The Wind Turbine Rotors of the Future: A Research Agenda from the Big Adaptive Rotor Project

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1 National Renewable Energy Laboratory
2 Sandia National Laboratories

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List of Acronyms

AI/ML	artificial intelligence/machine learning
AWAKEN	American WAKE experimeNt
BAR	Big Adaptive Rotor
BEM	blade element momentum
CFD	computational fluid dynamics
IEA Wind TCP	International Energy Agency Wind Technology Collaboration Programme
NREL	National Renewable Energy Laboratory
OC6	Offshore Code Comparison Collaborative, Continued, with Correlation and unCertainty
RAAW	Rotor Aerodynamics, Aeroelastics, and Wake
Sandia	Sandia National Laboratories
WETO	Wind Energy Technologies Office

Executive Summary

This report outlines a research agenda to support the design of the wind turbine rotors of the future. It is authored by researchers who have been working on the Big Adaptive Rotor (BAR) and related initiatives at the National Renewable Energy Laboratory and Sandia National Laboratories. The U.S. Department of Energy's Wind Energy Technologies Office has funded BAR since 2018. The learnings from the BAR project have been documented in numerous publications; see Johnson et al. (2021) for a list of publications from the first 3 years, and the References section of this report for newer publications.

Blades for both land-based and offshore wind turbines continue to scale up thanks to numerous innovations. The longer blade designs are possible thanks to new materials and manufacturing concepts, segmentation and other logistic solutions, novel control strategies and load management strategies, and economies of scale. The rotor upscaling has however also generated a list of unresolved critical challenges in wind turbine rotor technology. This report discusses these challenges and corresponding opportunities, which are here organized according to the following five broad topic areas:

- Aero-servo-hydro-elastic predictivity
- Probabilistic design and improved standards
- Manufacturing and materials advancements
- Rotor sentience and controls
- New rotor concepts.

This research agenda involves several authors and is well-aligned with the broader wind energy roadmap defined during the International Energy Agency Wind Technology Commercialization Programme 109th Topical Expert Meeting on the Grand Challenges of Wind Energy (see Veers et al. 2019, 2023).

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1 Introduction

1.1 Background, Motivation, and Goals

Wind energy has been successful over the past decades, accounting for 10.2% of the electricity production in the United States in 2023. The story of wind energy is one of continuous innovation. While the basic architecture of wind turbines has remained relatively unchanged for 30 years, with commercial installations mostly limited to three-bladed upwind rotors, the embedded innovation over time has led to order-of-magnitude (factor of 10) reductions in levelized cost of energy. This drop has been primarily supported by a continuous increase in wind turbine size—wind turbines today are by far the biggest rotating machines on Earth and represent the second largest contribution to new installed capacity in the United States after solar energy (Wiser et al. 2022).

The wind industry designs, tests, manufactures, and fields a new product line at a larger scale every couple of years. Nonetheless, progress in wind energy science is slower than industry, and the understanding of the physics behind modern wind turbines is incomplete. The consequences of such limited knowledge are greater uncertainty, higher risks, and limited options for innovation. Today, researchers, designers, and operators still cannot explain important phenomena that the latest large and flexible wind turbines experience in the field.

Global economic trends such as high costs of raw materials combined with high interest and inflation rates threaten the deployment goals set by governments to convert electricity systems to renewables before 2050 (or even much earlier). Sustaining the ongoing trend of cost reduction requires continuous research and development. As a result, this report proposes a research agenda for the wind turbines of the future, focusing on rotor technology. The goal is to share the agenda with the wind energy community to catalyze efforts and advance the state of the art. Also, this report can be used to inform research efforts funded by the U.S. Department of Energy's Wind Energy Technologies Office (WETO) once the Big Adaptive Rotor (BAR) project is completed. The agenda also hopes to inform related program areas, such as systems engineering, controls, high-fidelity and engineering modeling, and offshore wind, among others.

1.2 The Big Adaptive Rotor Project

In 2018, WETO started the BAR project with partner laboratories, namely the National Renewable Energy Laboratory (NREL), Sandia National Laboratories (Sandia), Oak Ridge National Laboratory, and Lawrence Berkeley National Laboratory. BAR completed its first 3-year phase in 2021 (Johnson et al. 2021). In BAR Phase II, NREL and Sandia researchers focused on the techno-economic assessment, detailed design, and experimental validation necessary to further mature the technology readiness level of very large, rail-transportable blade designs identified in BAR Phase I as promising technologies for the next generation of land-based wind turbines. BAR Phase II has also greatly expanded the capabilities in numerical design to evaluate new concepts, especially highly flexible rotors and rotors equipped with distributed control devices.

BAR Phase II was organized into the following three tasks:

- Task 1 conducted a techno-economic analysis investigating the value of wind turbines equipped with highly flexible blades and distributed aerodynamic control devices.
- Task 2 focused on narrowing modeling gaps and on the development and validation of the numerical tools used to design, analyze, and optimize existing and future wind turbines. Researchers have been advancing the state of the art in numerical modeling both at the single turbine level and within a wind farm. Special focus has been dedicated to accurately model the complex deformations and the unsteady aeroelastic effects experienced by highly flexible rotors.
- Task 3 focused on the generation of validation data for the new suite of advanced engineering design tools developed within Task 2. This was done by:
    - Quantifying the edgewise structural damping of wind turbine blades
    - Assessing the feasibility of downwind rotors
    - Investigating the failure of composite materials and structures subjected to complex static and fatigue loading
    - Supporting the WETO-funded Rotor Aerodynamics, Aeroelastics, and Wake (RAAW) project.

