 2023b]

The alternative material systems based on reinforcement fiber or composite manufacturing form were also compared for use in the edgewise reinforcement. Pultruded E-glass and the heavy-tow textile carbon fiber both produced mass and cost savings for use in the edgewise reinforcement as shown in the figure below revealing the opportunity for improvements in this component and meriting further study. The use of carbon fiber in the edgewise reinforcement produced the most notable material cost reduction of 33% for the heavy-tow textile carbon fiber. The mass and cost savings observed when using carbon fiber in edgewise reinforcement demonstrate a clear opportunity of this design approach. The use of carbon fiber in edgewise reinforcement requires manufacturing studies to understand the challenges and costs with integration of pultruded carbon fiber in the leading and trailing edge of wind blades. The use of pultruded fiberglass (E-glass) in the edgewise reinforcement resulted in a blade mass reduction of 2% and associated reinforcement material cost reduction of 1% compared to infused E-glass.



(a) Optimal edgewise reinforcement design constraint performance

(b) Optimal edgewise reinforcement properties

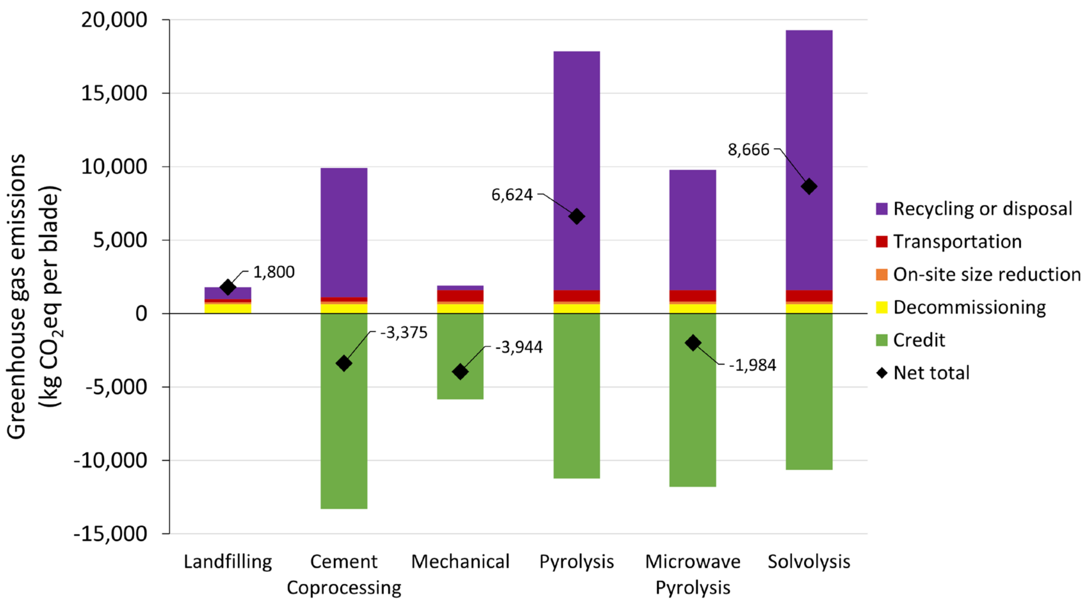
Edgewise reinforcement optimization results using three study materials. (Graphic by Brandon Ennis) [Ennis et al., 2023b].

This project revealed that there are opportunities to improve the cost-performance of carbon fiber in wind blades, including the use of these improved carbon fiber systems in additional regions of wind blades. However, there is a need for better integration between carbon fiber manufacturers and turbine Original Equipment Manufacturers

(OEMs) to realize these opportunities. Pultruded E-glass did not reveal as a favorable comparison to infused E-glass for the spar cap or edgewise reinforcement components in terms of material cost but was seen to reduce the weight. Higher performing glass fibers, such as S-glass and H-glass systems, may produce greater mass savings compared to pultruded E-glass, but a study is needed to assess the cost implications for these more expensive systems. The most likely opportunity for these high-performance glass fibers is in the edgewise reinforcement, where the increased strength will reduce the damage accumulation of this fatigue-driven component.

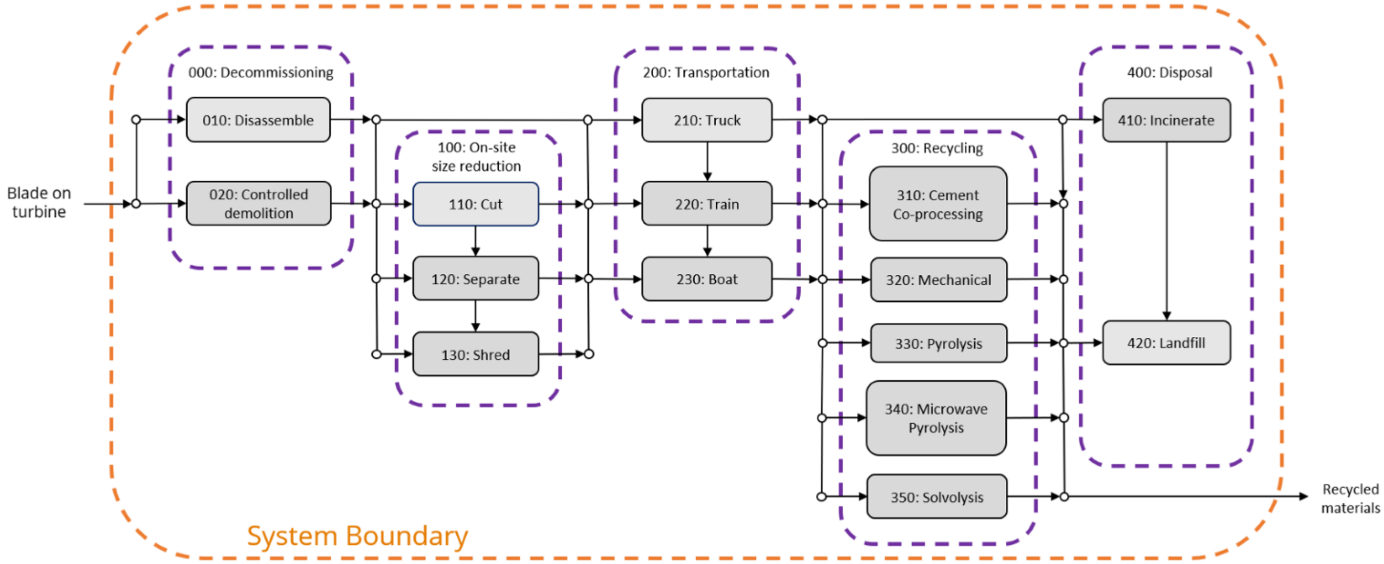
3.6 Wind Turbine Blade Recycling Assessment

Most wind turbine blades reaching end-of-life are sent to landfills where embedded cost, energy, and materials are lost. To avoid landfilling future blades, a broad range of recycling and material recovery approaches have been proposed as solutions in the U.S., each with benefits, challenges, and varying levels of technical maturity. While these approaches are all capable of recovering various forms of materials for use in secondary markets, there are tradeoffs between material circularity, environmental emissions, and cost-effectiveness for the U.S. market. A detailed comparison of Life Cycle Assessment (LCA) greenhouse gas emissions and material yields from a range of wind turbine blade recycling approaches in the U.S. has been performed and includes baseline results, as well as a variety of sensitivity and scenario analyses that look at the impact of process modelling uncertainty, future energy mixes, and other critical input parameters. Overall, results show that cement kiln co-processing, mechanical recycling, and microwave pyrolysis have the lowest net greenhouse gas emissions, as shown in the figure below.



Life cycle GHG emissions of end-of-life and recycling approaches. [Sproul et al., 2023]

The accuracy of LCA is dependent upon having a detailed understanding of mass and energy used in each recycling approach. Since most wind blade recycling approaches are in early stages of deployment, there are a lack of publicly available mass and energy use data. As a result, process models were developed to estimate mass and energy data. The general framework for process modeling is shown in the figure below. In this framework the system boundary begins with a wind turbine blade that has reached the end of its operational life on the turbine and ends with the production of recycled materials. Within the system boundary, the wind turbine blade goes through various options for decommissioning, size reduction, transportation, recycling, and disposal. Each block within the framework represents a process model for a given step.



Process model framework of wind turbine blade that has reached end-of-life. (Graphic by Evan Sproul)

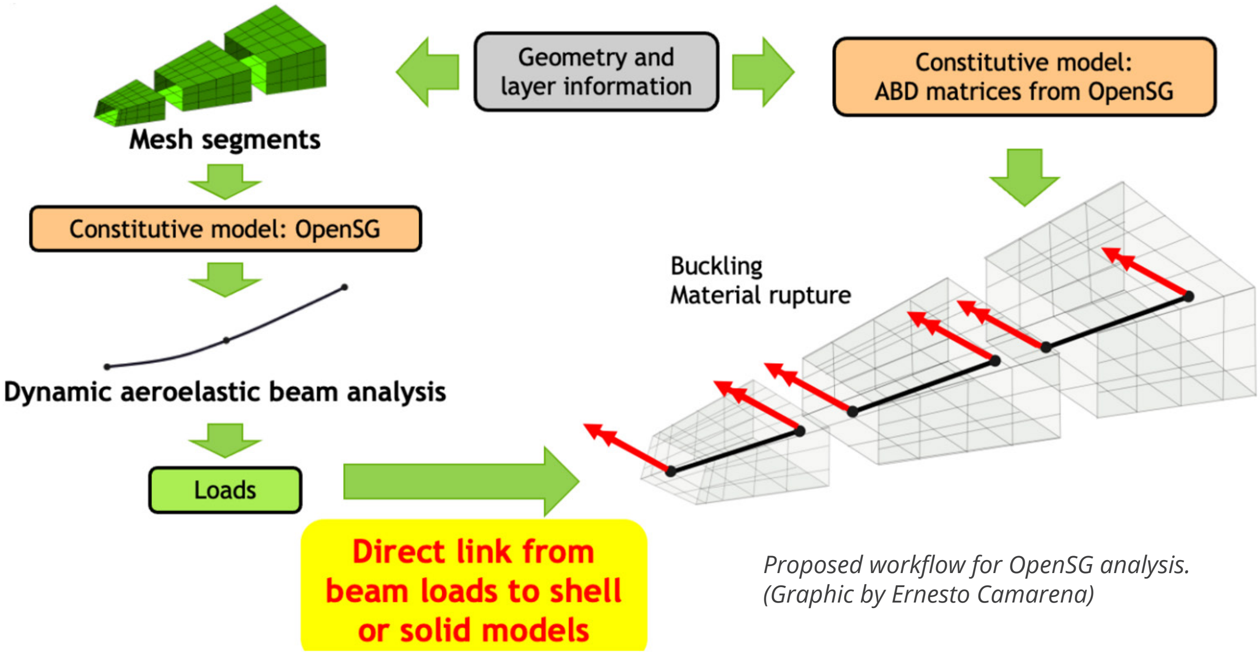
Results indicate that there are multiple approaches for wind turbine blade recycling that could result in net greenhouse gas emissions similar to or below that of landfilling. While many of these options can recover materials or energy from the wind turbine blades, each approach has a unique set of economic and environmental trade-offs. Evaluating these trade-offs at an early stage of development is critical to ensure that solutions are optimized to ensure an overall increase in the sustainability and circularity of wind turbine blades. The results also show that there are many ways to reduce the net greenhouse gas emissions of these approaches, including cleaner electricity grid mixes and low-emission fuels for thermal energy. While this analysis helps enable a comparison of different recycling approaches, there are remaining research and market challenges to be addressed.

First, the value of recovered products is critical to this analysis and requires more detailed investigation for representative secondary markets to increase certainty. This includes understanding potential U.S. markets for recycled products, as well as the physical characteristics that are important in those markets. Second, many of these approaches are at a low technology readiness level and have only been demonstrated at laboratory or pilot scale. Optimizing these approaches while scaling them up will be critical for their success. Last, greenhouse gases are just one of many important metrics that must be considered when assessing the tradeoffs of different recycling approaches. Ultimately, more analysis is needed to quantify and compare the costs, circularity, and other environmental impacts of each approach to ensure future sustainability.

3.7 Holistic Multi-fidelity Wind Farm Design Optimization and Model Coordination

The Holistic, Multi-Fidelity Wind Farm Design Optimization and Model Coordination project was kicked-off this year in partnership with NREL. The DOE Wind Energy Technologies Office has invested significantly in the development of open-source turbine and plant engineering and design simulation tools, spanning the fidelity spectrum from single-component to full-system studies while addressing many use cases, such as conceptual design, load case analysis, turbine or plant controls, full plant analysis, and many others. This project provides portfolio-wide coordination of development roadmaps of Wind Energy Technologies Office supported simulation tools for design and engineering analysis, especially at the low- to mid-fidelity levels. This coordination allows for targeted development to address capability gaps, cohesive multi-fidelity studies, and better community support and engagement. A series of application studies that leverage the portfolio in a cohesive, multi-fidelity approach demonstrate new design methodologies and innovation pathways for increased performance.

