Sandia National Laboratories

SANDIA WIND ENERGY PROGRAM

FY20 ACCOMPLISHMENTS

Geoffrey T. Klise, 08821 Department Manager

Prepared by Sandia National Laboratories
Albuquerque, New Mexico 87185
SAND2021-2508 O

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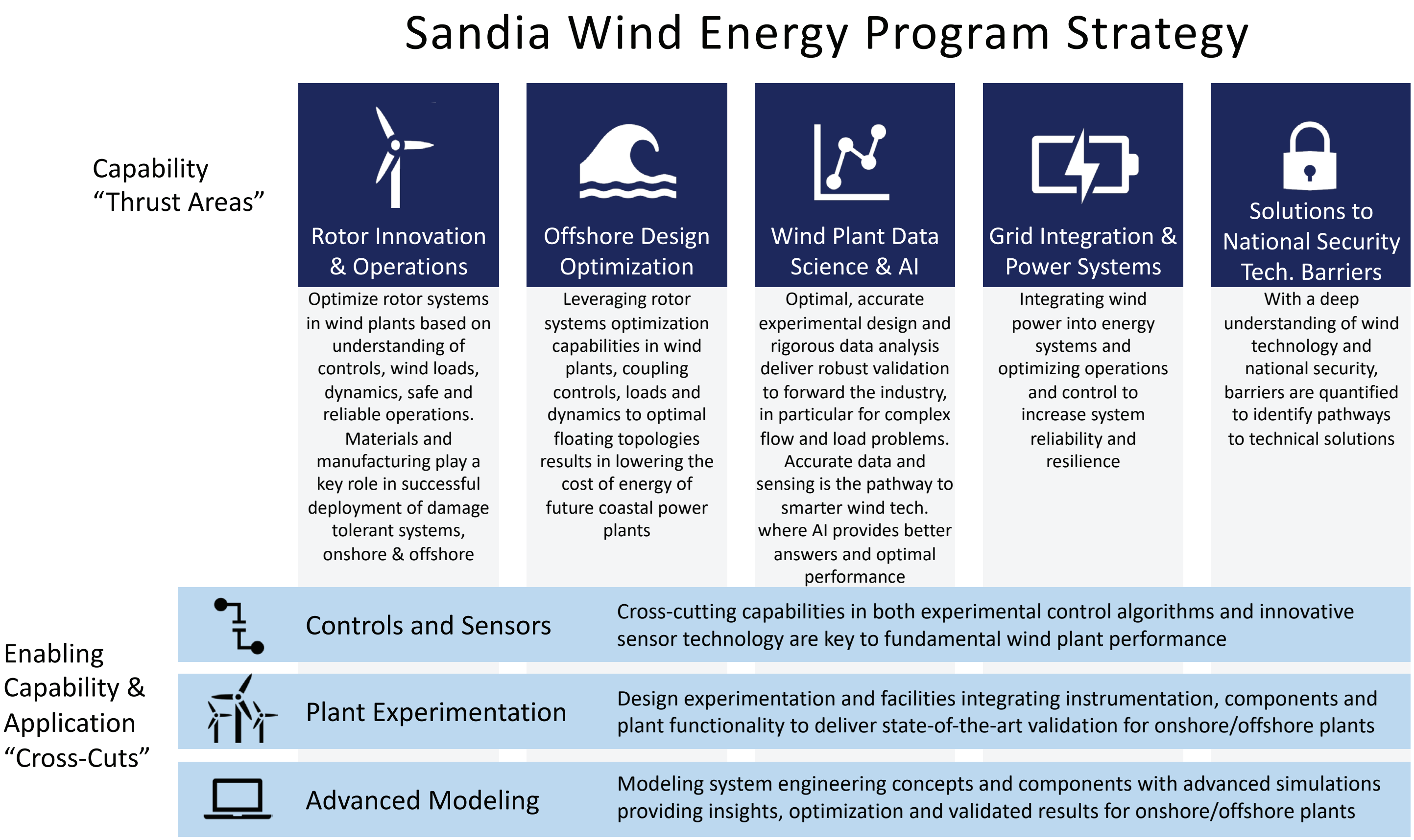
INTRODUCTION

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

This report summarizes Fiscal Year (FY) 2020 accomplishments from Sandia National Laboratories Wind Energy Program. The portfolio consists of funding provided by the DOE EERE Wind Energy Technologies Office (WETO), Advanced Research Projects Agency-Energy (ARPA-E), DOE Small Business Innovation Research (SBIR), and the Sandia Laboratory Directed Research and Development (LDRD) program. These accomplishments were made possible through capabilities investments by WETO, internal Sandia investment, and partnerships between Sandia and other national laboratories, universities and research institutions around the world.

Sandia's Wind Energy Program is primarily built around core capabilities, with 25 staff members leading and supporting R&D at the time of this report. Staff from other departments support the program by leveraging Sandia's unique capabilities in other disciplines.

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



Capability "Thrust Areas" and "Cross-Cuts"

CONTENTS

1. HIGHLIGHTS

1. HIGHLIGHTS

1.1. News Articles

Image Credit: U.S. Air Force photo/ Capt. Jason Goins

1.1.1. Report: Can deployable wind turbines decrease reliance on liquid fuels during military and disaster response?

https://energy.sandia.gov/report-can-deployable-wind-turbines-decrease-reliance-on-liquid-fuels-during-military-and-disaster-response/

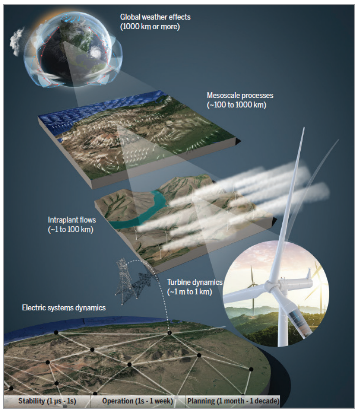
Sandia National Laboratories (Sandia), Idaho National Laboratory (INL) and the National Renewable Energy Laboratory (NREL) recently published a report assessing the opportunity for deployable wind energy systems to meet the energy needs of defense and disaster response activities. The report is the first public deliverable from the Defense and Disaster Deployable Turbine (D3T) project, funded through the distributed wind portfolio of the U.S. Department of Energy Wind Energy Technologies Office.

Image Credit: Getty Images

1.1.2. Sandia researchers identify commercial viability of carbon fiber composites for wind turbine blades

https://energy.sandia.gov/sandia-researchers-identify-commercial-viability-of-carbon-fiber-composites-for-wind-turbine-blades/

Researchers at Sandia, Oak Ridge National Laboratory (ORNL), and Montana State University recently completed a two-year study demonstrating the commercial viability of cost-competitive carbon fiber composites selected for use in wind turbine blades. Sandia researcher Brandon Ennis was among those presenting the final test results and project progress at the CompositesWorld 2019 Conference in Knoxville, TN., during a pre-conference seminar Tuesday, Nov. 19.



1.1.3. Sandia researcher part of international team challenging scientists to reach Wind Energy potential

https://energy.sandia.gov/sandia-researcher-part-of-international-team-challenging-scientists-to-reach-wind-energy-potential/

A new journal article published in Science, “Grand challenges in the science of wind energy,” invites researchers to confront certain challenges in hopes of driving innovation that will make wind energy the world’s primary source of low-cost electricity generation. Sandia’s Wind researcher Josh Paquette is part of the international team of scientists led by staff from NREL that produced this work.

Image Credit: NREL’s Josh Bauer and Besiki Kazaishvili

1.1.4 Wind program patent breathes new life into turbine siting

https://energy.sandia.gov/wind-program-patent-breathes-new-life-into-turbine-siting/

Sandia researchers Chris Kelley and David Maniaci and former Sandian Brian R. Resor have developed a wind turbine blade design that would allow for the closer placement of turbines, thanks to a faster dissipating wake.

Image Credit: Sandia, Chris Kelley

1.2. Meetings, Workshops, Webinars

1.2.1. Offshore Wind Turbine Radar Interference Mitigation Technical Interchange Webinars and Targeted R&D Meetings

As part of DOE's role in the Wind Turbine-Radar Interference Mitigation (WTRIM) Working Group, Sandia coordinated and facilitated a series of webinars that focused on offshore wind development and the potential impact to various radar systems.

The purpose of these webinars was to facilitate an exchange of information between the offshore wind industry, radar experts, and federal agencies to discuss research needs for offshore wind development that may impact sensitive radar systems. The goals of these technical interchange meetings include building relationships between key industry stakeholders and agencies around offshore wind-radar issues, obtaining government and industry perspectives on potential impacts of offshore wind on radar missions, as well as obtaining a better understanding of the future direction of the offshore wind market.

Six publicly announced webinars were held via GoToWebinar that addressed various aspects of offshore wind turbine development and its potential impacts to radar systems.

- Offshore WTRIM Working Group Priorities and EU/UK Perspectives
- US Offshore Project Review and Approval Process
- Marine Navigation Radar Systems
- Oceanographic High Frequency Radar Systems
- Air Traffic Control Terminal Radar Systems
- Long-Range Radar Systems
- These webinars are available online at: https://www.energy.gov/eere/wind/articles/offshore-wind-turbine-radar-interference-mitigation-webinar-series

1.2.2. US Patent and Trademark Office Tech Fair 2020

Chris Kelley presented on Wind Turbine R&D at Sandia National Laboratories to hundreds of patent examiners at the virtual 2020 US Patent and Trademark Office (USPTO) Tech Fair. This presentation provided a primer on wind turbine aerodynamic design topics, such as low specific power, low induction rotor design, and low cost carbon fiber.