1.3 Research Topic Areas Beyond BAR

Along with BAR, WETO has been funding RAAW and the American WAKE experimeNt (AWAKEN), which have been generating unique and invaluable experimental datasets. The availability of these new datasets unleashes new validation opportunities, which will benefit existing and future numerical models that will support the research and development of future wind turbine rotors. In parallel to these two efforts, WETO has been funding several other projects that have advanced the state of the art of multidisciplinary and multifidelity analysis, design, and optimization of wind turbine rotors, such as systems engineering, controls, high-fidelity modeling, and offshore wind, among others.

This report is organized according to following five topic areas:

- **Topic Area 1–Aero-Servo-Hydro-Elastic Predictivity.** The evaluation of new technologies must go through load and performance assessments. For such assessments, aero-servo-hydro-elastic models are the key element to accurately predicting the behavior of wind turbines beyond the envelope of what is already known. However, these models are affected by several approximations in the inputs and in the assumptions, generating uncertainty in the outputs, especially at the scale relevant to the next generation of offshore wind turbines. Continuous effort is needed to improve the aero-servo-hydro-elasticity of wind turbines, with a special focus on the rotor.
- **Topic Area 2–Probabilistic Design and Improved Standards.** Wind turbine rotors have recently been impacted by quality issues that have generated severe consequences to wind turbine manufacturers and wind farm developers. This topic area aims to improve

the methods used to design and test novel blade structure by adopting probabilistic approaches to account for manufacturing defects and damage. This topic area also aims to inform the definition of international design standards, which are key to advancing the state of the art.

- **Topic Area 3–Manufacturing and Materials Advancements.** Innovative manufacturing technologies are key to moving a design from a numerical model to a tangible product and advancing the state of the art. Special focus is needed to enabling technologies, automation, and solutions supporting high-throughput factories. Research around new materials is also part of the scope.
- **Topic Area 4–Rotor Sentience and Control.** Future wind turbine rotors will evolve toward more digitalization and widespread adoption of "smart" technologies. In particular, the control system will increasingly account for the dynamic environment impacting the wind turbine, its dynamic response, and the system-level impact of the control strategies.
- **Topic Area 5–New Rotor Concepts**. The innovations developed within the first four topic areas will inform the technoeconomic analysis of new, or renewed, concepts to advance the state of art in all rotor system components.

These five topic areas align with the three topic areas for research and development of the wind turbine identified during the 109th Topical Expert Meeting held in Boulder, Colorado, on February 28 and March 1, 2023, and organized by the International Energy Agency (IEA). Veers et al. (2023) documents the findings of the workshop, in which the importance of verified and validated predictive numerical tools was highlighted numerous times, together with the need to update design methods and standards, design smarter wind turbines that become an integral element of complex electricity markets, and minimize the social and environmental impact of wind turbines. This agenda is instrumental to reaching the research goals defined in the 109th Topical Expert Meeting.

Note that in this document intentionally we do not split the discussion between land-based and offshore rotors. Land-based and offshore wind turbines are designed, analyzed, and optimized according to different design criteria. Among other factors, these differences include the following:

- Due to the larger size of offshore turbines, gravity loading is more important than for land-based turbines.
- Storm loads are higher than operational loads for offshore turbines, whereas the opposite is often true for land-based machines.
- Offshore rotors operate at higher tip speeds and suffer from erosion more than land-based rotors.
- The capital cost of an offshore wind turbine is a much smaller fraction of the total plant cost and the requirements on transportation, installation, reliability, and operations and maintenance costs are higher.

Nonetheless, the issues from each of the five topic areas apply to both applications and this report helps shed light on the most pressing priorities for both land-based and offshore installations. Also, advancements in land-based wind technology can be transferred to offshore wind technology, and vice versa.

In the rest of this report, we detail the work needed in the five topic areas by discussing existing challenges and proposed solutions.

2 Aero-Servo-Hydro-Elastic Predictivity

The second grand challenge of wind energy identified by Veers et al. (2019) "Aerodynamics, structural dynamics, and offshore wind hydrodynamics of enlarged wind turbines" is directly relevant to this work. In this category, several areas of research are identified where the unifying line is a focus on predictive and validated numerical tools. Note that across disciplines, a multifidelity approach is recommended to deliver the right balance of accuracy and computational cost. Also, artificial intelligence/machine learning (AI/ML)-derived surrogate models are growing in popularity and offer the possibility of transferring knowledge from experiments and high-fidelity simulations to engineering models, especially to replace underperforming physics-based models in design and analysis tools.

2.1 Airfoil Aerodynamics

2.1.1 High Reynolds Numbers and Mach Numbers

Large wind turbine blades—both land-based and offshore—have airfoil sections along their span that operate at Reynolds numbers that can easily exceed 10 million and Mach numbers that can locally exceed 0.3. Recent research suggests that airfoils located toward the blade tip can experience the phenomenon known as intermittent transonic flow, and hence risk increased fatigue damage (De Tavernier and von Terzi 2022). Aeroacoustics emissions in such conditions are uncertain. As the Mach number increases, the assumption of incompressible flow underlying many commonly used aerodynamic tools (e.g., XFOIL, RFOIL, NALU-Wind) is increasingly challenged. Impact on phenomena like transition, separation, and unsteady aerodynamics will need both quantification and accounting.

WETO is currently working in this area within the Holistic, Multi-Fidelity Wind Farm Design Optimization and Model Coordination project. Additional work will be needed to strengthen the existing research and support the development of validated tools for the design and analysis of airfoils operating at high Reynolds and Mach numbers. A hybrid approach that combines numerical and experimental wind tunnel work with contemporary design tools that allow for true system-optimal large rotors will be critical for the performance and operability of future rotors.

2.1.2 Unsteady/High Angle-of-Attack Airfoil Aerodynamics

Unsteady airfoil aerodynamics models aim to characterize complex dynamic phenomena arising at the airfoil level. The models show deficiencies in terms of theory, implementation, and validation. Recent work at NREL on dynamic stall modeling augmentation using ML techniques offers a glimpse of how these deficits can be fixed (Vijayakumar et al. 2019; Ananthan et al. 2020). Also, gaps exist when combining rotational augmentation and unsteady airfoil aerodynamics. Lastly, the effect of compressibility on unsteady aerodynamic was studied for helicopters, but not for wind turbines.

