Sandia National Laboratories

SANDIA WIND ENERGY PROGRAM

FY24 ACCOMPLISHMENTS

Geoffrey T. Klise - Wind Energy Computational Sciences
Joshua A. Paquette - Wind Energy Design & Experimentation

Prepared by Sandia National Laboratories
Albuquerque, New Mexico
SAND2025-13549R

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology & Engineering Solutions of Sandia, LLC.

Available to DOE and DOE contractors from

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@osti.gov
Online ordering: http://www.osti.gov/scitech

Available to the public from

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd.
Alexandria, VA 22312

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.gov
Online order: https://ntrl.ntis.gov/NTRL/

U.S. DEPARTMENT of ENERGY
NNSA National Nuclear Security Administration

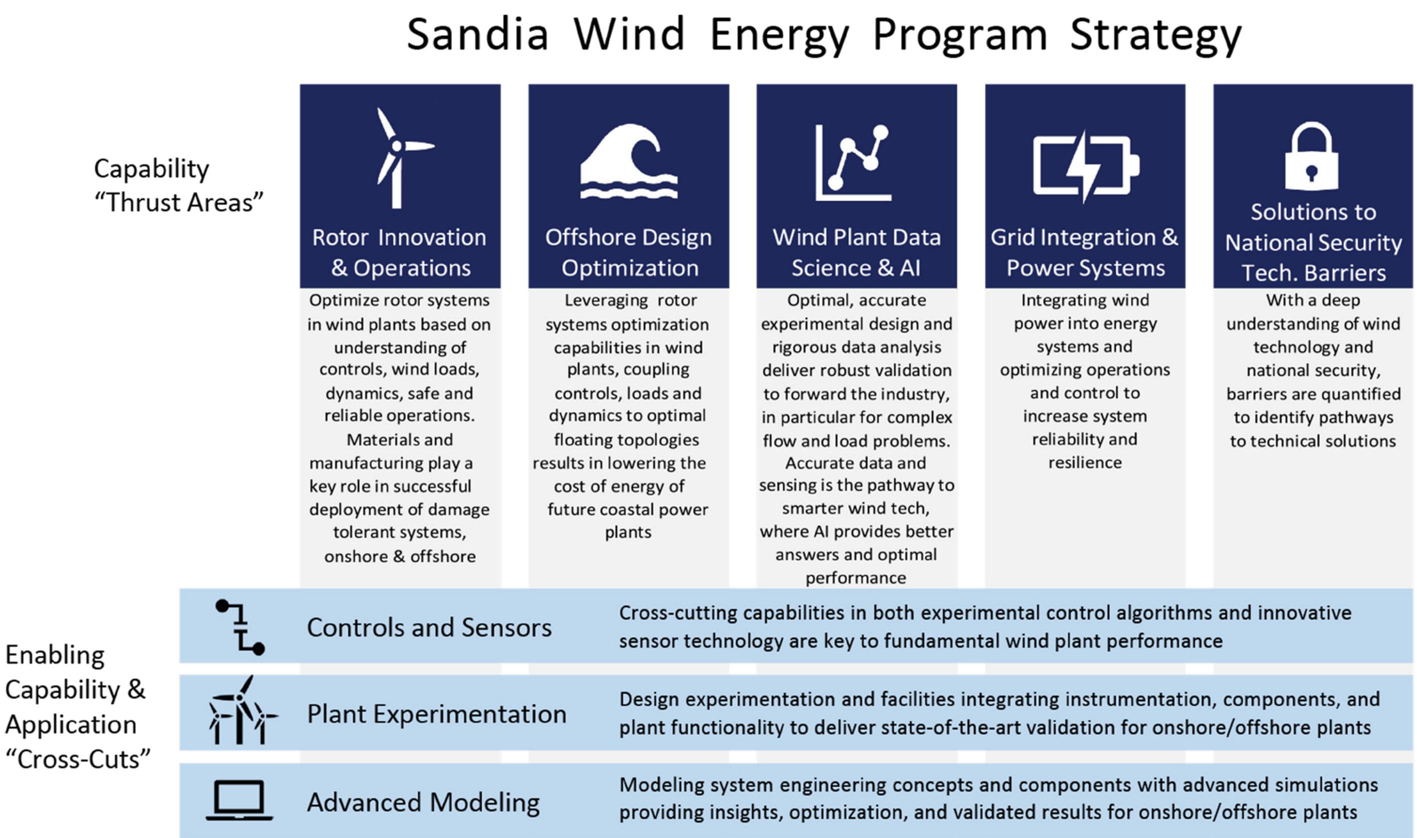
INTRODUCTION

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

This report summarizes Fiscal Year 2024 accomplishments from Sandia National Laboratories Wind Energy Program. The portfolio consists of funding provided by the DOE EERE Wind Energy Technologies Office (WETO), DOE Technology Commercialization Fund (TCF), 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. 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"

CONTENTS

1. Highlights 6

1.1 Lab News 7

1.2 California Communicator 7

1.3 Blog Posts 7

1.4 Social Media 8

1.5 Funding 8

2. Swift Facility 9

3. Rotor Innovation & Operations..11

3.1 Rotor Aerodynamics, Aeroelastics, and Wake..12

3.2 Blade Durability and Damage Tolerance 12

3.3 Big Adaptive Rotor (BAR)..14

3.4 Carbon Fiber Material Design for Targeted Performance Enhancement..15

3.5 Wind Turbine Blade Recycling Assessment 17

3.6 Holistic Multi-fidelity Wind Farm Design Optimization and Model Coordination..18

3.7 Distributed Wind Aeroelastic Modeling (dWAM)..19

3.8 Additively-Manufactured System-Integrated Tip (AMSIT)..20

3.9 Evaluation of Alternative Glass Fiber Formulations for Edgewise Reinforcement of Large Rotors 20

3.10 Novel Blade Root Attachment and Pitch Bearing System 21

3.11 Advanced Blade Tip and Root Sculpting for 5% Power Increase with Negligible Change in Bending Moment..21

3.12 Airborne Wind Energy Testbed 22

4. Offshore Wind 23

4.1 O&M Offshore Roadmap 24

4.2 Active Hybrid Mooring (AHM)..24

5. Wind Plant Data & Artificial Intelligence 26

5.1 Floating High Fidelity Modeling (HFM)..27

5.2 American WAKE ExperimeNt (AWAKEN) 27

5.3 OpenTurbine 29

5.4 Advanced Control and System Design for Offshore Wind..29

5.5 The Assessment Robot for Resilient Optimized Wind Energy ARROW(e)..30

5.6 Foundational Artificial Intelligence for Wind Energy 31

5.7 Simulations of Wake Interactions behind Individual-tower Multi-rotor Wind Turbine Configurations..31

5.8 Path to Nationwide Deployment of Wind-based Hybrid Energy Systems 32
5.9 Deep-Array Reduction of Wake-Induced Losses (DARWIN) Offshore Wind Turbine Controller 33
5.10 Machine/reinforcement learning to teach coordinated controllers how to reduce wake losses....... 34

6. Grid Integration & Power Systems....... 35

6.1 Wind Hybrid Interconnection Platform (WHIP) 36
6.2 Wind Interconnection Standards Platform (WISP)....... 37
6.3 An Assessment of Wind-Hybrid Microgrids in Puerto Rico Using Microgrid Design Toolkit 38
6.4 Wind Farm Models for Transmission Fault Protection Studies....... 38
6.5 Wind Weasel 39
6.6 Machine Learning-Based Intrusion Detection Systems (IDS) for Wind Networks 40

7. Solutions to National Security Technology Barriers....... 41

7.1 Wind Turbine Radar Interference Mitigation 42

8. Wind Energy Standards and Collaboration Tasks 43

8.1 IEC Standards 44
8.2 IEA Wind Task 43: Digitalization 44
8.3 IEA Wind Task 46: Erosion of Blades 44

9. Intellectual Property 45

9.1 Patents Filed 46
9.2 Invention Disclosures 46
9.3 Software Copyright 46

10. Publications 47

10.1 Journal Articles 48
10.2 Conference Papers and Proceedings 49
10.3 Reports....... 51

1. HIGHLIGHTS

1. HIGHLIGHTS

1.1 Lab News

August 8, 2024

3D-printed part adds value to wind power

https://www.sandia.gov/labnews/2024/08/08/3d-printed-part-adds-value-to-wind-power/

1.2 California Communicator

July 29, 2024

3D-printed part adds value to wind power

https://wp.sandia.gov/8000/2024/07/29/3d-printed-part-adds-value-to-wind-power/

1.3 Blog

June 27, 2024

Offshore wind roadmap addresses operations and maintenance challenges and opportunities

https://energy.sandia.gov/news/offshore-wind-roadmap-addresses-operations-and-maintenance-challenges-and-opportunities/

1.4 Social Media

Registration is now open for the 2024 Sandia Blade Workshop

https://energy.sandia.gov/news/2024-sandia-blade-workshop-registration-is-now-open/

2024 Sandia Blade Workshop

https://energy.sandia.gov/news/2024-sandia-blade-workshop/

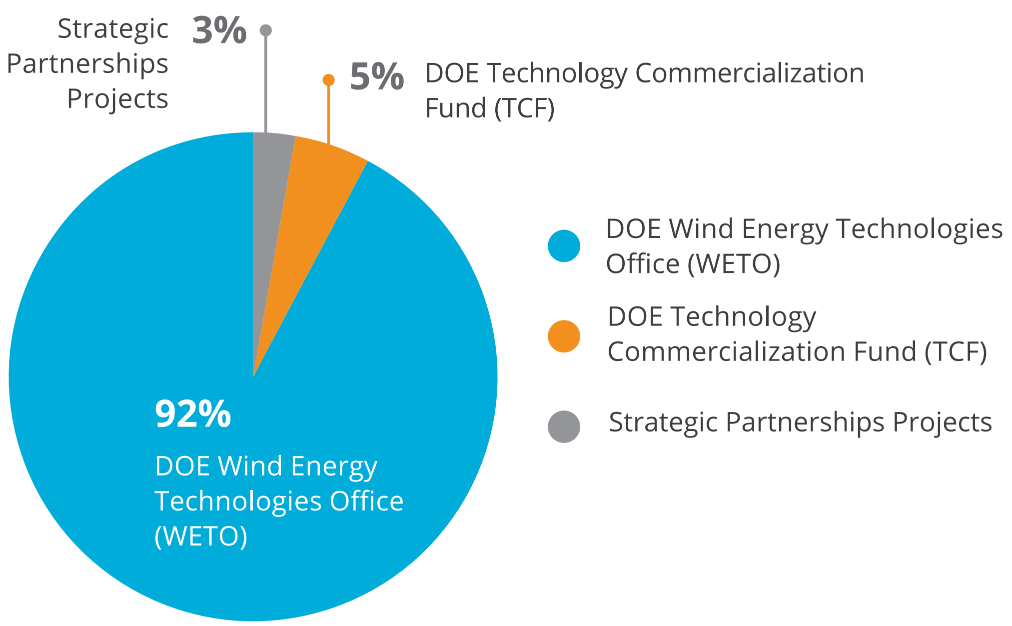
Sandia Wind Energy Technologies Program takes lead for six incubator awards

https://energy.sandia.gov/news/sandia-wind-energy-technologies-program-takes-lead-for-six-incubator-awards/

Making operations and maintenance a breeze

https://www.linkedin.com/posts/sandia-national-laboratories_making-operations-and-maintenance-a-breeze-activity-7217542504676511744-9GWb?utm_source=share&utm_medium=member_desktop

1.5 Funding



This chart represents funding sources from FY2024

2. SWIFT FACILITY

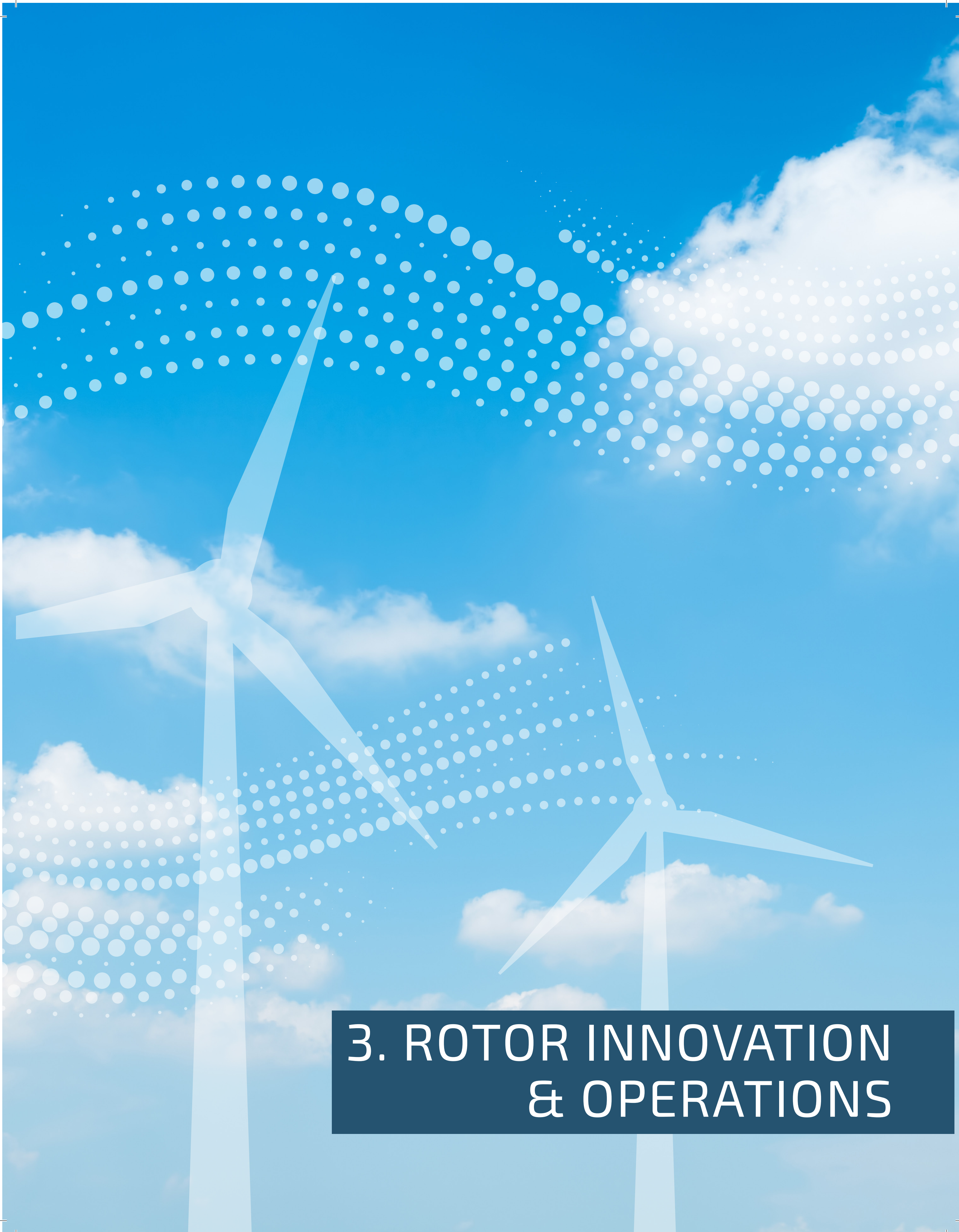
2. SWIFT FACILITY

In Fiscal Year 2024, the Scaled Wind Farm Technology (SWiFT) facility continued its transition to a user model in preparation for hosting more external customer funded projects. The SWiFT team relocated into a new office and high-bay space with available offices for visiting researchers. Commissioning on the A2 Turbine was completed, increasing operational capability to two fully turbines (A1 and now A2). Continued progress was made on commissioning the B1 Turbine. With two fully operational turbines, TotalEnergies and Sandia partnered to complete field testing of aerodynamic sensors at the SWiFT facility.

The microgrid capability at SWiFT neared completion, with the signing of a Sandia-Texas Tech University (TTU) Global Laboratory for Energy Asset Management and Manufacturing (GLEAMM) Multi-Organizational Work Agreement between Sandia, GroupNIRE, and GLEAMM. This agreement serves as a foundational document outlining the roles and responsibilities of each organization in order to foster a cooperative environment for future research partnerships. The team at SWiFT made significant advancements by installing and commissioning remote operating switches for the microgrid connection, enhancing its functionality and control for safe and reliable operations. This collaboration culminated in the successful completion of commissioning activities, allowing the microgrid to operate in an islanded state, and demonstrating crucial data collection capabilities that set the stage for future joint research efforts.

New front office and high-bay location for research conducted at SWiFT (Photo by Johnny Luevano).

Aerodynamic sensor installation on one of the SWiFT Turbines (Photo by Johnny Luevano).