1.2.3. Evaluation of Novel, Low-Cost Carbon Fiber Materials for Use in Wind Turbine Blade Design

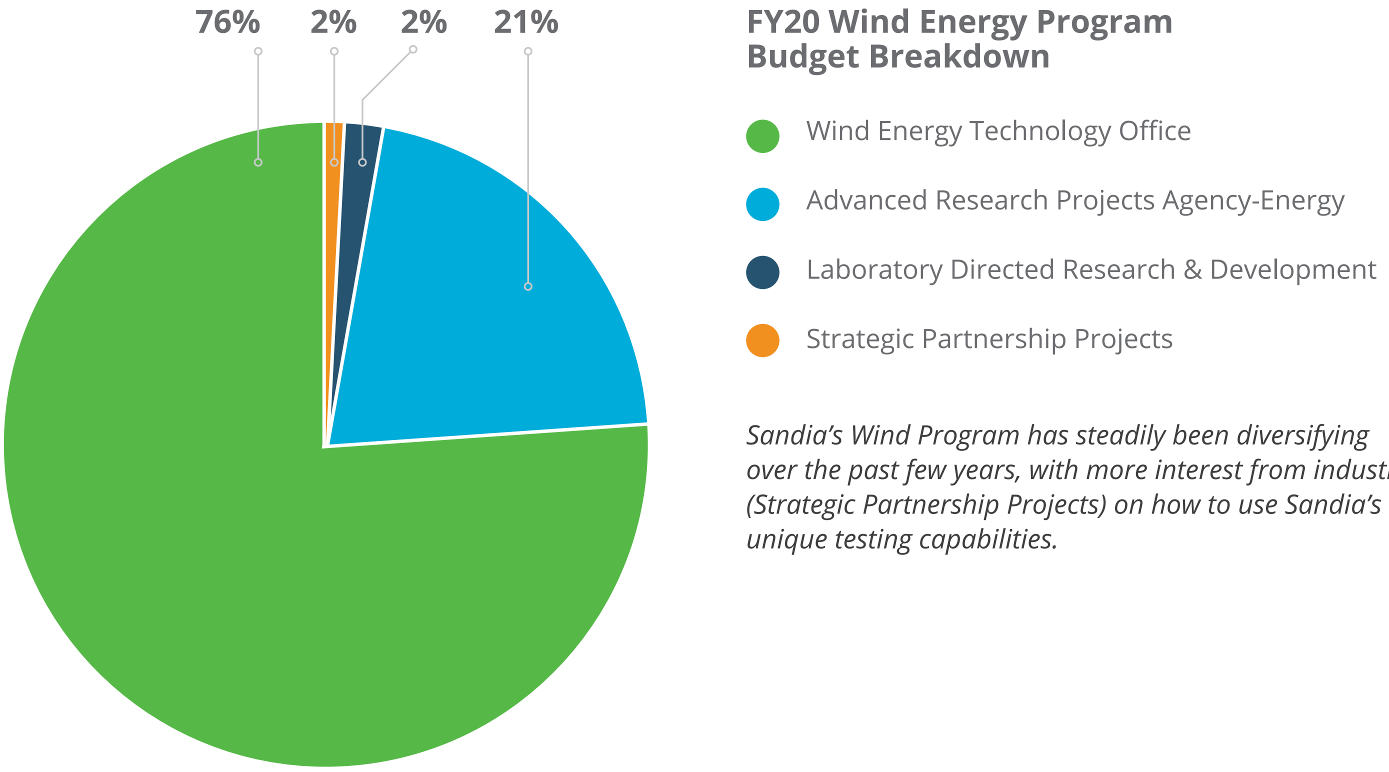
Brandon Ennis, Bob Norris, Sujit Das and David Miller presented *Evaluation of Novel, Low-Cost Carbon Fiber Materials for use in Wind Turbine Blade Design,* during a Pre-Conference Seminar at the Carbon Fiber Conference 2019, in Knoxville, TN.

To learn more, see section 1.1.2 or visit Evaluation of Novel, Low-Cost Carbon Fiber Materials for use in Wind Turbine Blade Design.

1.2.4. IEA Topical Experts Meeting #98: Erosion of Wind Turbine Blades

Sandia researchers David Maniaci and Josh Paquette presented on *Turbine Blade Design* during the IEA Topical Experts Meeting #98: Erosion of Wind Turbines Blades in a workshop organized with VTT (Finland) and DTU (Denmark), in Roskilde, Denmark in February 2020.

1.3. Funding



Sandia's Wind Program has steadily been diversifying over the past few years, with more interest from industry (Strategic Partnership Projects) on how to use Sandia's unique testing capabilities.

2. SWIFT FACILITY

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The Sandia team supported the lift and installation of the National Rotor Testbed (NRT) Rotor onto the Scaled Wind Farm Technology (SWiFT) Turbine A1 in July 2020 in Lubbock, TX. This coordinated event was preceded by several months of planning, which included the development of a new rotor installation procedure and accompanying job safety analysis (JSA) document in partnership with Sandia safety engineering and other subject matter experts (SMEs) at Sandia.

Lifting straps connected to the NRT rotor in preparation for the lift and installation onto SWiFT Turbine A1.

Due largely to the amount of effort and diligence that went into the planning, the lift and rotor installation took little time to complete, using two heavy lift mobile cranes provided by a local vendor and SWiFT partner, Marks Cranes. The SWiFT Facility site team then performed all necessary installations and connections of the NRT data acquisition (DAQ) system and integration with the turbine which, when combined with the SWiFT meteorological (MET) A tower instrumentation, began to produce high quality data immediately.

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

Fully assembled SWiFT Turbine A1 with the NRT Rotor.

SWiFT site personnel with Sandia safety engineering inside manlift basket preparing to remove the lifting straps from the NRT rotor following installation onto SWiFT Turbine A1.

2.1. GLEAMM Microgrid Connection

Sandia partnered with Texas Tech University (TTU) and Group NIRE to design and begin construction on a power and communications intertie between the SWiFT facility and the nearby TTU Global Laboratory for Energy Asset Management and Manufacturing (GLEAMM) microgrid assets. Once completed, this connection will allow the SWiFT wind turbines and the GLEAMM microgrid assets to operate together either in a grid-connected configuration or to disconnect from the grid and operate in an islanded mode. The communication between two systems will make it possible for a microgrid dispatch controller located at the GLEAMM site to send control signals to the wind turbines, photovoltaic arrays, batteries, and controllable loads to balance the power generation and load consumption of the system.

The system will be highly reconfigurable to explore a variety of ways to operate the power system for various objectives including improving power quality on power grids and operational strategies to integrate more distributed energy resources on local grids for the benefit of consumers. The power line has been trenched between the SWiFT site and the GLEAMM microgrid and initial components like an isolation switch have been installed with other major components such as transformers on order. The electrical connection will be completed in Fiscal Year 2021.

GLEAMM Site at left and SWiFT turbines at right.

3. ROTOR INNOVATION & OPERATIONS

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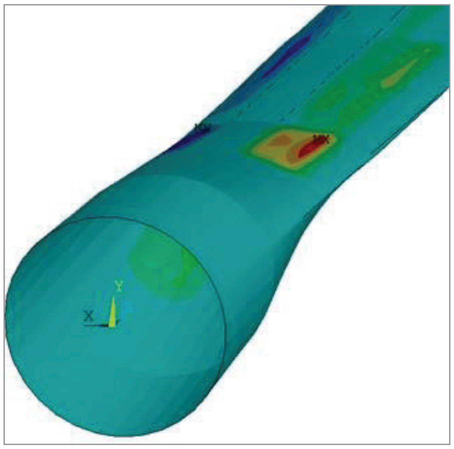
3.1. Rotor Wake

In Fiscal Year 2020, the Rotor Wake Project successfully installed the NRT rotor at the SWiFT facility in Lubbock, TX. The installation was a culmination of a scaled wake rotor design, manufacturing in ORNL's 3D printed mold, design load case simulations, debris throw analysis, root remediation to overcome manufacturing defects, and a safe rotor lift. The Rotor Wake project advanced state of the art aerodynamic blade design for higher capacity factor turbines, and reduced land/sea lease areas for small wake rotor designs. The NRT rotor was installed July 2020 after a successful, safe lift during the COVID-19 pandemic. The rotor is now undergoing commissioning tests to begin the NRT design verification experiment. The NRT rotor is collecting data from all 3 blades including distributed strain, temperature, and acceleration. ATA Engineering visited and successfully conducted modal testing to ensure there are no vibration issues. The NRT blade design documentation has also been released publicly including an aeroelastic model, manufacturing drawings, and blade instrumentation for collaboration and validation efforts within DOE. https://github.com/ckelley2/NRT

US Patent 10,400,743 was issued in 2019, and in Fiscal Year 2020, a DOE Technology Transfer Opportunity was announced specifically for small businesses to apply to license and commercialize this technology developed in the Rotor Wake Project. This patent outlines a rotor design that can reduce sea/land area needed for wind farms, which can lead to lower capital costs.

Data collected at SWiFT during a past wake steering experiment has been used in an international benchmark as part of the IEA Task 31. Researchers used the time-correlated wind turbine performance, blade sensors, and wake measurements to validate their codes' performance. The benchmark was published in the *Wind Energy* journal by Doubrawa et al., *Multimodel validation of single wakes in neutral and stratified atmospheric conditions,* Volume 23, Issue 11, 2020.

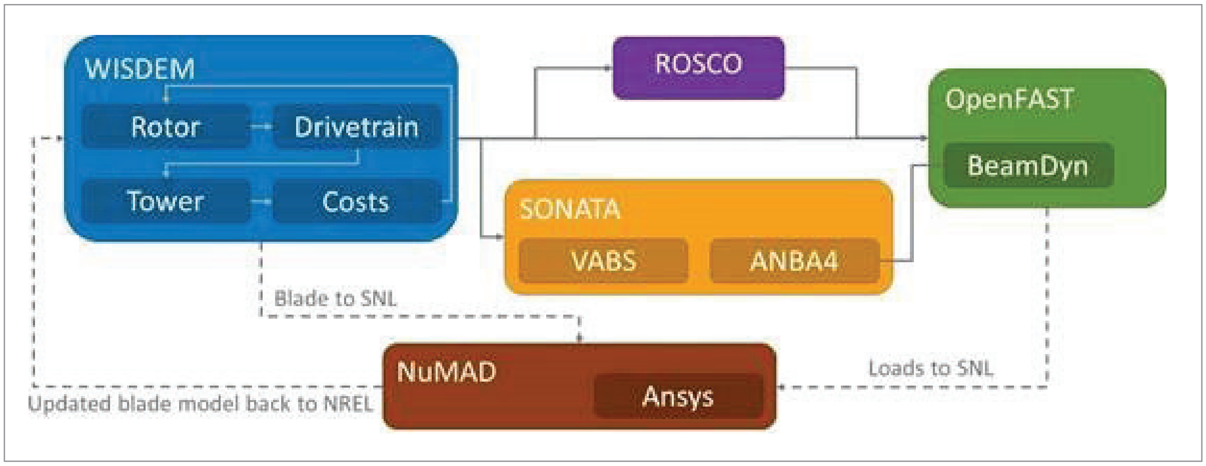


Finite element analysis showing the strain inside a BAR blade design.

3.2. Big Adaptive Rotor

The Sandia-led Big Adaptive Rotor (BAR) project seeks to identify needed technology and science required to build the next generation of high energy capture rotors. Along with partners NREL, ORNL, and Lawrence Berkeley National Laboratory (LBNL), the project has discovered the market potential of such machines, designed multiple open-source reference models, and analyzed a multitude of potential innovations that can bring these future machines to market.