During off-design or extreme load scenarios, wind turbine airfoils experience angles of attack outside of the traditional focus region, such as the deep stall region (e.g., for angles of attack above 25 degrees). The performance of airfoils operating at large angles of attack is poorly characterized today. This is a key knowledge gap and modeling challenge for wind turbines.

An effort that integrates sub or full-scale field measurements—such as those proposed in the RAAW experiment and described in Madsen et al. (2022)—with wind tunnel experiments and with analytical/numerical model development is recommended. Such an approach would upgrade this key capability, which is necessary to predict and manage the loads experienced by the next generation of rotors more effectively.

2.1.3 Soiling and Leading-Edge Erosion

During their lifetime, wind turbine blades suffer from soiling and leading-edge erosion. These two phenomena are caused by atmospheric particulates, bugs, rain, hail, sea-spray salt, and so on. They effectively alter the outer shape of the blade at the leading edge and affect loads, noise, and performance. These problems are more severe for offshore rotors that commonly operate at higher tip speeds. Additionally, such concerns are driving research programs such as the Blade Leading Edge Erosion Programme[1] in the United Kingdom, the Durable leading edges for high tip speed wind turbine blades project[2] in Denmark, and the Blade Durability and Damage project at Sandia.[3] These research efforts are focused on improving testing and modeling to design blades that are more resistant to soiling and erosion. The following actions are recommended to advance the state of the art in this area of research:

- Develop new blade/airfoil leading-edge design and manufacturing concepts to improve erosion resilience. This endeavor will improve the wind turbine blade lifetime but also enable higher tip speeds, thereby reducing drivetrain costs. To realize this goal, innovation is sought in design, manufacturing, and materials.

- Conduct a more comprehensive characterization of the performance of soiled and eroded airfoils to bridge the gap between modeling and field data. This characterization needs to align with measurements of soiling and erosion and the levels that are monitored during inspections. Such an investigation will require improved physics-based modeling of the phenomena (e.g., turbulence and transition models in numerical tools, multiphase and multiphysics simulations) and wind tunnel/field testing that aligns with recent publications (such as Meyer Forsting et al. 2023). A collaborative effort across the value chain would lead to accurate modeling of as-manufactured blades. Also, dynamic models for soiling and erosion would help quantify the ever-evolving rotor performance and would improve the accuracy and certainty of wind farm economic performance.

The combination of experimental observation, AI/ML approaches, and accurate modeling approaches at various fidelity levels should be pursued to assess the performance of leading-edge erosion technology solutions and limit the risks on both land-based and offshore wind turbines. The International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP) Task 43 on leading-edge erosion is a platform where research efforts can be accelerated.

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[1] https://ore.catapult.org.uk/stories/blade-leading-edge-erosion/
[2] https://www.duraledge.dk/the-duraledge-project
[3] https://energy.sandia.gov/programs/renewable-energy/wind-power/rotor-innovation/rotor-reliability/blade-reliability-composite-materials/

2.2 Rotor Aerodynamics Fidelity Beyond Two-Dimensional Blade Element Momentum Theory

From an aerodynamic perspective, wind turbine rotors are still mostly designed based on simplified blade element momentum (BEM) theory. The theory was originally developed for stiff rotors that lie in the rotor plane, but is now applied to highly flexible, tilted, coned, and swept rotors. BEM relies on a lifting-line formulation that does not capture the full three-dimensionality of the flow. The current paradigm has seen flat aerodynamic power coefficients in modern rotors whose design was driven by levelized cost of wind energy. Overcoming the BEM-imposed weaknesses in current design/analysis loops can help the industry to reach the next plateau of performance. This section covers two paths forward, vortex methods and computational fluid dynamics (CFD), to better incorporate three-dimensional (3D) aerodynamic effects in blade design for an overall improvement of performance and loads management.

The physics-based insights on the flow physics derived from both paths can also be used to inform further improvements to the underlying BEM formulations that we expect those in the industry to continue using. Particularly challenging conditions where rotor improvements for BEM are expected are in the areas of load cases involving veer, gusts, and direction changes.

2.2.1 Enhancing Vortex Methods and Integrating With Multidisciplinary Design Analysis and Optimization Toolkits

Vorticity-based methods have been considered for many years to offer a good middle ground between BEM and high-fidelity CFD, both in terms of computational speed and accuracy. These methods also improve consistency and accuracy for loads and performance predictions of rotors experiencing sheared and skewed (inflow affected by tilt and yaw angles) flows, as investigated in the IEA Wind TCP Tasks 29 and 47 (Boorsma et al. 2023). While there is ongoing work within the WETO-funded offshore wind project to address this prediction gap, more can and needs to be done with the vortex methods pathway to help advance this solution.

The following challenges have prevented the wide adoption of vorticity-based methods as a design tool:

- Lack of consensus and rigor on how to set the main tuning parameters of the method (e.g., the regularization parameter); other parameters are also hard to set for nonexperts, ultimately limiting usability
- Lack of robustness with increased temporal and spatial resolution
- Significant computational time requirements compared to BEM (several orders of magnitude higher).

Peer researchers have adopted solutions (Li et al. 2022) that hybridize BEM and vortex methods to find a balance of added accuracy, reliability, and reduced computational time. We recommend investigating similar hybrid strategies to improve the robustness of the method and extend/evaluate newer developments that bring additional functionalities in terms of stability analysis, such as in Saetti (2024).

More robust and sped-up vorticity methods can be integrated into multidisciplinary design, analysis, and optimization frameworks to design the next generation of rotors. The Wind Energy with Integrated Servo-control (WEIS) framework would be a great candidate and could be used to characterize sensitivities, define best practices, and demonstrate its ability to achieve new system-optimal rotor designs.