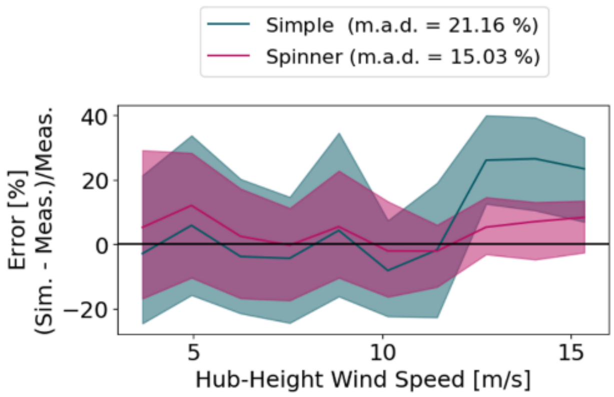
3. ROTOR INNOVATION & OPERATIONS

3. ROTOR INNOVATION & OPERATIONS

3.1 Rotor Aerodynamics, Aeroelastics, and Wake

The Rotor Wake project achieved significant milestones that advanced the understanding and modeling of wind turbine performance through innovative data assimilation techniques, and leveraging the abundant data collected during the rotor aerodynamics, aeroelastics, and wake (RAAW) experiment. This project was conducted as part of a cooperative research and development agreement (CRADA) with GE Vernova and National Renewable Energy Laboratory (NREL). This new data assimilation technique allowed us to simulate the exact timeseries of turbulent winds with a wind turbine aeroelastic model, OpenFAST, using the wind inflow as measured in the RAAW experiment from the spinner lidar instrument. We simulated a large portion of the RAAW experiment, totaling 1,689 ten-minute data periods, or 12 days.

Results of data assimilation simulations showed spinner lidar driven inflows have six times less computational cost but with equal or better turbine performance predictions than industry-standard turbulent inflow seeds generated statistically. For example, the turbine power error was reduced by 1% (from 6% to 5%), the tower fore/aft damage equivalent load (DEL) error was reduced by 6% (from 21% to 15%), and blade flapwise DEL error was reduced by 25% (from 30% to 5%) at high veer (50°) conditions. The following figure shows the reduction of tower fore/aft damage equivalent load error when using the new data assimilation approach, especially at high wind speeds (>11 m/s). We demonstrated spinner lidar driven inflows enable increased accuracy of turbine performance and loads predictions in aeroelastic models because the uncertainty of inflow turbulence generation from statistical models is eliminated and replaced with a spatial and temporal map of actual wind structures impacting the wind turbine rotor.



Tower fore/aft damage equivalent load error for "Simple" approach (industry standard) and new data assimilation approach from the "Spinner" lidar, across a range of wind speeds. Error closer to 0 is good and represents better prediction for the aeroelastic model. The color bands represent standard deviation from the median error. The mean absolute deviation (m.a.d.) of error across all wind speeds is shown in the legend (Graphic by Chris Kelley).

To enable this data assimilation process, we developed a code called RAAW Assimilation of Inflow Data (RAID). RAID enables and connects data processing from experiment, aeroelastic simulations, and calculation of turbine performance metrics from simulation outputs, all on the Sandia Flight high-performance computing resource. The RAID code implemented an induction correction to convert the wind measured by the spinner lidar near the rotor to a freestream velocity, a requirement for the aeroelastic simulation tool. RAID is a new capability and benefit to future experiments because it enables large numbers of simulations using data driven inputs to reduce atmospheric condition uncertainty for wind turbine model validation. This RAID code enables continued partnership and research with our industry partner, GE Vernova, in a new technology commercialization fund project.

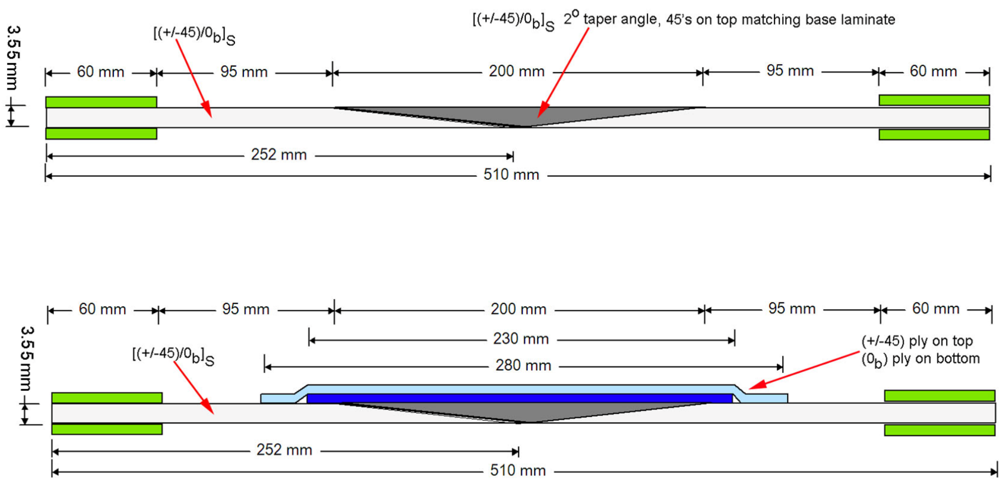
3.2 Blade Durability and Damage Tolerance

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.

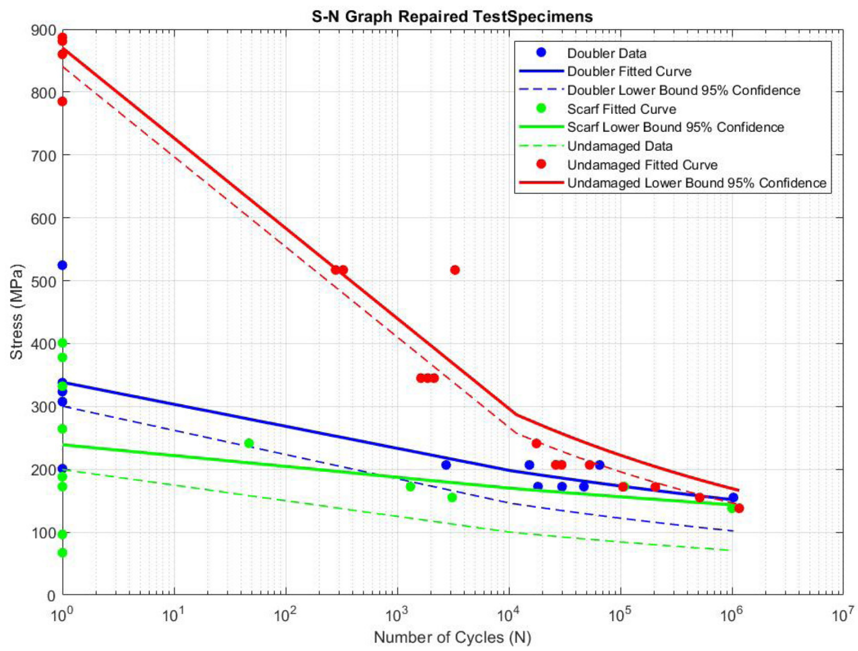
In Fiscal Year 2024, the project focused on five subject areas: Robotic Inspection, Damage Tolerant Materials and Repairs, Operations and Management Optimization, Lightning, and Erosion.

The Robotic Inspection task successfully implemented a microwave inspection system on the previously developed ARROWe crawler robot. The combination of phased-array ultrasonic and microwave inspection systems now allow for high-fidelity, non-destructive inspection of an entire wind blade.

For Damage Tolerant Materials and Repairs, the team conducted a detailed experimental and computational study of an alternative repair technique, called a doubler, which has the potential to reduce repair times and increase repair reliability. The work found that there was a potential for a 10x increase in repair reliability over conventional methods.



Traditional scarf and new doubler repair specimen design (Graphic by Josh Paquette).



Fatigue test results of undamaged, scarf-repaired, and double repaired specimens (Graphic by Josh Paquette).

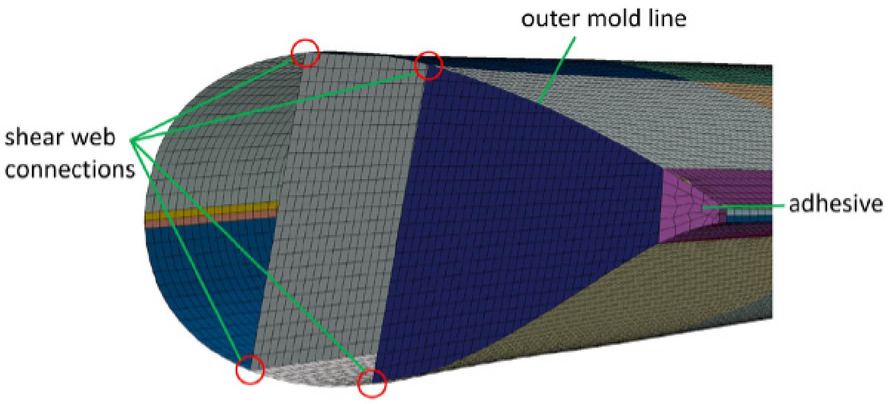
In the O&M Optimization task, the team is nearing release of a blade O&M optimization code, which allows for a user to conduct a probabilistic analysis of the cost and reliability of different inspection and repair strategies. This code incorporates historical learnings from blade reliability research and will be publicly available for industry and other researchers.

The Lightning task consisted of continued experiments from the prior fiscal year, where wind blade carbon fiber specimens were exposed to multiple simulated lightning strikes. This represents the field experience of many turbines in operation. The specimens were then subjected to strength and fatigue testing, which indicated small but measurable degradation. The results of this work are being used to inform new lightning protection and blade O&M standards.

Finally, the Leading-Edge Erosion task supported two major work packages of IEA Task 46: Erosion. The Atmospherics Effects work package, with partner Cornell University, produced publications on the atmospheric drivers of wind blade erosion, while the Operations Under Erosion work package developed the first open-source wind turbine reference model that includes erosion.

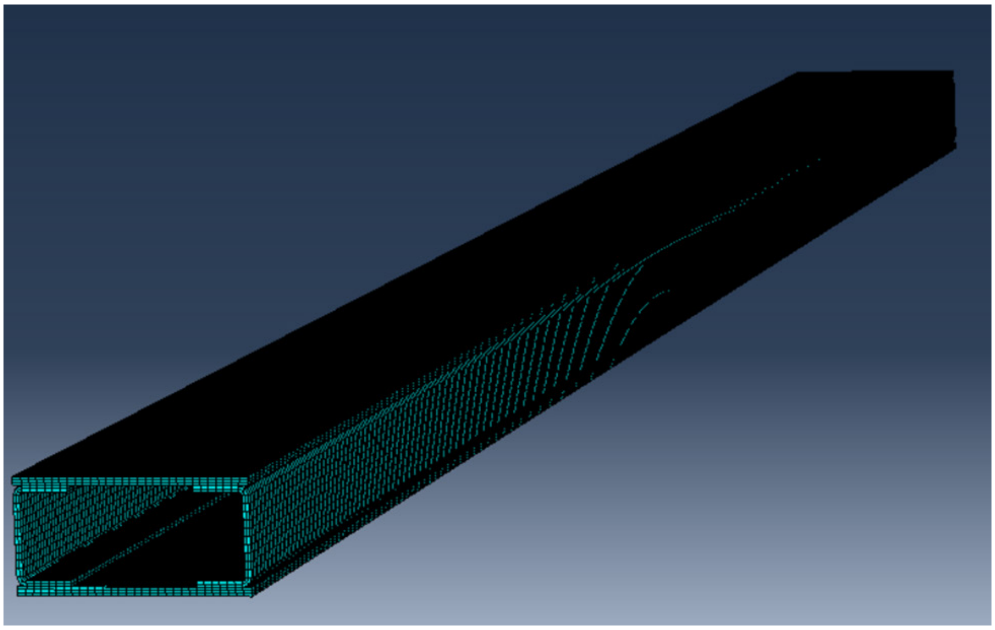
3.3 Big Adaptive Rotor (BAR)

The joint Sandia-NREL Big Adaptive Rotor (BAR) project, which aims to identify challenges associated with designing and manufacturing the next generation of large wind turbine rotors, completed its work in Fiscal Year 2024. Research focused on an examination of the impact that high-fidelity structural models have on blade design, and more accurate modeling of the structural damping of wind blades. High-fidelity modeling work compared analysis results from beam, shell, and solid element models, corresponding to low, medium, and high fidelity, respectively. The shell models were generated using the newest version of Sandia's wind blade modeling code, pyNuMAD, which has been significantly upgraded to include more blade design details. The highest fidelity solid element models, containing 73.7 million elements, were analyzed using Sandia's high-performance computing resources and Sierra Solid Mechanics software. The study revealed a significant improvement in accuracy for modeling stresses and strains throughout the blade structure through the use of higher-fidelity models, but also showed the ability of lower fidelity models to capture other parameters. The results will aide blade designers in knowing which fidelity of modeling to use and better understand the uncertainties that exist when using simpler models.



Sandia pyNuMAD-generated blade shell model, including adhesive joints (Graphic by Ernesto Camarena).

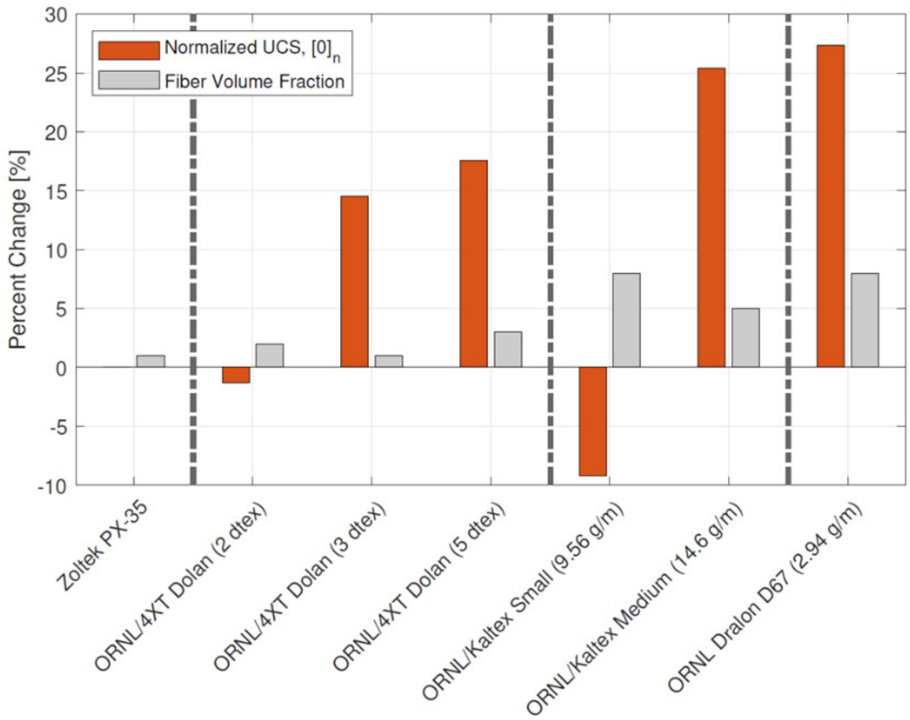
The research into blade damping focused on the ability to accurately predict the structural damping of blades from the material level up to the full blade. Damping is the ability of a structure to mitigate the effects of vibrations during operation and has become critical to blade designs as turbines have increased in size. The BAR project used state-of-the-art testing equipment at Sandia California to test composite coupons and beams, measuring the damping of each. These measurements were then used to predict the damping of a full wind turbine blade. This method will now be validated in a new project starting in Fiscal Year 2025, called STABLE, which will feature additional coupon and beam tests, along with a full-scale test of a modern turbine.



Beam damping design and FEA model (Graphic by Ernesto Camarena).

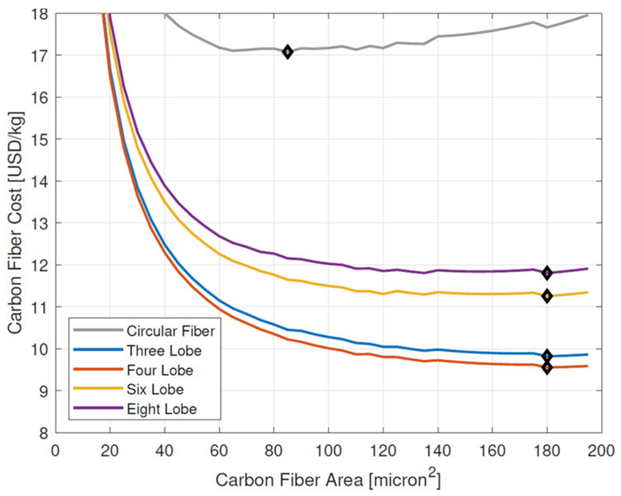
3.4 Carbon Fiber Material Design for Targeted Performance Enhancement

Carbon fiber has many benefits due to its weight and strength properties, however its usage in cost-driven industries such as wind energy and automotive is limited by its relatively high cost and the deficit in compressive strength relative to tensile strength. An appropriate goal for carbon fiber development for wind turbine blades is to increase the cost-specific compressive strength while maintaining the material stiffness. The Carbon Fiber Material Design project, in partnership with Oak Ridge National Laboratory (ORNL) and Montana State University, has developed carbon fiber material systems to assess the impact of carbon fiber size and shape on composite compressive strength and material cost. A series of carbon fiber geometry variants have been developed by ORNL including increasing size characteristics and/or the use alternative cross-sectional profiles. These carbon fibers were made using lower-grade textile precursor systems, but still show improvements in comparison to commercial carbon fiber systems as tested. Additionally, results indicate that increasing carbon fiber size correlates to increasing compressive strength as shown in the figure below for the Dolan and Kaltex precursor systems.



Compressive strength test results comparison of developmental carbon fiber materials, normalized to a 60% fiber volume fraction (Graphic by Brandon Ennis).