Recently, the focus of the project has been on the development of multiple variations of a 5MW turbine with 100m blades. Blades of this size would allow for deployment of wind in a much greater portion of the United States and allow machines to produce more consistent power across all wind speeds. However, these blades are not transportable using current design and manufacturing methods. To address this, the team has investigated highly flexible blades that can deflect during transport. Highly flexible blades, while light and transportable bring with them load, deflection, and controls challenges. Several solutions to these challenges have been investigated, including downwind machine configurations, novel carbon fiber materials, and advanced blade control systems. The NREL aeroelastic simulation tool OpenFAST and system optimizer WISDEM have been upgraded with more sophisticated aerodynamic and controls modules, while the Sandia structural design and optimization code NuMAD has been updated to perform detailed load simulations and determine the most efficient designs possible. Over the past year, the project has produced four journal articles on the topics of nacelle blockage, distributed aerodynamic controls, rail-transportable blades, and flutter.



Integrated Rotor Design Tools. *Image Credit: NREL, Bortolotti*

3.3. Arctura [ARPA-E]

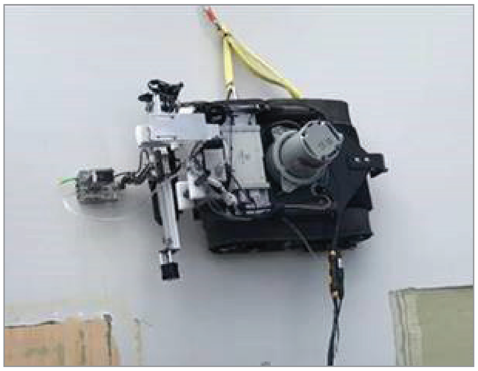
In Fiscal Year 2020, Sandia contributed in a few areas to the active aerodynamics project using plasma actuators with small business partner Arctura, the University of Texas at Dallas, and TPI Composites. Wind energy department staff performed detailed blade measurements with Sandia's metrology group. These measurements were then used by project partners to manufacture the wind tunnel model now being used to demonstrate the plasma actuator technology before being deployed for field testing at SWiFT. In addition, Sandia developed a test matrix for the field campaign ensuring enough data is collected at different wind speeds and fit within a 6-month window. This analysis was possible by leveraging existing work from a prior SWiFT Site Atmospheric Characterization report to know the probability of different wind speeds and turbulence levels at SWiFT. Sandia continues to work with project partners to integrate the necessary power electronics and wiring for the technology demonstrated in the field test.

3.4. Continuum Dynamics [SBIR]

The Continuum Dynamics SBIR project made progress in Fiscal Year 2020 towards developing the shape memory alloy active aerodynamic flaps. This year Sandia performed detailed blade measurements with its metrology group. These measurements of the blade geometry are now being used by partner TPI Composites to manufacture trailing edge sleeves which will fit precisely to the V27 blades to be tested at SWiFT.

3.5. Blade Reliability

The Sandia-led Wind Blade Durability and Damage Tolerance project is developing tools and experimental data sets to improve the reliability of wind blades. The work is divided into six tasks: inspection methods, effects of defects and repairs, blade life value modeling, lightning effects on carbon fiber, leading edge erosion, and damage accumulation monitoring. The inspection task produces tools and methods to find defects and damage in wind blades earlier and more accurately, both in the manufacturing plant and in the field.



Sandia ARROW(e) Inspection Robot. *Image Credit: Sandia, Dennis Roach*

The task has focused most recently on the development of an automated inspection robotic crawler that can be deployed from a wind turbine nacelle, attach to a blade, and complete a detailed inspection. The effects of defects and repairs task conducts experiments and develops analysis tools to understand how manufacturing defects impact wind blades and how damage can best be repaired. This work has recently led to publications on repair strength and damage-tolerant materials and structures. Lightning research looks at the impact of lightning strikes on the strength and fatigue resistance of carbon fiber materials that are increasingly used in wind blades. Recent experiments have exposed test coupons to 200 kA currents, representative of lightning strikes.

Leading edge erosion research has investigated the impact of erosion on turbine performance. A journal article was published on a model of performance impacts (David C. Maniaci et al. 2020 J. Phys.: Conf. Ser. **1618** 052082). Finally, damage accumulation monitoring seeks to develop methods to use common and innovative sensors to calculate the loads that a blade has undergone during operation. This will allow wind plant operators to optimize revenue production.

Carbon Fiber Lightning Testing. *Image Credit: Sandia, J. Tilles*

3.6. AeroMine [Sandia LDRD]

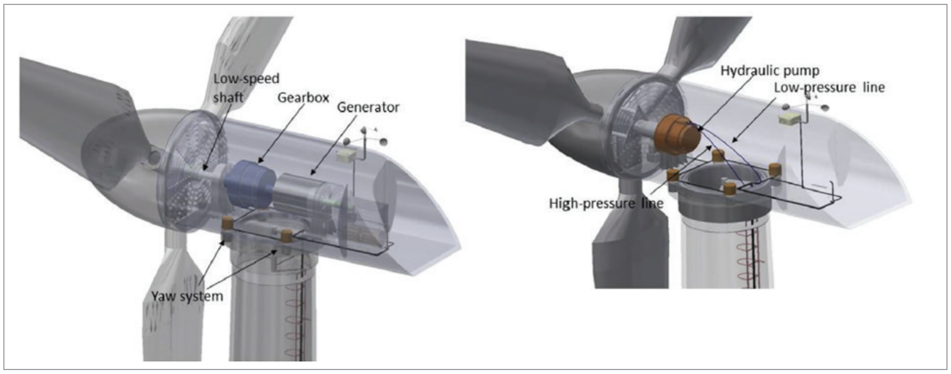
A pilot-scale (3 m tall) AeroMINE was built and tested at SWiFT in September 2020 as part of an LDRD-funded project. Major outcomes included the proof-of-concept at scale, and demonstration of negligible dependence to more than 30 degrees off-axis wind direction. A summer intern was hired to research optimal internal design, and an Academic Alliance partnership with the University of Illinois, Urbana-Champaign was initiated with Professor Andres Goza's group.

Arctic and Alaska engagement was furthered through exploration of the potential of AeroMINE as an alternative generation source for reducing diesel fuel to power remote DOE/DoD outposts. This includes potential icing testing on the North Slope and a potential collaboration with a St. Mary's, Alaska DOE-funded project.

Pilot-scale testing AeroMINE at SWiFT.
Image credit: Rebecca Gustaf

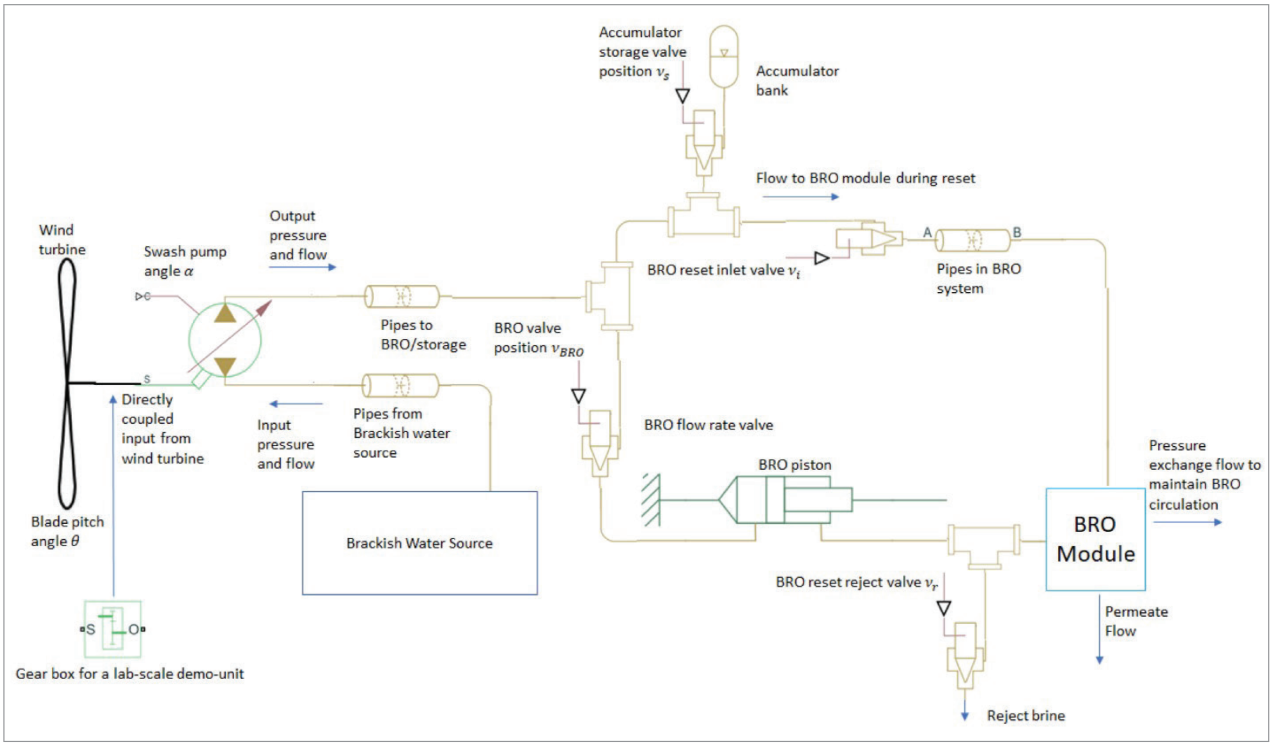
3.7. Hydraulic Wind Turbine [Sandia LDRD]

Sandia funded LDRD research into a hydraulic wind turbine concept in Fiscal Year 2020. This effort involves creation and simulation of a Hydraulic Wind Turbine (HWT) that pumps saline water into a reverse osmosis system for purification with no electric generator. The HWT uses a positive displacement hydraulic pump in place of a gear box and generator as illustrated below. This can reduce the total mass in the nacelle, potentially reduce maintenance costs, and eliminate need for a gear box. A hydraulic wind turbine can transmit energy in the form of pressurized fluid that can be used for electricity generation on the ground or for other processes. These advantages are greatest for utility scale (1-5MW) wind turbines. The associated high power, low speed hydraulic pump has not been created and must be designed and tested before utility HWT technology is feasible.



Conventional wind turbine (left) Hydraulic wind turbine (right). *Image Credit: Antonio Esquivel from Purdue University*

The direct use of mechanical energy can significantly increase energy efficiency and enable off-grid water desalination. A specialized reverse osmosis process called Batch Reverse Osmosis (BRO) has the potential to increase the energy efficiency even further. Such a system may meet DOE goals to create low-cost distributed water treatment technologies. A combined HWT-BRO system model as seen below is used to evaluate the energy efficiency achievable for the coupled dynamics of wind and reverse osmosis.



Combined HWT-BRO system with energy storage.