2.2.2 High-Fidelity CFD Modeling: Storm and Off-Design Cases

The recent development of exa-scale wall-resolved high-fidelity modeling capabilities, as well as maturation of hybrid CFD capabilities, can help characterize key phenomena that define the design drivers across wind turbine components. Sophisticated 3D CFD models and workflows have become more widespread, easier to use, and validated (Barlas et al. 2022), so their application to predict the turbine response to off-design conditions should become more common.

Loads generated during storms, defined in International Electrotechnical Commission design load cases 6.x, and loads in off-design cases such as DLC 1.4, namely the occurrence of a gust coupled with a direction change, are commonly estimated using traditional engineering models. In conjunction with unsteady stall modeling improvements (see Section 2.1 Airfoil Aerodynamics), we recommend the use of high-fidelity modeling to characterize these phenomena. Ongoing efforts funded by WETO include the Simulation-based Turbine design fOr hurricane Resilience and loads Mitigation project, and future research should focus on developing sufficiently comprehensive and high-certainty field datasets to validate numerical tools across fidelities.

2.3 High-Fidelity Structural Modeling and Testing

To support the design of more efficient blade structures, aerostructural design tools should include the use of high-fidelity structural models and design methods that are more appropriate to the new load envelopes experienced by modern rotors, from the material level up to the full rotor system. Reliable predictions of the structural behaviors of wind turbine blades can limit expensive and time-consuming testing to only the critical scenarios, thereby enabling cheaper and faster paths to market. The long-term goal should be to maximize the certification-by-simulation content like the aerospace industry has been able to achieve. Further, high-fidelity structural models can be used to simulate progressive damage in blades, which may allow for both fewer blade failures and reduction in blade mass due to excessive design margins.

2.3.1 High-Fidelity Structural Modeling

Blade structural designers are favoring full 3D brick elements over shell finite elements, which suffer from known limitations such as the imperfect prediction of blade torsional response and the imperfect modeling of critical areas such as the leading and trailing edge. The BAR project has added this capability in an initial form to Sandia's pyNuMAD blade modeling code.[4] Faster and more robust meshing techniques are needed to ensure that this transition achieves a better prediction of stresses, strains, fatigue damage, and ultimately failure.

WETO has recently funded a collaboration between Sandia and Purdue University to explore a new approach where the blade is modeled in 3D segments, and in which equivalent elastic

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[4] https://github.com/sandialabs/pyNuMAD

properties can then be fed to traditional beam models for aeroelastic simulations. The first results of the new approach, named OpenSG, are expected in the summer of 2025.

Other necessary improvements should tackle fatigue. The existing models for material fatigue accumulation based on the Palmgren-Miner rule are simplistic. Rotors experience low-cycle fatigue damage that is poorly modeled. Micromechanics models for composite materials offer a pathway to achieve more accurate fatigue predictions, especially when developed based on probabilistic approaches (see Section 3.1).

2.3.2 Quantification of Structural Damping

The BAR project highlights the importance of accurately estimating structural damping in composite blades and across the wind turbine system. Estimating structural damping accurately is needed to predict and prevent aeroelastic instabilities in the field, which usually appear on edgewise and torsional modes that are characterized by low aerodynamic damping. Currently, structural damping of blades cannot be predicted numerically and is quantified during full-scale blade structural testing, often with large uncertainty. The lack of numerical predictions limits the ability of blade designs to increase structural damping, as the manufacturing of new blade prototypes is lengthy and costly. In addition, the uncertainty in structural damping is not limited to the blades, but propagates across joints, actuators, the drivetrain, tower, and offshore support structures. The uncertainty in predictions lead to instabilities that are captured late during the prototype development process, sometimes so late that turbines have already been commercialized and installed.

BAR Phase II took some preliminary steps to add the ability to predict structural damping of wind turbine blades. A numerical approach has been added to pyNuMAD. The approach relies on quantifying structural damping at the material level in all three primary directions. Within BAR, structural testing at both the coupon and subcomponent levels is ongoing. This approach has been attempted in the past, but was never completed nor documented systematically, therefore a large effort is recommended to achieve the accurate prediction of structural damping for blades and across the entire wind turbine system in the long term.

2.3.3 Joints, Adhesives, Core, and Root Connections

Recent conversations within the Offshore Validation Experiment Planning Workshop, held at the University of Colorado Boulder on February 27, 2023, focused on large failure rates of modern blades due to complex loading scenarios, lack of subcomponent testing, and failure of blade roots. Indeed, blades not only comprise the primary shell made of composite materials but are complex structures made of bonding lines, sandwich core materials, prefabricated root connections sometimes made from a hybrid metal composite, and, increasingly, spanwise joints to alleviate logistics constraints in land-based blades. All of these areas have historically received limited funding, despite their importance in the performance of a blade during its lifetime. Indeed, blade failures often originate in one of these components, not in the spar caps or shell skin.

While the finite element modeling improvements mentioned in the previous section will help resolve these features at a higher fidelity in simulation, the validity and assumptions in broader modeling and techniques for designing, manufacturing, validating, and monitoring these features is uncertain and deserves more attention. The consequence of not targeting these areas is that industry is forced to adopt excessive safety factors, resulting in additional costs and unexpected failures.

2.3.4 Structural Testing

Closely related to modeling, design, and manufacturing, the testing of rotor blades might be reaching its limits in terms of facilities, duration, costs, and accuracy. In this scenario, the potential of subcomponent testing has not been fully explored (Rosemeier et al. 2019), and industry is typically testing only at the coupon level and full blade scale. The structural experiment currently ongoing within BAR Phase II represents a step in that direction, where complex loading scenarios can be reconstructed in the labs, and their impact on complex composite structures can be investigated probabilistically. Future efforts should build on these experiments, testing larger subcomponents and conducting detailed validation campaigns. Research should be focused on designing and testing metric-specific subcomponents, loading and testing methods for complex scenarios, articles to simulate production-type manufacturing quality, and digital twins.