A collaboration between Purdue University and Sandia was established to extend the well-known structural tool called VABS to be both open source and higher fidelity. The new code called OpenSG will go beyond 2D blade cross sections with 3D blade segments and 3D structural effects such as buckling. The code is expected to enhance the level of fidelity that is possible during blade design.



Proposed workflow for OpenSG analysis. (Graphic by Ernesto Camarena)

This project also aims to design high-Reynolds number airfoils well suited to very large offshore rotor blades using a combination of conventional engineering design tools and inverse design processes. The expertise and guidance of experienced professionals is being used to guide the airfoil design requirements and draft key needs for airfoil design, through existing research collaborations and an advisory panel with industry members. In Fiscal Year 2023 the work focused on the development of initial airfoil design requirements for the design process to take place in the subsequent project years. This work included gathering information from the wind industry and research communities.

3.8 Distributed Wind Aeroelastic Modeling (dWAM)

Aeroelastic modeling has become the primary method for the structural and performance assessment of any wind turbine especially for extreme conditions. This tool provides an understanding of the impact of design parameters on turbine loading and power performance before operating in the field, and for certification considering untestable conditions. Despite these advantages, the use of aeroelastic modeling in the distributed wind industry has been limited. For increased deployment potential, distributed wind turbine (DWT) designs must be optimized, resulting in a competitive cost of energy despite the challenges of operating at relatively small scales. Additionally, the DWTs must be certified to meet the requirements of industry standards, demonstrating modern turbine engineering, and gaining consumer confidence including insurers, lenders, and investors. Aeroelastic modeling tools are a key component in enabling these technology advancements to reduce the cost of distributed wind energy by improving performance and long-term reliability.

Global stakeholders, via IEA Wind Task 41, determined that "given the general need to continue to reduce costs for wind technologies through design optimization, the expectation is that turbine manufacturers will continue to shift to using aeroelastic simulation tools that reflect their current designs" and that "aeroelastic models allow further investigation of expected ranges of inflow conditions and permit more rapid innovation of turbine designs." While the project lead, NREL, has been working on developments related to horizontal axis wind turbines (HAWTs), Sandia has been working on developments for vertical-axis wind turbines (VAWTs).

In the past year, Sandia has made major improvements to the Offshore Wind ENergy Simulator (OWENS) software to facilitate these objectives. Some of the improvements have included:

Flow Energy Test and OWENS Simulated H-VAWT Turbines (Photo by XFlow, used with permission)

- Preliminary validation at the 10m Scale for a H-VAWT (pictured), adding on to prior validation at the 34m scale for a Darrieus VAWT.
- Garnering a broad user base from the national labs to industry to academia, including 11 licensees.
- Addressing user feedback including significant additions to documentation, examples, automated testing, portable precompiled binaries, automated design load case (DLC) execution, and a myriad of bug fixes.
- Adding coupling capability to the AeroDyn OLAF free vortex filament method enabling higher fidelity fully two-way aeroelastic simulation for both VAWTs and HAWTs.
- Preparations for an open-source version release in summer of 2024.

3.9 Additively-Manufactured System-Integrated Tip (AMSIT)

In Fiscal Year 2023, the Additively-Manufactured, System-Integrated Tip (AMSIT) team completed the aerodynamic design of a wind turbine blade tip and winglet that will be 3D printed (i.e. created by additive manufacturing, AM). This DOE AMMTO funded project is a collaboration between Sandia National Laboratories, Wetzel Wind Energy Services and Stratasys. The AMSIT project demonstrates how additive manufacturing can integrate four technologies: advanced blade aerodynamics, blade surface texturing, leading-edge erosion protection, and lightning protection, to improve performance, durability and resiliency of wind turbine blades and thus reduce levelized cost of electricity (LCOE) over the lifetime of the turbine.

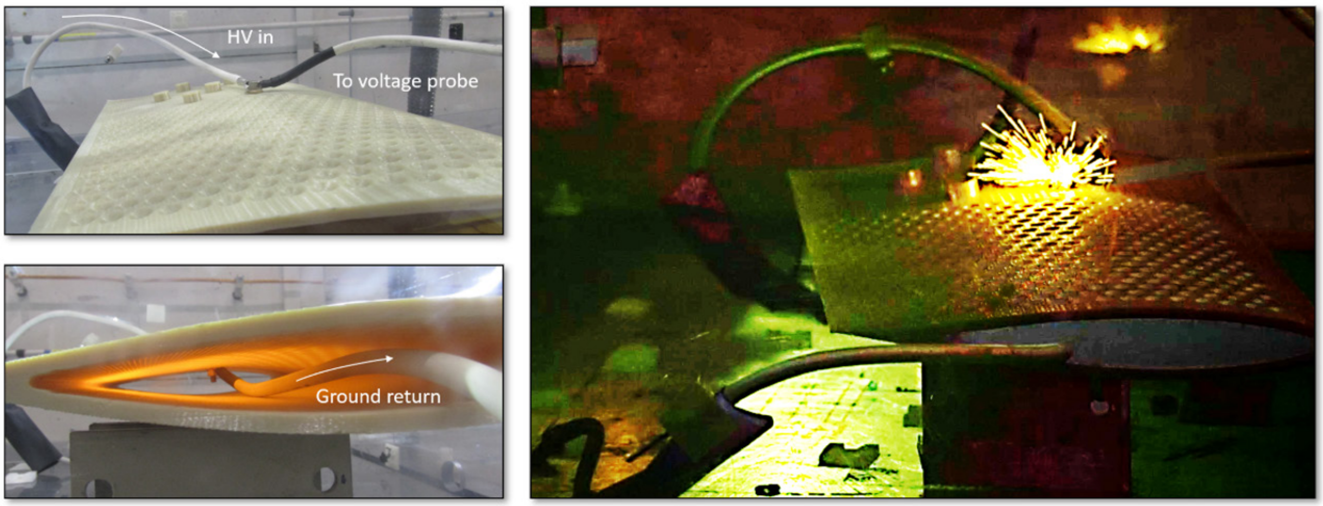
The team completed aerodynamic design and analysis, lightning survival experiments, a 13-meter blade was 3D scanned and the tip was cut off at the SWiFT site, the AM material was chosen based on mechanical and electrical properties, and a techno-economic analysis was completed. Two winglet designs were considered, one with a larger increase in lift (Maniaci, 2023), and one with a modest increase in lift but negligible increase in blade root bending moment. The aeroshell of this latter design is shown connected to an existing 13-meter base blade segment.

Rendering of the aeroshell of the AMSIT tip and winglet, mated to the base blade (Graphic by Brent Houchens)

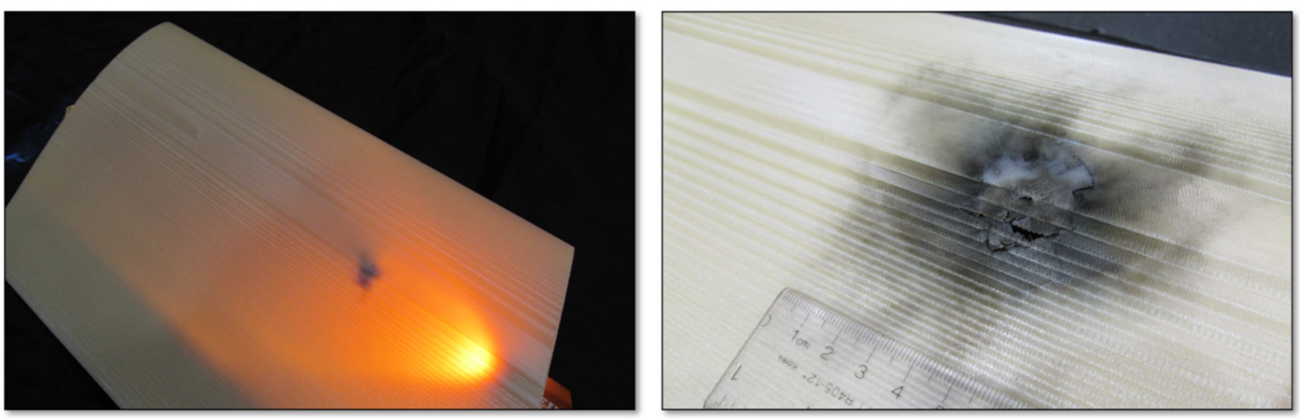
Lightning testing was performed on two candidate materials for scenarios with both a functioning lightning protection system (LPS) and no LPS (or a failed LPS). The selected final material suffered no damage with the mock LPS active, and acceptable damage when the mock LPS was removed.

Techno-economic analyses demonstrated that the cumulative impact of the four technologies resulted in a 4% reduction in LCOE in region 2 operation over the lifetime of a kW-scale turbine, without increasing the rating of the turbine or the maximum root bending moment of the blades. Extension to a MW-scale turbine had a much greater LCOE reduction of nearly 10% in region 2 operation alone (Houchens, 2023b).

Ongoing work in Fiscal Year 2024 includes finite element analyses to ensure the AM tip and winglet can withstand the critical loads envelope for a short-duration field test. This will be validated with assembly level lab experiments. Finally, a demonstration flight test will be conducted at SWiFT.



Candidate AM material with mock LPS, and a still image of arcing during an 8-kV, 96-kA test strike that produced no visible damage to the blade section (Photos by Brent Houchens)



Candidate AM material post lightning tests without an LPS from (left) a low-energy, sub-kA, high-voltage (kV) strike, and (right) a high-energy, 1-microsecond, 25-kV strike (Photos by Brent Houchens).

4. OFFSHORE DESIGN OPTIMIZATION

4. OFFSHORE DESIGN OPTIMIZATION

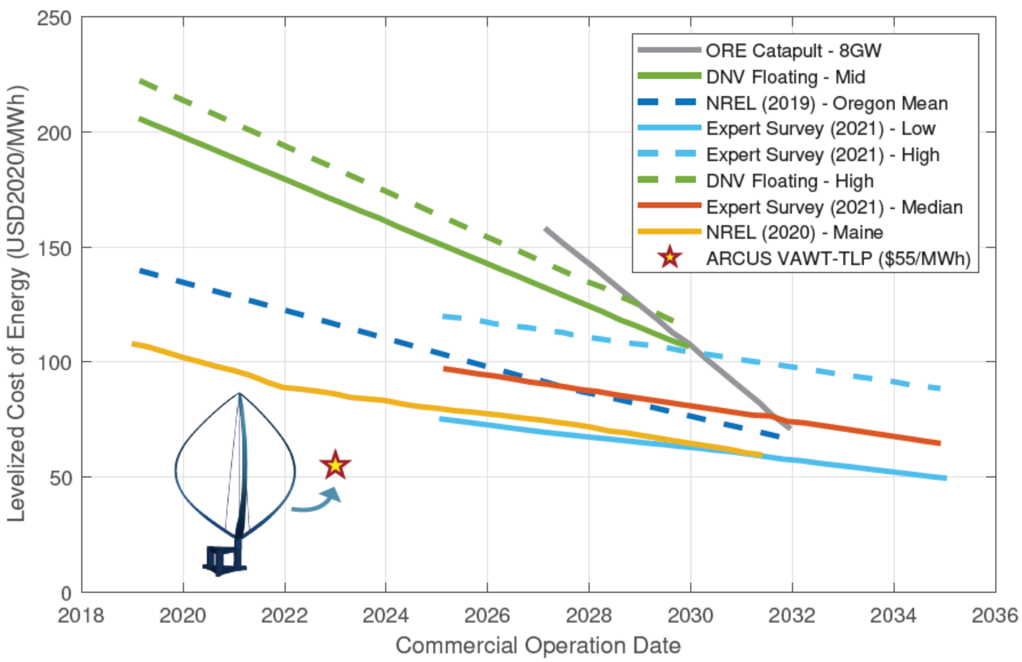
4.1 ARCUS Vertical-Axis Wind Turbine

The ARCUS vertical-axis wind turbine (VAWT) concept was developed in response to the ARPA-e ATLANTIS program call in 2019. Due to the high and complex system costs of floating offshore wind energy, the turbine represents only 20% of the levelized cost of energy (LCOE) compared to around 50% for land-based installations. The appropriate goal for the turbine in this application is to reduce not only its capital costs, but the capital and operational costs of the entire system. This award allowed the project team to develop the conceptual system design through component and system design optimization studies to exploit the complicated system cost-performance tradeoffs for floating offshore wind energy.