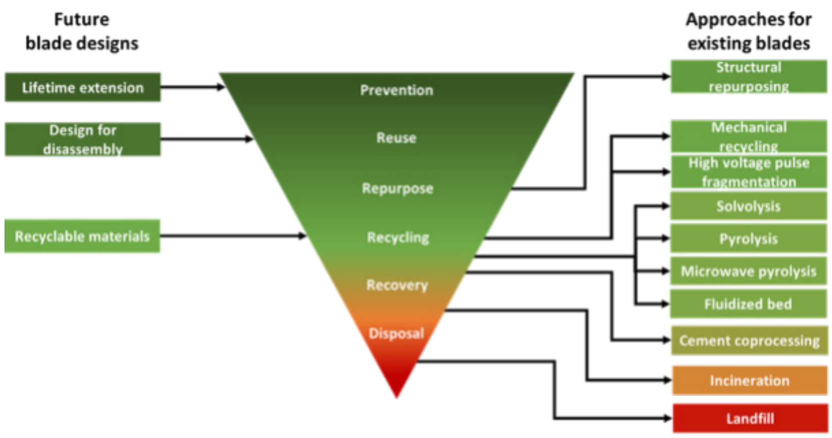
The testing results support the project hypothesis that larger carbon fibers can enhance the compressive strength of fiber reinforced polymer composites. These results complement the earlier work where non-circular carbon fiber geometries were identified that increase the carbon fiber area moment of inertia while reducing the costs, for a constant cross-sectional area. The most prominent commercial carbon fibers are all essentially round, but the project team has been developing three and six lobe carbon fibers to exploit the cost benefits of this design approach. The project work focused on identifying the combined carbon fiber characteristics (shape, size, tow count) that are optimal for exploiting cost-performance tradeoffs. The project team then developed cost models for the precursor production and carbon fiber conversion to assess the impacts of fiber characteristics on cost while analyzing the compressive performance of these shapes with a finite element micromechanical failure model. Results from the integrated cost modeling for a circular shape compared with representative multi-lobe shapes is shown in the figure below for 50K tow count systems. An interesting finding is that the multi-lobe shapes all prefer larger fiber area for cost minimization compared to circular fibers and result in carbon fiber material cost reductions of greater than 30%. Combined with the test result correlation of increased compressive strength in composites with increasing fiber area, the fiber pathways being explored show promise for outperforming conventional circular carbon fibers to enable the broad adoption of carbon fiber in wind turbine blades.



Carbon fiber cost trends from developed cost models for circular and multi-lobe geometries (numerical minima are indicated by the black markers) (Graphic by Brandon Ennis).

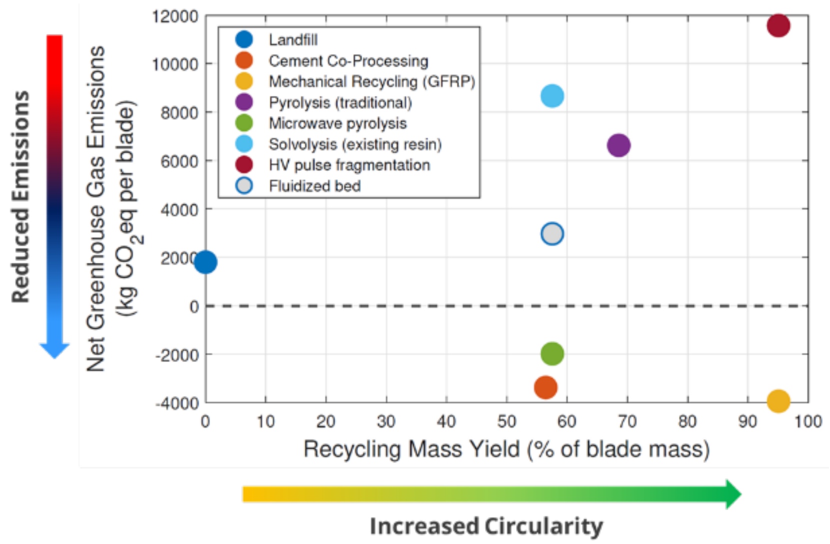
3.5 Wind Turbine Blade Recycling Assessment

Over 80% of a wind turbine is recycled at the end of its service life, though composite materials in some blades can be a difficult component to process. Deconstructing wind blade materials can be a costly and energy intensive process, with cost and energy demands typically increasing for processes that recover higher quality fibers. Several recycling technologies exist at various technology readiness levels, but are challenged by the added costs, emissions, and market adoption for the recovered materials. Approaches for further improving wind turbine blade lifetime sustainability are shown in the figure below including blade end-of-life recycling approaches based on thermal, chemical, and mechanical processes to deconstruct the composite waste stream into useful products for secondary markets.



Approaches for end-of-life wind turbine blades arranged from high to low circularity (top to bottom of inverted triangle) (Graphic by Evan Sproul).

As part of the Wind Turbine Recycling Assessment project, a team of researchers at Sandia, NREL and ORNL characterized the most promising near-term recycling approaches through formal life cycle assessment and techno-economic modeling. These analyses identified opportunities and challenges for specific recycling technologies, considering existing wind blade materials as well as future material approaches. An example from the project results is shown in the figure below for recycling technologies used for a waste stream representing current, fiberglass blades. In many cases, these multi-metric comparisons reveal competing objectives where, for example, net emissions are lower, but operational costs are higher. Comparing environmental impacts, it is apparent that some technologies are more circular (with higher material recovery rates), but with associated increases in net greenhouse gas emissions due to increased energy loads.



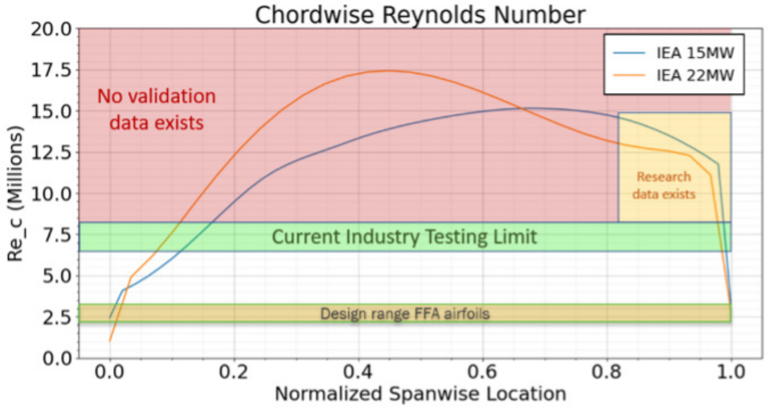
Metrics comparison from life cycle assessment for a fiberglass wind turbine blades (Graphic by Brandon Ennis).

For recovery of constituent materials in fiberglass wind blades, three technologies were found to have negative net emissions: cement co-processing, mechanical recycling, and microwave pyrolysis. However, challenges remain for these technologies. Cement co-processing has a more limited circularity, and the emissions would worsen with decarbonization of cement production. Market adoption is less certain for mechanical recycling and is dependent upon the final product form. Microwave Pyrolysis has a low technology readiness level and has higher variable operational costs due to the use of electricity in the process. High-voltage pulse fragmentation and fluidized bed are also at low technology readiness levels, resulting in uncertain energy estimates that affect both emissions and cost. Pyrolysis can produce high quality fibers separated from resin, but virgin fiberglass production has relatively low emissions so the additional energy to recover pure fibers is not as advantageous for conventional fiberglass as for higher performing fibers, such as carbon fiber. These analyses illustrate promise for recycling retired wind turbine blades with the ability to reduce emissions relative to production of virgin glass or carbon fiber. Continued study is recommended to advance these technologies at scale while addressing challenges for material adoption.

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

The Holistic, Multi-Fidelity Wind Farm Design Optimization and Model Coordination project continued its second year in partnership with NREL. This portfolio of models spans the fidelity spectrum from single-component to full-system studies and addresses 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 the WETO-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 will demonstrate new design methodologies and innovation pathways for increased performance.

An effort within the project aims to design high-Reynolds number airfoils well suited to very large offshore rotor blades using engineering design tools processes. The Open-Source Offshore (OSO) airfoil family preliminary designs were generated this fiscal year, with the goal of supporting the wind communities research and development needs by providing a common aerodynamic research platform for collaborative research and benchmarking. The image below illustrates the gap between the design range of current open-source airfoils (FFA airfoils) and the operating range of modern offshore reference turbines (the IEA 15MW and IEA 22MW model). The expertise and guidance of experienced professionals ensures this airfoil family meets the needs of modern wind turbine research. The concluding year of the project will include publicly releasing the OSO airfoil family and publishing the design process, tools, and details of the final designs.



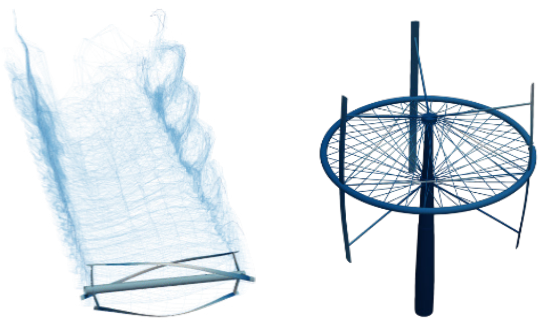
Existing public airfoils used in reference offshore turbine models are designed for smaller, slower turbines than current state of the art (Graphic by David Maniaci).

In addition, Sandia and Purdue University continue to develop the OpenSG code. It has the potential to enhance blade design fidelity and is an extension of the well-known structural tool called VABS (Variational Asymptotic Beam Section) to be both open source and higher fidelity, and be able to replicate VABS results for 2D cases, and demonstrate a new 3D capability.

3.7 Distributed Wind Aeroelastic Modeling (dWAM)

In Fiscal Year 2024, considerable improvements in modeling capabilities and certification pathways for vertical-axis wind-turbines (VAWTs), hydrokinetic crossflow turbines, and other novel concepts were made. Highlights include fully open sourcing the OWENS.jl (Offshore/Onshore Wind/Water Energy Simulator) toolkit including software for multi-body structural dynamics, VAWT/crossflow aerodynamics, automated sectional property pre-processing, and automated fatigue and ultimate failure post processing. These packages can be used within OWENS for an end-to-end simulation solution, or individually for other purposes. Improvements were made to the OWENS user interface, installation, documentation, examples, and the addition of an end-to-end demonstration video.

These developments help resolve both real and perceived barriers to certification for distributed wind archetypes and open new pathways for crossflow hydrokinetic design and certification that can be simulated with desktop computing resources. Images below show the rotor section of a marine hydrokinetic turbine with the vortex-line wake, and a novel hub and spoke supported VAWT including cable tensioning.



Sample crossflow hydrokinetic and novel distributed wind concepts modeled using the OWENS.jl toolkit (Graphic by Kevin Moore).

3.8 Additively-Manufactured System-Integrated Tip (AMSIT)

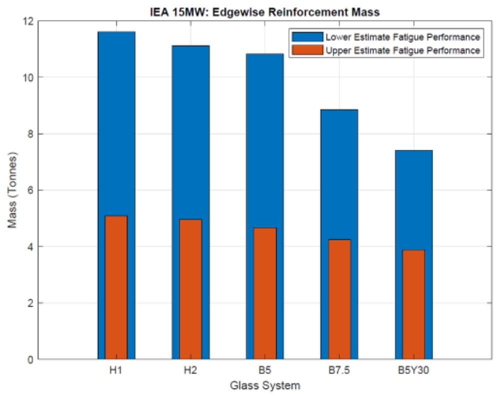
AMSIT tip and winglet mounted on a blade at SWiFT (Photo by Brent Houchens).

The Additively-Manufactured System-Integrated Tip (AMSIT) team, a collaboration between Sandia, Wetzel Wind Energy Services and Stratasys Direct Inc., took a major step in the use of 3D-printing for wind turbine blades and printed several blade tips and started proof-load testing at the National Institute for Aviation Research (NIAR). This DOE Advanced Materials and Manufacturing Technologies Office (AMMTO) funded project demonstrates how 3D-printing can bring advanced technologies, modularity, and rapid on-demand replaceable tips to wind turbine blade manufacturing and repair, while simultaneously reducing the levelized-cost-of-electricity (LCOE) produced.

AMSIT test article with in-plane, centrifugal, and normal loads applied at 80% of design load (Photo by NIAR).

A 3D printed tip was proof tested and survived at 190% of an extreme load case that might be encountered during a planned field test at SWiFT. In preparation for this flight test, an analysis to determine the operation time required to measure statistically significant differences in quantities such as power and root bending moments was investigated. This was parameterized to be relevant for any improvement in expected power production of between 1% and 10%, making it an excellent reference for any field experiments investigating the value of advances in aerodynamics of wind turbine blades.

3.9 Evaluation of Alternative Glass Fiber Formulations for Edgewise Reinforcement of Large Rotors



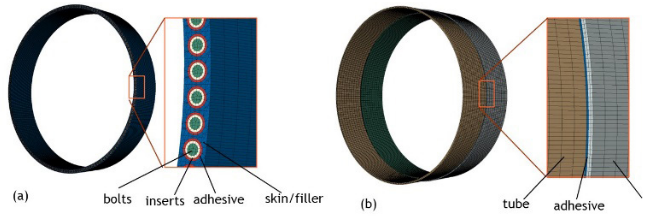
Graph of total edgewise reinforcement mass of the IEA 15MW reference blade after optimizing for the different glass fiber material systems. H1 and H2 are the Owens-Corning commercial fibers, B5 and B7.5 are B-glass with Beryllium Oxide (BeO) content of 5% and 7.5% respectively. B5Y30 has a BeO content of 5% and Yttrium content of 30%. The blue and red bars represent higher and lower estimates of the material fatigue slope exponents (Graphic by Ryan Clarke).

Edgewise reinforcement is a critical structural component for large wind turbine blades as it resists the gravitational loading cycle that occurs within each rotor revolution and helps to prevent coupled flap-edge aeroelastic instabilities. As blades continue to increase in length, they become exponentially more massive, and fatigue damage in the edgewise direction starts to drive the design. The edgewise reinforcement in commercial wind turbine blades is typically constructed using infused high-performance fiberglass such as Owens-Corning H-glass™; however, alternative fiberglass formulations such as B-glass variants present a compelling alternative. In this study, structural optimization of the edgewise reinforcement of two reference wind blades, a land-based 3MW turbine, and an offshore 15MW turbine are carried out to understand the effects B-glass may have in wind blade construction.

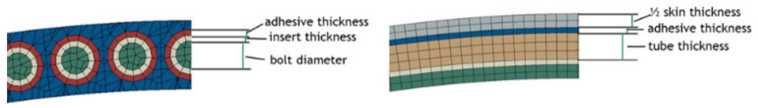
Results of this study show that for a reference land-based 3 MW wind turbine, B-glass is at least 67% more expensive, but offers potential weight savings of up to 4.6% of the blade mass and reduces the required fabric length in the edgewise reinforcement by 58%. For a reference offshore 15 MW wind turbine, B-glass is at least 38% more expensive, but provides weight savings of up to 8% of the blade mass (this represents 7 tonnes of material mass savings) and reduces the required fabric length by up to 65%. These advantages could lead to significant downstream benefits for the turbine system, potentially decreasing manufacturing time and costs. These findings suggest that B-glass could enhance the performance and efficiency of wind turbine blades. Additionally, it should be noted that the cost difference decreased, and the mass and fabric length savings grew when comparing designs using the 3MW and 15MW reference turbines, respectively, warranting further investigation into its application in edgewise reinforcement for large offshore wind blades of the future.

3.10 Novel Blade Root Attachment and Pitch Bearing System

Sandia conducted a study of a novel blade root and pitch bearing design to simplify manufacturing and construction, while improving reliability. The project proposes replacing the large number of root inserts in a modern wind blade with a bonded cylinder. To date, the project has made significant progress in demonstrating the potential for an alternative blade root-to-hub connection. The study revealed that likely hundreds of fasteners and inserts will be needed for future large blades, pointing to a potential process and operational reliability concern. The Sandia code, pyNuMAD, was modified to produce detailed blade root models using solid brick elements and the newly-added interface with ABAQUS. This added capability will allow for future research into blade roots within and beyond this project. Finally, the IEA 15MW blade root was analyzed using a conventional blade root insert design previously developed, and a root cylinder insert. The results show large reductions in all stresses for the bonded cylinder, and an approximate 50% reduction in adhesive stress, which meets the main project objective.



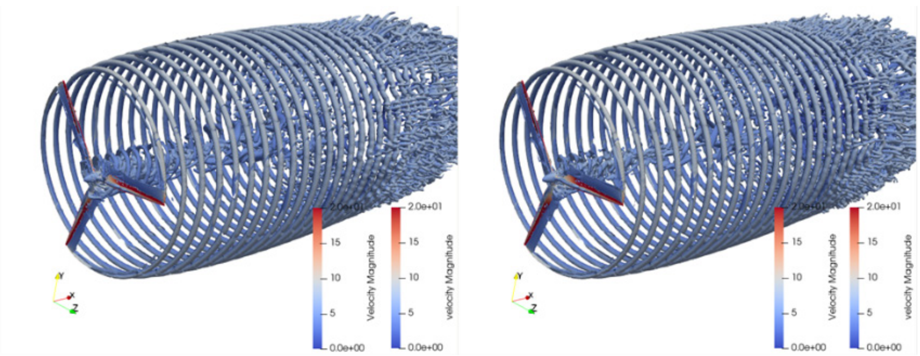
Blade root insert (a) and bonded cylinder (b) FEA models.