2.4 Aeroelasticity, Stability, and Resonance Phenomena

The fidelity of the aeroelastic modeling of wind turbines, both land-based and offshore, should keep advancing to improve the prediction of loads. Also, modern wind turbines increasingly suffer from phenomena of aeroelastic instabilities, which result in increased fatigue damage and risk of catastrophic failure of the system. Numerical models poorly capture these phenomena, and this knowledge gap should be addressed with urgency.

2.4.1 Improved Aeroelastic Modeling

Dedicated research efforts to enhance and validate numerical tool chains should increase the overall subsystem/component multibody modeling fidelity in the turbine system tools so that “rotor adjacent” elements in the loads path are represented sufficiently accurately to capture the complex system dynamics. Currently, aeroelastic system models often excessively simplify the modeling of elements such as the pitch bearings and actuators or the drivetrain components. Projects like RAAW show that numerical models that predict the performance, loading, and dynamic stability of land-based wind turbines can be reliable, but they are affected by several inputs and modeling uncertainties that impair their predictive capabilities. Completeness and availability of input/model data are critical to progress.

2.4.2 Operational Aeroelastic Stability

Instabilities can occur during operation when one or more aeroelastic modes are negatively damped and undergo some excitation. Wind turbine manufacturers are usually able to tune the numerical models to reproduce an instability when it is observed in the field and can implement solutions to mitigate the problem. Nonetheless, current physics-based design tools and modeling fidelities/best practices struggle to accurately predict instabilities, which are sometimes caught only in the prototyping phase. When this happens, designers incur significant costs to address them late in the product development cycle. Research work is necessary to advance the development and subsequent verification and validation of such capabilities, with a special focus on how to drive quality modeling inputs into system modeling e.g., testing and measurement techniques for estimating the elastic and aerodynamic damping of the system. Research work should also push toward probabilistic approaches, in contrast to the state of the art that solely relies on deterministic models.

2.4.3 Stall-Induced Vibrations and Vortex-Induced Vibrations

Complex phenomena such as stall- and vortex-induced vibrations are increasingly common in very large and flexible wind turbine rotors and towers. The phenomena of stall-induced vibrations and vortex-induced vibrations are intertwined with the research on high angles of attack (Section 2.1.1) and storms (Section 2.2.2). Indeed, these phenomena often occur in standstill conditions under large yaw offsets, which commonly occur during the construction phase of the wind turbine or during maintenance, or in idling conditions with extreme storms. The vibrations are detrimental to the structural integrity of the system and present a significant safety risk when technicians are working near or in the turbine. Both a building-block modeling approach as well as better full-system modeling of these phenomena have been a priority and are under investigation along with high-fidelity simulations and dedicated field experiments. WETO is funding a research project in this area and efforts should continue to narrow this knowledge gap.

2.4.4 Aerohydrodynamic Loading and Dynamic Stability of Offshore Turbines

Offshore wind turbines, both fixed bottom and floating, experience low-frequency, nonlinear, and irregular loading events, which:

- Couple aerodynamic and hydrodynamic effects (including wave-induced rotor motion that impacts aerodynamic loads)
- Accumulate fatigue damage along turbine components
- Coincide with and excite system frequencies.

These new hydrodynamic loading events, the fatigue accumulation process, and the stability of offshore wind turbines are physical phenomena that are critical to assessing the lifetime of an offshore wind turbine, and work continues to evaluate and improve relevant predictive capabilities, for example within the IEA Wind TCP Offshore Code Comparison Collaboration, Continued, with Correlation, and unCertainty (OC6) project. Specifically, Phase III of OC6 considered rotor aerodynamic loads and wakes resulting from surging and pitch rotors from floater-induced motion (Bergua et al. 2023; Cioni et al. 2023; Papi et al. forthcoming).

To develop accurate numerical engineering models, experimental data must be collected from operating offshore wind turbines, sufficiently representative subscale test rigs, or highly resolved numerical rigs. Next, that data must be integrated with laboratory testing or low-frequency fatigue damage.

2.5 Aeroacoustics

2.5.1 Airfoil and Rotor

Noise signatures of land-based wind turbines remain a critical design constraint, limiting rotor speed and consequently system design efficiency. The development of airfoil and rotor noise prediction tools and noise mitigation measures (e.g., serrations and low noise tips) has stalled over the last 5−10 years, with some limited research ongoing within the IEA Wind TCP Task 39 on quiet wind turbines. A reliable, low-noise airfoil design capability is still limited by turbulent boundary layer noise source characterization and modeling weaknesses—a barrier that could be addressed by combining incipient, high-fidelity blade-resolved CFD, wind tunnel measurements, and AI/ML techniques. Given the expense and complexity of such tasks, a consortium approach to encourage precompetitive collaboration across industry and academia is suggested for future work.

2.5.2 Wind Turbine and Farm Noise

As the share of land-based wind in the U.S. electricity mix increases, significant benefits to enabling easier deployment can come from the development and validation of the next-generation of farm-noise and noise-at-receptor modeling toolkits. Such modeling could accurately address the impacts of atmospheric conditions, terrain, and topological complexity, wakes, and propagation-to-receptor location in the wind farm environment. Numerical techniques like ray tracing have become increasingly accessible due to advances in graphics processing unit computing and are being used in aerospace aeroacoustic tools (Wu and Redonnet 2023). While existing noise models based on the 1968 Ffowcs Williams Hawkings theory are being implemented in current NREL tools, the use of new CFD and acoustic tools, augmented by AI/ML approaches to overcome gaps in current noise source representations, could result in unique and fast predictive capabilities that are not yet available to industry. Low-frequency noise emissions are still poorly understood and yet are being reported more often. Experimental datasets measuring noise in a wind farm are not available in the public domain, and this can be addressed by experiments at existing U.S. Department of Energy assets or collaborations with U.S. stakeholder owners and operators.