ARCUS is a towerless VAWT that replaces the traditional rigid tower with pre-stressed blades and tensioned center supports (U.S. Patent 11,421,650 B2), like a bow, which:

- Compared to a reference horizontal-axis wind turbine (HAWT) having the same swept area:
  - Enables a structurally efficient usage of turbine material
  - Results in a 30% mass reduction with a 70% lower center of gravity
  - Captures 45% more energy than is optimal for a HAWT
- Enables rotor area control for high wind speed load reduction
- Effectively enables tension-leg platforms (TLP) which have the lowest hull mass compared to alternative architectures
- Optimized system produces an estimated $55/MWh levelized cost of energy (LCOE)

The LCOE of the ARCUS-TLP system is compared to research and industry estimates for floating horizontal-axis wind turbine (HAWT) systems at various sites in the figure below. There are a wide range of estimates for this emerging industry, with the proposed ARCUS system enabling a shifted cost timeline relative to existing technologies. The ARCUS system enables the LCOE of a mature floating offshore wind industry to be realized in the near-term, progressing the cost curve by 10 or more years.



Levelized cost of energy comparison to HAWT systems at various study sites. (Graphic by Brandon Ennis)

Detailed design studies were performed for the ARCUS-TLP system including global performance analysis and a minimum scantling structural design, with results shown in the figure below. These tasks produced a baseline platform configuration with volumetric mass relationships for eleven regions of the platform hull, which were used to optimize from the baseline design for variable turbine loads and mass. Prior to this project, the bearing loads and design for VAWT systems had a high level of uncertainty. The loads carried through the drivetrain bearings for VAWTs are fundamentally different than HAWTs. For VAWTs, the bearings carry aerodynamic loads radially versus axially for HAWTs. Similarly, gravitational loads from the weight of the turbine are carried axially in the bearings for VAWTs compared to radially for HAWTs. Not only is the loading orientation shifted, but the center of pressure of the aerodynamic loads is at a high elevation away from realistic bearing locations resulting in radial bearing loads that are amplified. These high radial loads affect the bearing design and the support structure design that houses the bearings. The impact of the large radial bearing loads on the support structure was assessed through studying the opportunity for housing the drivetrain within the primary platform column. This design approach has two advantages to (1) efficiently reuse the existing material in the column and to (2) further reduce the center of gravity through lower placement of the drivetrain. It was found that the existing structure of the primary column required to satisfy the global loads needed only minor modification to withstand the radial bearing loads and provide an overall mass savings from other approaches where the turbine support would be located above the top of column.

The towerless ARCUS vertical-axis wind turbine concept and design methodology enables the competitiveness of floating offshore wind through unprecedented reductions in turbine mass properties with low drivetrain placement and efficient material usage. The topside mass savings further result in platform mass savings and enable tension-leg platforms, greatly reducing the system capital costs and resulting in a competitive levelized cost of energy estimate of $55/MWh. The system-level design process and control co-design optimization ensures that cost-performance tradeoffs have been exploited to meet the ATLANTIS program LCOE target, but challenges remain with introducing a radically new design concept to market. The continued progress of this technology and possibility of a U.S.-based VAWT manufacturer will rely on funding agencies and investors willing to accept the risk of a low technology readiness level (TRL) concept that can accelerate a sustained deployment of floating offshore wind energy in the U.S.

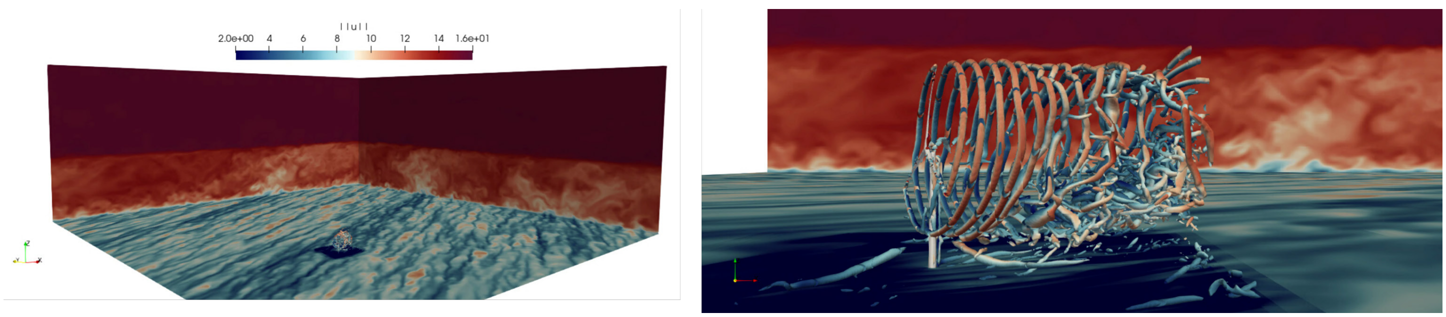
5. WIND PLANT DATA & ARTIFICIAL INTELLIGENCE

5. WIND PLANT DATA & ARTIFICIAL INTELLIGENCE

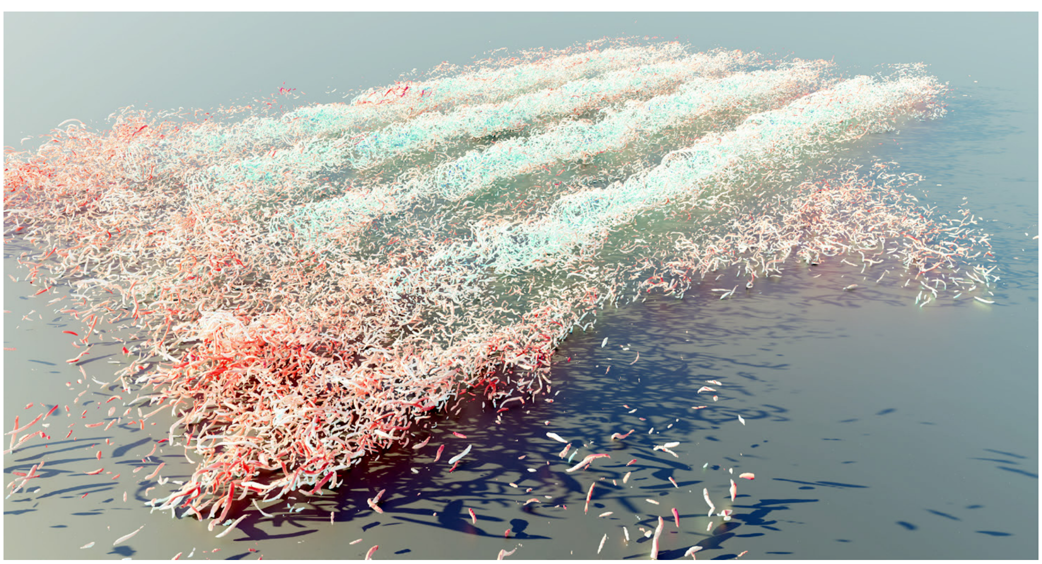
5.1 High Fidelity Modeling (HFM)

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.

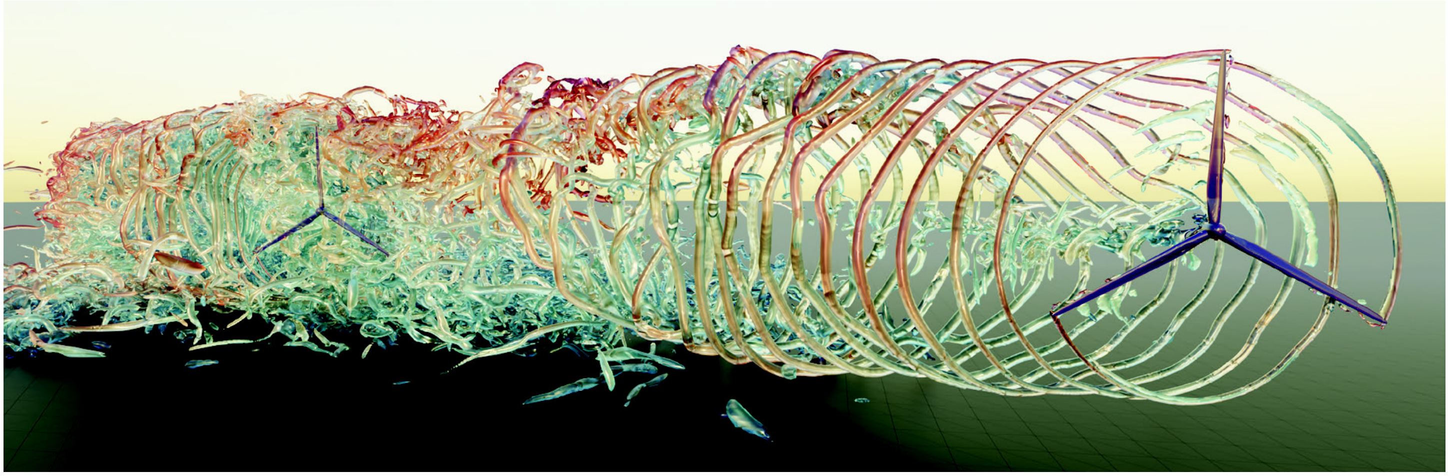
To date, HFM has implemented and validated state-of-the art models for wind turbine simulations, including turbulence models for blade-resolved simulations, fluid-structure interactions, fluid-controls interactions, complex terrain, ocean waves, and advanced actuator lines. During Fiscal Year 2023, HFM completed several milestones aimed at improving and validating fluid-structure interaction capabilities, AMR-Wind's atmospheric boundary layer modeling, and the hybrid solver (Nalu-Wind/AMR-Wind) two-phase flow for wind-water environments. HFM verified correct wave field modeling with the hybrid solver, thereby earning a "Go" recommendation from WETO on HFM's Go/No-Go milestone. In Fiscal Year 2024, HFM will further improve hybrid solver modeling capabilities for wind-water environments, including for cases with fixed solid bodies and moving meshes. The team will also further develop and validate its ExaWind codes and physics models for offshore wind, with the overarching goal of reducing the cost of wind energy by improving the understanding of the fundamental flow physics governing wind plant performance.



Snapshots from NREL 5-MW ExaWind simulation with rotor, tower, and full FSI enabled in a turbulent atmospheric flow with mean hub-height wind speed at the turbine's rated speed of 11.4 m/s. (Graphics by Ashesh Sharma,NREL).



AMR-Wind simulation results for a 20-turbine wind farm off the coast of New York, where wind turbine blades were represented as "actuator lines." Shown are iso-surfaces of q-criterion, which highlight vortical structures, colored by velocity magnitude. Simulation performed on GPUs on the Summit supercomputer under an ASCR Leadership Computing Challenge (ALCC) computer time grant. (Graphic by Shashank Yellapantula, NREL).

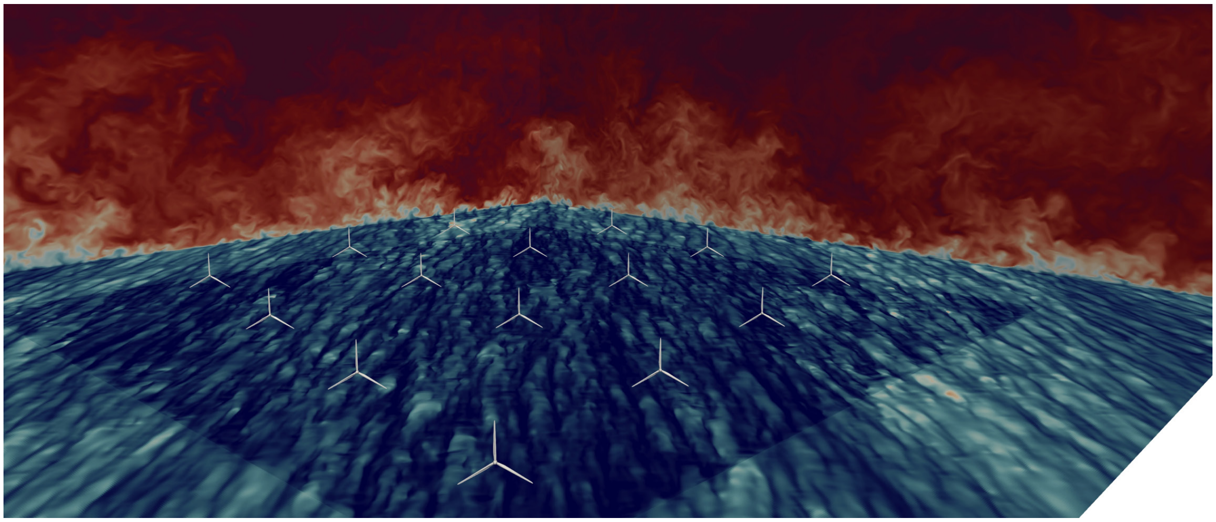


Representative two-turbine blade-resolved simulation with the ExaWind hybrid-AMR-Wind/Nalu-Wind solver on NREL's Eagle supercomputer. The simulation captures at least 8 orders of magnitude in spatial scales, going from 10-5 m for the blade boundary layers to the 103 m domain size. (Graphic by Shashank Yellapantula, NREL).