FEA model detail showing dimensions used for insert and bonded cylinder (Graphic by Josh Paquette).

3.11 Advanced Blade Tip and Root Sculpting for 5% Power Increase with Negligible Change in Bending Moment

Sandia led an incubator project partnered with NREL to explore advanced aerodynamic concepts to increase wind turbine power production with no increase in peak design loads. Advanced blade design tools (vortex methods and blade resolved computational fluid dynamics) were used to design unique blade and root geometries, demonstrating a 3%-5% power increase for no increase in design root bending moment for modern onshore and offshore turbines. The work focused on simulating the concepts using computational fluid dynamics analysis available through the ExaWind code suite on high performance computing systems to gain more confidence in the concepts. Visualizations of the wake impact of the technology are shown below.



Plots of wake velocity gradients (Q) for the inboard winglet (left) and baseline (right) cases. Q is the second invariant of velocity gradient tensor and is in units of 1/s^2, Positive values of Q show vorticity dominant areas (Graphic by David Maniaci).

3.12 Airborne Wind Energy Testbed

A collaboration between Sandia, Idaho National Laboratory (INL) and the University of Dayton Research Institute was formed to scope and design a U.S.-based airborne wind energy (AWE) test site. After successfully securing Incubator funding, the team investigated the needs of industry through meetings with more than 10 AWE companies. Early findings were presented at the 2024 Airborne Wind Energy Conference and Sandia staff visited two test sites in Germany and Ireland to better understand the strengths and shortcomings of each site.

Along with a team of interns at both laboratories, a procedure and tool was developed to evaluate potential test sites and early adopter communities for alignment with the benefits of airborne wind energy. This aided in the identification of five viable candidate test site locations and potential collaborations with tribal colleges and universities, as well as research universities, were identified. The team secured follow on Incubator funding for Fiscal Year 2025 to establish the AWESTRC (Airborne Wind Energy System Testing for Research and Commercialization) Consortium and move forward with planning a test site in the U.S.

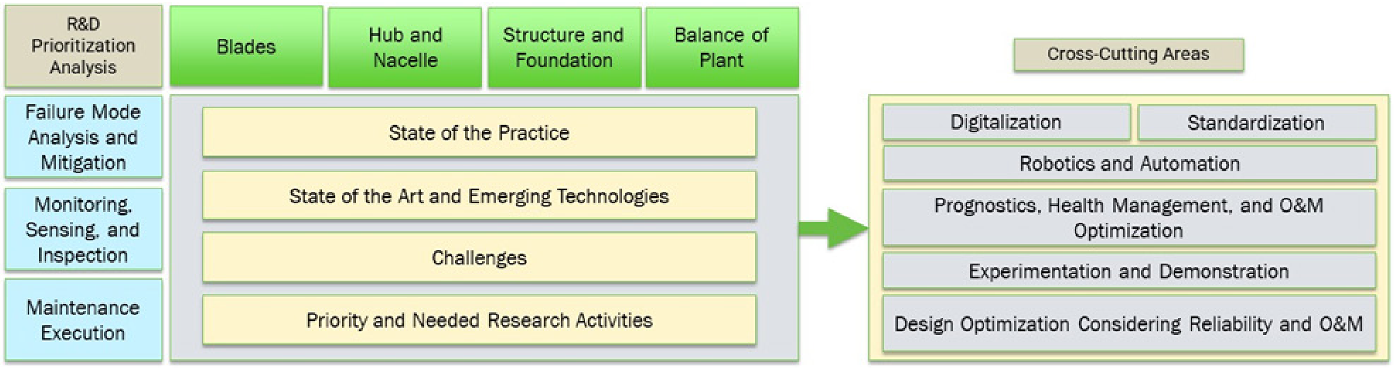
Photograph of the RWE test site in Ireland to observe a Kitepower test flight (photo by Brent Houchens).

4. OFFSHORE WIND

4. OFFSHORE WIND

4.1 O&M Offshore Roadmap

In May 2024, Sandia and NREL released "An Operations and Maintenance Roadmap for U.S. Offshore Wind Enabling a Cost-Effective and Sustainable U.S. Offshore Wind Energy Industry Through Innovative Operations and Maintenance." This report details challenges that will be faced in offshore wind O&M in the U.S. in the coming years, along with targeted areas for research and development to reduce cost and increase reliability. The report is the culmination of a year-long effort on the part of fifteen researchers from the national labs and dozens of industry interviews.



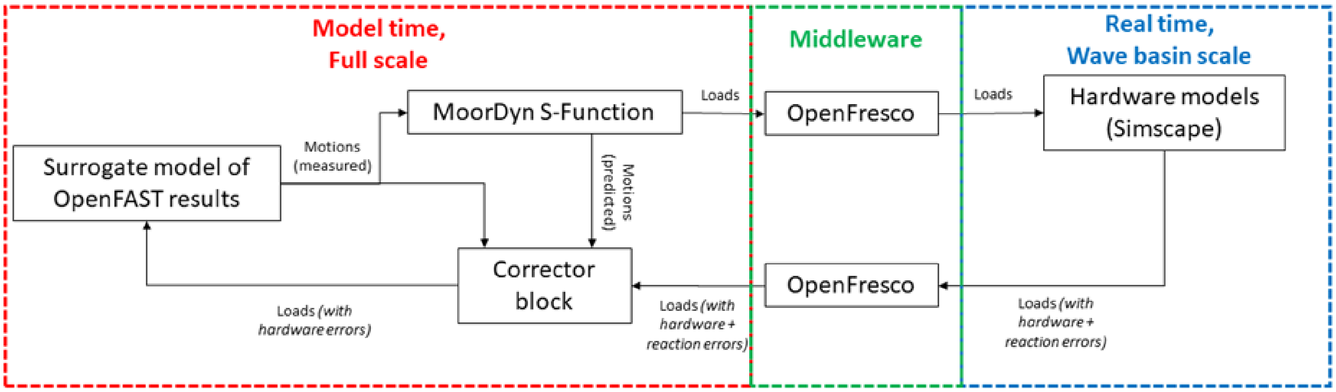
Roadmap Organization (Graphic by Josh Paquette).

4.2 Active Hybrid Mooring (AHM)

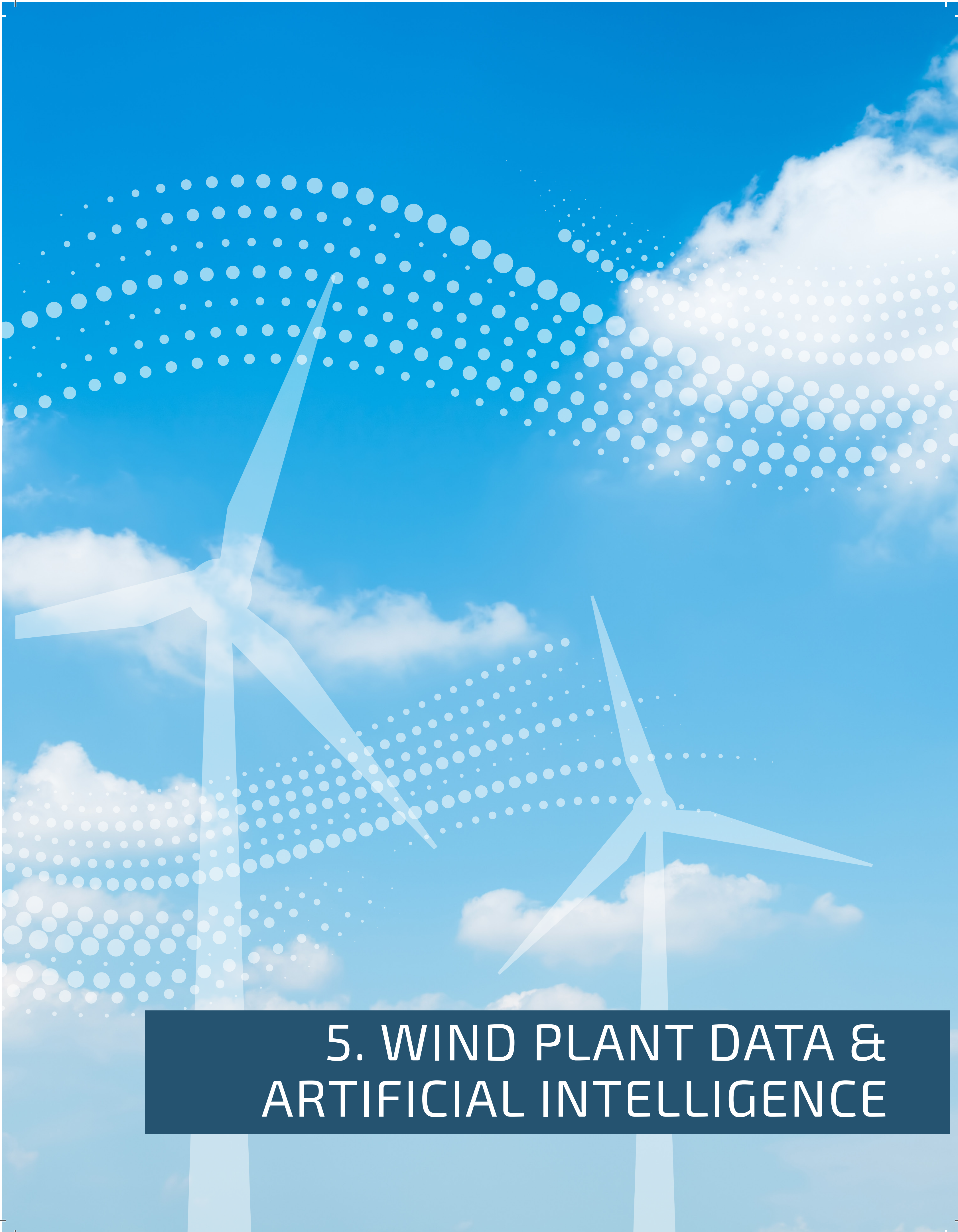
The Active Hybrid Mooring (AHM) Incubator project goal is to define and develop a representation of a six degree of freedom (6DOF) AHM system in Simulink to assess whether the speed and accuracy of the system is sufficient to warrant further investigation for a larger scale project. An AHM system combines a scaled physical test specimen in a wave basin coupled to a computer simulating mooring dynamics not achievable in the wave basin, allowing for accurate scale model testing in deep water depth or with shared mooring systems. To date, the project team has successfully designed a representative mooring system for the VolturnUS-S 15MW floating offshore wind turbine (FOWT) in 1,000-meter water depth to provide a baseline needed in the AHM system, with the results showing off-the-shelf actuators would be practical. The team also defined model configurations for the subsystems using the MoorDyn software package with a novel input strategy and chained hydraulic actuators represented in Simulink Simscape, respectively. The remainder of the project focused on verifying the existing models for speed and accuracy against OpenFAST simulations, increasing their complexity to enable six degree of freedom (6DOF) operation, and connecting the numerical and physical submodels into a single holistic model.

The verification phase of the project has shown promising results. For a one-directional linear wave case, the developed numerical model is computationally stable and operates 30% faster than real time using a 0.01 second time step with less than 5% error in applied forces, indicating the model is likely fast and accurate for the AHM design to operate successfully. Additionally, the Simscape model of a hydraulic actuator operates with less than 0.3% relative error when actuating mooring loads from an OpenFAST simulation of the VolturnUS-S 1,000-meter mooring system.

Going forward, the AHM project aims to verify the model against simulated conditions more representative of FOWT wave basin tests. This will expand the basic case explored in the project to date to include nonlinear higher-order wave conditions. Additionally, the project will assess whether the AHM system is capable of modeling shared mooring systems, which could be physically modeled using a single platform in the wave basin with the AHM numerical model actuating the shared mooring loads. This would provide a huge asset to wave basin testing with AHM systems.



Flowchart showing the operation of the verified active hybrid mooring (AHM) system (Graphic by Michael Devin).



5. WIND PLANT DATA & ARTIFICIAL INTELLIGENCE

5. WIND PLANT DATA & ARTIFICIAL INTELLIGENCE

5.1 Floating High Fidelity Modeling (HFM)

The High-Fidelity Modeling (HFM) project is a collaboration between Sandia and NREL to develop, validate, and verify the models, numerical algorithms, and best practices required for offshore and land-based wind farm simulations. This project is focused on applying the ExaWind code suite consisting of the Nalu-Wind and AMR-Wind LES solvers, as well as the OpenFAST turbine modeling code, in its simulations, and also uses the leadership class computational resources at Oak Ridge National Laboratory (ORNL) for its largest computations.

In Fiscal Year 2024, the HFM project demonstrated the abilities of the hybrid ExaWind solver in a geometry-resolved simulation of 16 NREL 5MW turbines in a neutral atmospheric boundary layer at 11.4 m/s hub-height wind speed. This simulation was the largest geometry-resolved wind farm simulation using ExaWind to date, and used a total of 1.7 billion mesh elements to resolve a wide range of scales: from the kilometer-long, large-scale atmospheric turbulent eddies down to centimeter scale at the turbine blade geometry. A total of 384 nodes (3072 GPU's and 21,504 CPU's) on the Frontier supercomputing cluster at the Oak Ridge Leadership Computing Facility (OLCF) were used for about 95 hours total during the computation. The results of the simulation were compared against equivalent actuator line turbine model computations, and illustrated where the choice of the model fidelity becomes important: In the near wake region, the geometry-resolved simulation better captured the flow immediately downstream of the rotor, but fewer differences were observed in the far wake region. Additional wind farm simulations of offshore simulations were performed in the HFM project to examine how momentum transfer occurs through the various rows of the wind farm.

Illustration of the vortical structures in the downstream wakes of the geometry-resolved, 16 NREL 5MW turbine simulation (Graphic by NREL).

Looking ahead to Fiscal Year 2025, the HFM project will develop a set of publicly available benchmark problems which will document the performance and accuracy of the ExaWind code suite. These benchmark problems will include representative cases of ExaWind's capabilities, including atmospheric boundary layers, two-dimensional and three-dimensional airfoil sections, and blade-resolved wind turbines in realistic inflows. External partners will also be encouraged to participate in the benchmark problems and compare various code results on these cases.

5.2 American WAKE ExperimeNt (AWAKEN)

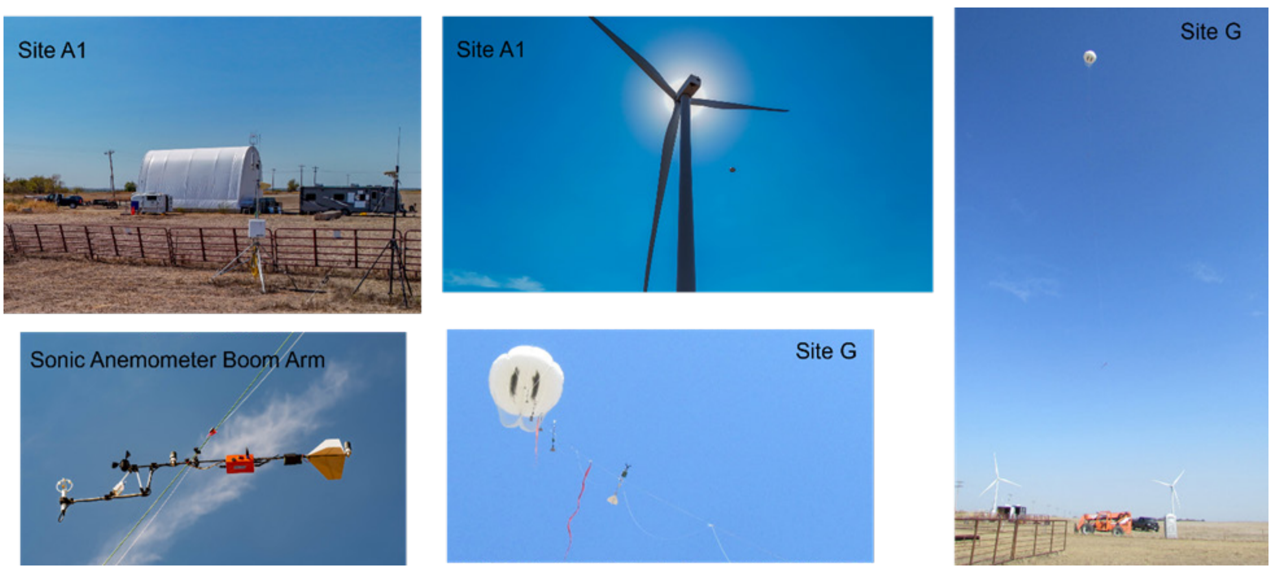
The American WAKE experimeNt (AWAKEN) is in its fourth year of the campaign, and aims to gather validation data that will illuminate: momentum transfer between the atmosphere and wind plants, turbulence development within the plants, the effects of upstream wind plant blockage, the behavior and control of wind plant wakes, and interactions between multiple plants. Insights gained from this campaign will help refine wind plant models, optimize their layouts, and enhance operational strategies, ultimately leading to increased power generation and improved reliability of wind farms.

This year, Sandia supported two universities in their participation in the AWAKEN project. Cornell University provided four lidar systems—two profiling lidars and two scanning lidars used to measure wind plant inflow and wake development, including the effects of wake steering control, deployed at two locations: one upstream of the King Plains wind farm and the other downstream. University of California, Berkeley, investigated the impact of atmospheric bores and associated gravity wave effects on wind plant performance using the Weather Research and Forecasting (WRF) large-eddy simulations (LES) and the generalized actuator disk (GAD) to model the wind turbines. These simulations are a key contribution to one of AWAKEN's testable hypotheses, which examines how atmospheric turbulent bursting events, such as gravity waves and bores, affect wind plant power production and loading.