3 Probabilistic Design and Improved Standards

Design methods and standards for wind turbine blade structures have improved over the years, but their deterministic core has not changed. This topic area identifies opportunities to improve the structural design of wind turbine rotors by adopting probabilistic approaches, which can predict the behavior of progressive damage and challenge existing design approaches based on top-down safety factors. This section also addresses some of the limitations of the international standards, which can be updated to be more adequate for very large rotors by modifying and adding design load cases and by improving the modeling of the inflow.

3.1 Probabilistic Design Approaches

The design of wind turbine rotors vastly relies on deterministic approaches, whereas wind turbines operate in an inherently stochastic environment. Past studies have focused on the following topics:

- Probabilistic approaches to extrapolate and estimate ultimate loads
- Uncertainty quantification and propagation approaches
- Design under uncertainty
- Probabilistic damage initiation and growth.

While the first family of studies has partially made its way into international standards, the latter three families of studies usually adopted simplified assumptions about the uncertainty affecting the inputs or basic design problems and stayed in the space of purely academic studies. The increased computational cost of such approaches has also been a major obstacle to adoption in industrial practice.

A path should be defined to strengthen probabilistic design tools and spread the use of such approaches. As a first step, the datasets obtained from the experimental campaigns RAAW and AWAKEN could be used to rigorously quantify input and output uncertainties. The output statistics of loads should be compared to the deterministic loads prescribed by the standards to build a strong case quantifying the advantages of adopting these new methods as well as the risks hidden behind deterministic approaches. Ultimately, probabilistic-based design approaches that rigorously account for uncertainties should aim to confidently reduce safety factors while achieving reasonable computational costs.

A second approach involves developing intrinsic methods, which reformulate the model in terms of stochastic variables. First steps have been taken at NREL in a recent project that received internal seed funding (Branlard et al., forthcoming). These approaches are complicated and specific expertise is required to advance the state of the art. The long-term potential is high, but there are many short-term roadblocks and additional research is recommended.

Finally, realistic distributions of manufacturing process flaws, along with the potential transportation and operational damage and the resulting impact on the blade structural resistance, can be modeled probabilistically (Lekou 2013) as an alternative to the partial safety factor method used by current standards. This approach allows for a direct prediction of the lifetime structural resistance, as well as identifies high-consequence input parameters and potential inspection intervals and repair determinations.

3.2 More Realistic Design Load Cases

International design standards were developed 30 years ago for kilowatt-scale wind turbines and have not changed substantially since then. As a result, standards are now prescribing conditions that are potentially far from reality for the size of current and future wind turbines. The changes in inflow hitting modern wind turbines across their rotor disk are much greater and rotors operate at the upper limit and sometimes beyond the atmospheric boundary layer, experiencing phenomena like low-level jets. Large rotors have significant variations across the rotor, making gust cases unrealistic, especially for offshore rotors. Also, wind turbines are rarely installed as single units, whereas the nature of standards is still very turbine centric. The next two subsections propose the research projects that are needed to investigate and overcome these limitations.

3.2.1 More Realistic Inflow

For the past 30 years, design criteria have specified the environmental conditions that wind turbines must be able to safely operate in. The intent has always been to define conservative requirements and avoid the need to simulate site-specific conditions, such as the distribution of stable, unstable, and neutral atmospheric conditions; the frequency and amount of shear or veer in the inflow; and the detailed characterization of turbulence.

Research is recommended to develop inflow models that capture the distinct physics of stable, neutral, and unstable inflow. Neutral inflow is well-captured, but the other states are not. Research should also investigate what combination of atmospheric conditions should be used in design.

The modeling of the inflow of both land-based and offshore wind turbines needs to be improved. Offshore, the inflow is influenced by sea conditions, but numerical models do not yet capture this coupling phenomenon. Accounting for that coupling requires three-dimensional CFD tools that model both the sea and atmosphere and accurately resolve the interface between water and air. Such tools are being developed and will need validation to support these investigations. Capturing these effects in engineering models and their impact on the design process should also be assessed. In addition, offshore wind energy development will increasingly be deployed to areas that experience tropical cyclones. The physics of such storms are not well-understood, and their modeling is currently inaccurate (see Section 2.2.2). The consequences of this knowledge gap are delays in the deployment of offshore wind turbines and additional costs linked to extra-cautious design safety factors, as well as extra financing costs.

We believe that more realistic design load cases would be of value; for example, to go beyond the coherent gust with direction change, marked Case 1.4 in the International Electrotechnical Commission standards, which is simultaneously an active design driver and an unrealistic inflow condition for large rotors. This effort aims to inform future updates of the international design standards, showcasing the value and challenges behind more realistic design load cases.

3.2.2 Plant Effects

Most turbines operate in large-scale wind farms, where wakes effects are consistently present, but design load cases are mostly evaluated for unimpeded flow. In practice, there is a site-suitability analysis for the specific location of each turbine to determine if the margin is great enough for operation in the enhanced turbulence caused by the wakes of surrounding turbines. However, the design and optimization process would benefit if wakes were modeled within the design procedures. Research efforts should be dedicated to adopting higher-fidelity models that model wakes within design and comparing design solutions between existing and next-generation approaches. Rotor technology solutions, such as rotor designs and control strategies that energize wakes, could arise. Recent WETO funding within the Offshore Wind System Design and Tool Validation project has supported an initial comparison between turbulent inflow modeled in the wind farm solver FAST.Farm and the turbulence models prescribed by the standards (Doubrawa et al. 2023). The results of this activity will inform future efforts.