5.2 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 2023, ExaWind completed its capstone ECP Challenge Problem on Frontier, the world's first exascale supercomputer. The ExaWind software suite of codes has been built to perform high-fidelity simulations of wind turbines and wind farms. ExaWind's key physics solvers are AMR-Wind, Nalu-Wind, and OpenFAST. The model configuration for the challenge problem included the key ExaWind physics capabilities, namely hybrid-RANS/LES turbulence models, turbulent atmospheric inflow, and fluid-structure interactions between the Nalu-Wind near-body solver and the OpenFAST turbine model (with nonlinear-beam finite elements). For the challenge problem, 16 NREL 5-MW reference turbines were modeled, driven by a turbulent atmospheric boundary layer (ABL) precursor simulation, which was for neutrally stable flow and with a hub-height mean wind speed of 11.4 m/s. The demonstration simulation was executed for 200 timesteps on 4096 Frontier nodes (i.e., 32,769 graphics compute die (GCD)s which is about 44% of Frontier), well exceeding the challenge-problem minimum criteria.



ExaWind's hybrid Nalu-Wind / AMR-Wind solver blade-resolved simulation, run on Frontier. (Graphic by Paul Crozier)

5.3 OpenTurbine

OpenTurbine is a new, open-source wind turbine structural dynamics simulation code designed to meet the research needs of the Wind Energy Technologies Office and the broader wind energy community for land-based and offshore wind turbines. OpenTurbine is being developed at Sandia and NREL in synergy with development of the ExaWind code suite. It will provide high-fidelity, highly performant structural dynamics models that can couple with lower fidelity aerodynamic/hydrodynamic models like those in OpenFAST, and high-fidelity computational fluid dynamics (CFD) models like those in the ExaWind code suite (Described in Section 5.2 above). Importantly, OpenTurbine will adhere to modern software development best practices and will be "performance portable" in that it will run effectively on modern computing platforms. OpenTurbine will be designed to address shortcomings of wind turbine structural models and codes that are important to the success of Wind Energy Technologies Office supported modeling efforts.

During Fiscal Year 2023, the new OpenTurbine software development ecosystem was established, and essential capabilities were implemented, including a time integrator, and a nonlinear system solver. A rigid body dynamics demonstration was performed, and work was started on a nonlinear beam element appropriate for wind turbines. More details about OpenTurbine, along with source code, are publicly available at: https://github.com/Exawind/openturbine.

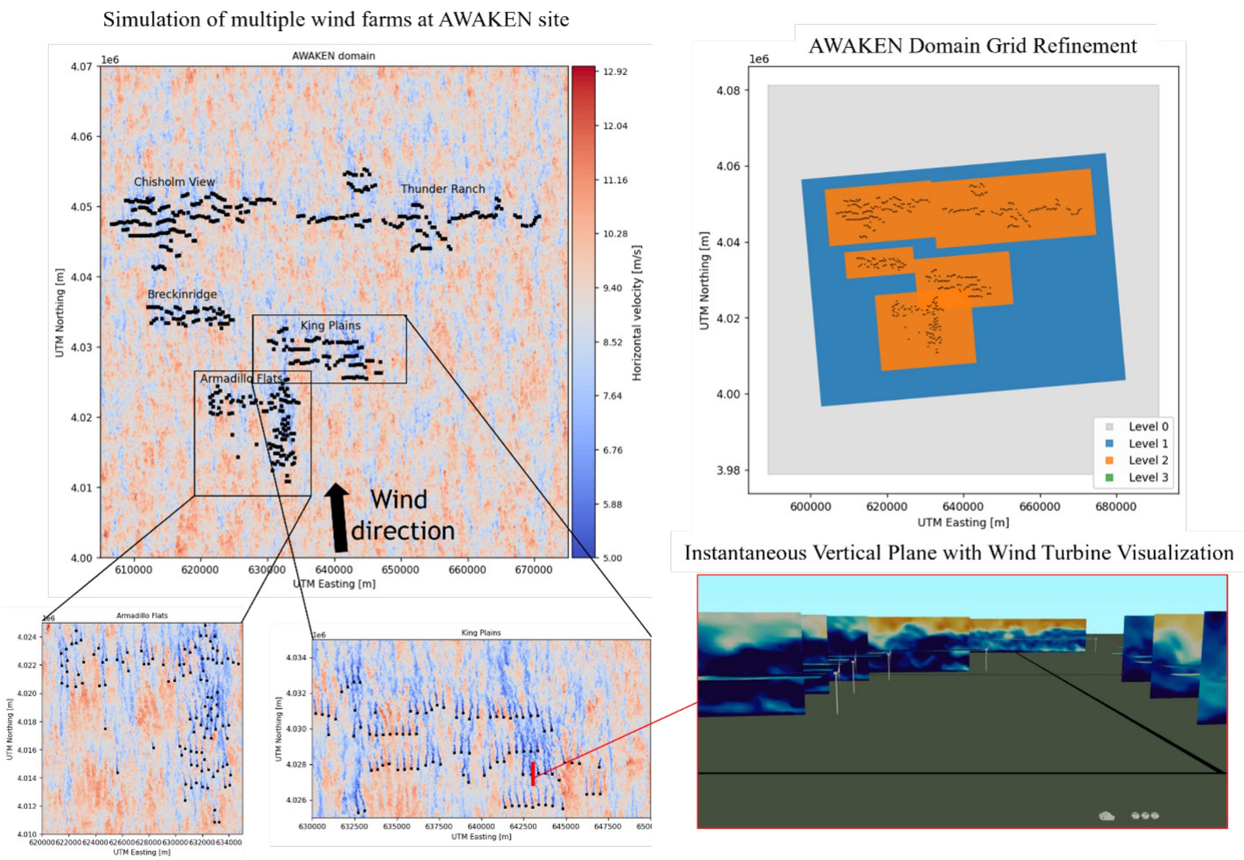
During Fiscal Year 2024, OpenTurbine's new capabilities will be demonstrated on a rotor structural dynamics problem, and results will be compared against OpenFAST. A controller with pitch control of blades will also be implemented. Finally, a demonstration will be performed of rotor dynamics that include fluid structure interactions and a pitch control system on GPUs and CPUs.

5.4 American WAKE ExperimeNt (AWAKEN)

The American WAKE experimeNt (AWAKEN) will improve understanding of the interaction between wind plants and the atmosphere by capturing validation data, including atmospheric observations and turbine responses, across five wind plants in north central Oklahoma. AWAKEN is a partnership involving many laboratory, industry, and university partners. This year, data has been collected from over 50 unique instruments, including scanning lidars, dual doppler radar, and meteorological stations at 13 field sites and on four wind turbines.

Image of AWAKEN Site A1, showing an instrumented turbine with nacelle mounted lidars and Atmospheric Radiation Measurement (ARM) mobile facility with scanning lidar and additional meteorological instruments. (Image by Thomas Herges)

Sandia's contributions to AWAKEN in Fiscal Year 2023 include a multiparty CRADA, helping to install turbine instrumentation, leading one of the largest large-eddy simulations ever conducted, developing simulated instrumentation, and working to deploy the Sandia tethered balloon system and university partner instruments for Fiscal Year 2024. A highlight of research in Fiscal Year 2023 was the large, 21 billion element, high-fidelity computation that used the ExaWind/AMR-Wind LES solver to simulate a 100 km × 100 km domain containing 541 turbines under unstable atmospheric conditions matching previous measurements. The turbines were represented by Joukowski and OpenFAST coupled actuator disk models. Results of this qualitative comparison illustrate the interactions of wind farms with large-scale ABL structures in the flow, as well as the extent of downstream wake penetration in the flow and blockage effects around wind farms. Analysis of this large simulation coupled with the simulated instruments will inform the creation of validation benchmarks in Fiscal Year 2024, further validating the ExaWind solvers, and informing the AWAKEN testable hypotheses.



AMR-Wind Simulation using Summit of five wind plants in the AWAKEN domain in north central Oklahoma. Image shows the grid refinement regions, atmospheric inflow, wind turbine wakes. (Graphic by Tommy Herges)

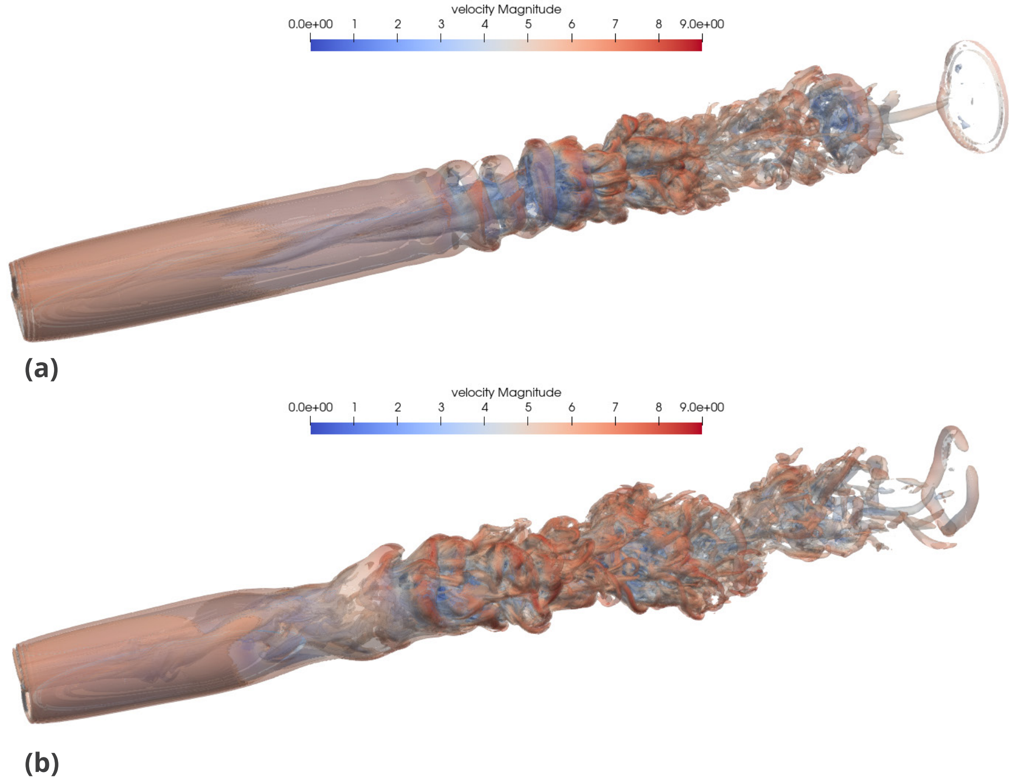
5.5 Advanced Control and System Design for Offshore Wind

To fully realize the potential of offshore wind plants and provide optimum value to the grid, research into the control of offshore wind plants is needed to greatly reduce the cost and improve the expected value of offshore wind energy. This project, led by NREL and in its first year of funding, will develop control solutions to enable the safe and reliable operation of floating wind turbines to help support the development of floating offshore wind plants in deep-water regions of the U.S. coast.

Sandia's role stems from expertise in wake stability predictions, high-fidelity wake modeling, and data-driven wake analysis. During the first year of the project, Sandia and NREL collaborated to develop new functionality for NREL's Reference Open-Source Controller (ROSCO) that includes a novel implementation of active wake control (AWC) (see figure below). Specifically, Sandia developed a method for implementing AWC in which periodic structures are added to the wake to improve wake recovery using sinusoidal collective or individual pitch actuation (e.g., the helix method) based on the normal modes framework from the classical theory for stability of axisymmetric jets. This new functionality will allow the team to design and evaluate different AWC strategies within high-fidelity flow-modeling environments during the rest of the project. Additionally, the software upgrade has been released to the public domain as [V2.8.0] to enable the wind energy industry and academia to implement and test AWC approaches.

Sandia also contributed to the IEA Wind Task 44: Wind Farm Flow Control general meeting that gathered feedback on wind farm flow control from different stakeholders, including academia, wind energy developers, and consultants. This meeting was co-located with the IEA Wind Task 44 mini symposium at the 2023 Wind Energy Science Conference held in Glasgow, Scotland. Sandia's presentation at the mini symposium shone light on the underlying connection between the AWC strategies being considered by wind energy researchers and the classical theory, models, and experiments from research in the adjacent fluid-dynamic communities on axisymmetric jets and bluff-body wakes, which are each fields with rich knowledge that can inform the nascent AWC approaches in the wind energy community. Notes from these IEA Wind Task 44 activities, as well as a literature review produced by Sandia on the state of the art of AWC technology, are being collated into a 10-year strategic plan for wind farm flow control research to be delivered to the DOE Wind Energy Technologies Office by NREL.

This project originated as a successful late-start LDRD funded through the Sandia Energy & Homeland Security Portfolio's Climate Innovation Tournament.



