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An Operations and Maintenance Roadmap for U.S. Offshore Wind

Enabling a Cost-Effective and Sustainable U.S. Offshore Wind Energy Industry Through Innovative Operations and Maintenance

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Disclaimer

Authors

The authors of this report are:

Josh Paquette, Michelle Williams, Ryan Clarke, and Michael Devin, Sandia National Laboratories

Shawn Sheng, Chloe Constant, Caitlyn Clark, Jason Fields, Vahan Gevorgian, Matt Hall, Jason Jonkman, Jon Keller, Amy Robertson, Latha Sethuraman, and Jeroen van Dam, National Renewable Energy Laboratory.

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Contributors:

Aaron Barr, Charles Coppins, Daniel Liu, and Srinivasan Santhakumar, Wood MacKenzie
Guiju Song, Alexandra Hof, and Charles Theurer, General Electric
Miriam Noonan and David Vallee, Cierco Energy
Feng Zhao, Global Wind Energy Council
Marie-Lou Picherit, Ørsted
Katharine York, Simone Stuart-Cole, and Wooyong Song, ORE Catapult
Weiping Pan and Zhu Zhang, Goldwind
Jeffrey Elberling, Samuel Hawkins, and James Saunders, Siemens Gamesa Renewable Energy
Stephen Montecalvo and John Barinaga, Avangrid
Amir Nejad, Norwegian University of Science and Technology
James Carroll and David McMillian, University of Strathclyde
Sally Shenton, Generating Better UK
Peter Tavner, Durham University
Athanasios Kolios, Technical University of Denmark
James Martin, Gulf Wind Technologies
Ken Lee, EDF
William Erdman, Cinch Inc.
Arturo Andersen Chinbuah and Alistair Morris, Carbon Trust
Mel Schultz, National Offshore Wind Research and Development Consortium
Maximilian Friese, Ramboll
Curtis Fox, Electric Power Research Institute
Philip Tortora, IntelStor
Aubryn Cooperman, Pat Moriarty, and Walt Musial, National Renewable Energy Laboratory.

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List of Acronyms

AI	artificial intelligence
CBM	condition-based maintenance
DLC	design load case
DOE	U.S. Department of Energy
ETIPWind	European Technology & Innovation Platform on Wind Energy
GW	gigawatt
IEC	International Electrotechnical Commission
kV	kilovolt
LPS	lightning protection system
m	meter
ML	machine learning
NOWRDC	National Offshore Wind Research & Development Consortium
O&M	operations and maintenance
OEM	original equipment manufacturer
PHM	prognostics and health management
R&D	research and development
RBDO	reliability-based design optimization
ROV	remote operated vehicle
SCADA	supervisory control and data acquisition
TRL	technology readiness level
WTTC	Wind Technology Testing Center

Executive Summary

The United States is currently experiencing rapid growth in the offshore wind energy market, with a pipeline of over 52 gigawatts (GW) (Musial et al. 2023), coupled with state targets of 112 GW. Even considering future wind turbine sizes, this amount represents thousands of new wind turbines installed in a diverse set of environments, each with unique challenges in design, installation, and maintenance. While much can be learned from European and Asian experience with offshore wind energy over the past two decades, it is important to understand the circumstances of the United States. This report explores operations and maintenance (O&M) of offshore wind energy for the United States, based primarily on other countries' experience but also including U.S.-specific considerations (e.g., highly varied climates, ambitious domestic deployment goals, lack of a sufficiently large and skilled workforce with offshore wind experience, and limited vessels for maintenance). The report also provides a roadmap for needed activities to ensure reliability and cost-effectiveness of future installations.

The roadmap was informed through dozens of interviews and a few stakeholder engagement activities representing a wide cross section of the industry, including representatives from original equipment manufacturers, owner/operators, consulting companies, certification agencies, service providers, and researchers. The top O&M challenges identified for offshore wind energy in the United States include:

- **Increase of component and wind turbine size at a fast pace:** Offshore wind turbines are getting bigger (e.g., 15-22 megawatts), with new turbine models introduced at a fast pace (e.g., every 2 to 3 years or less). As a result, a lot of newer offshore wind projects are built using turbine technologies that are not fully matured. This lack of maturity can lead to high finance, reliability (e.g., premature component failures), and safety risks. For the newest turbine technologies on the market, too few turbines may be installed and these may have limited time in operation, making it hard to identify reliability issues and solutions. As a result, there is a need to quantify uncertainty with new technologies to better support financial and O&M decision-making.
- **Unplanned maintenance:** Unplanned maintenance can lead to costs that are often not accounted for during the development stage of a wind energy project, and can also lead to expensive repairs. As a result, there is a need to reduce the frequency of major component overhauls or replacements throughout a wind turbine's design life, and to consider maintainability as a metric during the turbine design or project development stage.
- **Inconsistent objectives for wind turbine manufacturers, wind plant developers, and wind plant owners:** Wind turbine manufacturers and wind plant developers are responding to market conditions driven by site suitability and financial conditions. This leads to a focus on production and development over a shorter time window (e.g., 5 years) with less consideration of O&M costs or risks throughout the entire life of the

turbines or projects. Wind plant owners, on the other hand, need to minimize O&M costs and maximize turbine reliability and project revenue over a much longer time window (e.g., 20–25 years) or throughout the entire life of a project. Another factor making the dynamics among wind turbine manufacturers, developers, and owners more complex is warranty or service contract terms.

- **Low data processing efficiency, lack of standardization, and lack of confidence in models developed using data**: With many sensors and a large amount of data from offshore wind turbines and plants, there is a huge potential to use advanced digital and data analytics technologies to gain insight into asset performance and site conditions. However, there is a lack of standardized or recommended practices, which are important for improving data processing efficiency. In addition, various models developed using data (e.g., machine-learning algorithms) are challenged with gaining trust from end users due to the lack of explainable connections with the underlying physics that these models are supposed to describe.
- **Floating offshore wind technologies with more dynamic loading conditions and components:** In addition to wind turbines, attention also needs to be paid to floating offshore wind support structures. The whole system is subject to combined dynamic loads caused by both wind and wave conditions. Therefore, adding more components (e.g., mooring lines, dynamic cables, and active ballast systems) makes the O&M for floating offshore wind technologies more challenging. Although there are many lessons that can be learned from the oil-and-gas industry in this area, the economics of offshore wind are different, and this is reflected in lower O&M budgets.
- **Permitting, marketing, supply chain, and workforce challenges:** Permitting is an extensive but important process in ensuring compliance with worker health and safety and environmental regulations. Yet, requirements in different markets can add extra costs. For example, lack of service vessel availability can lead to high O&M costs. Limited and costly rare earth materials or parts can pose high supply chain risks. Finally, there is a limited workforce with little offshore wind O&M experience.

To address these challenges, we recommend the following research and development (R&D) topic areas:

- **Failure analysis and mitigation:** This topic area includes investigating and characterizing fundamental material properties that govern degradation processes for mission-critical wind turbine or balance-of-plant components and can be used in component design, prognostic operations, and end-of-life decision support (e.g., decommission, life extension, or recycling). The topic area also includes modeling and analysis research that considers component reliability degradation, potential repairs or prevention methods, as well as developing and validating various methodologies and tools.

- **Monitoring, sensing, and inspection:** This topic area includes either continuous data acquisition using permanent instrumentation on the wind turbine and balance of plant, or periodical data acquisition using anything from turbine-mounted sensors to a full suite of monitoring or inspection solutions.
- **Maintenance execution:** This topic area involves various activities that enable wind plant maintenance, which is determined based on wind turbine or balance-of-plant component conditions. Also included are training or R&D activities to help address future workforce or logistics needs for performing maintenance. This topic area also covers analyzing, evaluating, and implementing various maintenance strategies that are based on inspections, monitoring, modeling, and analysis to minimize costs and maximize safety, performance, and reliability.
- **Design optimization considering reliability and O&M:** This topic area includes the methodologies and tools needed for new offshore wind turbine or plant design by considering reliability, O&M needs, and comprehensive costs (e.g., parts, labor, and vessels) throughout the entire lifecycle of the wind turbine or plant. Based on historical experience of certain turbines or balance-of-plant components, new solutions can be developed with improved performance and maintainability at a lower cost. One critical piece for this topic area to be successful is the feedback loop from the field to the wind turbine or component designers and manufacturers so that quality of future products they deliver to the industry can be improved.
- **Prognostics, health management, and O&M optimization:** By targeting mission-critical components (e.g., blades, drivetrains, towers, and support structures), this topic area focuses on modeling and analysis for anomaly detection, fault diagnostics, prognostics, O&M optimization, and decision-making to support O&M needs during both project development and operations.
- **Digitalization, robotics, and automation:** This topic area includes the use of digital technologies to improve existing or enable new business processes; provide opportunities to increase project value and revenue; employ robotics for wind plant O&M; and automate tasks traditionally done by people to reduce technician health and safety risks.
- **Standards and recommended best practices:** This topic area covers industry standards and recommended best practices that are needed for offshore wind O&M.
- **Experimentation and demonstration:** This topic area includes various scales of wind turbine or plant testing, from the lab and prototype to full scale. These activities are extremely valuable in helping reduce risks with O&M innovations through validation.