3.2.3 More Tractable Probabilistic Design Space

Standards prescribe a list of design load cases that can be run in an aeroelastic solver to estimate wind turbine loads during extreme events. The list has been expanded from land-based wind energy applications and fixed-bottom offshore applications to floating offshore applications. The design process for offshore wind turbines involves orders of magnitude more load case simulations than land-based wind turbines due to the possible variations in inflow conditions (e.g., shear, turbulence), sea-state conditions (e.g., height, period, current, tides, storm surges), directionality, and wind turbine operation. Sweeping all the parameter space referenced in the offshore design standards could lead to nearly 10 million simulations. Each simulation takes at least a few minutes to complete, making a quick design turnaround impractical, if not impossible. Therefore, identifying, prioritizing, and downselecting the essential load cases are key steps in the design process. More efficient approaches of identifying design-driving load cases are important to advancing offshore wind turbine design.

Related to the probabilistic design space is the treatment of wind/wave stationarity and how it is handled in the load case simulations in terms of numbers of simulations of a given length. Wind is known to be stationary between 10 minutes and 1 hour, and waves are known to be stationary between 1 and 12 hours. Running fewer, longer simulations may not be realistic for wind loading, and running more short simulations may not be realistic for wave loading. Approaches for identifying the appropriate number and length of design-driving load cases is important to advancing offshore wind turbine design.

4 Manufacturing and Materials Advancements

Wind turbine blades keep getting longer and heavier while designs and material systems are increasingly optimized. However, manufacturing processes have not kept up and blades are still manufactured with labor-intensive processes that are prone to mistakes. One result of the lag in technology innovation is lower reliability. The following sections recommend research in manufacturing and materials advancements to address the challenge of low blade reliability and blade recyclability.

4.1 Manufacturing Process Automation

The manufacturing of wind turbine blades is still based on vacuum-assisted resin transfer molding, which is a labor-intensive process with inconsistent production quality, relatively low factory throughput, and unsustainable production costs in countries characterized by high labor rates. These challenges are worsening with longer and heavier blades. Automation represents an opportunity to not only reduce costs but also rethink how wind turbine blades are designed and manufactured. For example, recent efforts have returned promising metrics by combining thermoforming shells made of a thermoplastic resin and 3D printing a reinforcement (Bortolotti et al. 2022). In this scenario, research efforts should integrate automation into the design models, explore the existing trade-offs, and test the most promising solutions in both subscale and full-scale field prototypes.

In addition to automating material layup during molding operations, opportunities exist in automating post-molding operations, such as trimming, grinding, and sanding. Currently, these steps are particularly challenging for manual operators that must perform them by working at height with respirators and full personal protective equipment (Huth 2023). The automation of quality inspections provides an opportunity to reduce human error and subjectivity, thereby improving the reliability of the blade leaving the manufacturing plant. Automating wind blade repair methods both in the factory and in the field will provide a consistent process for completing these necessary repairs. Increased automation in wind blade manufacturing may result in lower direct labor content to produce wind blades while improving reliability, which will help lower costs and increase domestic wind blade manufacturing in the United States.

4.2 Quality Automation and Integration Into Digital Twins

In wind turbine blade manufacturing, researchers are investigating quality assurance technologies to be adopted across all manufacturing steps, from material cutting and infusion to finishing operations. The potential impact of these technologies is significant, as most blade material failures are not caused by fatigue of the primary composite material but rather manufacturing defects and flaws.

The current design practice compares the strength and fatigue adequacy of the blade's load-carrying material to the strains induced during operation with safety factors based on full-blade manufacturing process control. Design criteria are derived from idealized material coupon testing. Blades are inspected to find flaws in adhesive joints, lack of material wetting, voids, gaps, and others, and repaired depending on the severity of the flaws. However, the strength assessment and lifetime expectancy of the blade are usually not updated by the inspection results.

Research that helps connect data measured in a factory (including flaws) to its expected life will lead to a better balance between initial cost/time-to-market and life cycle costs.

A key enabler to adopting quality assurance innovations besides finding ways to reduce the impact on cost and factory footprint will be their automation to deliver speed and deployment at scale. These new sensors can be of several types, such as 3D scanners used during material layup to capture detailed positional data for each layer of reinforcement and core. A 3D map of temperature profiles during wind blade production can also provide valuable information, such as localized material properties and potential defects. The automated collection of data detailing how the blade was manufactured can become a digital twin model, which can then be useful for optimizing manufacturing processes, predicting component maintenance and life intervals, and supporting root cause analysis for any future reliability or performance issue. Also, digital twins developed during manufacturing can then support improvements in structural testing (see 2.3.3). Many of these approaches can be matured and demonstrated to a technology readiness level of 5 or 6 in an accelerated fashion at facilities like NREL's Composites Manufacturing Education and Technology facility.

4.3 Recyclable Blades

Conventional blades are challenging to recycle and, at the end of their life cycle, are usually incinerated or disposed of. This trend is not sustainable and requires urgent solutions. Recent research efforts have successfully designed and manufactured blade tips made of thermoplastic resins that can potentially be recycled (Bortolotti et al. 2022). Also, all major wind turbine blade manufacturers have announced products that could be recycled.[5,6,7] However, several challenges persist. To start, many, if not all, of these blades are claimed to be recyclable, but have not yet been recycled. Also, making a prototype blade recyclable might not be the same as recycling at an industrial scale, both in terms of technical challenges and financial feasibility. Therefore, developing the supply chain to allow for wind turbine blade recycling that is economically viable will take time and financial investment to achieve. Not all materials can be easily recycled, like paint, conventional adhesive, and sandwich core. Also, thermoplastics are known to suffer from creep, a phenomenon that is hard to replicate in a laboratory setting. Nonetheless, recyclable blades could offer advantages in the field of aeroelastic stability, with the thermoplastic resin possibly generating higher structural damping (Murray et al. 2021). In addition, fiberglass is a low-value material that is challenging to cost-effectively recycle because of the decline in material properties and significant energy required during the recycling process. Overall, given the ambitious deployment goals that governments have been defining, additional research in this sector is needed to limit the amount of waste generated and to support the wind energy industry in its transition to blade recycling.