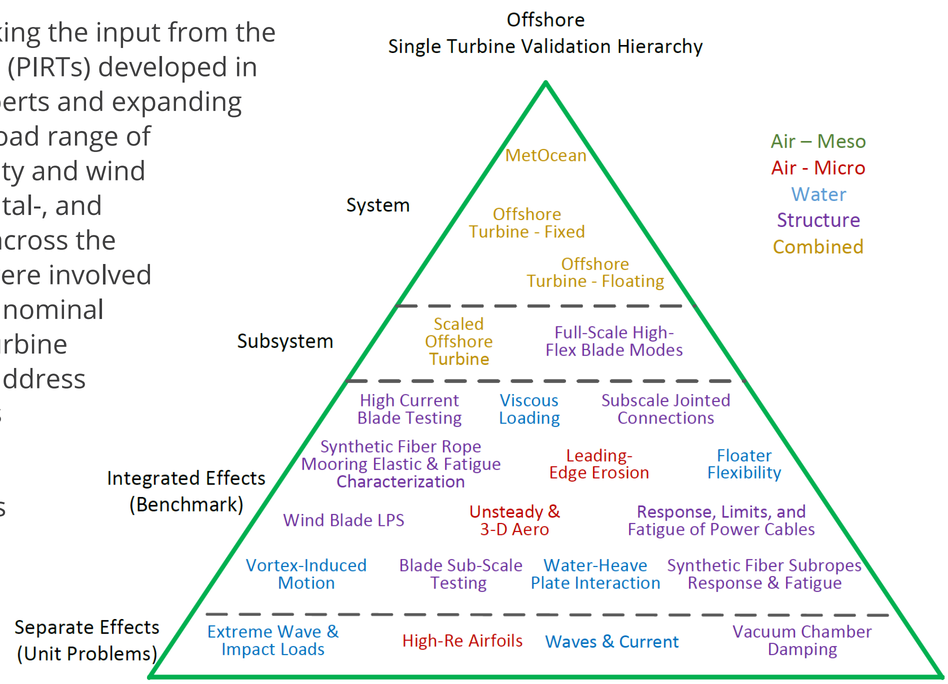
Rendering of the wake behind an NREL 2.8 MW wind turbine under (a) standard operation and (b) employing active wake control. Shown are iso-vorticity surfaces, colored by velocity magnitude. (Graphic by Lawrence Cheung)

5.6 Offshore Field Measurement Campaign Planning

The reliance of offshore wind energy applications on computational modeling is expected to grow considerably with high impact on risk-based investment decisions. It is solely in the role of the DOE to plan and execute multiple scales of publicly accessible validation experiments targeted at establishing the credibility of these computational models for wind industry use such that they can be trusted for investment decisions. The Offshore Field Measurement Campaign Planning project is the first step in developing a validation-focused program for offshore wind energy technology. This effort coordinated the validation needs of the suite of computational models that will be developed and applied in the offshore wind program, identifying validation experiments that target the unique needs for offshore wind energy.

The Fiscal Year 2023 effort focused on taking the input from the Phenomena Identification Ranking Tables (PIRTs) developed in the previous year with subject matter experts and expanding it considerably to include input from a broad range of stakeholders from the research community and wind industry. Over 140 Validation-, experimental-, and computational-focused individuals from across the wind industry and research community were involved to ensure a balanced plan. Hierarchies of nominal experiments were developed for single turbine (figure at right) and wind plants that will address the highest priority model validation gaps identified in the PIRT analysis.

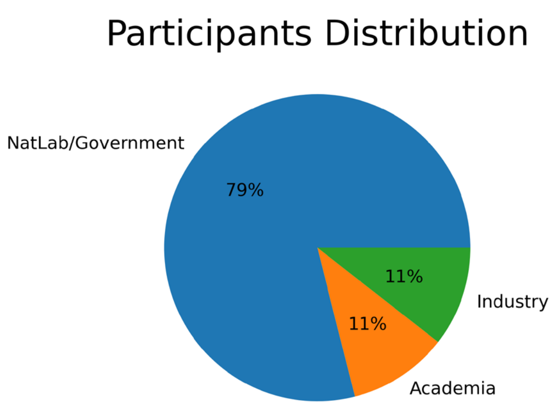
These experiments have formed the basis of an offshore validation experiment roadmap that can help guide the coordination of future offshore experiment and instrumentation development efforts.



Offshore Single Turbine Validation Hierarchy. (Graphic by David Maniaci)

5.7 Foundational Artificial Intelligence for Wind Energy

During Fiscal Year 2023, Sandia researchers, in collaboration with NREL, initiated an effort to understand needs and opportunities offered by the new fields of machine learning (ML) and artificial intelligence (AI) for wind energy. Following a decade of significant investments by the DOE Wind Energy Technologies Office in high-fidelity modeling, the wind energy modeling and simulation endeavor is ready to take advantage of evolving AI/ML strategies, which have demonstrated their potential in areas like control, optimization, multi-fidelity modeling, uncertainty quantification, and design. In the



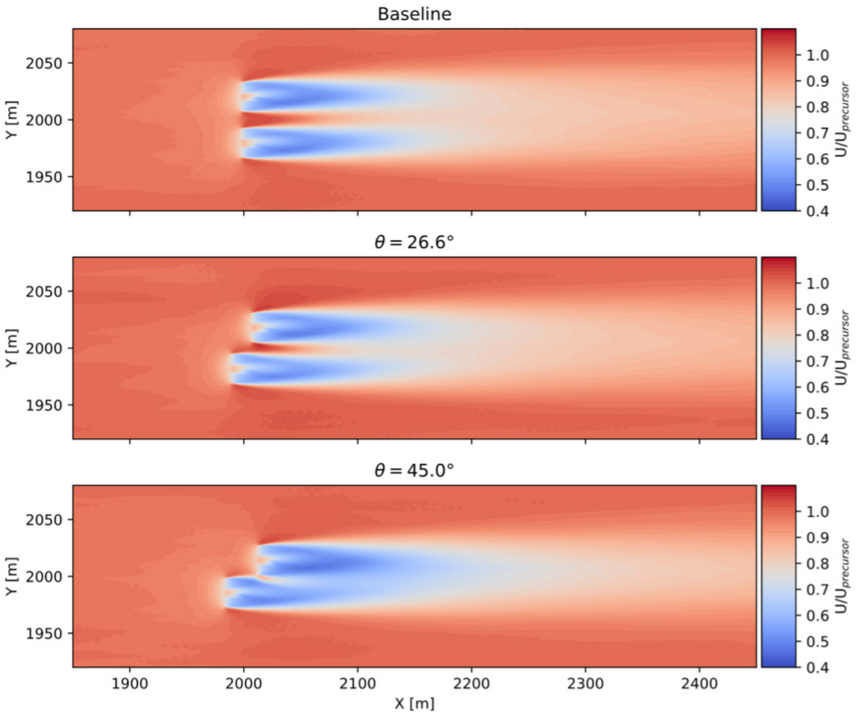
context of this project, NREL and Sandia organized a workshop in June 2023 to bring together wind experts (38 participants across national laboratories, industry, and academia) and foster discussions around these topics. A report summarizing the workshop outcomes is in preparation for release in Fiscal Year 2024.

5.8 Simulations of Wake Interactions behind Individual-tower Multi-rotor Wind Turbine Configurations

As a part of a Strategic Partnership Project (SPP), Sandia used high fidelity simulations to analyze the wake behavior behind closely spaced, paired-rotor configurations. Using multiple wind turbine rotors on single tower structures has been previously proposed to increase wind turbine energy capture without increasing turbine blade lengths, but the additional mechanical complexity in the yaw and tower designs is disadvantageous. In collaboration with Hamilton Consulting, LLC, a newer concept using standard turbines on closely spaced, individual towers was explored.

In this project, large eddy simulations (LES) using the ExaWind/Nalu-Wind code studied how the wakes from pairs of closely spaced rotors, separated by a hub-to-hub distance of 1.5 rotor diameters (D), evolve downstream compared to isolated, single turbine wakes. Of particular interest were wind directions where the wake turbulence of one rotor enters the swept area of a very close downwind rotor, causing lower power output, fatigue stress, and changes in wake recovery. Results indicated that the on-design wind direction wake behavior is consistent with previous literature, and for an off-design wind direction of 26.6 degrees, there was little change in power and far-wake recovery. Results suggest there is a range of wind conditions where this concept may be advantageous. However, for wind directions of 45 degrees, there were significant rotor-wake interactions producing an increase in power but also increases in far-wake velocity deficit and turbulence intensity.

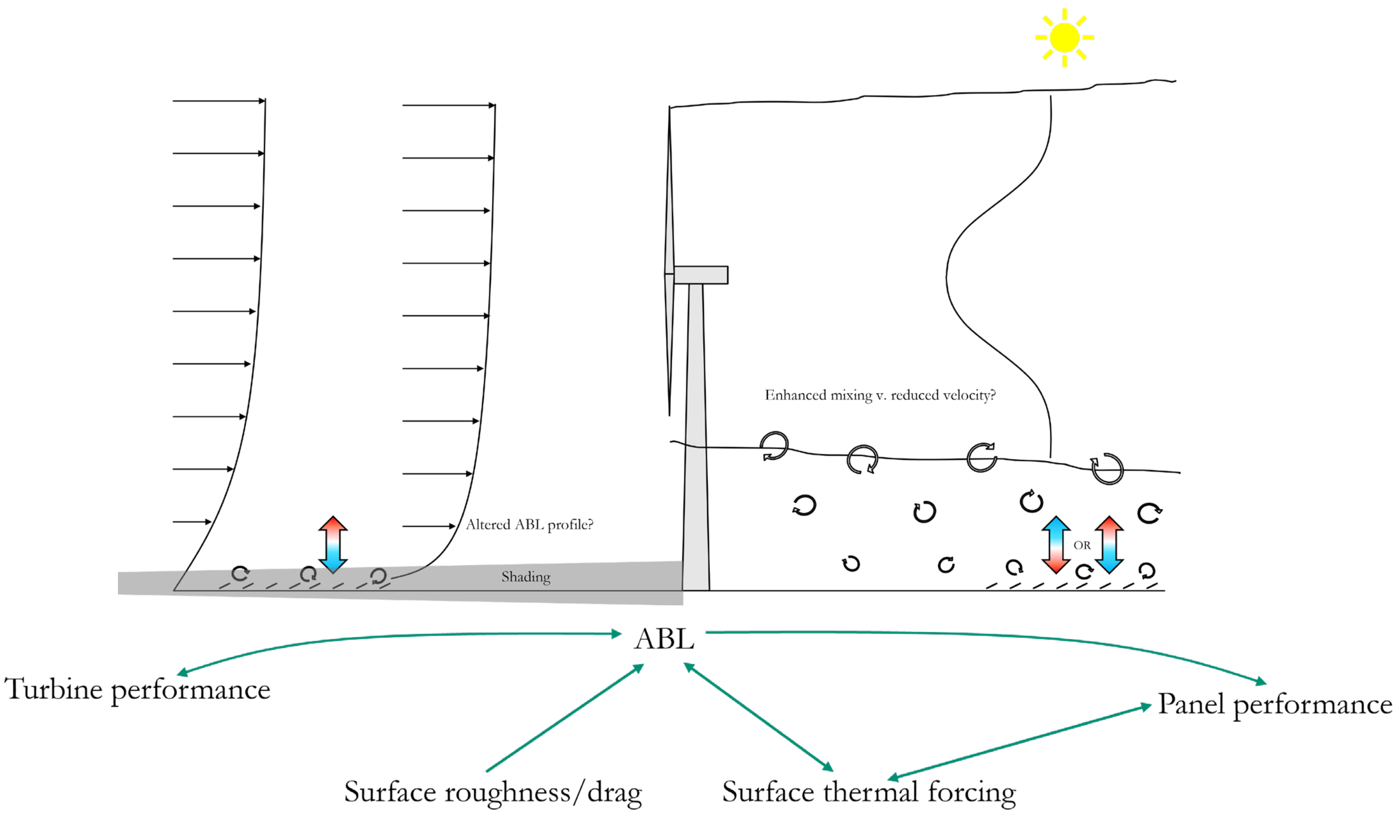
This work was published and presented to an international audience as a part of the 2023 Wake Conference in Visby, Sweden (Brown, 2023b). Current work focuses on high-fidelity simulations of additional rotor pair configurations, as well as comparison of the simulation results with lower order fidelity models for use in analyzing full wind farm layouts.



Wake contours of normalized mean streamwise velocity U/Uprecursor, on the hub-height plane at three wind configurations: Baseline (0 degrees), 26.6 degrees, and 45 degrees. The two turbines are both Vestas V27 models placed at hub-to-hub distance of 1.5 diameters. (Graphic by Ken Brown).