Sandia-led journal publications examined a model intercomparison of the atmospheric boundary layer, turbines, and wakes within an AWAKEN wind plant; the effects of atmospheric updrafts and downdrafts on wind turbine wake behavior; and a new model for wind turbine induction and blockage. Additionally, Sandia was awarded 250,000 node-hours on the Summit Oak Ridge Leadership Computing Facility cluster to conduct extremely large simulations of wind plants. This allocation enhanced the scale of simulations that the team could contribute to the Phase 1 AWAKEN Benchmark, conducted as part of the International Energy Agency (IEA) Wind Technology Collaboration Programme (TCP) Task 57: Joint Assessment of Models (JAM).

Additionally, the Sandia Tethered Balloon System (TBS) was deployed for a two-week campaign. Two TBS units were operated simultaneously, one located upstream of the wind plant and the other located within the wind plant. The TBS units have been enhanced as part of both the AWAKEN and DOE Atmospheric Radiation Measurement (ARM) projects to improve turbulence estimates using boom arm motion compensation, with the goal of creating cost-effective mobile met towers. The TBS data will be used to improve understanding of turbulence development and momentum entrainment within the wind plant under different atmospheric stability conditions.

Finally, Sandia continued its efforts to organize and prioritize instrumentation development, which includes finalizing publication of the Wind Energy Instrumentation Development Roadmap and leading the IEA Wind TCP Technical Experts Meeting (TEM) 110 on Instrumentation Development. Meeting participants learned more about the challenges facing instrumentation development and about the process that will be used to establish methods for identifying and deploying key instruments in support of an upcoming IEA task.



Images of the TBS deployment at the AWAKEN Site A1 and Site G. Site A1 is located upstream of the King Plains wind farm to the south and Site G is located upstream of the final row of downstream turbines to the north (Photo by Tommy Herges).

5.3 OpenTurbine

OpenTurbine is an open-source wind turbine structural dynamics simulation code designed to meet the research needs of the DOE 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. 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 2024, a proof-of-concept version of OpenTurbine was completed that was coupled to the ROSCO controller and the AeroDyn BEMT solver. The IEA 15-MW test case demonstrated how the new tightly coupled OpenFAST and OpenTurbine could solve the problem in a more stable manner, compared to prior results from the standard OpenFAST loosely coupled model. For the demonstration, OpenTurbine was more than five times faster than OpenFAST on a MacBook Pro M1. These proof-of-concept studies provided confidence in the OpenTurbine modeling and software development approaches. More details about OpenTurbine, along with source code, are publicly available at: https://github.com/Exawind/openturbine.

During Fiscal Year 2025, an Application Programming Interface (API) will be developed for OpenTurbine for rigid bodies coupled to geometry-resolved CFD and with spring-based mooring lines; the API will be designed in collaboration with the HFM team to couple with ExaWind. Release will include documentation and a regression test suitable for floating platform dynamics where a simple model is used to mimic hydrodynamic restoring forces. Floating platform capabilities will be limited to rigid bodies with six degrees of freedom.

Model	**GitHub ID**	**Time Step**	**Simulation Wall-Clock Time**	**Wall-clock time per simulated time (smaller is better)**
OpenTurbine	22157a20ff	0.01 s	35 sec	1.2
OpenFAST (tightly coupled)	3f0e899d1b	0.01 s	194 sec	6.5
OpenFAST 3.5.3 (loosely coupled)	3.5.3	10^{-6} - 0.01 s	N/A	N/A

OpenTurbine simulations are about five times faster than the tightly coupled OpenFAST (Graphic by Paul Crozier).

5.4 Advanced Control and System Design for Offshore Wind

To fully realize the potential of offshore wind plants and provide optimum value to the grid, improved plant-level control is needed to reduce wake effects (i.e., aerodynamic interactions between neighboring turbines that reduce energy production) and improve the expected value of wind energy.

The Control and System Design for Offshore Wind Turbines and Wind Plants project completed its second of three years of funding in partnership with NREL and approached the wake-control problem from a more fundamental perspective. To gain widespread acceptance in industry, wake-control technology must strike a balance between improving wind-plant power production while not adversely impacting turbine reliability. Sandia is addressing this problem by pulling back the curtain on the fluid-dynamic processes underpinning cutting-edge wake-mixing strategies. Specifically, the team deployed a combination of wake stability predictions, high-fidelity wake modeling, and data-driven wake analysis to improve fundamental understanding of wake-mixing processes, and these findings were published in a journal article.

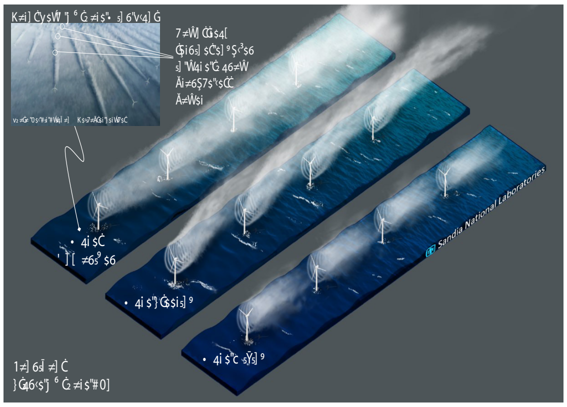
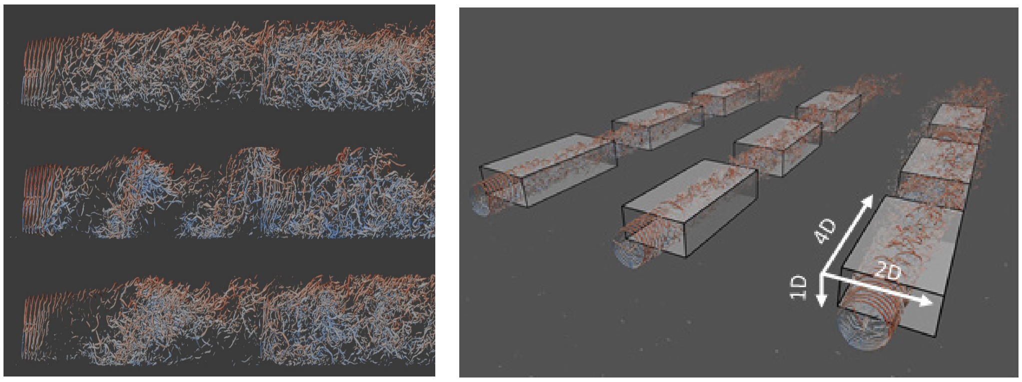


Illustration of wake effects on columns of offshore turbines with different wake-control strategies employed (Graphic by Eric Lundin).



Rendering of large-eddy simulation results for 15-MW turbines. Left: the three turbines in the near ground are employing an active pitching strategy to reduce wake effects on downstream turbines. The boxes indicate control volumes around the individual turbine wakes that are used to quantify wake recovery. Right: a side-view comparison of two wake-mixing strategies compared to a baseline case with no wake-control (Graphic by Gopal Yalla).

5.5 The Assessment Robot for Resilient Optimized Wind Energy ARROW(e)

The ARROW(e) Technology Commercialization Fund (TCF) project kicked off with project partners CIC NDT, and EDF Renewables. Fiscal Year 2024 research focused on feasibility and successful integration of selected ultrasonic modalities, as well as software and hardware design and upgrades to support closed loop control. Hardware and Software tasks for closed loop included design of the printed circuit board (PCB) to enable access to robot communication infrastructure, and interface with feedback and other subsystems; trackball design for an application-agnostic way to get feedback on robotic vehicle states of motion and orientation; and software design to integrate feedback and communication subsystems with control algorithms and state machines within a common real-time controller hardware platform. Remaining upgrades, testing, and integration will take place in Fiscal Year 2025.

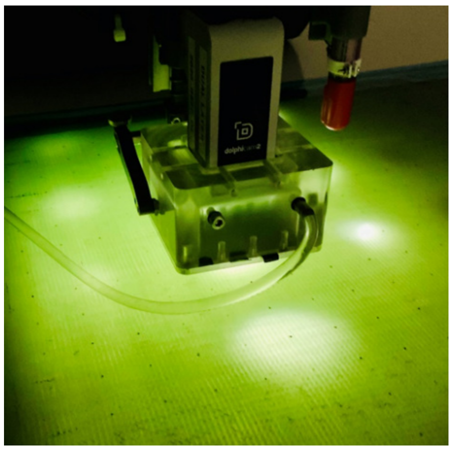


Image of ultrasonic sensor demonstration on laboratory test article (Photo by Michelle Williams).

5.6 Foundational Artificial Intelligence for Wind Energy

Virtually all applications of interest in wind energy pose a formidable challenge for existing machine learning (ML) or artificial intelligence (AI) methodologies due to the limits associated to the acquisition of data. In practice, researchers are often faced with either sparse observational data or high-fidelity numerical simulations that, due to their computational requirements, significantly limit the number of available simulations that can be employed for the training of ML/AI models.

In Fiscal Year 2024, Sandia's effort within this project focused on exploring multi-fidelity strategies that, by combining datasets with varying degree of accuracy, can potentially lower the data requirements associated to the data with the highest information content (with observational data or high-fidelity simulations). The team explored the possibility to extend the training of our random Fourier Neural Networks (rFNNs) to multi-fidelity datasets in collaboration with the University of New Mexico. We have also explored the possibility of improving the efficiency of multi-fidelity ML algorithms in collaboration with the University of Notre Dame by modifying existing architectures with the introduction of linear or non-linear encoding networks, i.e., variable transformations to be determined during the training, that maximize the utility of low-fidelity data with respect to the available, limited, high-fidelity data.

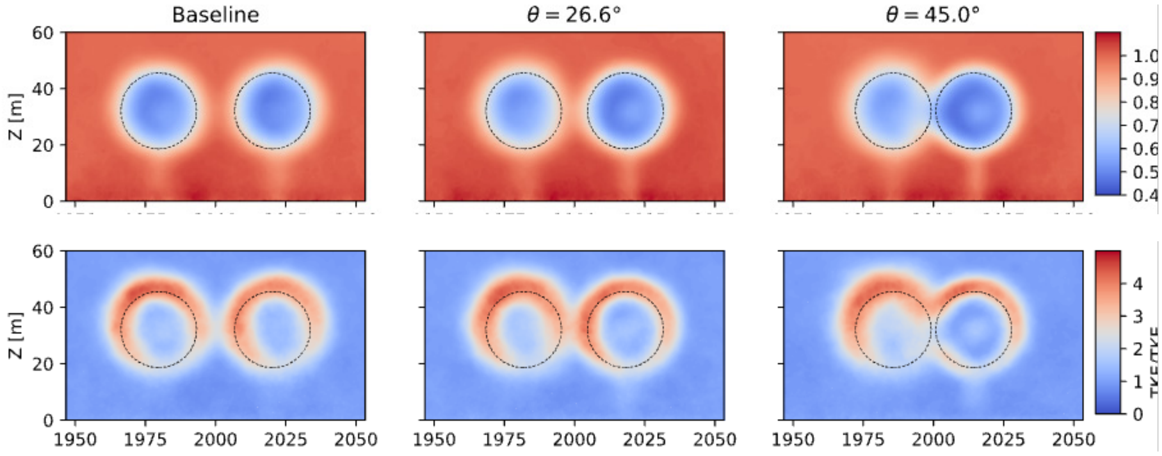
Finally, Sandia and NREL have utilized the knowledge acquired during the activities described above to develop and communicate to the DOE Wind Energy Technologies Office a roadmap detailing the demonstration of these multi-fidelity ML/AI technologies on offshore wind energy applications for Fiscal Year 2025.

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

As part of a Strategic Partnership Project (SPP) with Hamilton Consulting, LLC, Sandia used high-fidelity large eddy simulations (LES) to perform trade studies investigating the impact of various closely spaced, paired-rotor configurations on turbine power and wake behavior. Closely spaced rotors potentially offer higher wind farm performance by maximizing existing land use area without necessitating larger rotor diameters. The first study explored the effect of increasing the downstream angle between two turbines positioned side-by-side with 0.5 rotor diameter (D) tip-to-tip spacing. It was shown that the relative power coefficient decreased on the upwind turbine and increased on the downstream turbine; an angle of 45 degrees between the turbines produced the most optimal 1.2% increase over the isolated turbine cases. The second trade study analyzed the effect of different 1.5D, 2.25D, and 3.0D hub-to-hub spacings between two turbines. Shorter spacings of 1.5D and 2.25D elevated the relative power coefficient compared to the 3D spacing case. The third trade study involved four-turbine simulations with two pairs of rotors and analyzed the impact on 8D and 16D downstream spacing between the turbine pairs. Wake losses for the second row of turbines were shown to be between 7-16% with higher losses for closer spacing.

Turbine wake contours and downstream wake profiles of the horizontal velocity magnitude and turbulent kinetic energy (TKE) were also examined from the above LES cases. Of particular interest for the 2 turbine runs, a 1.5D hub-to-hub spacing was shown to create a significantly different wake profile shape especially far downstream (>5D) compared to the turbine pairs with larger spacings. Also, for the 4 turbines runs, the wake profiles downstream of the 2nd turbine showed significant differences in the near-wake (<3D) as a 8D downstream spacing significantly increased the wake deficit compared to 16D downstream spacing. The LES runs were supplemented by low-cost engineering model simulations using FLORIS to assess its capability for modeling closely spaced rotors. FLORIS did reasonably well in modeling the wake profiles further downstream from 2.5D to 10D. However, the FLORIS results generally struggled modeling the near-wake region and over-predicted wake velocity deficits, along with showing decreased accuracy with closer turbine spacing.

This collective work helped inform Hamilton Consulting, LLC of the efficacy of different closely spaced, paired-rotor designs and its applications for full wind farm layouts. The introduction of low-cost FLORIS simulations into this project and comparisons with LES also allowed for its use by expanding the design space to include larger turbine models.

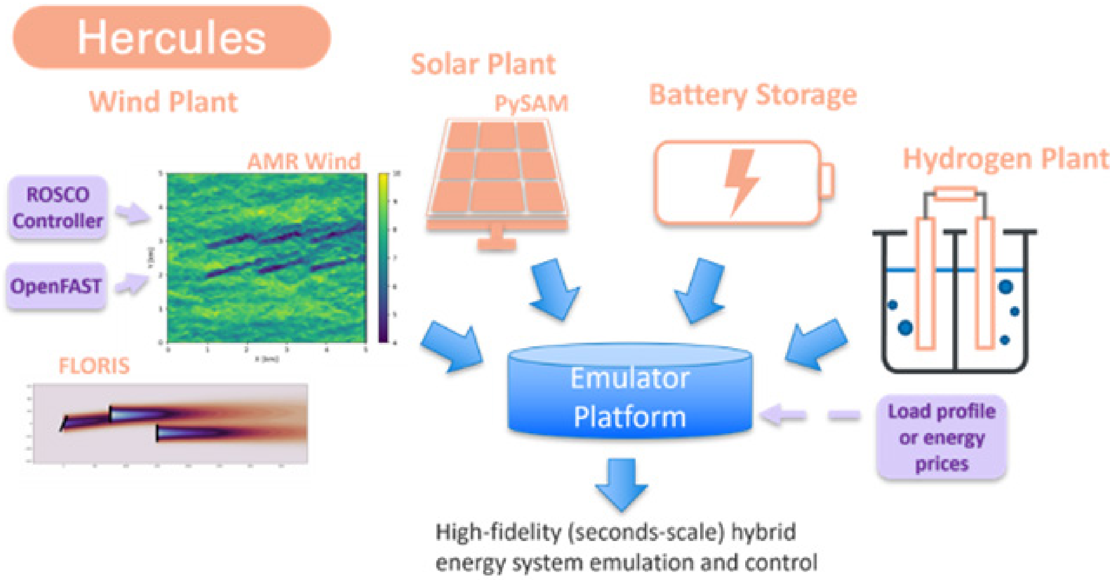


Comparison of rotor plane contours of ten-minute averaged normalized velocity (top) and turbulent kinetic energy (below) at 1D downstream distance for three different two-turbine configurations: 0 degrees, 26.6 degrees, and 45 degrees downstream angle (Graphic by Ken Brown).