4. OFFSHORE DESIGN OPTIMIZATION

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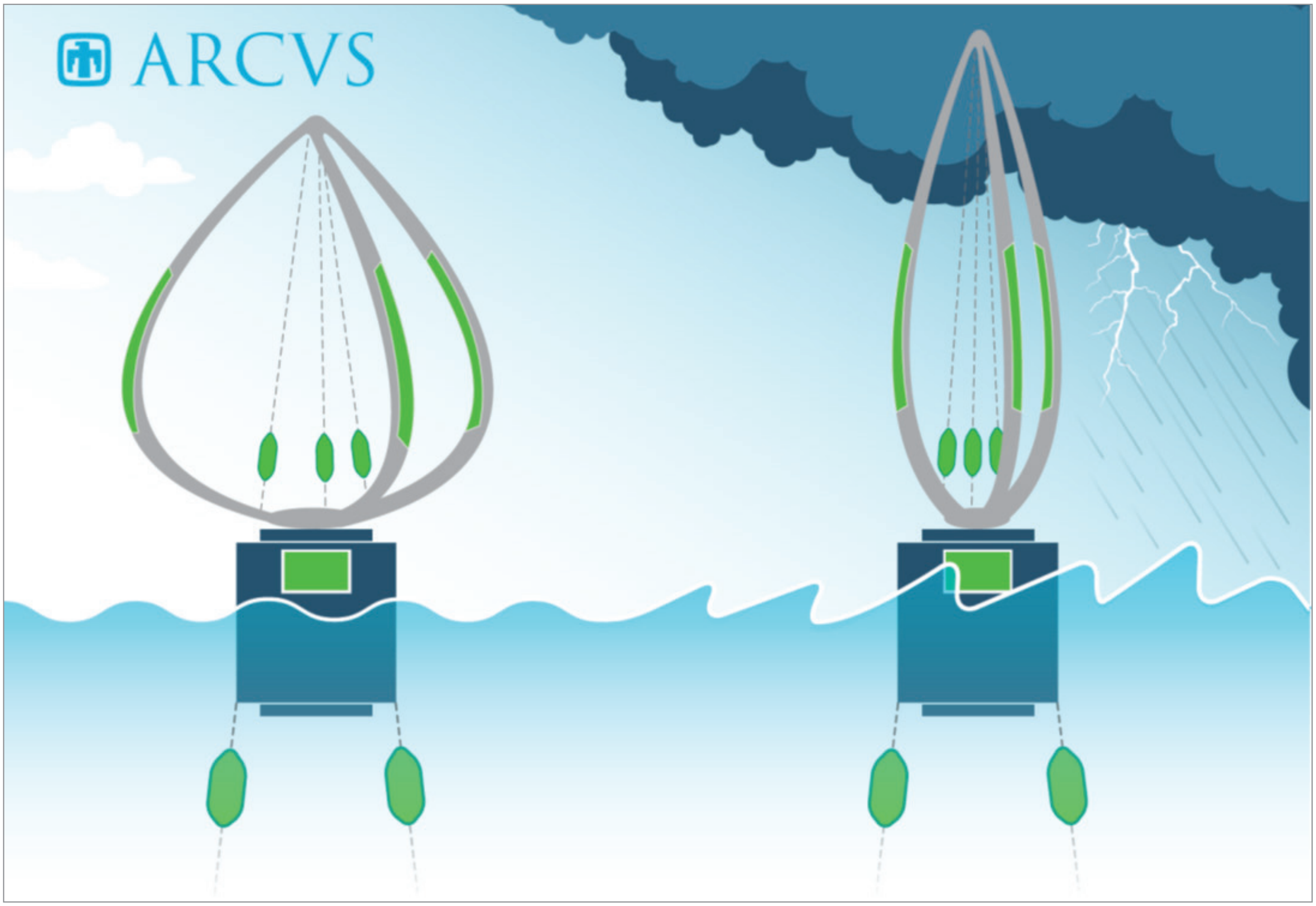


The ARCUS Darrieus VAWT has been designed by Sandia to address the high costs of floating offshore wind; patent-pending.

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

The Advanced Research Projects Agency-Energy (ARPA-E) has awarded Sandia and its partners a project within the ATLANTIS program to study a novel vertical-axis wind turbine (VAWT) designed using advanced optimization methods which optimize the full system concurrently, leveraging tradeoffs between system components and control methods. ARCUS is a Darrieus VAWT which removes the rigid tower and replaces it by using prestressed blades and much less massive tensioned guy wires. In the previous 5 MW VAWT studies at Sandia, the tower accounted for over 80% of the rotor mass. ARCUS results in an even lower tower top mass and roll/pitch mass moments of inertia than traditional VAWTs, greatly minimizing platform and system costs.

In the traditional approach to platform design, mass and inertia are used to ensure operational stability and reduce turbine motion, resulting in heavy and expensive platforms. Instead of designing the platform to eliminate the motion of the turbine, the project team will design the oscillating turbine-platform system to operate safely within a given frequency response. A very light platform and active mooring systems will control motion of the turbine to be within the design conditions.

ARCUS will enable this platform design and control approach, which will be less sensitive to platform motion than a horizontal axis wind turbine (HAWT). VAWTs have power performance and loads that are less sensitive to platform motion due to the vertical rotation and low center of gravity allowing for greater motions with less impact to power production or structural loads. The ARCUS turbine will be studied through designing the rotor, platform, and drivetrain concurrently using advanced control co-design methodologies developed within the project.

To satisfy project goals there are four main inter-related tasks for (1) analysis tool development, (2) detailed turbine and platform design, (3) system control co-design optimization, and (4) control design for physical implementation. The work within Fiscal Year 2020 has focused on the need for analysis capabilities for floating VAWTs across varying fidelity levels to enable the full system control co-design optimization studies, which are vastly more complex and computationally expensive than what is done currently. Some of the major accomplishments within the project for Fiscal Year 2020 include:

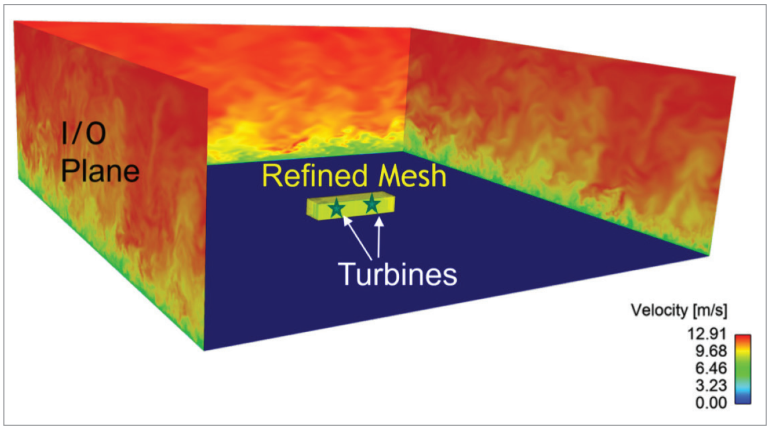
- Filing a non-provisional patent application for the towerless ARCUS design concept which enables shape morphing as a means of control in high winds and storm conditions
- Development of the Offshore Wind Energy Simulator (OWENS) multibody finite element code to capture the coupled physics for floating VAWTs and efficiently perform aero-hydro-servo-elastic design simulations
- Incorporation of the “Actuator Cylinder” and “Double Multiple Streamtube” aerodynamic models for VAWTs (equivalents to the Blade Element Momentum theory for HAWTs)
    - Development of a solution approach for the aerodynamic models termed the “Rotating Point Iterative” method which enables a 5-10x speedup with negligible changes in the solution accuracy
    - Identified model corrections to enable simulation of curved, deforming blades with solutions matching a higher-order aerodynamic model
- Incorporation of a boundary element method solver based on potential flow theory to calculate hydrodynamic forces on generic platform geometries, enabling optimization of the platform hull within the design studies
- Work has begun with commercial partner FPS Engineering and Technology to perform discrete studies to identify optimal hull configurations for the tension-leg platform to be optimized within the project
- A low-fidelity turbine-platform structural model has been developed that will be used for identifying optimal control pathways by performing optimization within the pseudo-spectral time domain including aerodynamic and hydrodynamic forcing
    - Rotor flexibility is being added to this dynamical model to enable higher level design constraints to be added within the future optimizations using this tool
- Work is ongoing between Sandia and NREL to couple OpenFAST modules InflowWind, HydroDyn, and MoorDyn to OWENS which will enable turbulent flow simulations and use of the verified open-source hydrodynamic solvers

5. WIND PLANT DATA SCIENCE & ARTIFICIAL INTELLIGENCE

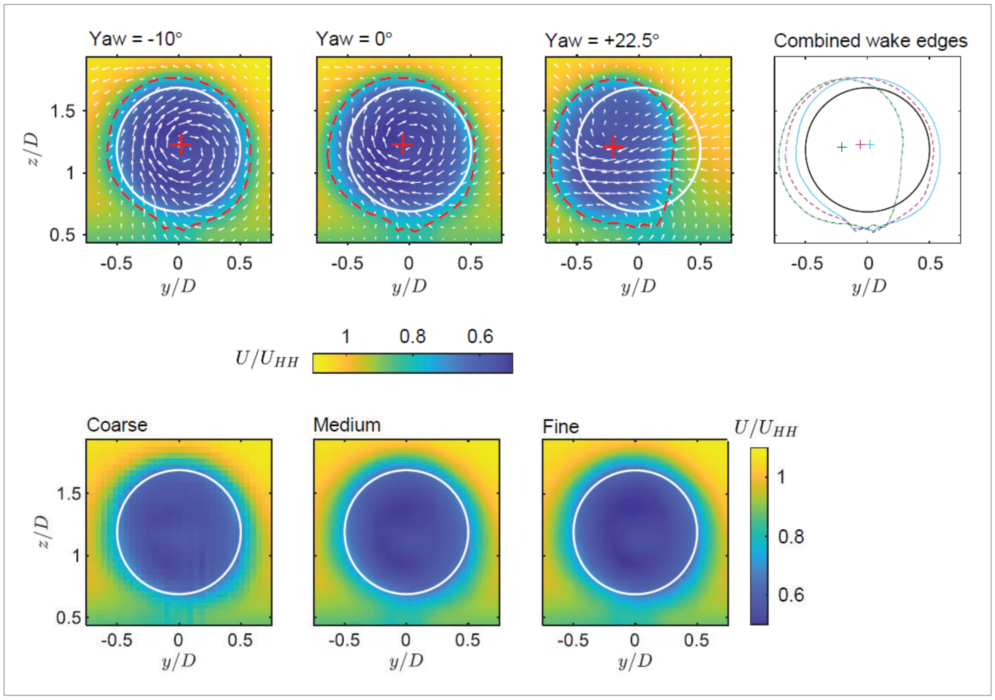
5. WIND PLANT DATA SCIENCE AND ARTIFICIAL INTELLIGENCE

5.1. Verification & Validation/Uncertainty Quantification

The Verification, Validation, and Uncertainty Quantification (V&V/UQ) project ensures that the predictive capability of the suite of computational models being developed across the Atmosphere to Electrons (A2e) program is established through formal verification, validation, and uncertainty quantification processes. Multi-million dollar decisions are made using computational models for wind energy applications; this project establishes the processes to build trust in these models. It is accomplishing this goal by coordinating validation activities across A2e, developing and applying formal V&V/UQ processes, and ensuring that any V&V gaps are addressed. Uncertainty Quantification (UQ) is critical for quantitative model validation focused on enabling predictive numerical simulations in research studies and advanced engineering design, as it codifies the assimilation of observational data; the characterization of errors, uncertainties, and model inadequacies; and forward predictions with confidence for untested / untestable regimes. In Fiscal Year 2020, the report *Wind Energy High Fidelity Model Verification and Validation Plan* was published, which gives a comprehensive assessment of model validation needs for wind energy and is being used as the basis for planning several large-scale validation experiments. The V&V/UQ team has also demonstrated several novel uncertainty quantification techniques on wind energy problems, including multilevel-multifidelity forward UQ of Nalu-Wind, multifidelity inverse UQ using the WindSE model, and multilevel optimization under uncertainty. Additionally, a validation study of Nalu-Wind was completed for wake deficit strength and deflection under neutral inflow conditions.