5.9 Path to Nationwide Deployment of Wind-based Hybrid Energy Systems

In Fiscal Year 2023, this project in partnership with NREL produced a simulation roadmap based on a literature review of possible physical interactions between co-located wind energy and solar photovoltaics installations. The possible physical interactions include the shading of panels by the turbines, and also the much less investigated effects of large arrays of solar panels on the atmospheric boundary layer (ABL), which may potentially affect the operation of wind turbines. Similarly, wind turbines also alter the ABL, which could have effects on the heating and cooling of solar panels if they were placed within a wind farm. There is no existing literature that has directly studied these interactions, so the team's review and recommendations for future work were based on closely related studies. Results indicated that the effect of these interactions on the power production of co-located wind and solar is most likely very small or even negligible, but, given the lack of direct investigation, there remains high uncertainty. The simulation roadmap laid out a path to analyze these interactions through a series of high-fidelity computational fluid dynamics simulations such that the effects could be better understood and parameterized.



Possible physical interactions that could occur between co-located solar photovoltaic panels and wind turbines. These include shading of the panels, changes to the atmospheric boundary layer through changes in surface heating and roughness, and that these are further functions of the performance of both the panels and the wind turbine. (Graphic by Dan Houck)

6. GRID INTEGRATION & POWER SYSTEMS

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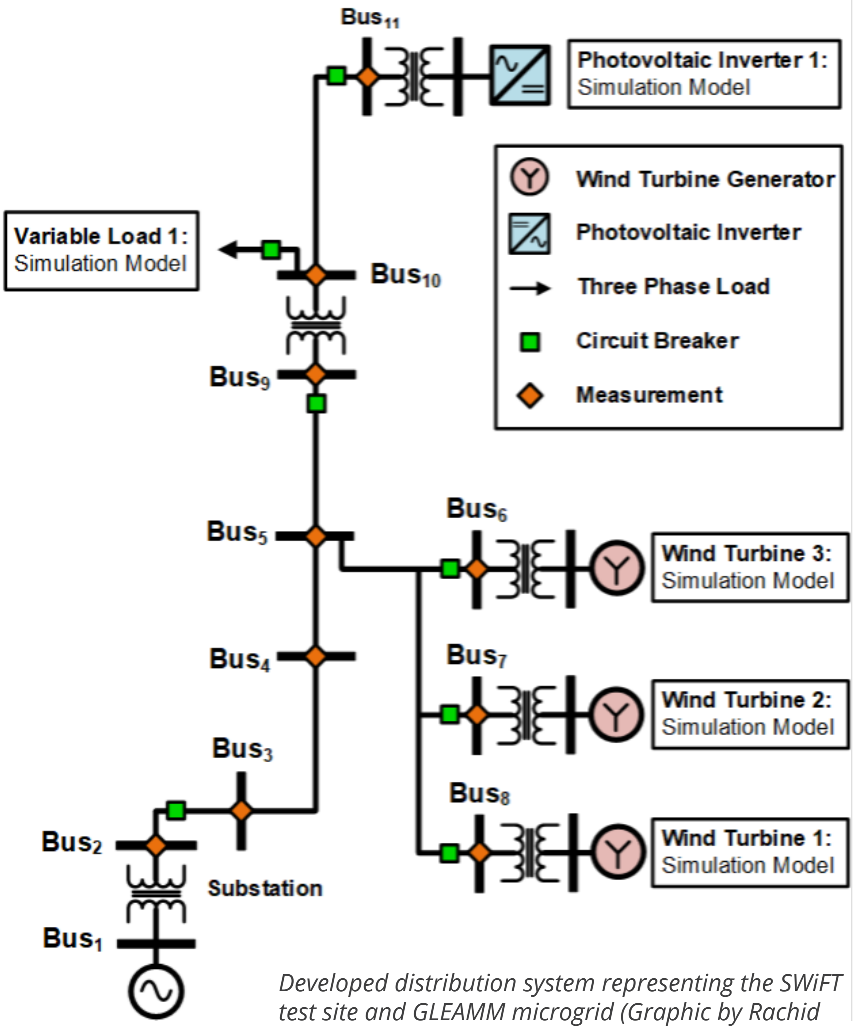
6.1 Wind Hybrid Interconnection Platform (WHIP)

Sandia has developed a distribution system composed of SWiFT test site and the Texas Tech University (TTU) Global Laboratory for Energy Asset Management and Manufacturing (GLEAMM) microgrid. The figure at right illustrates the one-line diagram of the distribution system, including the SWiFT test site and TTU GLEAMM microgrid. The distribution system is composed of 6 transformers, 11 buses, and 8 distribution lines. For this analysis, the simulation model considers the three SWiFT wind turbine generators (WTGs), each rated at 200 kVA for a total of 600 kVA. The system also considers a variable load rated at 500 kW and a photovoltaic (PV) inverter rated at 150 kVA, both located at the GLEAMM microgrid.



Developed distribution system representing the SWiFT test site and GLEAMM microgrid (Graphic by Rachid Darbali)

Developing Autonomous Controls for wind and solar power converters

Sandia demonstrated the ability of a wind turbine generator and a PV inverter to jointly provide voltage regulation in a distribution system using Volt-Var Curve (VVC) control. A simulation model of a distribution system is used to evaluate the performance of the VVC control. For this simulation, the model considers three WTGs, a PV inverter, and a variable load that creates voltage variability.

Results illustrate that the wind turbine generator and PV inverter can maintain the system voltage within ANSI limit requirements.

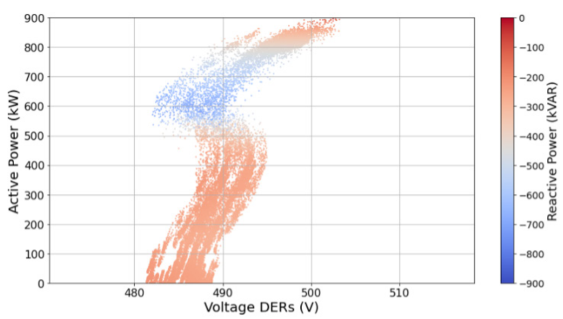
Machine Learning Controls for a Single Wind Turbine power converter

In addition to traditional autonomous controls, Sandia developed a wind turbine generator reactive power controller for fast voltage regulation utilizing Machine Learning (ML). The controller is tested on a simulation model of a real distribution system. Real wind speed, solar irradiation, and load consumption data is used. The controller is based on a Reinforcement-Learning Deep Deterministic Policy Gradient (DDPG) model that determines optimum control actions to avoid significant voltage deviations across the system.

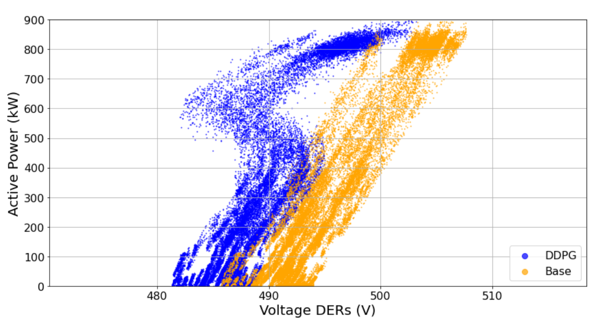
The simulation results for the proposed DDPG controller illustrate that the bus voltages in the middle and far-end of the system are raised by about 0.01 p.u. In addition, reactive power injection is heavily used (0.7 p.u. in average), and active power generation is just slightly affected.

Machine Learning Controls for Multiple Wind Turbines

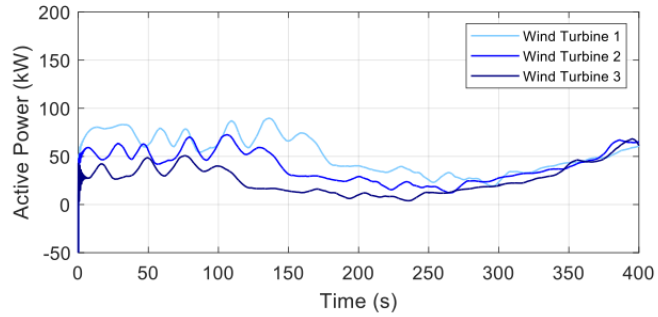
The work performed in utilizing ML to control a single wind turbine generator was expanded to include controlling multiple generators to provide voltage regulation. This work proposed a Multi-Agent Reinforcement Learning (MARL) voltage regulation method for distribution systems with wind turbines. The control employs reactive power injection or absorption in three wind turbine generators to regulate feeder voltages.



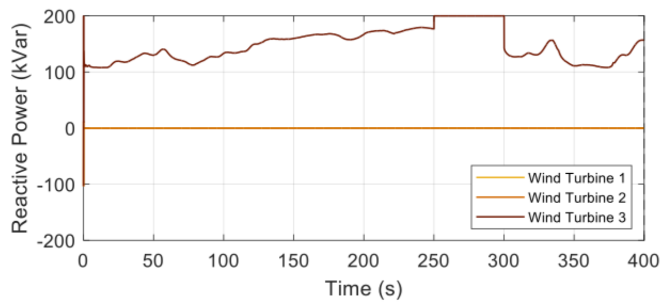
Wind turbine generator's measured reactive power injection for local distributed energy resource voltage/active power injection (Graphic by Rachid Darbali)



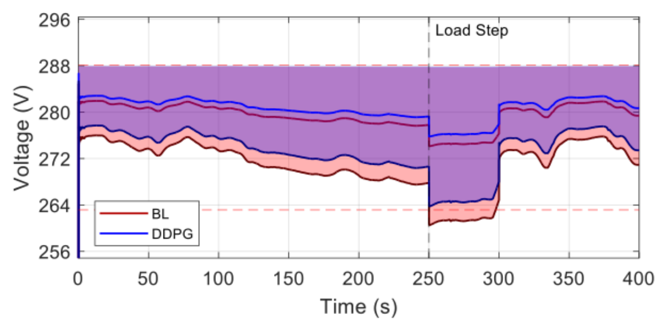
Wind turbine generator's active power and voltage regulation effect (Graphic by Rachid Darbali)



(a) Active Power



(a) Reactive Power



(a) System Voltage

Simulation Results obtained by employing a DDPG voltage regulation control on the developed distribution system (Graphic by Rachid Darbali)

The proposed controller has been proved to bring median and mean voltages closer to 1 p.u. and to reduce standard deviation. The control achieves the maximum regulation effect between 0.6 and 0.8 p.u. active power injection, as there is still enough headroom for reactive power control, and voltage regulation benefits out-weigh control action penalization.

Experimentally Testing Autonomous Controls for Wind Turbines

This effort experimentally demonstrates the ability of a wind turbine generator to provide voltage regulation in a distribution feeder. Experimental results are obtained by deploying the volt-var control in a wind turbine emulator connected to a real-time simulation model of a distribution feeder using a Power Hardware-in-the-Loop platform. The real-time simulation model of the distribution feeder along with simulation models of wind turbine generators are simulated using an Opal-RT OP5600 real-time simulator. Experiments consider the wind turbine emulator operating simultaneously with two simulated wind turbine generators in the real-time simulation environment, each one providing volt-var control to regulate voltage deviations caused by a variable load at the end of the distribution feeder.

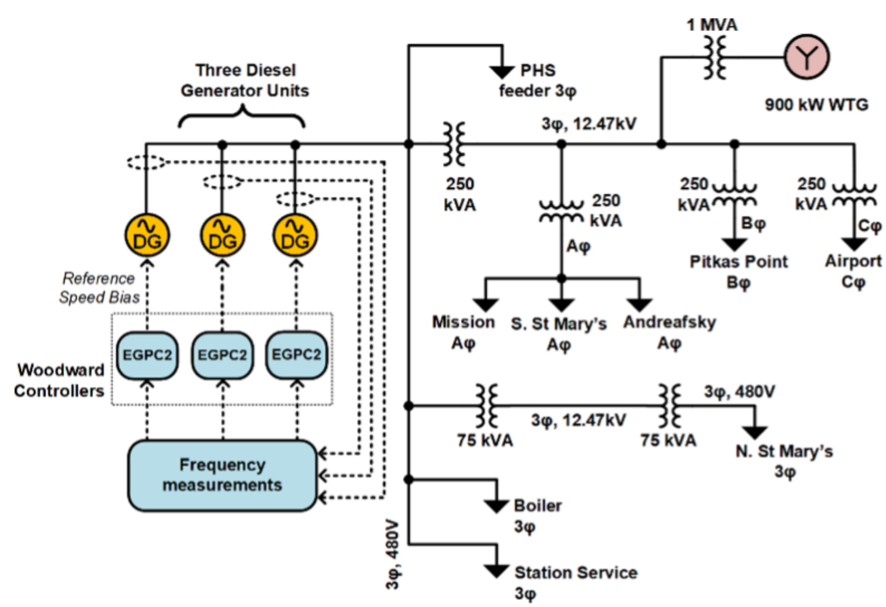
Power Hardware-in-the-Loop Experimental Results for the SWiFT Wind Turbine Generators Active Power (Photo by Jon Berg)

The experimental results show that the wind turbine emulator can provide voltage regulation using volt-var control ensuring that the average system voltage is within the desired limits.