Various R&D activities under each topic area are recommended in this roadmap. Research institutions in the public sector will be most effective at conducting the recommended R&D activities by:

- Engaging in fundamental research, technological development, and proof-of-concept demonstrations

- Conducting lower technology readiness level (TRL), fundamental R&D, or applied R&D to help move technologies from lower TRLs to medium or higher TRLs
- Leading consortia to bring together a broad range of stakeholders, from designers to owners and operators
- Developing testing facilities and pilot projects and performing experiments and demonstrations

The efforts of the research community should be complemented by the activities in the private sector. These may include:

- Evaluating, demonstrating, and commercializing technology
- Performing higher-TRL activities that help transfer the R&D outcome to market
- Providing guidance on industry needs
- Sharing data or facility access (e.g., wind turbines or plant as a pilot) for technology demonstration
- Using experimentation and demonstration facilities owned and operated by the public sector

Through dedicated efforts in the topic areas and various R&D activities as identified in the roadmap, the U.S. offshore wind energy fleet can become more cost-effective and sustainable with enhanced performance, reliability, and lifespan.

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1 Introduction

The United States is at the beginning of an anticipated wide-scale deployment of offshore wind energy. The wind energy industry has grown significantly over the past 4 decades, with over 144 gigawatts (GW) of installed capacity on land and comprising 10% of electrical generation in the United States at the end of 2022 (Wiser et al. 2023). Moving offshore entails changes in the lifetime economics of wind plants, as well as new and increased risks. Perhaps chief among these risks are the challenges of performing already difficult and costly operations and maintenance (O&M) activities at sea. Although much can be learned from European offshore wind energy experience over the last 30 years, and that of Asia more recently, U.S. installations will differ in terms of resource, geography, weather, logistics, environmental concerns, and markets. In offshore O&M, the United States can also draw from offshore oil and gas and other marine operations. Integrating industry experiences and the unique conditions that shape U.S. offshore wind O&M into a comprehensive research and development (R&D) strategy will enable researchers in government, academia, and industry to effectively address short-, medium- and long-term high O&M cost challenges to offshore wind deployment and improve the health of this rapidly growing industry. This roadmap can contribute to the vision described in the 2023 *Advancing Offshore Wind Energy in the United States* report by the U.S. Department of Energy (DOE) (DOE 2023), namely that offshore wind energy is not only a critical part of the nation's decarbonized economy and climate solution, but is also developed in a way that is economic, reliable, sustainable, just, and timely (Figure 1). The *Advancing Offshore Wind Energy in the United States* strategy also highlights installation and O&M innovation needs (e.g., installation techniques to accommodate larger wind turbines and reduce transportation risks, intelligent operations enabled by refined simulation and monitoring, and remote and autonomous maintenance) to ensure safety, reduced costs, and lessened impacts on the ocean environment.

Figure 1. All-of-government offshore wind energy vision (DOE 2023)

1.1 Purpose

This report presents an industry and academia-informed roadmap for needed activities, with a focus on R&D of new operations and maintenance technologies and processes to enhance the cost-effectiveness, efficiency, performance, and reliability of O&M at offshore wind sites. The complimentary roles that the public or private sectors play in the recommended activities will be briefly discussed.

1.2 Background

This roadmap leverages land-based wind plant O&M experiences and related offshore wind roadmaps and projects to focus on O&M challenges applicable to the U.S. offshore wind energy market, including floating technologies. The roadmap time horizon goes to 2035, which exceeds most previous research and innovation roadmaps (NOWRDC 2023; ETIPWind 2020),and categorizes potential R&D efforts as short term (now-3 years), medium term (~ 4-7 years), and long term (~ 8-12 years). Additionally, this roadmap highlights public-sector R&D investment opportunities based on the following considerations:

- High risk and high reward opportunity
- Fundamental R&D with longer development times or applied R&D to help speed up technology adoption and deployment
- Challenges not typically addressed by the private sector alone.