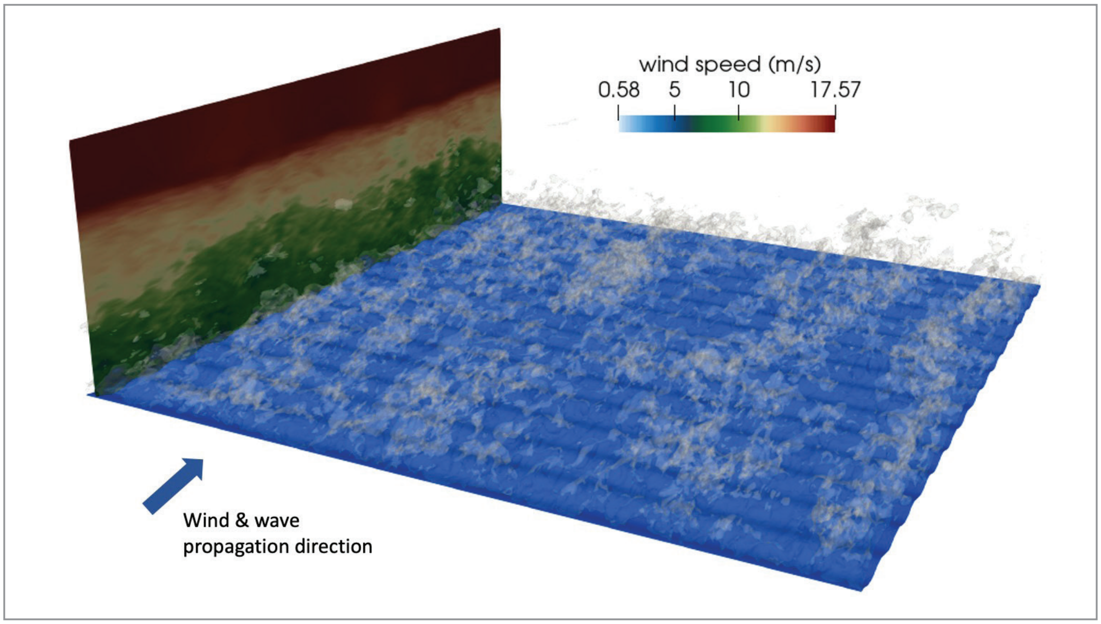
Location of mesh refinement regions and turbines in the Nalu-Wind simulation domain used for verification and validation for inflow, turbine loads, and wake strength and deflection.



The effect of yaw on wake deflection 2D downstream (top) and the effect of mesh resolution (coarse, medium, fine) on simulated wake velocity contours (bottom) as part of the verification and validation of Nalu-Wind. The white circle indicates the rotor location.

5.2. High Fidelity Modeling (HFM)

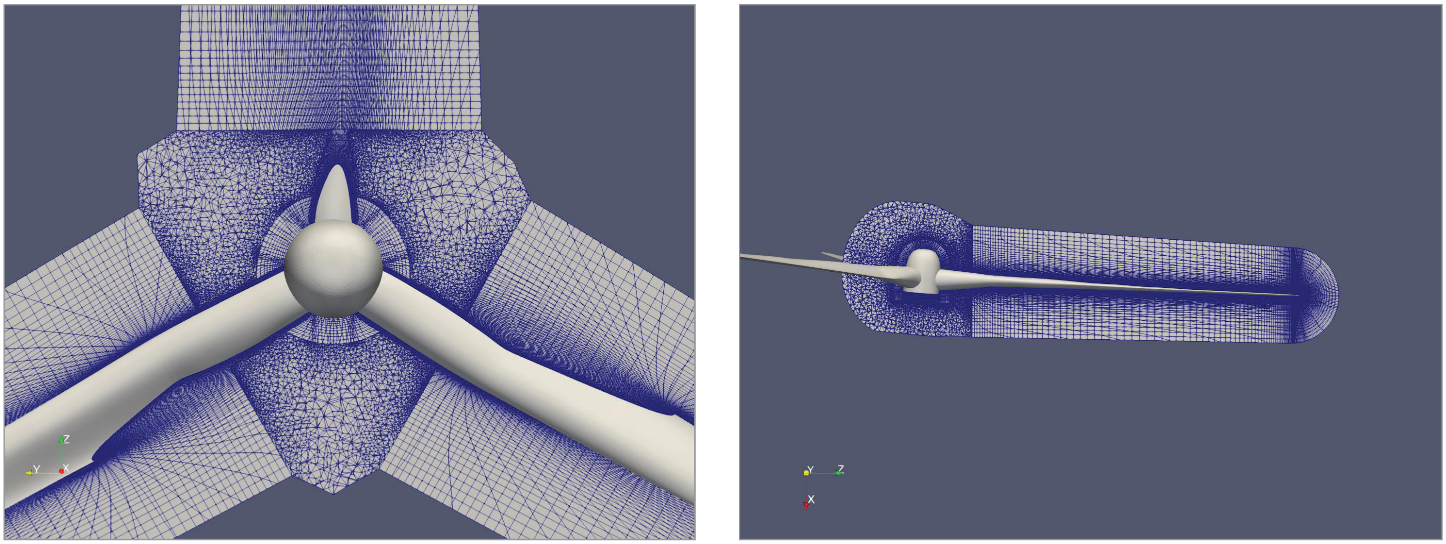
The joint Sandia-NREL High-Fidelity Modeling (HFM) project is funded out of the DOE Wind Energy Technologies Office's A2e program and is closely affiliated with the ECP-funded ExaWind project. HFM is focused on developing, verifying, and validating the models, numerical algorithms, and software engineering embodied in the Nalu-Wind, AMR-Wind and OpenFAST codes that are necessary for predictive offshore and land-based wind farm simulations. During Fiscal Year 2020, HFM equipped and verified Nalu-Wind and AMR-Wind for performing atmospheric boundary layer simulations under all density-stratification stability regimes. Additionally, Nalu-Wind now has the features required for simulating flow in complex terrain. HFM also worked to validate the high-fidelity, nonlinear BeamDyn model against experimental results in the literature, and high-fidelity shell-type finite-element models for long, flexible beams and the IEA 15-MW blade. Nalu-Wind's new marine atmospheric boundary layer capability was highlighted in the DOE Wind Energy Technologies Office's Fall 2020 R&D newsletter: https://www.energy.gov/eere/wind/wind-rd-newsletter#news



Simulation of wind over waves using the Nalu-Wind flow solver.
Image Credit: NREL's Georgios Deskos

5.3. ExaWind

The multi-institutional (NREL, Sandia, ORNL, University of Texas at Austin) ExaWind project is part of DOE's Exascale Computing Project (ECP) and aims to create a computational fluid and structural dynamics platform for exascale predictive simulations of wind farms. The ExaWind project is closely affiliated with the HFM project that is funded by the DOE Wind Energy Technologies Office's A2e program. During Fiscal Year 2020, ExaWind made huge gains in converting its core computational kernels to be able to be portable and performant on next-generation high-performance computing hardware, including Graphical Processing Units (GPUs). The ExaWind team has also demonstrated the viability and optimality of a novel hybrid-solver approach wherein the near-turbine flow is resolved with an unstructured grid (using ExaWind's Nalu-Wind software package) and the background flow is resolved with a structured grid (using ExaWind's AMR-Wind software package). Furthermore, the team has established new performance benchmarks on GPUs and Central Processing Units (CPUs) for wind energy problems that feature blade-resolved simulations with moving meshes.