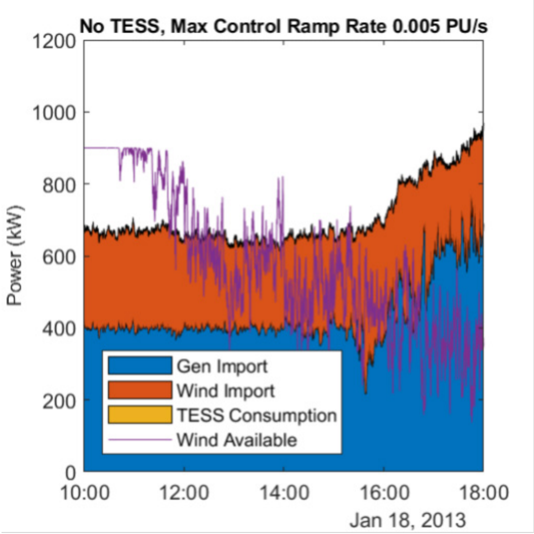
Providing Solutions to Communities in Alaska

Sandia, in collaboration with Alaska Center for Energy and Power (ACEP) used an open-source software tool: Micro Grid Renewable Integration Dispatch and Sizing (MiGRIDS) to investigate the benefits and impacts of several methods to reduce or replace spinning reserve capacity (SRC) and regulating requirements on diesel generation for St. Mary's, Alaska.

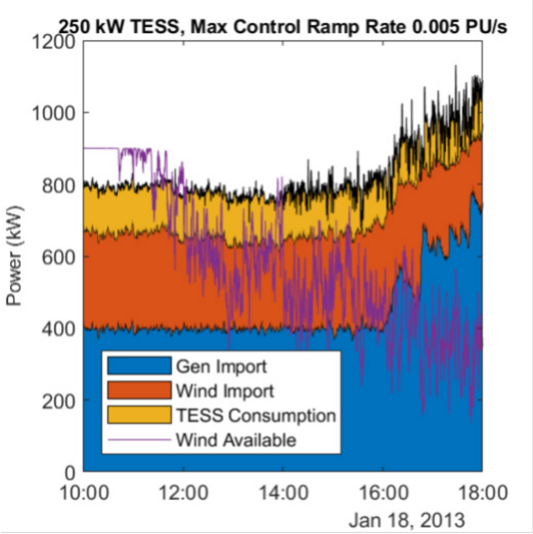
Simulations were conducted with and without a thermal energy storage system (TESS) under three levels of controllability: 0.005 pu/s to test a system with low controllability, 0.025 pu/s for a system with moderate controllability, and 0.1 pu/s for a system with high controllability.



Simulation Results obtained by employing an autonomous voltage regulation control on the developed distribution system. (Graphic by Rachid Darbali)



Time series of power imported from the wind farm and DG along with the available wind power for a low controllability scenario with no TESS. (Graphic by Rachid Darbali)



Time series of power imported from the wind farm and DG along with the TESS consumption and available wind power for a low controllability scenario with a 250 kW TESS. (Graphic by Rachid Darbali)

Simulation results show that the addition of a TESS reduces the variability of WTG imports to the grid, thereby reducing variability of the DG generation as well. Furthermore, a significant underloading event slightly before 16:00 was avoided by using a TESS. There was a sharp increase in available wind, and due to the limited controllability of the WTG output, the DG had to operate below its minimum optimal loading of 400 kW. The TESS also reduced underloading of the DG.

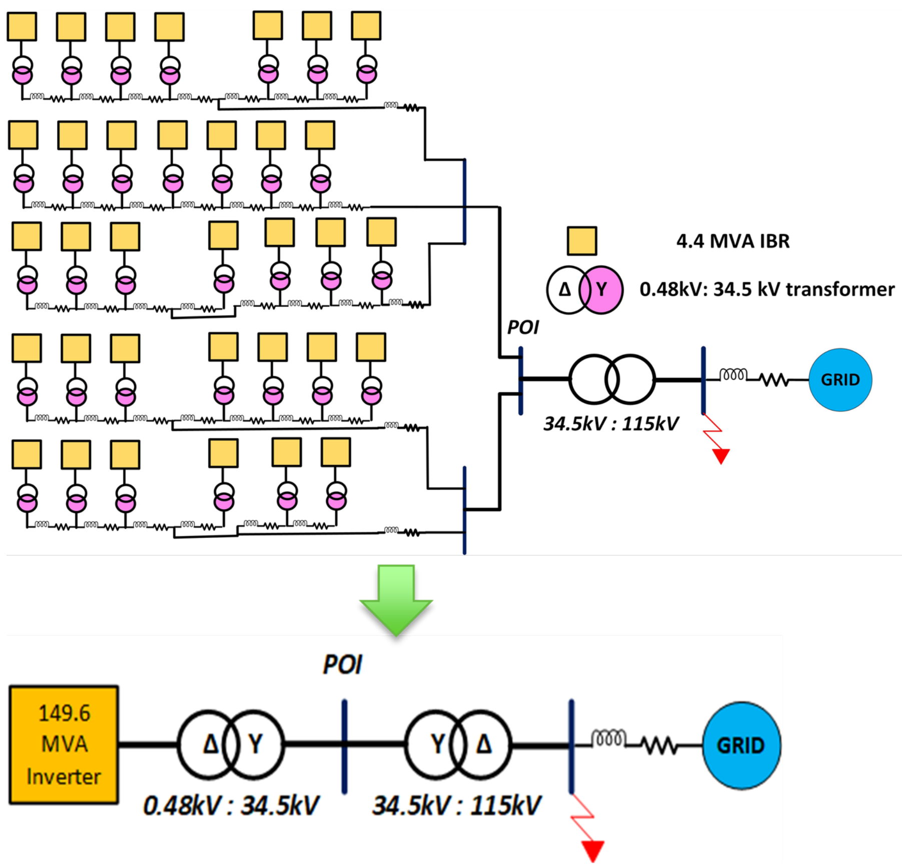
6.2 Wind Farm Models for Transmission Fault Protection Studies

With increasing penetrations of inverter-based resources (IBR), the impact on existing power systems protection infrastructure is critically important. IBR (PV, energy storage, Type III and Type IV wind turbine generators (WTGs)) response to faults in the system is partially or fully controlled by the power electronic converters used to interface with the power system. This response is nonlinear and controlled by proprietary controls, which makes it challenging to create phasor domain short circuit models that are required by commercial short circuit analysis programs.

This project is developing advanced standardized phasor domain short circuit models of Type III and Type IV wind turbine generators (WTGs) for faults. These models can be used for transmission protection design in commercial short circuit analysis programs without needing proprietary manufacturer information. The techniques include the ability to model hybrid wind systems, the collector system, and advanced controls such as grid-forming inverters.

In Fiscal Year 2023, we developed detailed switching models of Type IV WTG for comparison between dynamic electromagnetic transient (EMT) timeseries simulations and short circuit models used for fault protection studies. The results showed that power electronic switching models produced the same results as average inverter control models during faults. It was also identified that the wind farm collector topology and impedance can be ignored for transmission protection studies. While previous work had shown that this was true for Type I and Type II WTG, this was the first time the impact of the collector system had been shown for Type IV WTG fault results.

Finally, methods were developed for equivalent hybrid wind plants, including grid-forming controls, for short circuit studies. Grid-forming controls can provide benefits in weak or low inertia systems, and they change the response of the system to faults. It was demonstrated how hybrid systems with Type IV WTG, PV, and energy storage can be aggregated for accurate fault studies.



Complex models of each wind turbine and power electronic switching device can be aggregated into a single simplified model for transmission protection studies (Graphic by Matt Reno)

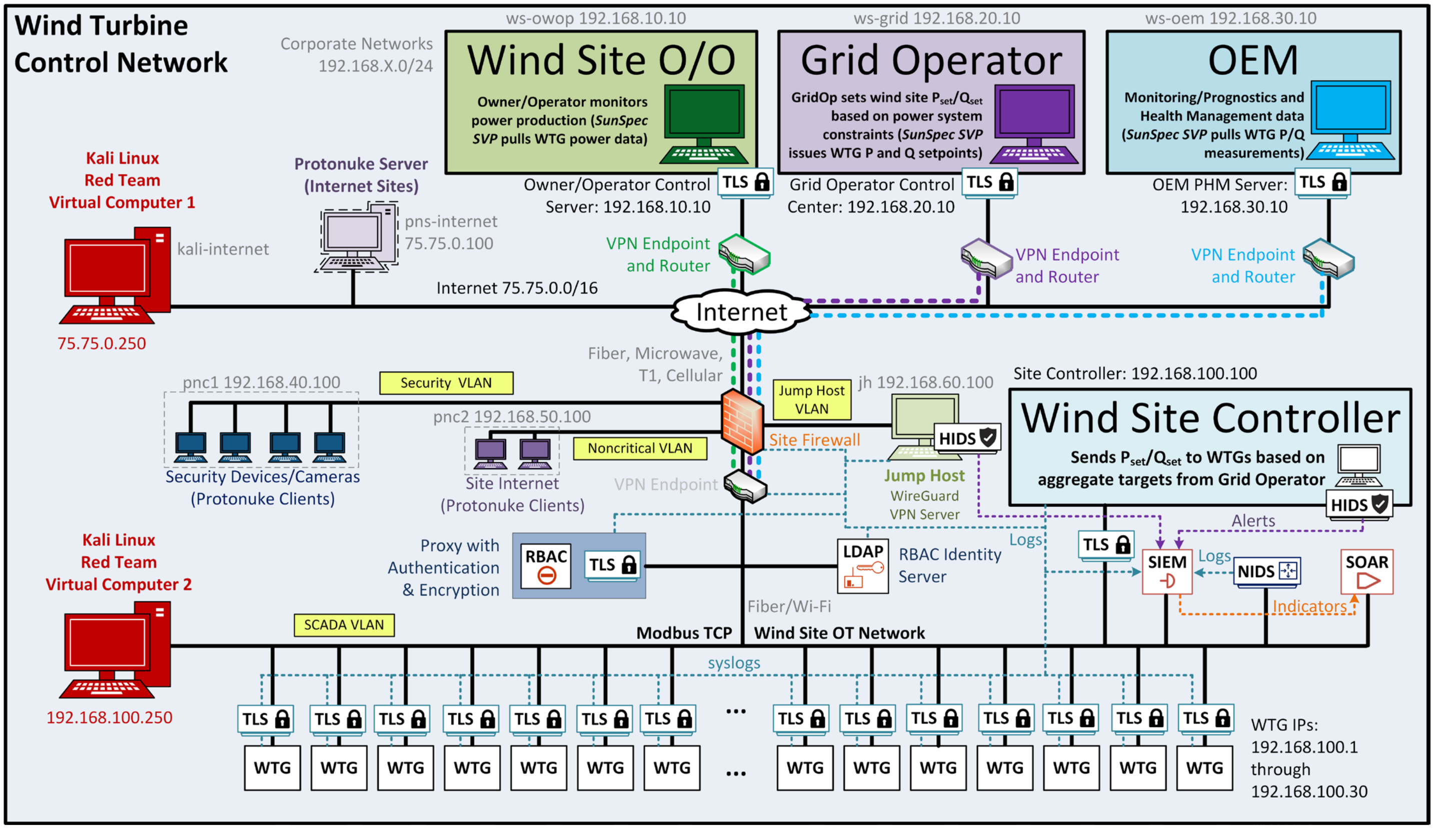
6.3 Cyber Hardening

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 2023, Sandia published a final project report entitled, "Hardening Wind Energy Systems from Cyber Threats" (Johnson, 2023). During this project, Sandia and Idaho National Laboratory (INL) constructed wind networks in a co-simulation environment designed for evaluating cyber resilience metrics through repeatable execution of cyber-attack scenarios. Multiple hardening technologies that will increase cyber-resilience performance and maintainability in wind-specific applications were evaluated. The networks were 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

Five different wind site network topologies were implemented to represent phased introduction of the cyber hardening features in various combinations. Cyber and physical impact metrics were created to correlate security technologies to resilience improvements.

To enable other researchers to work with the attack, detection, and response datasets, a separate simulation environment was created capable of simulating the flow of data into the Security Operation Center's alert database.