1.2.1 Maintenance Strategies

In this roadmap, we categorize maintenance into five strategies, which were adapted from literature and industrial practices based on the definitions and discussions in (Peycheva 2019; Hanly n.d.): corrective (or reactive), preventative, condition-based, predictive, and prescriptive, as shown in Table 1. For the latter three strategies, it is necessary to conduct health monitoring of mechanical and structural components, use advanced data analytics for anomaly detection, employ fault diagnostics and prognostics, and have access to a well-maintained database with failure and usage history. Both condition and structural health monitoring can be accomplished based on existing (e.g., supervisory control and data acquisition system) or dedicated (e.g., accelerometers) instrumentation. The monitoring can be continuous through permanently installed sensors, or periodic through inspections. All these strategies can be executed for wind turbine or balance-of-plant components. Which one is appropriate for a component of interest can be decided through a reliability-centered maintenance analysis (General Electric 2020). A typical wind plant needs to adopt a comprehensive set of maintenance strategies, from corrective to condition-based maintenance (CBM), predictive, or prescriptive, due to the various degrees of criticality and risks from different types of failures associated with many turbines and components.

Table 1. Maintenance Strategies

Strategy	Summary	Setup Cost	Advantages
Corrective (or Reactive)	Repair after a breakdown or failure has occurred	Low	The best strategy for low-priority equipment
Preventive	Maintenance is scheduled on a regular basis in advance either based on time or usage before a failure occurs	Medium	Best strategy to implement without detailed knowledge of component condition
Condition-Based	Maintenance on an as-needed basis based on equipment condition evaluated through measurement, observations, modeling, and data analytics	High	Timely condition monitoring provides many insights into asset's behavior and its projection
Predictive	Use sensors and data to detect trends in the health of a system and predict when failure will occur	High	Earlier detection of failure than condition-based and more cost savings
Prescriptive	Use sensors, data, and advanced analytics (based on modeling, analysis, and database, and so on) to determine root causes of a potential failure so specific corrective action can be prescribed	High	Earlier detection of failure than predictive, substantial cost savings, and highly effective

Maintenance can also be categorized as scheduled and unscheduled. Reactive maintenance can normally be considered as unscheduled, while scheduled maintenance can include preventative, condition-based, predictive, and prescriptive maintenance. Depending on whether a heavy-duty crane is used, the maintenance can also be separated into up-tower repairs that do not need a heavy-duty crane and down-tower major component replacements where heavy-duty cranes are needed.

1.2.2 Land-Based vs. Offshore Wind Operations and Maintenance

There are similarities between land-based and offshore wind applications. Both land-based and offshore wind turbines typically operate in variable conditions, such as changing wind speeds and directions; intermittent operation with many starts and stops; and transient and sometimes high loads from wind, the grid, and emergency stops. Wind turbines are also typically placed in remote locations, which can be challenging to access for maintenance. This limited accessibility is in addition to harsh environmental conditions, such as exposure to contamination and wear from dust and debris (e.g., sand, dirt); wide temperature ranges with the environmental temperature reaching about −30° Celsius (C) and drivetrain temperatures reaching about +100°C; high humidity and water ingress; nacelle and blade icing events; and lightning strikes. Both land-based and offshore wind turbine components can experience complex failure modes. At the plant level, balance-of-plant system components can also fail in dramatically different ways.

Land-based wind energy in the United States is a mature industry, and as such, plenty of lessons learned can be transferred to offshore wind energy. However, there are some unique features with offshore wind O&M in contrast to land-based plants:

- **Accessibility.** Offshore wind accessibility depends on vessels or helicopters and can be dramatically reduced due to wind and waves, farther distance from shore, and ice over water for certain regions. There are extensive logistical concerns unique to the marine environment, including safety risks during personnel transfer from service vessels to fixed or floating platforms. The cost of failure is also higher, as even a very low-cost part (e.g., a cooling fan in a converter cabinet) can be expensive to replace due to difficult accessibility. In addition, undersea cables and structures could become exposed by scour and are much harder to monitor and maintain due to the offshore water environment than cable infrastructure on land.
- **Environmental**. Offshore environments have additional and/or increased environmental hazards, such as salt spray, humidity, and lightning.
- **Scale.** Offshore wind turbines are and will likely continue to be larger than land-based turbines due to the economics of developing offshore wind and easing of transportation constraints. The increased scale creates additional challenges with component inspection, maintenance, and repair.
- **Electrical infrastructure.** Cables between wind turbines and the offshore or onshore substation and grid are underwater and not only subject to loads from waves but have a higher risk of damage than land-based wind plants. An offshore substation poses unique challenges as well, such as needing its own foundation or supporting structure.