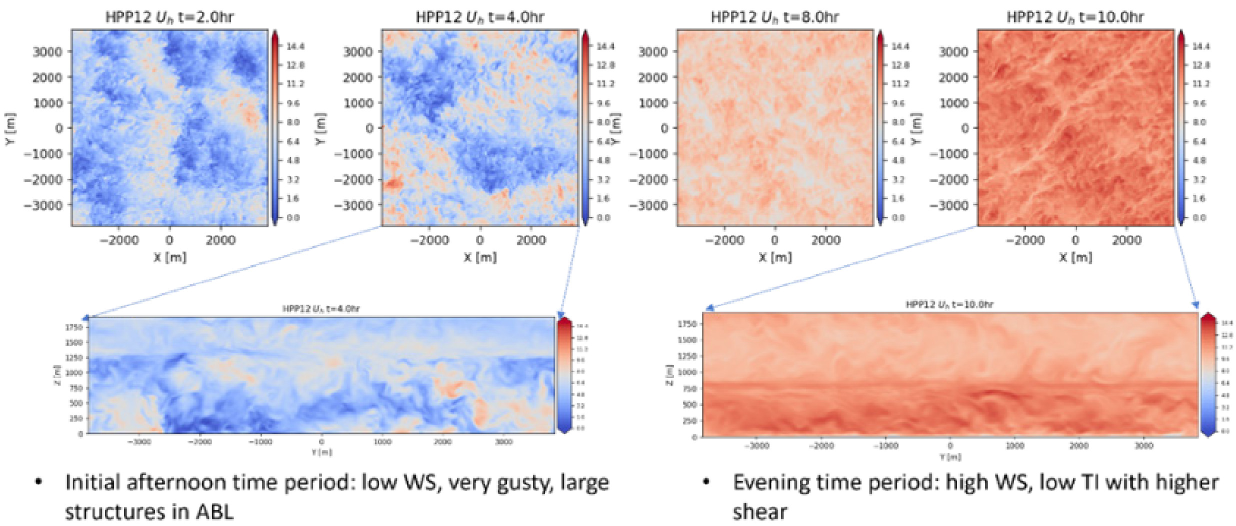
5.8 Path to Nationwide Deployment of Wind-based Hybrid Energy Systems

Working with NREL and Pacific Northwest National Laboratory (PNNL), Sandia contributed to the first demonstration of the new simulation tool, Hybrid Energy and Control Using Large Eddy Simulations (HERCULES), using a supervisory controller developed by PNNL and a reference hybrid power plant. The goal of this new code is to provide an efficient means of modeling the control and output of hybrid power plants.

To ensure testing under realistic conditions, the Sandia team sourced and filtered coupled wind and solar irradiance data to use as realistic inputs to the simulation. This process began by identifying the necessary measurements of atmospheric conditions, including wind speeds, temperature, surface heat flux, and solar irradiation, from an Atmospheric Radiation Measurement (ARM) facility in the central plains of the U.S. This facility realistically coupled inputs to synchronized simulations of a wind farm and a solar photovoltaic farm as if they were part of a co-located wind-solar-storage hybrid power plant. Sandia used measurements of wind speed and temperature over multiple heights as well as measurements of surface heat flux to create a meso-microscale coupled precursor to use as the inflow to a high-fidelity simulation of the wind throughout a large wind farm domain over an 8-hr period including a day-to-night transition. NREL used the precursor inflow to model a wind farm as part of the first demonstration of HERCULES using the PNNL-developed supervisory controller.



Schematic of the HERCULES hybrid plant emulator.



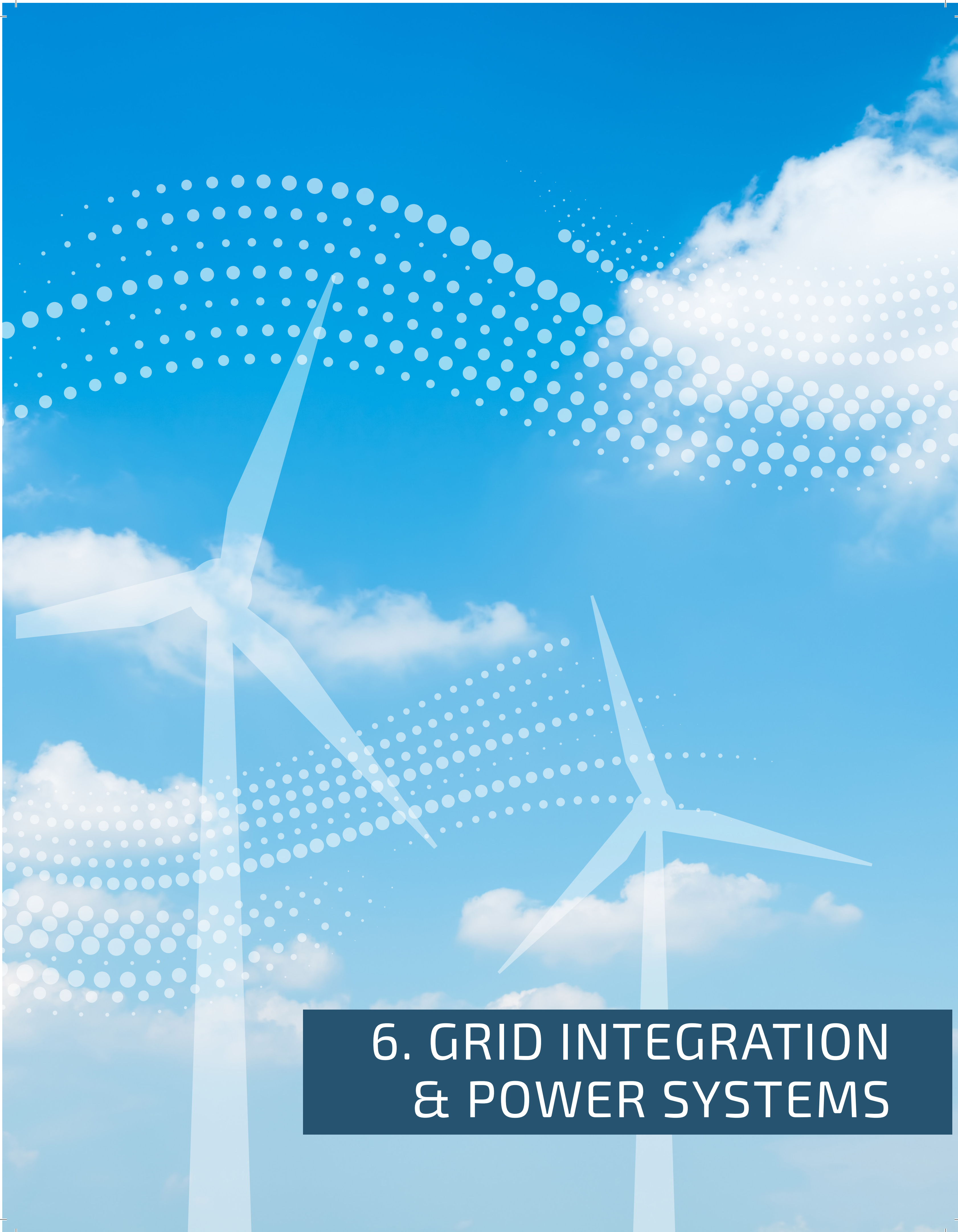
Images of the flow field from the meso-microscale coupled precursor developed at Sandia for the HERCULES demonstration (Graphics by Dan Houck).

5.9 Deep-Array Reduction of Wake-Induced Losses (DARWIN) Offshore Wind Turbine Controller

Sandia partnered with GE Vernova on the Deep-Array Reduction of Wake-Induced Losses (DARWIN) project. This investigation, funded through the DOE's Technology Commercialization Fund, has facilitated transfer of expertise in wake-modeling and control from Sandia to the U.S.'s largest wind-turbine Original Equipment Manufacturer (OEM). The project involves numerical experiments on wake-control technology applied to open-source and proprietary GE turbines. Selected results from this work were shared with the wind-energy community at the 2024 NAWEA Conference held in New Brunswick, NJ in October 2024.

5.10 Machine/reinforcement learning to teach coordinated controllers how to reduce wake losses

Finally, Sandia led an incubator project exploring the feasibility of leveraging machine/reinforcement learning to teach coordinated wind-turbine controllers how to reduce wake losses. Leveraging Sandia staff expertise in autonomous sensing and control, open-source reinforcement learning algorithms were trialed on wind plants using the dynamic wake meandering model FAST.Farm. Results from this ongoing work include determining the stability of convergence and the scaling as the number of wind turbines in the plant increases.



6. GRID INTEGRATION & POWER SYSTEMS

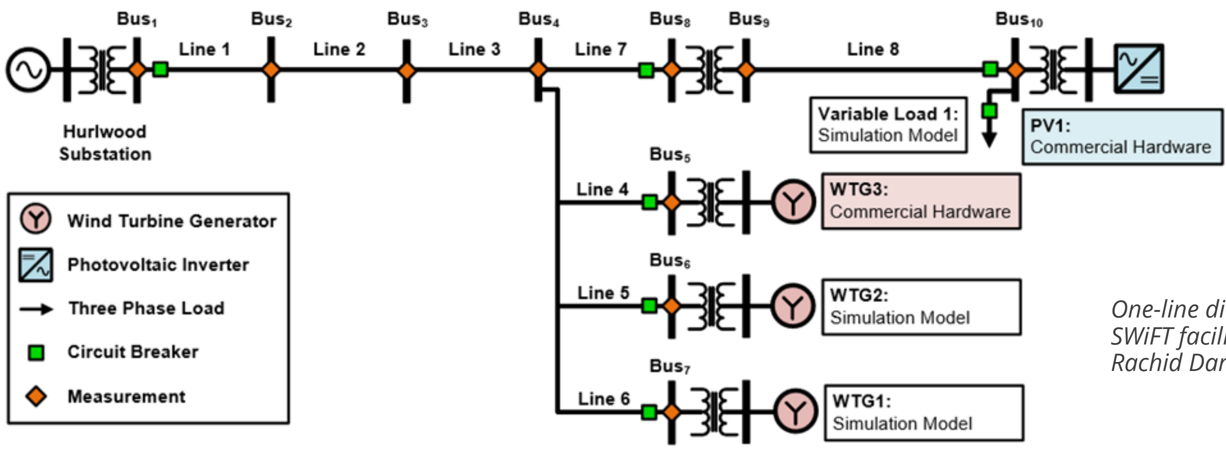
6. GRID INTEGRATION & POWER SYSTEMS

6.1 Wind Hybrid Interconnection Platform (WHIP)

Control, Optimization, and Coordination of Solar and Wind Distributed Energy Resources

Distributed Energy Resources (DERs) such as solar photovoltaic arrays and wind turbine generators continue to be installed in the U.S. The variable nature of DERs creates several challenges for utilities and system operators related to maintaining voltage and frequency. Power grids that incorporate a variety of distributed energy generation must be capable of maintaining system voltage in the allowable range against potential disturbances caused by load variations and variable renewable energy generation. Advances in grid support functionalities enable wind turbines to provide reactive power in order to provide voltage regulation. New grid standards are requiring DERs to provide voltage regulation across distribution networks. Volt-Var Curve (VVC) control is an autonomous grid-support function that provides voltage regulation based on the relationship between voltage and reactive power. However, VVC only provides voltage regulation at the point of DER interconnection, and regulating actions follow a pre-defined rule with little flexibility. Therefore, there is a need for data-driven control methods, such as those based on Reinforcement Learning (RL), which can leverage system-wide measured data, and provide a customized and adaptive solution for voltage regulation across the entire system.

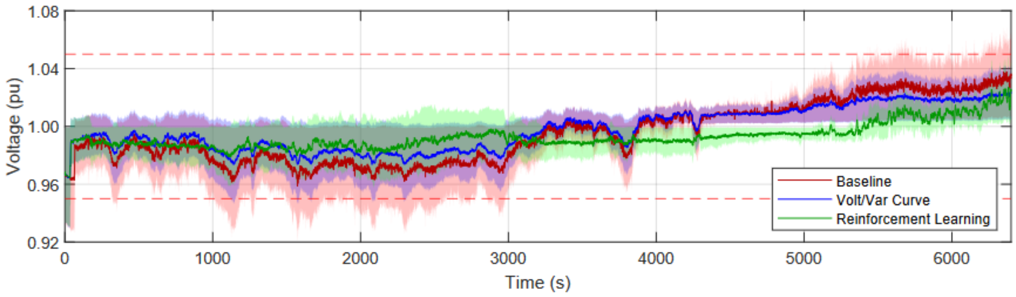
In this project, we assess the voltage regulation ability of a MARL-based controller in a hybrid system that includes wind and solar DERs. Each DER device is controlled by a separate RL agent. The goals are to optimize the voltage profile across a distribution feeder while ensuring consistency in neighboring agents' actions. The considered test case is a digital twin of a distribution grid in Lubbock, Texas. The training takes place in a simulated environment, and the performance is validated using commercial wind and solar inverters in a power hardware-in-the-loop platform. Reactive power setpoints are commanded to the inverters using commercial communication protocols. The simulations are conducted with variable wind speed, solar irradiation, and load profiles to demonstrate the robustness of the approach. The performance of the controller is compared to that of a traditional VVC. Experimental results using real DER hardware are more effective than other voltage regulation methodologies and demonstrate the suitability of the controller for field applications. The authors have previously explored the voltage regulation capabilities of wind turbines using data-driven controllers in a simulated environment, although this is the first time that it is demonstrated in hybrid systems and with real hardware equipment and commercial communication protocols. The power system used in this work represents the Scaled Wind Farm Technology (SWiFT) facility located in Lubbock, Texas. The following illustrates the one-line diagram of the SWiFT facility distribution system.



One-line diagram of the SWiFT facility (Graphic by Rachid Darbali).

The following figure provides a comparative analysis of the system voltage profiles under the three control strategies. The shaded regions in the figure represent the maximum and minimum nodal voltages across the system, while the solid lines denote the average system voltage. The RL controller exhibits three key advantages:

- maintaining system-wide voltages closer to the nominal value of 1 pu,
- significantly reducing the range between the maximum and minimum nodal voltages, and
- effectively mitigating abrupt voltage swings caused by rapid generation variations.



Experimental results comparison for SWiFT facility system voltage (Graphic by Rachid Darbali).

6.2 Wind Interconnection Standards Platform (WISP)

The WISP project is focused on developing a platform that will facilitate the certification and re-certification of distributed wind power converters, reduce costs and execution time for distributed wind installations, and ultimately increase the adoption of distributed wind technology. Sandia is working with DERSec to develop the WISP tool that will accelerate the maturation of IEEE 1547-2018 standard compliance testing and provide a "plug and play" solution that will accelerate the development of distributed wind power converters.

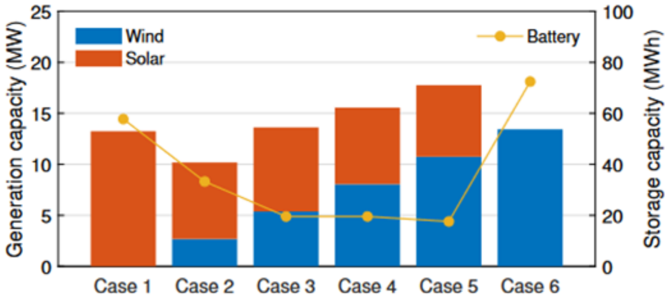
For Fiscal Year 2024, the WISP project focused on developing institutional agreements, identifying the market and customers for the WISP outcomes, and starting the development of a Matlab/Simulink model of a distributed wind turbine and three-phase power converter that complies with voltage ride through, frequency ride through, volt-VAR control and frequency watt control as specified by IEEE 1547 standards. Partnerships were also established with the University of New Mexico and the University of Puerto Rico – Mayaguez.

Power converter provided by Windurance (Photo by Rachid Darbali).

6.3 An Assessment of Wind-Hybrid Microgrids in Puerto Rico Using Microgrid Design Toolkit

In recent years, Puerto Rico has struggled with unreliable power supply and frequent blackouts. The island's vulnerability to natural disasters, due to its isolation from any mainland grid, highlights the need for resilient and reliable energy solutions. Microgrids have emerged as a promising solution for rural communities in Puerto Rico, helping to enhance grid resilience and reliability. Wind energy generation can be a suitable resource for microgrids, as it diversifies sources of electricity generation and decentralizes power production. This work focuses on the integration of wind turbine generators into a microgrid consisting of photovoltaic systems and an energy storage system (ESS). For this microgrid analysis, the Microgrid Design Toolkit (MDT) is utilized. The MDT is a decision support software tool aimed to assist microgrid designers in the initial stages of the design process. It helps users find the optimal settings for a microgrid based on the desired optimization objectives. Several MDT analyses have been conducted for various communities in Puerto Rico, as documented in the literature. However, these studies primarily considered diesel generators, solar energy, and energy storage, without evaluating the potential of distributed wind energy. The contributions of this work are as follows: 1) assessing the renewable resources, specifically wind and solar, in Puerto Rico; 2) conducting MDT analysis for microgrids based on wind, solar, and energy storage at selected candidate locations; and 3) providing a preliminary understanding of integrating wind energy into microgrids across various locations.

Microgrid solutions were analyzed for eight locations with high wind resources. An example result for one location, Las Mareas, compared to the solar-only scenario reveals that the integration of wind resources results in a reduction in the required energy storage size, with Case 5 yielding the smallest battery size. Findings show that wind energy integration has the effect of reducing the required energy storage size in wind-abundant areas. The findings also indicate that mixed wind and solar cases effectively reduce required storage size compared to extreme cases relying on a single energy resource.



Microgrid solutions for Las Mareas at various wind integration levels, optimized targeting 100% energy availability (Graphic by Rachid Darbali).