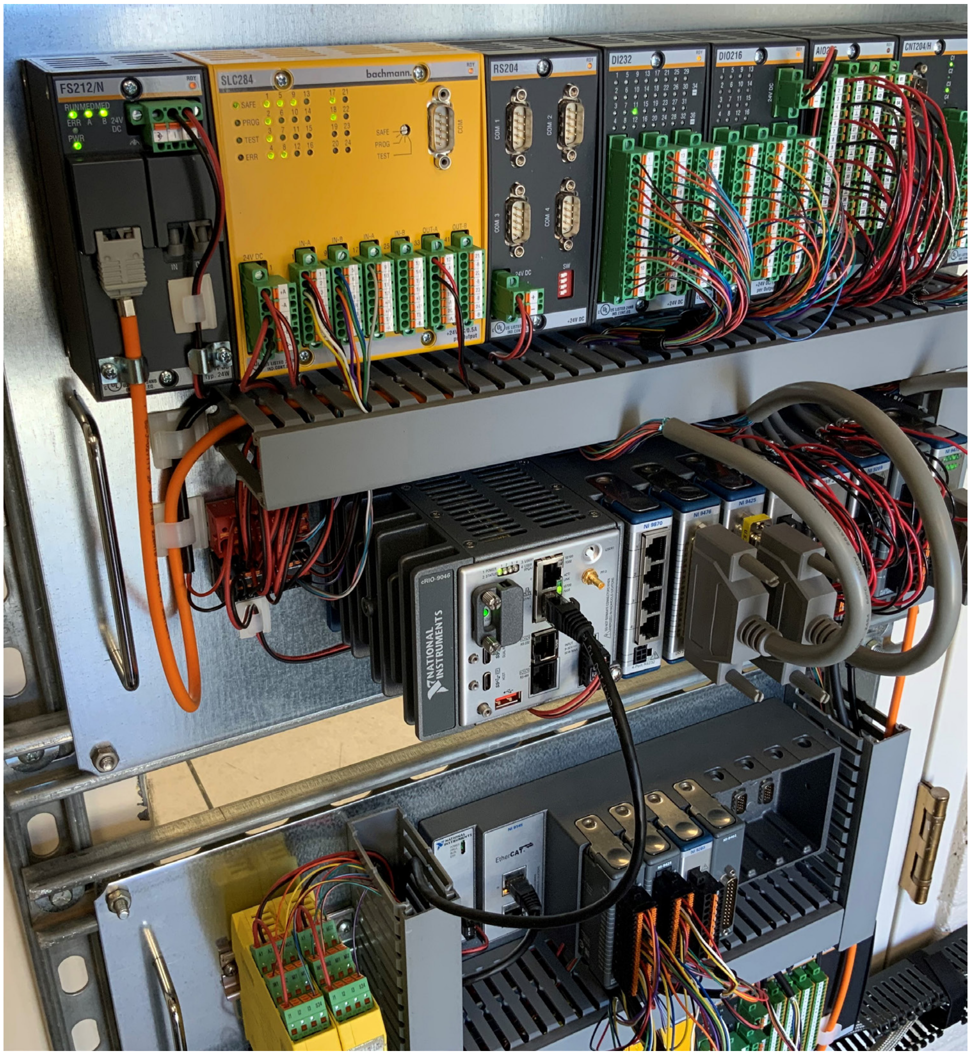


Wind site cybersecurity hardening features built into the networking simulation environment. (Graphic by Jay Johnson)

6.4 Wind Weasel

The industrial control systems which maintain safe operation of critical infrastructure such as electrical power plants are attractive targets to cyber threats. Cybersecurity defenses play a critical role in maintaining reliable operation of our electrical grid. Approximately 10 years ago, Sandia proposed WeaselBoard as a control system monitoring tool designed to detect high-impact attacks and zero-day exploits of Programmable Logic Controllers (PLCs).

In this project, the WeaselBoard concept is applied to industrial control systems (ICS) which regulate power and maintain safe operation of wind turbines. During Fiscal Year 2023, Sandia began construction of a wind turbine emulator (WTE) which will become a testbed for WeaselBoard technology tailored to characteristics of a wind turbine's ICS. The project team completed initial assessments of the EtherCAT fieldbus communication used by the WTE and began implementation of detection rules designed to identify abnormal system behavior.



Wind turbine emulator under development at Sandia's Distributed Energy Technologies Laboratory (DETL). (Photo by Jon Berg)

7. SOLUTIONS TO NATIONAL SECURITY TECHNOLOGY BARRIERS

7. SOLUTIONS TO NATIONAL SECURITY TECHNOLOGY BARRIERS

7.1 Wind Turbine Radar Interference Mitigation

Memorandum of Agreement Signed for Wind Turbine Radar Interference Mitigation Working Group

In early Fiscal Year 2023, Sandia National Laboratories helped deliver a Memorandum of Agreement (MOA) for the establishment of the Wind Turbine Radar Interference Mitigation (WTRIM) Working Group. The MOA was signed by the Department of Defense, the Department of Energy, the Federal Aviation Administration, the National Oceanic and Atmospheric Administration, and the Bureau of Ocean Energy Management and established a general framework for the cooperation and coordination to develop the means to mitigate impacts from wind turbines to radar systems and missions.

The goals of the interagency effort include:

- Developing near-term (5 years), mid-term (10 years), and long-term (20 years) goals focusing on technology-driven mitigation solutions. These will be primarily technology-driven, but may also extend to policy and legislative proposals, as necessary.
- Creating and executing a plan to implement workable solutions that includes a process for the Parties, in accordance with each Party's authorities and limitations on the use of appropriations, to commit funding necessary to execute the near-, mid-, and long-term mitigation.

This MOA can be found at: https://www.energy.gov/sites/default/files/2023-08/wind-turbine-radar-interference-mitigation-strategy-memorandum-of-agreement.pdf

Updated Federal Interagency Wind Turbine Radar Interference Mitigation Strategy

Sandia was a core contributor to the updated Federal Interagency Wind Turbine Radar Interference Mitigation Strategy. This strategy document elaborates on and serves as the action plan for the Memorandum of Agreement for the Wind Turbine Radar-Interference Mitigation Working Group. Sandia contributed to the development of this strategy and coordinated with the other WTRIM Working Group Memorandum of Agreement signatories. The objective of the strategy is to address wind turbines' interference with critical radar missions, ensuring the long-term resilience of radar operations in the presence of wind turbines, and removing radar interference as an impediment to future wind energy development by 2035.

To achieve these strategic objectives, the WTRIM Working Group will coordinate actions within three broad themes:

Theme 1	Improve the capacity of government and industry to evaluate the impacts of planned wind energy installations on sensitive radar systems.
Activity 1.1	Develop improved modeling and simulation tools to aid in the siting and evaluation of planned wind facilities and assessment of potential mitigation measures.
Activity 1.2	Evaluate emerging WTRIM issues and identify effective pathways to mitigation as appropriate.
Theme 2	Develop and facilitate deployment of mitigation measures to increase the resilience of existing radar systems to wind turbines.
Activity 2.1	Facilitate rapid deployment of current off-the-shelf mitigation measures.

Activity 2.2	Develop and facilitate deployment of hardware and software upgrades to make existing radars more resilient to the impacts of wind turbines.
Activity 2.3	Improve the capacity of existing automation and command and control systems to mitigate wind turbine interference impacts to radars.
Activity 2.4	Explore at-the-turbine mitigation methods that reduce the radar impact of wind turbines.
Theme 3	Encourage development of next-generation radar systems that are resistant to wind turbine radar interference.
Activity 3.1	Collaborate with developers of next-generation radar systems so the systems are designed to be highly robust against wind turbine interference.

The Federal Interagency Wind Turbine Radar Interference Mitigation Strategy can be found here: https://www.energy.gov/sites/default/files/2023-08/federal-interagency-wind-turbine-radar-interference-mitigation-strategy_082023.pdf

8. WIND ENERGY STANDARDS AND COLLABORATION TASKS

8. WIND ENERGY STANDARDS AND COLLABORATION TASKS

8.1 IEC 61400-5 Blade Design Standard

Sandia continues to lead the IEC 61400-5 Blade Design Standard. This standard, which was released in 2020, was the culmination of over 10 years of work by dozens of blade design and manufacturing experts. In Fiscal Year 2023, an amendment to the standard was finalized, removing conflicts with newly released certification standards and addressing several errors and ambiguities. The standards team also began planning for drafting of the second edition of this standard.

8.2 IEC 61400-2 Small Wind Turbines

Sandia contributed to the upcoming 4th revision to the 61400-2 standard for small wind turbines as an active observer. Several areas are in process of being updated, including: adopting mid-sized wind systems as large wind is becoming increasingly specialized; addressing design requirements to meet modern design methods including reasonable safety and knockdown factors due to updated material databases and fracture mechanics knowledge; updating guidelines for failsafe braking and controls; updating aeroelastic simulation options and requirements for certification, especially for Vertical Axis Wind Turbines (VAWTs).

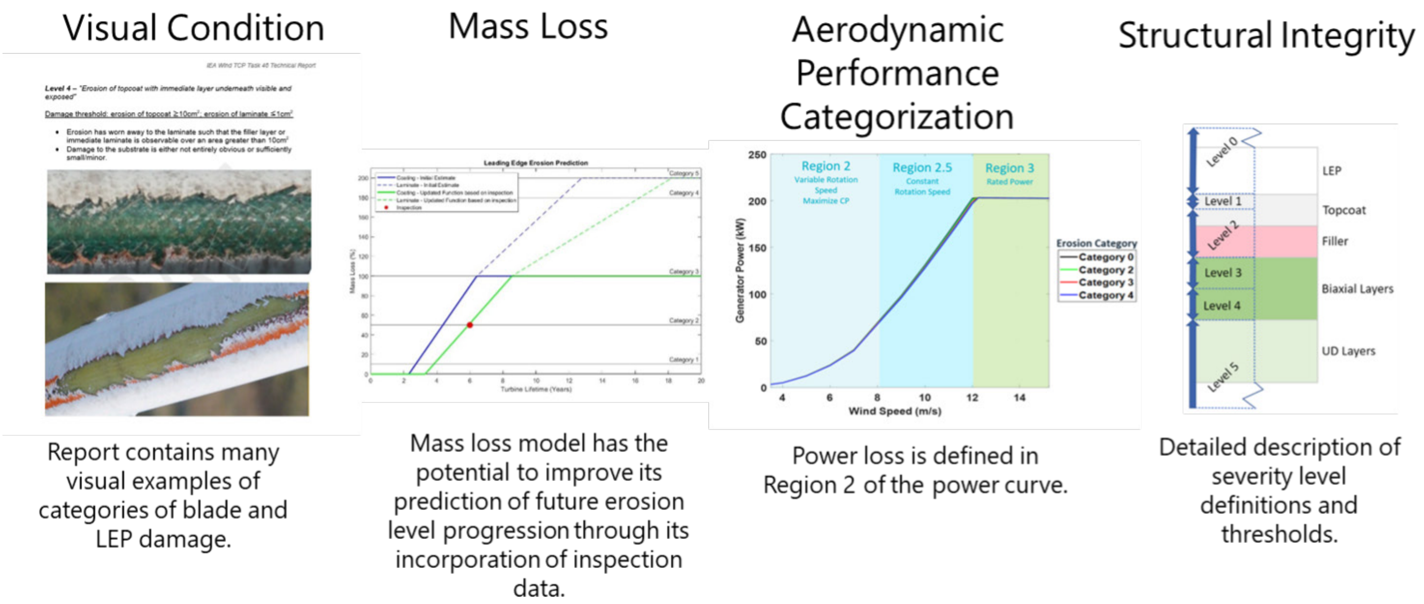
8.3 IEA Wind Task 43: Digitalization

Sandia is a member of the IEA Task 43 on the subject of Digitalization in wind energy. Sandia worked with Aalborg University in Denmark to create a probabilistic leading edge erosion model that uses widely available inspection photos to predict future erosion via a well-established physics model.

8.4 IEA Wind Task 46: Erosion of Blades

Wind turbine blade leading edge erosion has a major impact on onshore and increasingly offshore wind farm energy costs, driven by a loss of aerodynamic efficiency and regular repair/replacement costs. Task 46 of the International Energy Agency (IEA) Technology Collaboration Programme (TCP) is comprised of 40 organizations from 12 countries, focused on improving the understanding of the drivers of leading edge erosion, the geospatial and temporal variability in erosive events, the impact of erosion on the performance on wind plants, and the cost/benefit of proposed mitigation strategies.

Sandia directly leads Work Package 3 on Operation with Erosion and supports Cornell University to coordinate Work Package 2 on Climatic Conditions. In Fiscal Year 2023, the collaboration enabled by Task 46 resulted in a report on blade erosion characterization, merging a range of currently used erosion classification systems into a unified approach (Maniaci, 2023). The work on hydrometeor (rain and hail) size distributions and the impact on erosion was published by Cornell and is being used to support work of the Climatic Conditions Work Package (Letson, 2023).



Wind turbine blade leading edge erosion can be characterized by four categories: visual condition, mass loss, aerodynamic loss, and structural integrity. The Leading Edge Erosion Classification System report created through IEA task 46 presents a common system to integrate these modes of categorization. (Maniaci, 2023) (Graphic by David Maniaci)

9. INTELLECTUAL PROPERTY

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9.1 Patents Awarded

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9.5 Software Copyright

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