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[5] https://www.lmwindpower.com/en/stories-and-press/stories/news-from-lm-places/zebra-project-achieves-key-milestone-with-first-prototype-of-recyclable-blade

[6] https://www.vestas.com/en/media/company-news/2023/vestas-unveils-circularity-solution-to-end-landfill-for-c3710818

[7] https://www.siemensgamesa.com/en-int/explore/journal/recyclable-blade

5 Rotor Sentience and Controls

The IEA Wind TCP 109th Topical Expert Meeting on the grand challenges of wind energy, held in Boulder, Colorado, on February 28 and March 1, 2023, highlighted the need to advance the sensors and control systems of future wind turbines (Veers et al. 2023). Wind turbines operate autonomously in a dynamic environment and contemporary trends discussed earlier—complex wind turbine dynamics, deviations between the design intent and actual "as-manufactured" structures, and meteorological-ocean site-specific conditions—imply that effective loads and performance management require more awareness of rotor state and of the environment surrounding them. We refer to this combination of "situational" and "flow" awareness as "rotor sentience".

While there are several rotor sensor technologies in the market, much of the advancements in the field have come via model-based predictive control techniques supported by control techniques of sensor fusion and combined analytical/numerical state estimation. In addition, rotor system holistic design has been improving with more integrated rotor system testing (e.g., blade and pitch system rigs), simulation (e.g., accounting for pitch system metrics in controls design), and condition monitoring (e.g., analytics with ML approaches to watch pitch system components). The following research areas are needed to advance rotor sentience:

- **Sensor development**. The industry should develop accurate and reliable sensors that characterize the states of blade and pitch system components. These sensors should be low cost and easy to integrate with the wind turbine system, both in terms of hardware and software.
- **Fault-tolerant control**. Fault-tolerant control is becoming increasingly important for the industry, as wind turbines are equipped with an increasing number of sensors. Downtime and operations and maintenance activities cause significant expenses. Therefore, research and development are required to include knowledge of the component states into the controller strategy and allow the turbine to operate safely (potentially using de-rating) despite the detection of faults. Production losses can be significantly limited by developing a fault-tolerant control solution. Such a solution would keep the wind turbine operating at reduced capacity and in a fail-safe state instead of performing an emergency stop when a sensor or a component fails.
- **Controls and simulation**. NREL's Reference OpenSource Controller (ROSCO) has narrowed the gap between sophisticated industrial controllers and publicly available open-source controllers used by the research community (Abbas et al. 2022). ROSCO needs more development to keep up with advancements in the industry to maintain the ability to advance research in rotor loads/event management and sensing technologies. By doing so, the research community will be able to investigate the right trade-offs between operational design and system loads, performance, and reliability.
- **Digital twins**. Digital twins and structural health monitoring are deployed on assets in the field to inform operations and maintenance and next-generation designs. These techniques can be improved, and sensor fusion and state estimation are key parts of digital twins (Branlard et al. 2024).

New controller developments should also be tested, and NREL's Flatirons Campus with its GE 1.5-megawatt and Siemens 2.3-megawatt wind turbines represents a premiere location to conduct ambitious experimental campaigns. The two large wind turbines currently run thanks to their proprietary controllers, but the NREL research team has already investigated the possibility of replacing the industrial controllers with open-source ones.

6 New Rotor Concepts

The combination of better predictive aero-servo-hydro-elastic tools, improved probabilistic design approaches, and advancements in manufacturing technologies and materials as well as sensors and controls will allow for the continuous integration of technological innovations in conventional three-bladed upwind rotors. Regarding new (or renewed) wind turbine rotor concepts, Johnson et al. (2019) conducted a qualitative assessment of promising rotor concepts for land-based wind energy applications. The concepts of highly flexible rotors, upwind or downwind, and distributed aerodynamic control devices were identified as the most promising. An update from the BAR project 4 years later is discussed here.

The investigations within BAR Phase I and II have shown that downwind rotors struggle to build a compelling business case for land-based applications (Bortolotti et al. 2021). However, downwind rotors might offer a better platform for floating wind turbines. The nacelle tilt of downwind rotors would compensate the pitching of the floating platform and hence increase power compared to a conventional upwind rotor. The natural yaw-aligning capability of downwind rotors is also promising for floating applications with limited yaw stiffness.

The second phase of BAR also thoroughly investigated distributed aerodynamic controls mounted along either the leading or the trailing edge of wind turbine blades. The value proposition for these new technologies has been a barrier to adoption for decades, and BAR Phase II landed on similar conclusions (Abbas et al. 2023). The concerns about blade reliability and life cycle implications of more moving parts represent big barriers, and the BAR team has not been able to identify large enough advantages that would help overcome these concerns.

In parallel to BAR, research and development studies ongoing in industry have been advancing other rotor concepts. One example is the radical new concept of a guywire-supported rotor, which was investigated by Vestas and brought to technology readiness level 6 (de Vries 2023). The wires help mitigate gravity loads and the guywire concept has the potential to unlock savings in blade stiffness, strength, mass, and ultimately costs. The multirotor turbine concepts such as the one prototyped by Vestas in 2017 (van der Laan et al. 2019) or the one being developed by the Norwegian company WindCatching[8] also continue to make progress, although none of these concepts has reached the commercialization stage yet.

The research community has also worked to evaluate and advance innovative concepts (Watson et al. 2019). For example, the Denmark Technical University and the University of Strathclyde have been working on the X-rotor (Carrol 2022), which combines the architecture of a vertical-axis wind turbine with small rotors flying at high speed. Similar rotors were proposed for horizontal-axis wind turbines (see page 78 in Jorgensen et al. 2021).

As we look to the future, we see an opportunity for fresh ideas, especially when including offshore applications.

[8] https://www.windcatching.com

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