1.2.3 Distinct Challenges with Floating Offshore Wind Operations and Maintenance

Floating offshore wind systems introduce several distinct challenges in terms of O&M compared to fixed-bottom designs. First, the support structure being flexible with dynamic forces from marine environment results in greater dynamic motion, leading to increased uncertainties in load, which can be a long-term risk factor. The increased load necessitates careful monitoring and maintenance to ensure structural integrity. This topic is addressed in detail in Section 3.3.

Additionally, the dynamic motion of the support structure poses difficulties for maintenance activities, requiring specialized access and work procedures. Accessing and performing maintenance on floating systems often involves floating-to-floating operations, which demand specialized vessels equipped with motion compensation to improve stabilization and enable fast and reliable service year-round. Alternatively, towing the platforms back to shore for maintenance is an option, although this approach is costly because of the time needed for disconnection, towing, and reconnection, as well as the challenge of finding suitable weather windows for safe operations. A complication with towing is that it may potentially introduce additional fatigue to the turbine and floating substructure, and the frequency of towing should be optimized by considering the fatigue load impacts. Mooring lines and active ballast systems need attention as they are completely new for floating offshore wind with unique failure modes.

Furthermore, floating offshore wind turbines feature electrical cables that hang from the floating substructure rather than being secured to the foundation. These cables experience increased motion and must be designed, monitored, and maintained accordingly to ensure proper functionality.

The operation of a floating offshore wind plant also presents unique challenges. Control systems must maintain platform stability to limit dynamic motion. The control system's ability to influence system dynamics enables load reduction and innovative turbine positioning within the wind plant, potentially improving overall plant-level performance and reliability. Ongoing research in this area aims to identify specific cost or turbine component life-saving opportunities in the operation of floating offshore wind plants (Kang et al. 2017).

Floating offshore wind will also be subject to challenges regarding port availability when being towed to shore for major maintenance, as the number of ports with the necessary water depths and height clearance in sheltered waters is limited. Port depth requirements will be determined by the type of floating platform used in nearby offshore wind plants in which the port is expected to service. In 2023, one turbine in the Kincardine floating offshore wind farm, 10 miles off the coast of Scotland, was towed to Rotterdam, over 400 miles away, due to lack of an available local port with the quayside cranes capable of handling major maintenance for the turbines (Thomas 2023). The Hywind Scotland project, commissioned in 2017 with five turbines and rated capability of 30 megawatts (MW), plans to have significant maintenance done in 2024 by towing the turbines to Wergeland Port in Norway through a close collaboration with the turbine manufacturer Siemens Gamesa (Muthoni 2024). During this period, the plant is expected to be down for 3 to 4 months. The lessons learned can help shape future offshore wind energy projects.

1.2.4 Brief Overview of Related Roadmaps or Projects

There are several related offshore wind roadmaps that are briefly reviewed in this subsection and summarized in Table 2:

- The National Offshore Wind Research and Development Consortium (NOWRDC) developed their first R&D roadmap in 2018 and regularly revise the document to incorporate stakeholder feedback and market changes. The latest version is 4.0 (NOWRDC 2023). The scopes of the NOWRDC R&D roadmaps encompass a broad range of R&D topics, with O&M as one focus of its third research pillar, which also covers installation and supply chain. The time horizon of each roadmap version is 7 years out. In NOWRDC's latest roadmap, O&M research and development topics include innovations (e.g., offshore wind digitalization through advanced analytics), O&M strategies and tools (e.g., drones or robots), and floating wind O&M (e.g., moorings and anchors). The NOWRDC roadmap also provides sample project ideas, which will be referred to in later sections of this roadmap where applicable.
- The European Technology & Innovation Platform on Wind Energy (ETIPWind) developed a roadmap dedicated to O&M in 2020 (ETIPWind 2020a); however, it is not