6.4 Wind Farm Models for Transmission Fault Protection Studies

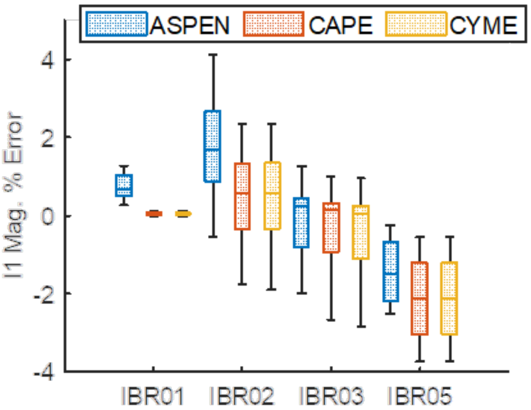
With increasing penetrations of inverter-based resources (IBR), the impact on existing power systems protection infrastructure is critically important. IBR (PV, energy storage, Type III and Type IV wind turbine generators) response to faults in the system is partially or fully controlled by the power 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 a collaborative effort with Siemens and Clemson University to develop advanced standardized phasor domain short circuit models of Type III and Type IV wind turbine generators 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 2024, we developed controls for a variable-speed doubly fed induction (Type-3) wind turbine generator with a fault response that complies with the new IEEE-2800 standard requirements. The model is conceived in electromagnetic transient (EMT) platform. The results showed that power electronic switching models produced the same results as average inverter control models during faults. Additionally, since wind farms comprise numerous machines, inverters, pad-mounted transformers, and collector cables, an aggregated farm equivalent model was proposed to avoid detailed EMT modeling of each component while maintaining accuracy in modeling the farm's fault response. While previous work had shown that this was true for Type I and Type II wind turbine generators, this was the first time the impact of the collector system had been shown for Type III fault results.

The updates have also been directly included into Siemens Gridscale X Advanced Protection Assessment, formerly known as PSS®CAPE, a commercial short circuit modeling software used by utilities. Several improvements include software algorithm options for faults that are remote from the wind turbine generator, Type III adding stator negative-sequence current and inverter side negative-sequence according to IEEE 2800, Type IV adding negative-sequence current controls based on IEEE 2800, and incorporating IBR into power flow solution.

An analysis of the ability for commercial short circuit software to represent inverter-based resources was performed. It showed that the voltage-controlled current source (VCCS) implementation is software allowed for accurate inverter-manufacturer specific models that did not provide negative sequence currents. With newer controls providing negative sequence current during faults, the positive sequence VCCS table is no longer applicable, and the generic converter interfaced models in short circuit software cannot be customized to the inverter. The VCCS tables are also not applicable for Type III wind turbine generators that provide negative sequence current.



Voltage-controlled current source (VCCS) model in commercial short circuit software provides highly accurate results for four different inverter-based resource (IBR) vendors (Graphic by Matt Reno).

6.5 Wind Weasel

Cybersecurity defenses play a critical role in maintaining reliable operation of our electrical grid. The Wind Weasel project is applying one of Sandia's intrusion detection concepts called Weasel Board to an industrial control system commonly found in wind turbines. The Weasel Board concept, detailed in patent number US 9,032,522 B1 "PLC Backplane Analyzer for Field Forensics and Intrusion Detection," has been applied successfully in defense-related applications and is now being tailored for wind energy cybersecurity research.

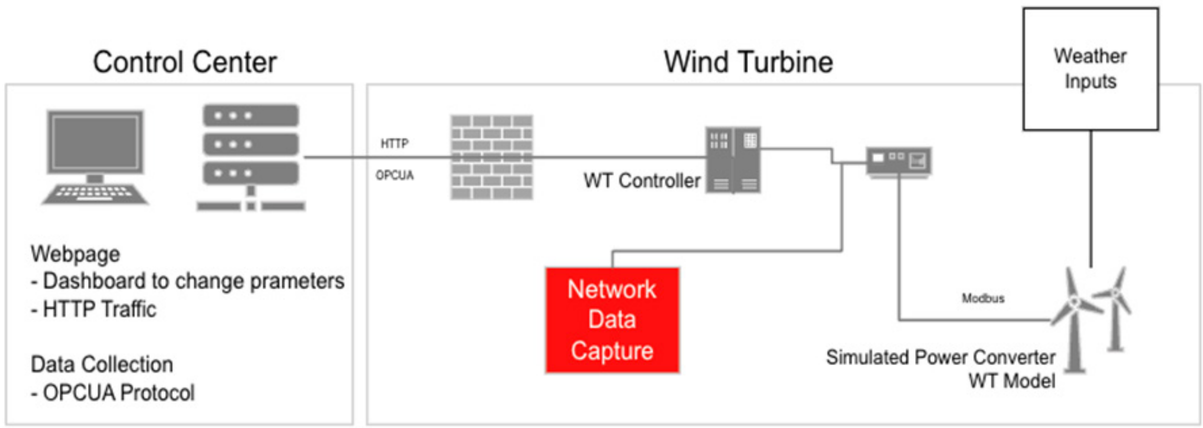
During Fiscal Year 2024, Sandia designed and fabricated a circuit board which will enable live capturing and monitoring of communication within a Bachmann M200-series Control System. All utility-scale wind turbines have a similar industrial control system (ICS) or programmable logic controller (PLC) that regulates the wind turbine's behavior. The Wind Weasel circuit board plugs into the control system's backplane which is the common communication channel between the central processing unit and physical devices such as pumps, brakes, motors, temperature sensors, fans, heaters, coolers, and of course the electric generator and power conversion system. With direct access to all communication between these components, Wind Weasel will be able to characterize normal wind turbine behavior and detect any deviations which might indicate a cybersecurity attack.

6.6 Machine Learning-Based Intrusion Detection Systems (IDS) for Wind Networks

Wind energy's widespread adoption is revolutionizing the power grid, leveraging advanced grid support capabilities and seamless communication between utilities and turbines. Advanced control features empower grid operators with enhanced capabilities, yet significantly broaden the power system's vulnerability to cyber-physical attacks. There are several locations in wind sites where network traffic could be analyzed to provide high-fidelity data and cyber-physical situation awareness on adversary actions, e.g., insider threats and false data injection attacks. However, the potential of harnessing this threat intelligence remains untapped as existing commercial solutions do not provide capabilities for high-dimensional analysis and cyber-physical data fusion solutions.

Sandia is leading the "Machine Learning-Based Intrusion Detection Systems for Wind Networks" project funded by the DOE Wind Energy Technologies Office that focuses on the development of a network intrusion detection system (NIDS) for a wind farm. Sandia, NREL and INL are creating an end-to-end, plug-n-play, physics-informed Machine Learning (ML) pipeline that spans from performing real-time deep packet inspection for different wind farms communication protocols, e.g., Modbus, OPC UA and EtherCat, to accurately identify instances of suspicious wind network activity and raising alerts. Multiple state-of-the-art ML models have been developed, such as Long Short-Term Memory-based Autoencoders and Isolation Forests for cyber-physical wind data fusion and threat detection.

The team published their initial machine learning development and evaluation work regarding an ML-based NIDS for wind farms to an early Fiscal Year 2025 conference. Additionally, a provisional patent was filed that describes the ML-based NIDS pipeline for cyber-physical analysis and threat detection. The pipeline is deployed and tested in several wind sites, including the Wind Turbine Emulator in the Distributed Energy Technologies Laboratory at Sandia as well as the GE 1.5 MW turbine at NREL's Flatirons campus.



Wind Turbine Emulator setup at Sandia (Graphic by Georgios Fragkos).

7. SOLUTIONS TO NATIONAL SECURITY TECHNOLOGY BARRIERS

7. SOLUTIONS TO NATIONAL SECURITY TECHNOLOGY BARRIERS

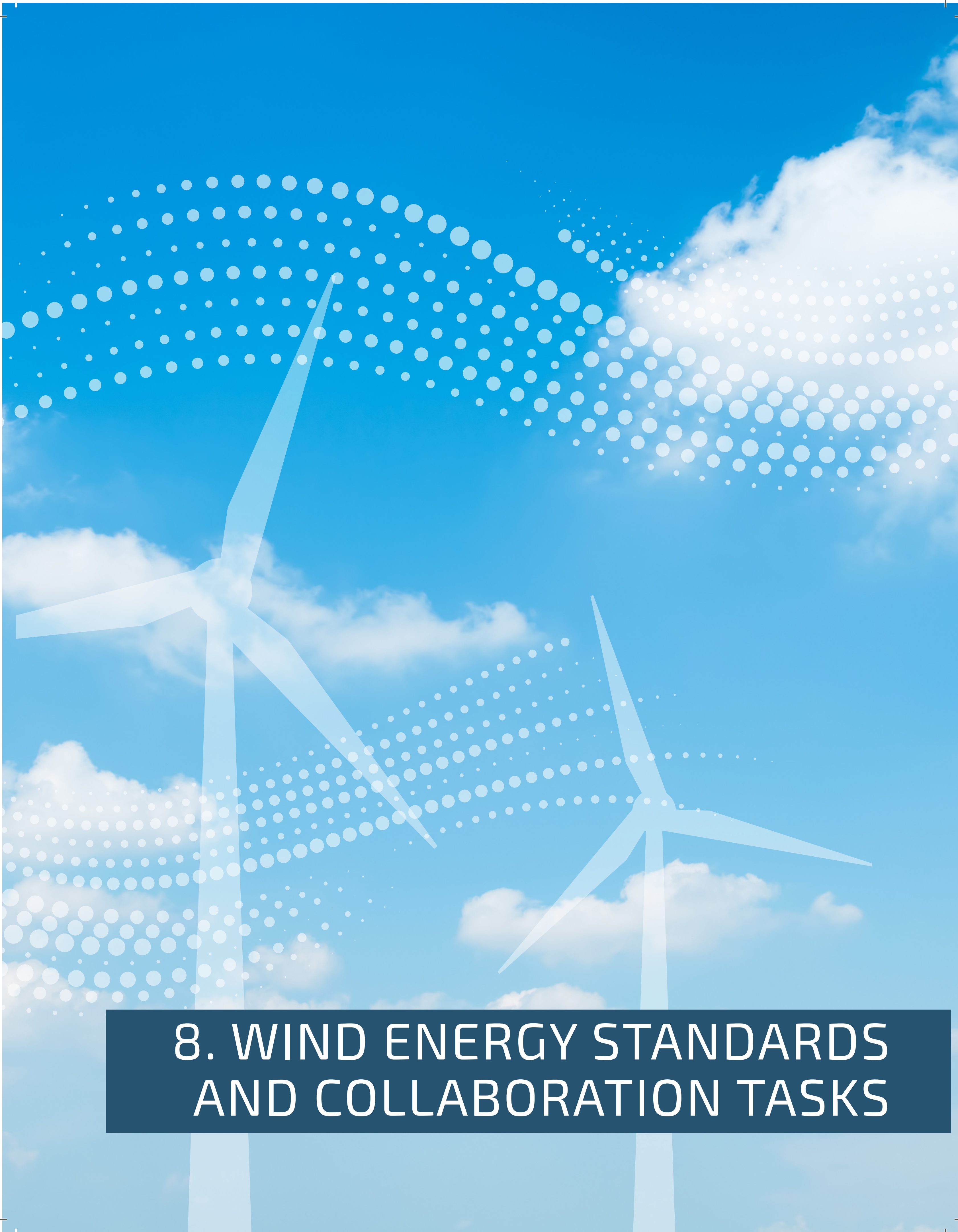
7.1 Wind Turbine Radar Interference Mitigation

Sandia continued its role as coordinator and facilitator of the Wind Turbine Radar Interference Mitigation (WTRIM) Working Group. The WTRIM Working Group includes representatives from the Department of Energy, the Department of Defense, the Federal Aviation Administration, the National Oceanic and Atmospheric Administration, and the Bureau of Ocean Energy Management and was established to encourage cooperation and coordination amongst these federal agencies to develop the means to mitigate impacts from wind turbines to radar systems and their missions.

In early Fiscal Year 2024, Sandia supported the DOE with their release of a Request for Information (RFI) regarding Challenges and Opportunities at the Interface of Wind Energy and Radar Technology (https://www.energy.gov/eere/wind/articles/doe-seeks-information-coexistence-wind-turbines-and-radar). This RFI sought information and input primarily on siting challenges of wind energy developers related to radar interference:

- Potential mitigation technologies at the radar and/or turbine level that currently exist or are in development to address wind turbine-radar interference;
- Commercialization and market adoption of wind-radar interference mitigation measures, and what obstacles need to be overcome to accelerate commercialization and maximize adoption;
- Effective solicitation process, Funding Opportunity Announcement (FOA) structure, and implementation strategies to enable the commercialization and market adoption of wind-radar interference mitigation measures.

Responses from the RFI were received in early 2024 from research institutions such as federally funded research and development companies, universities, non-profits, wind turbine manufacturers, wind farm developers and consultants, radar manufacturers, radar operators, and radar modeling and simulation companies. Responses varied from simple email replies to detailed mitigation techniques as well as general recommendations for the WTRIM WG.



8. WIND ENERGY STANDARDS AND COLLABORATION TASKS

8. WIND ENERGY STANDARDS AND COLLABORATION TASKS

8.1 IEC Standards

Sandia continued to lead the IEC 61400-5 Blade Design standard, which consists of over 40 contributors from 12 countries. This year, the committee completed Amendment 1, which improves upon the first edition of the standard that was released in 2020. Additionally, the committee began planning for work on drafting Edition 2, which will start in 2025. Sandia also contributed to IEC 61400-24 Lightning Protection, which is currently drafting Edition 3 of the standard, as well as IEC 61400-32, a new standard that is focused on Blade Operations and Maintenance. Sandia contributed to the upcoming 4th revision of the 61400-2 standard for small wind turbines, with a focus on helping to generalize the certification standard to encompass a broader range of concepts as well as providing specific guidance for VAWTs.

8.2 IEA Wind Task 43: Digitalization

Sandia is a member of IEA Task 43: Digitalization. This year, staff worked with other researchers from institutions in Europe to further develop a tool to predict the growth of erosion on wind turbine blades, and optimize inspections and repairs.

8.3 IEA Wind Task 46: Erosion of Blades

Research done as part of the leading edge erosion task under the Blade Durability and Damage project is aligned with IEA Task 46: Erosion of Blades, with staff managing two of the work packages on Atmospheric Effects and Operations with Erosion. The results of this work in Fiscal Year 2024 were studies on the impact of water droplet size on erosion and an analysis of erosion classification ratings, and benchmarking aerodynamic models used for predicting annual energy production loss due to erosion.

9. INTELLECTUAL PROPERTY

9. INTELLECTUAL PROPERTY

9.1 Patents Filed

SD16065: Cheung, L., K. Brown, D. Houck, N. deVelder, and C. Westergaard. "Systems, Methods, and Tools for Active Wake Control of Wind Turbines." US non-provisional patent application submitted 09/26/2024, Application No. 18/898,090; International Application filed 9/26/24, Application No. PCT/US24/48658.

SD16836: Ennis, B. L., R. E. Norris, R. J. Clarke, and E. Camarena. "Non-Circular Carbon Fiber for Cost-Specific Compressive Strength." US provisional patent application submitted 07/16/2024, Application No. 66/393,335 63/672,103.

SD16498: Ennis, B. L. and M. C. Devin. "Asymmetric Floating Platform Architectures for Off-Centered Loaded Platforms." US non-provisional patent application submitted 05/28/2024, Application No. 18/675,349; International Application filed 05/28/2024, Application No. PCT/US24/31218.

SD16661: Ennis, B. L., E. Huang, T. K. Das, and P. Krishnaswamy. "Integrated Drivetrain for Offshore Vertical-Axis Wind Turbines." US provisional patent application submitted December 2023, Application No. 63/606,650; International Application filed 12/5/24, Application No. PCT/US24/58654.

SD16834: Fragkos, G. "Machine Learning-Based Intrusion Detection Systems and Methods for Wind Networks." US provisional patent application submitted October 2024, Application No. 63/706,851.

9.2 Invention Disclosures

SD16914: Motes, G., and R. Clarke. "Wireless Dielectric and Fatigue Sensor." Disclosed 09/24/2024.

SD16848: Kelley, C. "Wind Turbine Concrete as a Collector of Heat Energy." Disclosed 06/26/2024.

SD16700: Ennis, B., R. Clark, and J. Paquette. "Fatigue resistant composite adhesive joint." Disclosed 01/11/2024.

SD16691: Kelly, C., T. Herges, A. Hsieh, K. Brown, D. Houck, and N. deVelder. "Method to create more accurate flow fields for simulations." Pursuing CR protections. Disclosed 01/02/2024.

9.3 Software Copyright

pyNuMad 1.0.0 Released October 19, 2023 - https://github.com/sandialabs/pyNuMAD/releases

SCR1617.1: Moore, K., B. Owens, and M. Devin. "Offshore Wind ENergy Simulation Toolkit (OWENS)." Commercial Version 1.0, updated 11/06/2024.

SCR1617.2: Moore, K., B. Owens, and M. Devin. "Offshore Wind ENergy Simulation Toolkit (OWENS)." Open Source version 1.0, disclosed 02/21/2024.

SCR3090.0: Maniaci, D., and C. Karcher. "Wind Turbine Airfoil Design Tools." Open Source; disclosed 8/15/24.

SCR30892.1: Kelley, C., T. Herges, K. Brown, D. Houck, and N. deVelder. "RAAW Assimilation of Inflow Data." Commercial Software; disclosed 8/15/24.

10. PUBLICATIONS

10. PUBLICATIONS

10.1 Journal Articles

Brown, K., P. Bortolotti, E. Branlard, M. Chetan, S. Dana, N. deVelder, P. Doubrawa, N. Hamilton, H. Ivanov, J. Jonkman, C. Kelley, and D. Zalkind. "One-to-one aeroservoelastic validation of operational loads and performance of a 2.8 MW wind turbine model in OpenFAST." Wind Energy Science (2024). https://doi.org/10.5194/wes-9-1791-2024

Brown, K., G. Yalla, L. Cheung, N. deVelder, D. Houck, J. Frederik, E. Simley, and P. Fleming. "Comparison of wind-farm control strategies under realistic offshore wind conditions: wake quantities of interest." Wind Energy Science (Forthcoming).