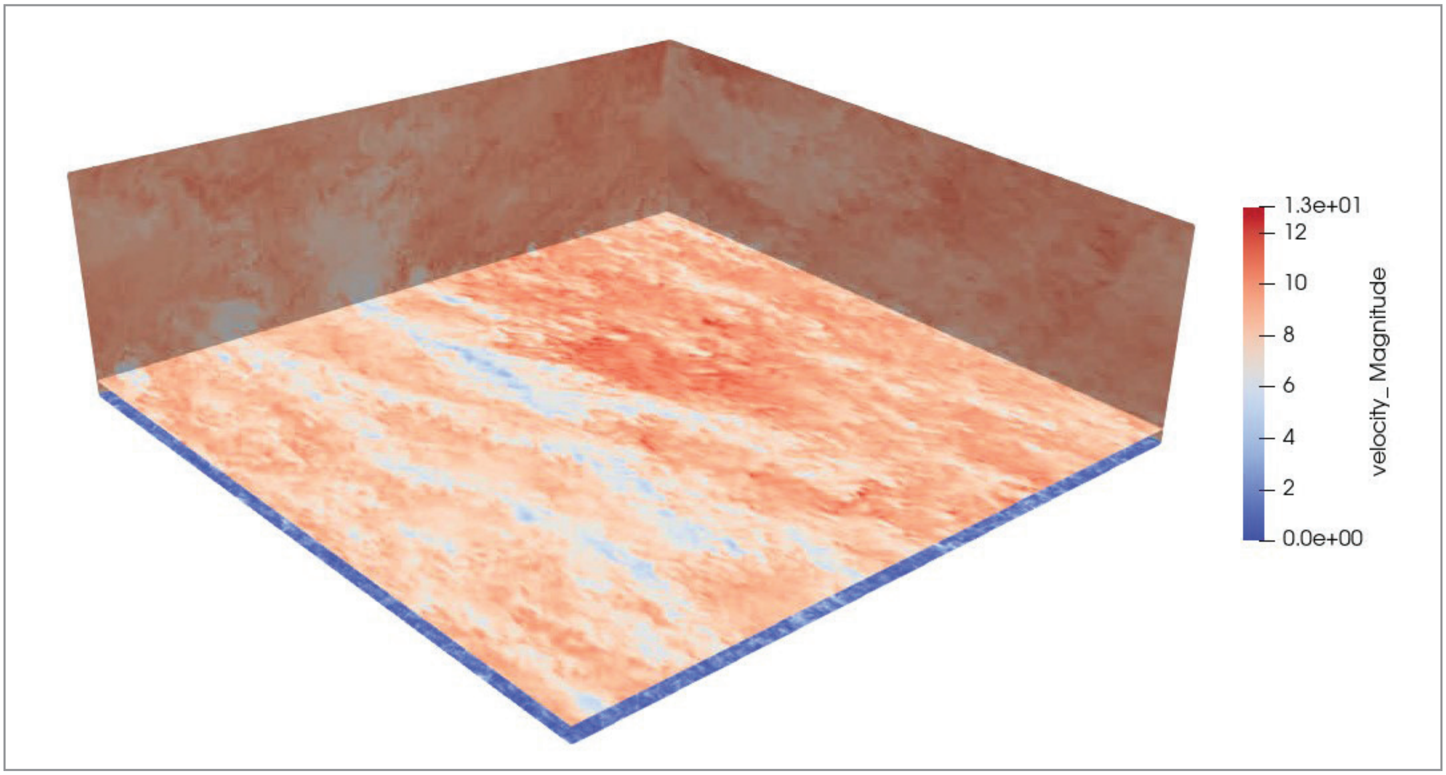
Front view of the NREL 5-MW near-body mesh (left), and side view of the NREL 5-MW near-body mesh (right), used to model the NREL 5-MW rotor with Nalu-Wind. The hybrid mesh consists of a structured, hyperbolically extruded mesh on the rotor blade.

5.4. AWAKEN

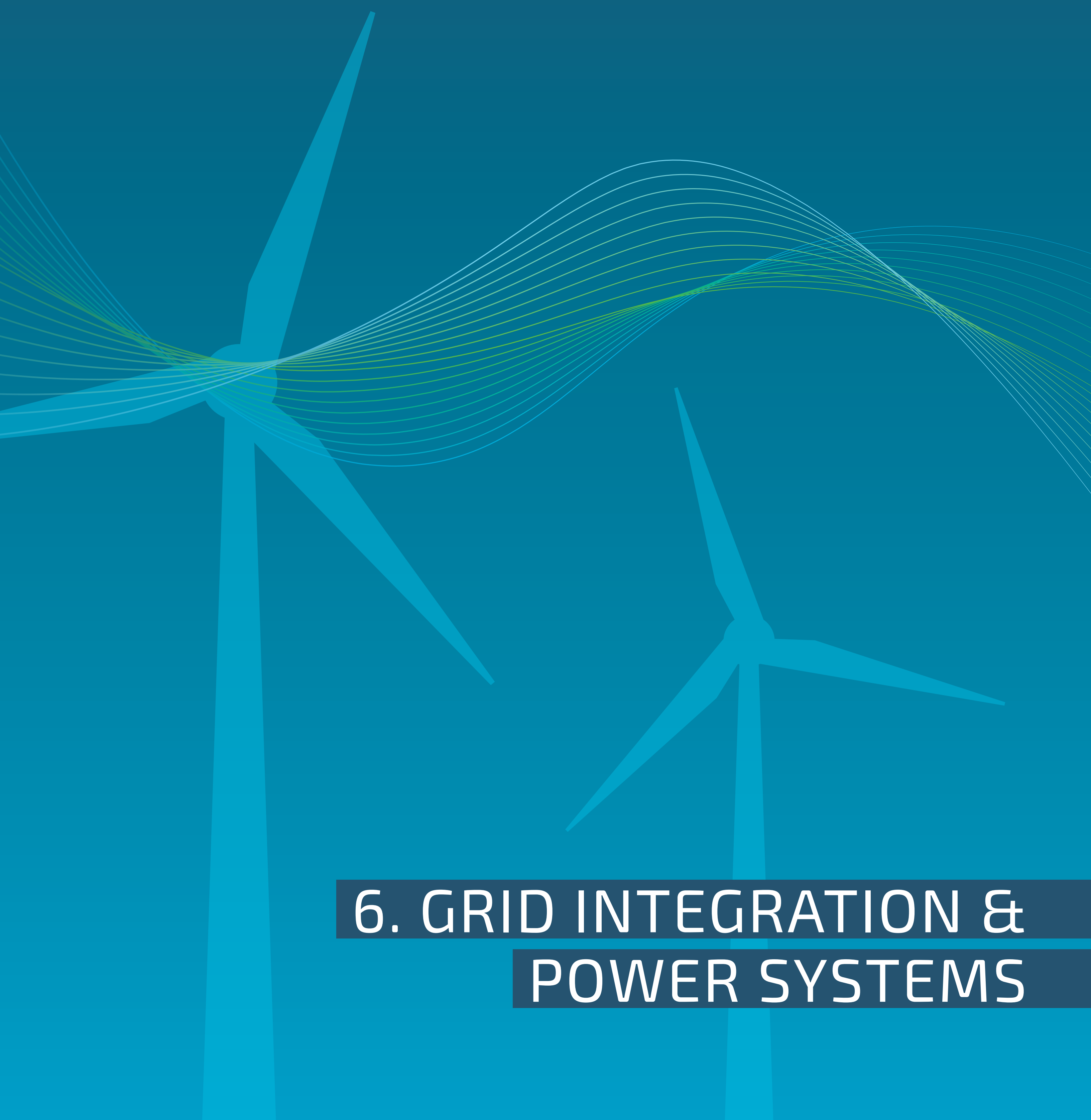
The American WAKE experimeNt, or AWAKEN, is a landmark international wake observation and validation campaign occurring in the US Midwest. Data gathered during the AWAKEN project will be used to further validate wind plant models and lead to both improved layout and more optimal operation of wind farms with greater power production and improved reliability. This year, as part of the AWAKEN project, Sandia focused on creating the Instrumentation Development Roadmap and performing high-fidelity Nalu-Wind simulations for field campaign planning.

The Instrumentation Development Roadmap will provide a powerful tool for informing which measurements and instrumentation are necessary to adequately capture the wind turbine and wind plant phenomena important to the AWAKEN project and future DOE field campaigns. Once the roadmap is completed it will guide and highlight gaps in instrumentation for wind plant validation and offers insights on what technologies need to be developed. Fiscal Year 2020 work kicked off through successful hosting and organization of an international collaboration meeting on instrumentation development at the AIAA SciTech and AMS Annual Meeting to engage with instrumentation developers across aerospace research and atmospheric sciences. Since then a small group of researchers from the national laboratories and academic institutions have been creating the roadmap framework for mapping between instrumentation, wind plant phenomena, AWAKEN science goals, and high-fidelity modeling validation needs. The preliminary framework has been completed and is ready for feedback from the larger instrumentation development community before finalizing the roadmap later in Fiscal Year 2021.

High-fidelity Nalu-Wind simulations are being run to ensure proper experimental design for capturing the necessary measurements. The figure below shows a sample precursor of the inflow that will be used to look at wind plant blockage of a wind plant near the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site.



Sample Nalu-Wind inflow precursor over a 4 KM×4 KM domain with unstable atmospheric stratification, matching similar atmospheric conditions to what occurs at the ARM SGP site.

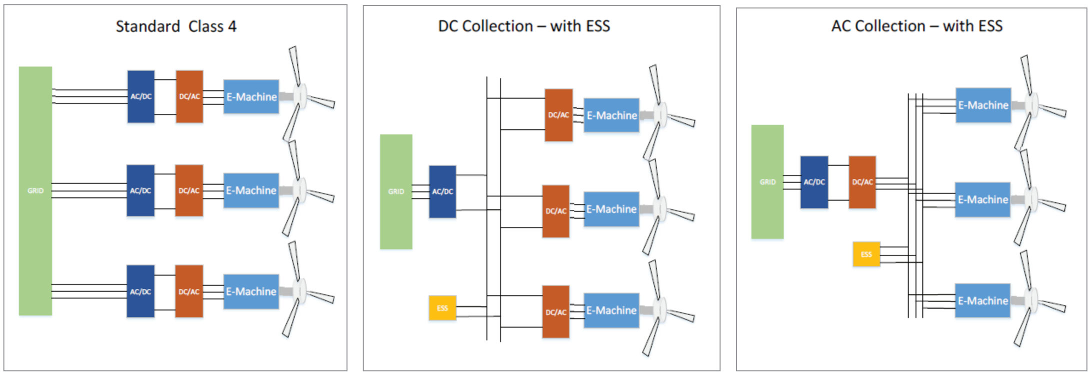


6. GRID INTEGRATION & POWER SYSTEMS

6. GRID INTEGRATION & POWER SYSTEMS

6.1. Wind Farm Controls

The technical approach for this project is to develop representative reduced order models (ROM's) that capture the critical coupled dynamics of wind turbine/wind farm mechanical-electrical systems, and develop an advanced nonlinear control and agents/informatics architecture that will seamlessly integrate and harmonize an Energy Storage Systems (ESS). The nonlinear control design will encompass a distributed/decentralized approach that identifies where and how much ESS is required to operate efficiently. The mechanical-electrical Wind Turbine (WT) coupled models concentrate on Type IV generator systems as part of a collective DC and collective AC (utilizing power packet networks) electric power grid design interface for the complete wind farm. The goal is to identify power electronic and ESS component reduction and simplifications for efficient increases in wind farm power production and cost savings. In Fiscal Year 2020, the project verified control performance using ROMs for both a DC and AC collective case using a 3 wind turbine farm model. This initial effort sets up research into the next stage of the project where Power Packet Networks (PPNs) are used to minimize power electronics and ESS requirements by allocating different elements of power phases, signals, diagnostics, control and communications into different frequencies.



Alternative DC or AC wind farm layouts utilizing PPN network controls.