Camarena, E., E. Anderson, and K. Bonney. "Aeroelastic effects of adhesive bond lines." (In Review). https://doi.org/10.22541/au.170664377.77106999/v1

Cheung, L., K. Brown, P. Sakievich, N. deVelder, T. Herges, D. Houck, and A. Hsieh. "A Green's Function Wind Turbine Induction Model That Incorporates Complex Inflow Conditions." Wind Energy (2024). https://doi.org/10.1002/we.2956

Cheung, L. C., K. A. Brown, D. R. Houck, and N. B. deVelder. "Fluid-Dynamic Mechanisms Underlying Wind Turbine Wake Control with Strouhal-Timed Actuation." Energies (2024). https://doi.org/10.3390/en17040865

Cheung, L., G. Yalla, K. Brown, N. deVelder, A. Hsieh, T. Herges, D. Houck, D. Maniaci, P. Sakievich, and A. Abraham. "Modification of wind turbine wakes by large-scale, convective atmospheric boundary layer structures." J. Renewable Sustainable Energy (2024). https://doi.org/10.1063/5.0211722

Davis, O., G. Geraci, and M. Motamed. "Deep Learning Without Global Optimization by Random Fourier Neural Networks." SIAM Journal on Scientific Computing (2024). https://arxiv.org/abs/2407.11894

Fredrik, J., K. Brown, G. Yalla, L. Cheung, N. deVelder, D. Houck, E. Simley, and P. Fleming. "Comparison of wind-farm control strategies under realistic offshore wind conditions: turbine quantities of interest." Wind Energy Science (In Review). https://doi.org/10.5194/wes-2024-164

Fritz, E., C. Kelley, and K. Brown. "On optimizing the sensor spacing for pressure measurements on wind turbine airfoils spacing for pressure measurements on wind turbine airfoils." Wind Energy Science (2024). https://doi.org/10.5194/wes-9-1713-2024

Houchens, B. C., E. G. Sproul, J. C. Berg, P. G. Caserta, M. H. Hernandez, D. R. Houck, H. Lopez, D. C. Maniaci, G. Monroe, J. Paquette, S. Rodriguez, J. N. Tilles, N. B. deVelder, M. Williams, C. H. Westergaard, T. McIntosh, J. A. Payant, and K. Wetzel. "Techno-Economic Analysis of Additively-Manufactured Wind Turbine Blade Tips That Enable Technology Integration." Wind Energy (2024). https://doi.org/10.1002/we.2950

Houck, D., N. deVelder, D. Maniaci, and B. Houchens. "Method to predict the minimum measurement and experiment durations needed to achieve converged and significant results in a wind energy field experiment." Wind Energy Science (2024). https://doi.org/10.5194/wes-9-1189-2024

Houck, D. R., N. B. deVelder, D. C. Maniaci, and B. C. Houchens. "Method to predict the minimum measurement and experiment durations needed to achieve converged and significant results in a wind energy field experiment." Wind Energy Science (2024). https://doi.org/10.5194/wes-9-1189-2024

Hsieh, A., L. Cheung, M. Blaylock, K. Brown, D. Houck, T. Herges, N. deVelder, D. Maniaci, G. Yalla, P. Sakievich, W. Radunz, and B. Carmo. "Model Intercomparison of the ABL, Turbines, and Wakes Within the AWAKEN Wind Farms under Neutral Stability Conditions." Journal of Renewable and Sustainable Energy (In Review). https://pubs.aip.org/aip/jrse/article/17/2/023301/3338915/Model-intercomparison-of-the-ABL-turbines-and

Norris, R. E., B. L. Ennis, R. J. Clarke, D. A. Miller, D. D. Samborsky, F. Xiong and E. Camarena. "Initial Assessment of Alternative Carbon Fiber Geometries for Design of Cost-Effective Compressive Performance: Size Effect Studies." (In Review). https://doi.org/10.1016/j.compositesb.2025.112181

Rybchuk, A., L. A. Martinez-Tossas, S. Letizia, N. Hamilton, A. Scholbrock, E. Maric, D. R. Houck, T. G. Herges, N. B. deVelder, and P. Doubrawa. "Ensemble-based, large-eddy reconstruction of wind turbine inflow in a near-stationary atmospheric boundary layer through generative artificial intelligence." Wind Energy (In Review): https://arxiv.org/abs/2410.14024

Sproul, E. G., S. A. Khalifa and B. L. Ennis. "Environmental and Economic Assessment of Wind Turbine Blade Recycling Approaches. (In Review). https://doi.org/10.1021/acssusresmgt.4c00256

Yalla, G., K. Brown, L. Cheung, D. Houck, N. deVelder, and N. Hamilton. "Understanding power and load trade-offs of active wake control using spectral proper orthogonal decomposition." (In Preparation).

Yalla, G., K. Brown, L. Cheung, D. Houck, N. deVelder, and B. Jayaraman. "Actuation-induced entrainment dynamics simulated on a large-scale wind plant domain." (In Preparation).

10.2 Conference Papers and Proceedings

Anderson, E., M. Blaylock, R. Haluza, C. Seeley, and S. Bakhmatova. "Modeling and Validation of Bird Strike Impacts on Offshore Turbine Blades." NAWEA/WindTech 2024, New Brunswick, New Jersey, USA, Oct. 30-Nov. 1, 2024.

Anderson, E., M. Blaylock, S. Schneider, D. Johnston, S. Kramer, G. Chang, and L. Cheung. "Bird and Bat Collision Force Calculations for Blades of an Offshore Wind Turbine." NAWEA/WindTech 2024, New Brunswick, New Jersey, USA, Oct. 30-Nov. 1, 2024.

Bidram, A., M. J. Reno, T. Patel, D. J. Kelly, and Y. Alkraimeen. "Modeling of Inverter-Based Resources for Protection Studies Considering Momentary Cessation." IEEE Innovation Smart Grid Technologies Latin America, San Juan, Puerto Rico, Nov. 6-9, 2023.

Brown, K., L. Cheung, N. deVelder, T. Herges, A. Hsieh, M. Blaylock, G. Yalla, R. Knaus, D. Maniaci, and B. Hirth. "Estimating Uncertainties from Dual-Doppler Radar Measurements of Onshore Wind Plants Using LES." The Science of Making Torque from Wind, Florence, Italy, May 28-June 1, 2024. Journal of Physics: Conference Series. Vol. 2767. No. 9. IOP Publishing, 2024. https://doi.org/10.1088/1742-6596/2767/9/092111

Cheung, L., P. Mohan, K. Brown, and M. Henry de Frahan. "Data generation workflow for meso/microscale coupled offshore wind farm simulations." NAWEA/WindTech 2024, New Brunswick, New Jersey, USA, Oct. 30-Nov. 1, 2024.

Cheung, L., G. Yalla, P. Mohan, A. Hsieh, K. Brown, N. deVelder, D. Houck, and M. Henry de Frahan. "Modeling the effects of AWC on wake behavior through large scale coherent structures." NAWEA/WindTech 2024, New Brunswick, New Jersey, USA, Oct. 30-Nov. 1, 2024.

Cheung, L., K. Brown, G. Yalla, N. deVelder, T. Herges, A. Hsieh, D. Houck, M. Blaylock, and D. Maniaci. "Modification of inflow turbulence due to blockage effects." NAWEA/WindTech 2024, New Brunswick, New Jersey, USA, Oct. 30-Nov. 1, 2024.

Choi, J., J. E. Quiroz, R. T. Brito, R. Darbali-Zamora, E. E. Aponte-Bezares and M. S. Lave. "An Assessment of Wind-Hybrid Microgrids in Puerto Rico Using Microgrid Design Toolkit." 56th North American Power Symposium (NAPS), El Paso, Texas, USA, 2024. https://doi.org/10.1109/NAPS61145.2024.10741697

Davis, O., G. Geraci, and M. Motamed. “Deep Learning without global optimization by random Fourier features.” 18th Copper Mountain Conference on Iterative Methods, Copper Mountain, Colorado, USA, April 14-19, 2024.

Davis, O., G. Geraci, and M. Motamed. “Deep Learning without Global Optimization by Random Fourier Features.” Los Alamos National Laboratory workshop on Scale Bridging, Los Alamos, New Mexico, USA, April 26, 2024.

Davis, O., G. Geraci, and M. Motamed. “Surrogate modeling with Deep Random Fourier Features Residual Networks and Multi-Fidelity Information.” 16th World Congress on Computational Mechanics and 4th Pan American Congress on Computational Mechanics (WCCM 2024), Vancouver, Canada, July, 2024.

Fragkos, G., B. Jones, M. McCarty, V. Venkataramanan. “An Artificial Intelligent Intrusion Detection System for Wind Networks.” NAWEA/WindTech 2024, New Brunswick, New Jersey, USA, Oct. 30-Nov. 1, 2024.

Herges T., D. Houck, and C. Kelley. “Correlation of Blade Loading with Spinner Lidar Measured Inflow.” The Science of Making Torque from Wind, Florence, Italy, May 28-June 1, 2024. Journal of Physics: Conference Series. Vol. 2767. No. 4. IOP Publishing, 2024. https://doi.org/10.1088/1742-6596/2767/4/042039

Houchens, B., P. Caserta, M. Hernandez, D. Houck, D. Maniaci, J. Paquette, E. Sproul, J. Tilles, N. deVelder, M. Williams, C. Westergaard, J. Payant and K. Wetzel. “Design and Testing of an Additive Manufactured Tip for Wind Turbine Blades.” Sandia Blade Workshop, Albuquerque, New Mexico, USA, Sept.17-19, 2024.

Houchens, B., E. Lang and J. Gentle. “Development of an Airborne Wind Energy Testbed in the United States.” Airborne Wind Energy Conference, Madrid, Spain, April 25-26, 2024.

Houck, D., K. Brown, N. deVelder, P. Doubrawa, T. Herges, S. Letizia, and C. Kelley. “Validation of Inflow Creation Methods Using Data Assimilation Against SCADA Data: Trends from a field campaign.” NAWEA/WindTech 2024, New Brunswick, New Jersey, USA, Oct. 30-Nov. 1, 2024.

Hsieh, A., L. Cheung, M. Blaylock, T. Herges, D. Houck, K. Brown, W. Radunz, and B. Carmo. “Model Validation of the ABL, Turbine, and Wakes for AWAKEN Simulations under Neutral Stability Conditions.” NAWEA/WindTech 2024, New Brunswick, New Jersey, USA, Oct. 30-Nov. 1, 2024.

Kamala, S. R., J. Choi and R. Darbali-Zamora. “Unintentional Islanding Detection for Type-I Wind Turbine Generators Using Feeder Protection Relays: A Hardware-in-the-Loop Test.” 2024 56th North American Power Symposium (NAPS), El Paso, Texas, USA, 2024.

Moore, K. R., I. D. Brownstein, and H. K. Ross. “Critical design load case fatigue and ultimate failure simulation for a 10-m H-type vertical-axis wind turbine.” The Science of Making Torque from Wind, Florence, Italy, May 28-June 1, 2024. Journal of Physics: Conference Series, Vol. 2767, No. 7. IOP Publishing 2024. http://dx.doi.org/10.1088/1742-6596/2767/7/072025

Maniaci, D., R. Clarke, A. Reyna, R. Davies, A. Hsieh, and J. Paquette. “Measuring the Performance Impact of Erosion.” 5th International Symposium on Leading Edge Erosion of Wind Turbine Blades, Roskilde, Denmark, Feb. 6-8, 2024.

Maniaci, D., J. Naughton, S. Haupt, J. Jonkman, A. Robertson, M. Churchfield, N. Johnson, A. Hsieh, L. Cheung, T. Herges, and C. Kelley. “Offshore Wind Energy Validation Experiment Hierarchy.” The Science of Making Torque from Wind, Florence, Italy, May 28-June 1, 2024. Journal of Physics: Vol. 2767, No. 6. IOP Publishing 2024. http://dx.doi.org/10.1088/1742-6596/2767/6/062039

Mohazzem Hossain, S., T. Patel, S. Brahma, and M. J. Reno. “Modeling of Hybrid Farm in Grid Following and Grid Forming Modes for Short Circuit Studies.” IEEE Green Technologies Conference (GreenTech) Springdale, Arkansas, USA, April 3-5, 2024.

Moore, K., G. Bacelli, and K. Ruehl. "SYNERGIES Lightning Talks: Dispatchable Offshore Co-Gen Plants." SAND2024-06267PE.

Ojetola, S. T., T. R. Patel, S. Mohazzem Hossain, M. J. Reno, and S. Brahma. "Impact of Collector Network Aggregation of Solar and Type 4 Wind Farms for Short Circuit Studies." IEEE Green Technologies Conference (GreenTech) Springdale, Arkansas, USA, April 3-5, 2024.

Sproul, E. "United States Wind Turbine Blade Recycling Assessment." Sandia Blade Workshop, Albuquerque, New Mexico, USA, Sept. 17-19, 2024.

Williams, M., J. N. Tilles, D. Samborsky, and J. Paquette. "Understanding Effects of Multiple Lightning Strikes on Pultruded Carbon Fiber Wind Blades." International Conference on Lightning Protection, Dresden, Germany, Sept. 1-7, 2024.

Bagla, A., E. Camarena, and W. Yu. "Three-dimensional structural analysis of shell structures using MSG-based beam model." American Society for Composites 39th Annual Technical Conference, San Diego, California, USA, Oct. 21-24, 2024.

Yalla, G., "Understanding power and load trade-offs in active wake control." Sandia Blade Workshop, Albuquerque, New Mexico, USA, Sept. 17-19, 2024.

10.3 Reports

Anderson, E. M., A. G. Motes, E. G. Sproul, J. A. Paquette, and B. Mertz. "Investigation of an Intermittent Binary Control Strategy for Distributed Aerodynamic Control Devices for Load Alleviation in Wind Turbine Blades." SAND2024-03242, Sandia National Laboratories, Albuquerque, New Mexico, March 2024. https://www.osti.gov/biblio/2429999/

Cheng, Z., T. R. Patel, J. Holbach, and M. J. Reno. "Assessing Inverter-Based Resources Modeling Gaps in Commonly Used Short-Circuit Programs." SAND2024-13494, Sandia National Laboratories, Albuquerque, New Mexico, October 2024. https://doi.org/10.2172/2480122

Devin, M. C. "Anchoring Strategies for Marine Renewable Energy at the Sandia Water Impact Facility." SAND2024-01439, Sandia National Laboratories, Albuquerque, New Mexico, USA.

Ennis, B. L., R. Clarke, J. Paquette, R. E. Norris, S. Das, D. A. Miller, and D. D. Samborsky. "Optimized Carbon Fiber Composites in Wind Turbine Blade Design: Follow-On Studies." SAND2023-11080, Sandia National Laboratories, Albuquerque, New Mexico, October 2023. https://www.osti.gov/biblio/2430157/

Ennis, B. "ARCUS Vertical-Axis Wind Turbine Project Final Report." SAND2024-01431O, Sandia National Laboratories, Albuquerque, New Mexico, February 2024.

Herges, T. G., D. C. Maniaci, M. C. Debnath, R. M. Fao, N. M. Hamilton, R. Krishnamurthy, and J. W. Naughton. "Wind Energy Instrumentation Development Roadmap." SAND2024-14247, Sandia National Laboratories, Albuquerque, New Mexico, October 2024.

Herges, T., M. Blaylock, K. Brown, L. Cheung, N. deVelder, D. Houck, A. Hsieh, D. Maniaci, P. Sakievich, and G. Yalla. "High Performance Computing 2024 Annual report: AWAKEN the Wind." SAND2024-134970, Sandia National Laboratories, Albuquerque, New Mexico. https://www.sandia.gov/app/uploads/sites/165/2024/12/Sandia-HPC-Report-2024.pdf

Kamala, S. R., and M. J. Reno. "Impact of K-factor on Short Circuit Program Convergence for Inverter-Based Resources during Faults." SAND2024-15277, Sandia National Laboratories, Albuquerque, New Mexico, November 2024.

Muenz, U., S. Bhela, N. Xue, A. Banerjee, M. J. Reno, D. Kelly, E. Farantatos, A. Haddadi, D. Ramasubramanian, and A. Banaie. "Protection of 100% Inverter-dominated Power Systems with Grid-Forming Inverters and Protection Relays – Gap Analysis and Expert Interviews." SAND204-04848, Sandia National Laboratories, Albuquerque, New Mexico, April 2024.

Paquette J., M. Williams, R. Clarke, M. Devin, S. Sheng, C. Constant, C. Clarke, J. Fields, V. Gevorgian, M. Hall, J. Jonkman, J. Keller, A. Robertson, L. Sethuraman, and J. van Dam. "An Operations and Maintenance Roadmap for U.S. Offshore Wind – Enabling a Cost-Effective and Sustainable U.S. Offshore Wind Industry through Innovative Operations and Maintenance." United States Department of Energy, Office of Energy Efficiency and Renewable Energy, May 2024. https://www.energy.gov/sites/default/files/2024-05/operations-maintenance-roadmap-us-offshore-wind.pdf

Sandia
National
Laboratories

U.S. DEPARTMENT of ENERGY

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2025-13549R