6.2. Cybersecurity Roadmap

In July 2020, the DOE Wind Energy Technologies Office published the *Roadmap for Wind Cybersecurity* outlining the increasing challenges of cyber threats to the wind sites and control systems and presented a framework of activities and best practices that the wind industry can use to improve its cybersecurity. Sandia partnered with NREL and INL to draft the report with the aim to:

- Raise wind industry awareness of increasing cyber threats and vulnerabilities to wind technologies and industrial control systems
- Lay out a time-phased framework for addressing such weaknesses in the near-, mid-, and long-term
- Illuminate best practices that apply to the wind industry
- Identify research needs, gaps, and opportunities that might advance technology and strengthen protections
- Inform future R&D investments in this area

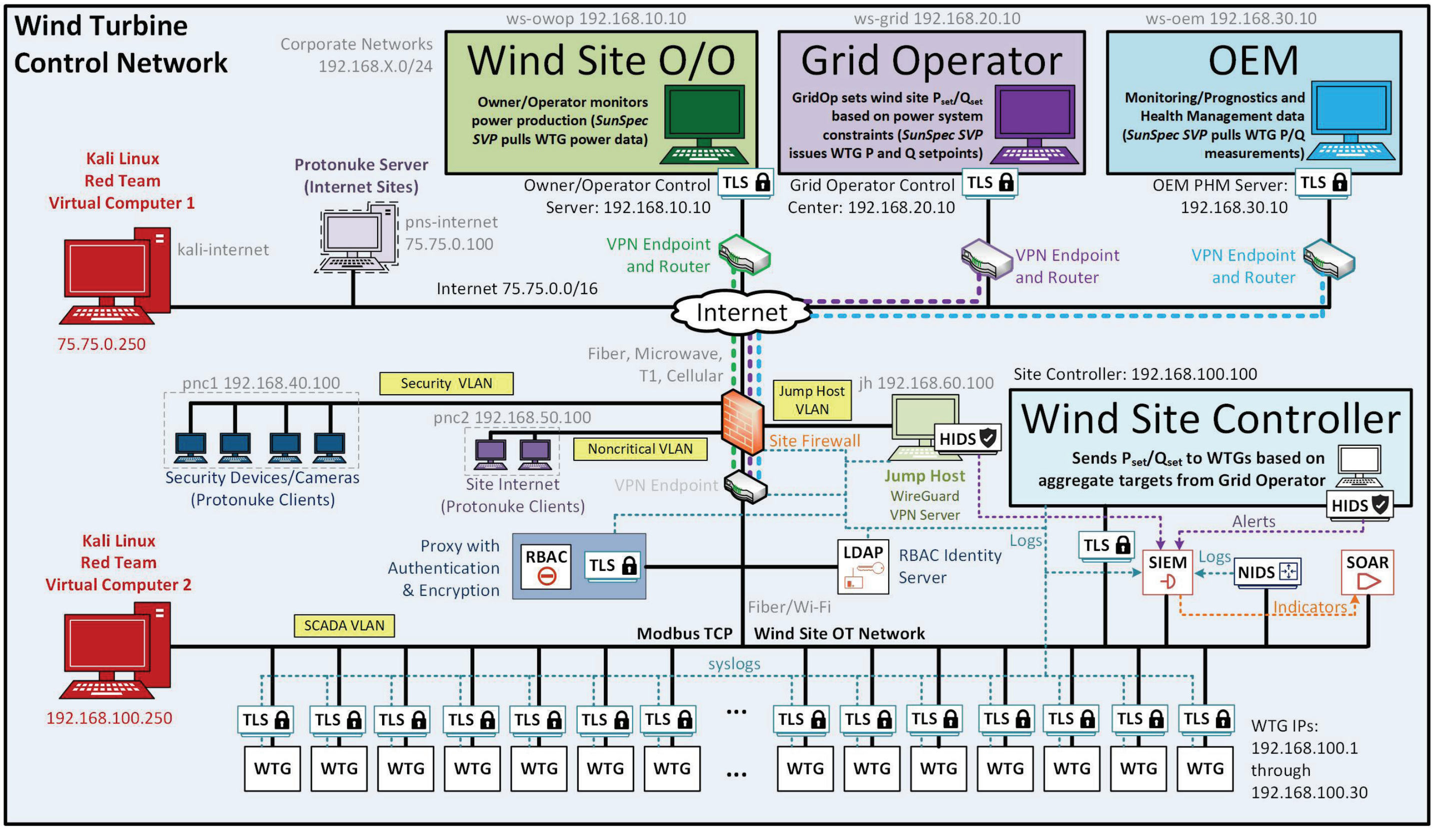
Although specific to wind, the Roadmap's strategies are likely applicable to other forms of energy and industrial control systems. As the percentage of wind and other renewable energy systems grows among power generators in the United States, cybersecurity for integrated control systems and related technology becomes an increasingly important and urgent matter. Strategies for cybersecurity assessment, protection, threat detection, response, and recovery include an array of wind-specific cyber-research and development, further development of standards and protocols, the promotion of best practices for cybersecurity, and expanded information sharing and engagement among wind energy stakeholders. Roadmap for Wind Cybersecurity (energy.gov)

6.3. Cyber Hardening

Large-scale deployment of wind energy is transforming today's power grid through sophisticated grid-support functionality and utility-to-turbine communications. These enhanced control features provide grid operators with new capabilities, but they also expand the power system attack surface significantly. Turbine vendors, plant operators, and utilities lack clarity on what security upgrades are necessary or most effective. In Fiscal Year 2020, Sandia and INL began investigating wind network hardening technologies that will increase cyber-resilience performance and maintainability in wind-specific applications. To do this, the team created a wind site network reference architecture based on wind industry feedback. This network was then built using the SCEPTRE co-simulation platform and represents the Electric Reliability Council of Texas (ERCOT) transmission power system, 30 wind turbine controllers, and wind site networking equipment. The team is in the process of adding several cyber hardening features to the communications network, including:

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

This network environment with the hardening features is shown in the figure below. The final phase of the project will be to conduct automated adversary-based assessments of the network with different security features in order to quantify the security improvements with each hardening element. Results from the project are regularly shared with the wind industry to disseminate updated cybersecurity findings with stakeholders.



Wind site cybersecurity hardening features built into the networking simulation environment.

6.4. MIRACL

In Fiscal Year 2020, Sandia completed two major deliverables to facilitate the broader goals of the multi-lab Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project. In the first deliverable, Sandia developed the first power system model of the turbines at the SWiFT facility interconnected with the nearby TTU GLEAMM microgrid assets and the local electrical cooperative distribution system. This model, developed in the MATLAB/Simulink software, will enable researchers to explore advanced wind turbine control technologies that could later be translated and tested on the actual wind turbines in a field experiment. The flexibility of the SWiFT and GLEAMM hardware and software systems facilitates the exploration of a wide variety of power system topologies including hybrid power systems and islanded microgrids.

For the second major deliverable, the Sandia team designed, constructed, and installed a SWiFT wind turbine emulator to support power hardware in the loop distributed power system analysis at the Sandia Distributed Energy Technology Laboratory (DETL). This system, pictured below, operating in the DETL facility, provides a capability for researchers to explore power systems with a blend of components represented by everything from pure software through actual hardware. The wind turbine emulator itself is a mix of these with the wind input to the rotor being replaced by a programmable motor drive while the generator, controller, and power electronics are represented by actual hardware that can be found on a wind turbine. This capability enables researchers to explore wind technologies in configurations that are expensive to replicate in the field or under scenarios that might be unsafe to conduct in a field test.

Power hardware-in-the-loop installed at the DETL *Image Credit: Sandia, Bret David Latter*

6.5. FlexPower [GMLC]

The Clusters of Flexible PV-Wind-Storage Hybrid Generation (FlexPower) project funded by the DOE Grid Modernization Laboratory Consortium (GMLC) through the Wind Energy Technologies Office aims at developing control schemes that enable wind and solar generation, coupled with energy storage systems, to operate in a similar fashion as conventional generation.

In Fiscal Year 2020, this work implemented a dynamic microgrid simulation model of a distribution system with wind and solar generation as well as energy storage and diesel generation. This model was implemented using MATLAB/Simulink and represents the TTU GLEAMM microgrid integrated with SWiFT wind turbines located at the Reese Technology Center in Lubbock, Texas. This system can operate in different configurations depending on the operation of the system switches (S), allowing different assets to be connected to the GLEAMM microgrid. Although the microgrid has four switches, S1 and S2 are normally closed, while switch S4 is normally open. Switch S2 can connect and disconnect the GLEAMM microgrid to the SWiFT test site (isolated) and S1 can connect the SWiFT test site to the Hurlwood substation (grid connected).

Additionally, this work has implemented detailed models of a solar photovoltaic plant, wind turbine generator, battery energy storage system, and diesel generator. These dynamic models are enabled with modulation control of active and reactive power. This functionality allows the injection of user defined waveforms at the point of interconnection of each model. Using this functionality, system transfer functions are determined then implemented using control system theory.

The flexibility of the system is demonstrated with dynamic simulations. An example of a 40 second simulation is shown in the figure below. Step changes in generation and load are made throughout the simulation to understand the stability and dynamic responses of the system. In this simulation, the GLEAMM microgrid is operating in islanded mode, but after a decrease in PV generation at 30 seconds, the GLEAMM microgrid connects to the SWiFT test site to help supply the load demand.

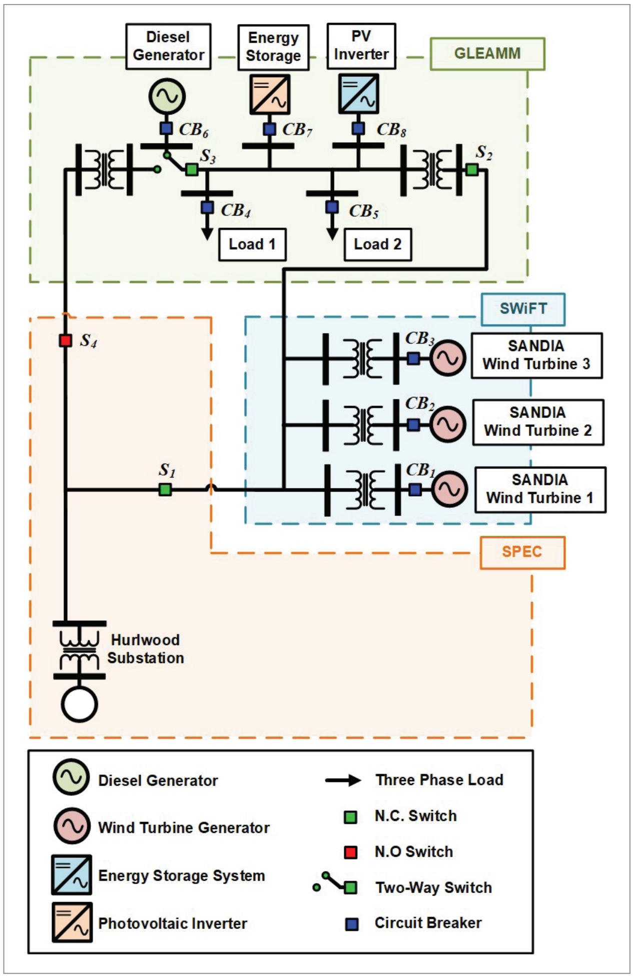
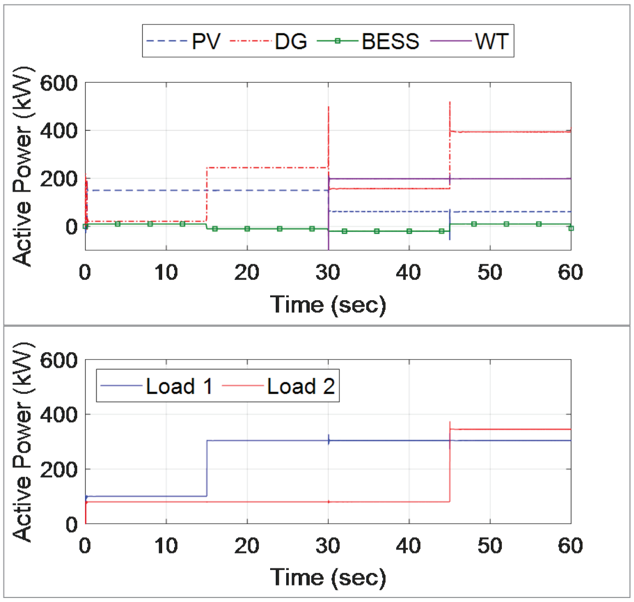


Diagram of the GLEAMM microgrid and SWiFT test site. Interconnection with South Plains Electric Cooperative (SPEC) is at the Hurlwood Substation.



Simulated Results for Generation Sources Active Power. (Top) Active Power (Bottom) Load Demand.

7. SOLUTIONS TO NATIONAL SECURITY TECHNOLOGY BARRIERS

7. SOLUTIONS TO NATIONAL SECURITY TECHNOLOGY BARRIERS

7.1. Defense and Disaster Deployable Turbine (D3T)

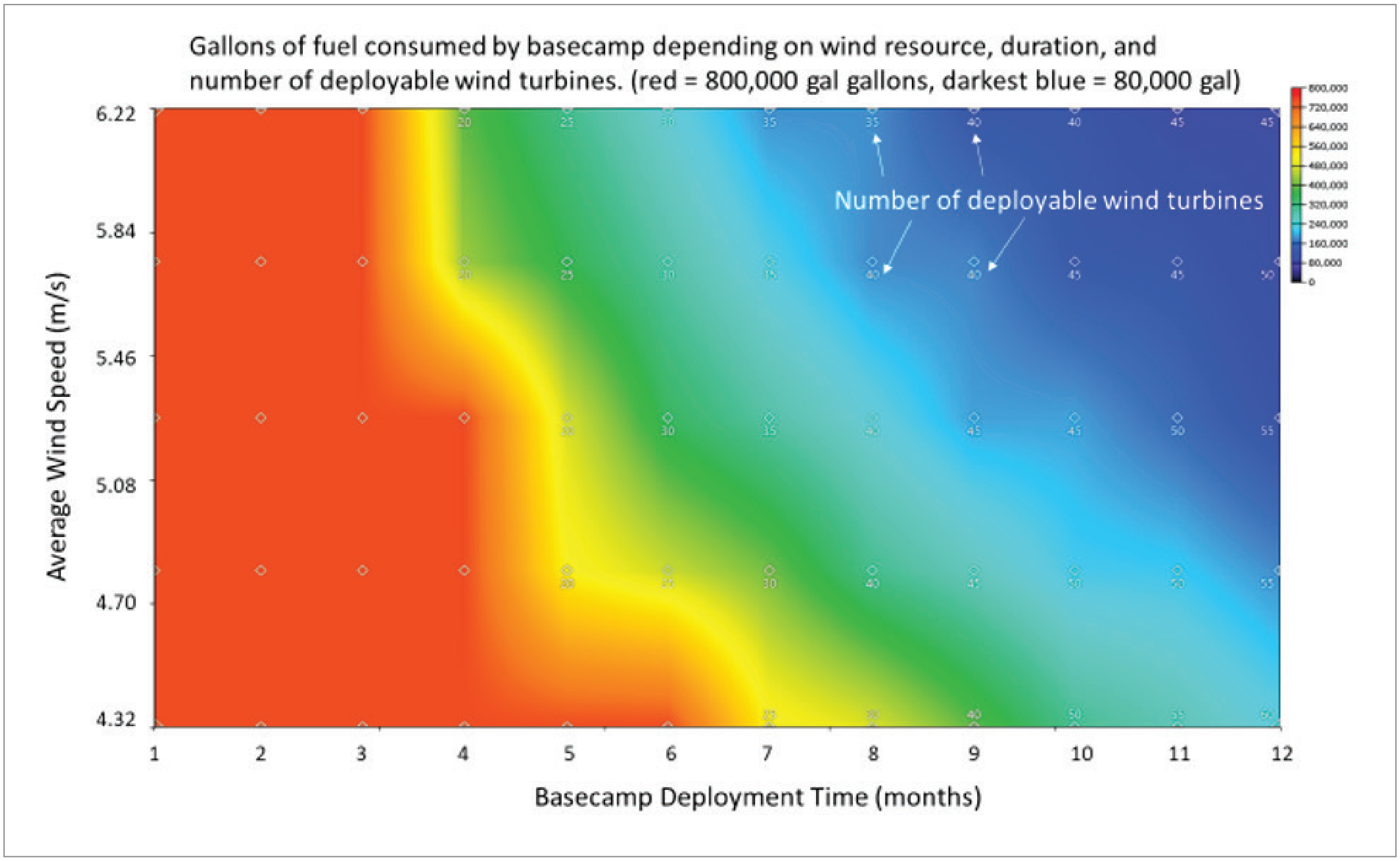
Sandia, INL and NREL published two reports in Fiscal Year 2020 that assessed the opportunity for deployable wind energy systems to meet the energy needs of defense and disaster response activities. These reports are the first public deliverables from the Defense and Disaster Deployable Turbine (D3T) project, funded through the DOE Wind Energy Technologies Office's distributed wind portfolio. The objective of the project is to explore the opportunity for deployable turbine technologies to meet the operational energy needs of the US military and global disaster response efforts.

7.1.1. Market Opportunities for Deployable Wind Systems for Defense and Disaster Response

The first report, *Market Opportunities for Deployable Wind Systems for Defense and Disaster Response*, provides a market assessment that was conducted over a year using public reports, presentations at topical conferences, and direct interviews with both military and industry stakeholders. It summarizes the operational energy strategy of the Department of Defense setting the context for alternatives to diesel fuel to meet its energy needs. The report continues with an estimate of the energy use of the military in missions where a deployable turbine could potentially serve as an alternative to the baseline use of diesel fuel in generators to provide electricity in remote locations. An overview of domestic and international disaster response is provided with a focus on the role of the military in providing energy to those operations. The report concludes with the technical considerations that would enable a deployable turbine to optimally meet military and disaster response energy needs considering the global wind resource, the technical design of the turbine, and the operational constraints of various military missions.

7.1.2. Computational Analysis of Deployable Wind Turbine Systems in Defense Operational Energy Applications

The second report, *Computational Analysis of Deployable Wind Turbine Systems in Defense Operational Energy Applications*, quantifies the potential benefits of wind energy provided by deployable wind turbines as measured by a reduction in both fuel consumption and supply convoys to a hypothetical network of Army Infantry Brigade Combat Team bases. Two modeling and simulation tools were used to represent the bases and their operations and quantify the impacts of system design variables that include wind turbine technologies, battery storage, number of turbines, and wind resource quality. The results of both tools show that wind turbines can provide significant benefits to contingency bases in terms of reduced fuel use (83% reduction) and number of fuel convoy trips (26% reduction) to resupply the bases. The match between the wind turbine design and wind resource and inclusion of battery storage are critical design considerations to achieve these savings. The figure below plots contingency base fuel consumption (color gradient) and deployed wind turbine quantity (diamonds) with axes of mission length and average wind speed. For missions lasting longer than 3 months, wind turbines provide a lower logistics burden compared to diesel generators as evidenced by the bluer areas and higher turbine counts.



Gallons of fuel consumed by basecamp depending on wind resource, duration, and number of deployable wind turbines.

7.2. Radar Interference Mitigation

As part of the Wind Turbine Radar Interference Mitigation (WTRIM) Working Group, Sandia hosted a series of webinars following the cancellation of an in-person Technical Interchange Meeting (TIM) caused by the COVID-19 pandemic. The purpose of these webinars was to facilitate an exchange of information between the offshore wind industry, radar experts, and federal agencies to discuss research needs for offshore wind development that may impact sensitive radar systems. The goals of these TIMs included building relationships between key industry stakeholders and agencies around offshore wind-radar issues, obtaining government and industry perspectives on potential impacts of offshore wind on radar missions, identifying research and development gaps, and obtaining a better understanding of the future direction of the offshore wind market.

Seven publicly announced webinars were held virtually that addressed various aspects of offshore wind turbine development and its potential impacts to radar systems. Additional smaller R&D meetings were held around specific radar systems to address R&D gaps. These webinars reached a broad audience including participants from the federal government, the wind industry, the radar community, academia, and mariners. Recordings and presentation material can be found on the Department of Energy's website: Offshore Wind Turbine Radar Interference Mitigation Webinar Series | Department of Energy.

8. WIND INDUSTRY STANDARDS DEVELOPMENT

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8.1. IEC 61400-5 blade design standard

The IEC 61400-5 blade design standard was published in Fiscal Year 2020. Sandia staff contributed to the technical content of this standard, as well as the final editing and publication. This standard, the first from IEC specifically for blades, represents a significant achievement for the wind energy industry, encouraging increased analysis and testing of designs to produce higher energy capturing rotors. Sandia also started planning for the creation of a committee to begin work on the next addition of the -5 standard in Fiscal Year 2021.

8.2. IEA Wind Task 46

Sandia worked with a group of international partners to propose a new IEA Wind Task on Erosion of Blades. This task will study the areas of climatic conditions that cause erosion, optimal operations and maintenance to reduce the effects of erosion, erosion-resistant materials and structures, and laboratory test methods. The outcome of the task will be a series of literature reviews and best practices documents, as well as recommendations for technology development and new standards.

8.3. IECRE Joint Working Forum

During Fiscal Year 2020, a new Joint Working Forum (JWF) under IECRE was initiated on Model Validation for wind energy, with one of the official US Technical Advisory Group representatives being elected from Sandia.

9. INTELLECTUAL PROPERTY

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10. PUBLICATIONS

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