specific to offshore. Topic areas were further categorized by priority: high and medium. R&D topics highlighted included automation; robotics and big data analytics; cybersecurity; as well as innovations (e.g., digital technologies) enabling performance improvement at the lowest possible cost (seen from a lifetime point of view); condition monitoring technology improvements; and minimization of staffing interventions. Lifetime assessment and condition monitoring, as well as digital tools for control and monitoring, were considered high priorities in the near term, and dynamic cable repair solutions, digital solutions for smart operations, and predicting environmental parameter predictions were considered high priorities in the medium term. For medium-priority areas, the near-term focus was on robotic inspection and repair methods, while the medium-term focus was on decommissioning strategies and technology, as well as solutions for operating in extreme conditions. Digitalization was a high priority for both the near and medium terms. In the medium term, component reliability and plant decommissioning were considered medium priority.

- The United Kingdom's Offshore Wind Innovation Hub developed a roadmap that is interactively accessible online and updated at least every 6 months. The scope covers offshore-wind-related topics. Specific to O&M, the topic areas are organized according to stages of the wind farm life cycle (Offshore Wind Innovation Hub n.d.-a). Operations priorities were categorized as commercial and strategy, coordination and people, and assets and technical. This roadmap considers a relatively longer time horizon (into the 2030s), and priorities include human robot interface techniques, next-generation vehicles (e.g., autonomous, reducing crew transfer costs), automated data processing, and non-diver-based substructure inspection. Maintenance priorities cover both service and reactive maintenance. The priorities for service by the end of 2023 include statutory inspections to decrease variations among countries along with planning via smart tools, and by the end of 2028, automated servicing. Under reactive maintenance, the focuses by the end of 2023 include condition monitoring systems and machine learning (ML) for component fault prognosis, and novel heavy-lift systems, and into the 2030s include autonomous systems for subsea surveys, as well as external blade and internal nacelle repairs and interventions.
- For floating offshore wind energy, there are 211.4 MW installed around the globe as of 2023 (Musial et al. 2023); however, that will increase dramatically in the upcoming decade. A recent roadmap from Offshore Wind Innovation Hub on floating offshore (Offshore Wind Innovation Hub n.d.-b) was released. There were a few topics laid out under O&M (i.e., O&M strategy for dynamic floating conditions, balance-of-plant condition monitoring, floating substructure lifetime assessment, major component change strategies, and access and egress). There were several other resources (ETIPWind 2020b) addressing floating offshore wind technology O&M research and development needs. The World Forum Offshore Wind released reports on major component replacements for

floating offshore wind technologies (World Forum Offshore Wind 2021, 2023) and highlighted innovation opportunities. These opportunities include novel connect-disconnect solutions for mooring lines and dynamic cables for off-site service, as well as crane technologies to support on-site services. The European Union's COREWIND project published a report (Schwarzkopf et al. 2020) that systematically outlines floating-wind-specific O&M requirements and monitoring technologies. They highlighted the importance of considering that floater motions not only influence accessibility but also ability for technicians to work, impacting O&M. Two other O&M innovation trends identified were risk-based inspections, and subsea-residential or remotely operated vehicles (ROVs) to replace divers.

Most of these efforts emphasized logistics needs, such as vessels with increased availability enabled by either handling higher wave heights or a larger supply for both fixed-bottom and floating offshore wind energy, crane-less maintenance, and assurance of technician safety. As summarized in Table 2, another common thread is robotics and automation, minimizing human interventions, along with the need for cybersecurity, as increased volume and types of data collection and transmission, especially wireless, are expected in offshore wind. A few other common topic areas center around digitalization, performance, and reliability improvements, and condition monitoring. For floating offshore wind, dynamic cables and mooring lines need special attention in terms of monitoring/inspection and may need novel service solutions. The current effort will take a different timeline by targeting the U.S. offshore wind energy market and the focus will be on R&D and technology innovation opportunities, not logistics, although some related activities will be briefly touched on.

Table 2. Summary of Related Roadmaps or Projects[1]

Effort	Timeline	Targeted Market	Dedicated to O&M	Offshore Only	Key O&M Innovation-Related Topic Areas	Update Intervals
NOWRDC Roadmap 4.0	2023–2030	United States	No	Yes	Digitalization through advanced analytics; O&M strategies and tools; floating offshore wind	1 to 2 years
ETIPWind Roadmap: Operations & Maintenance	2020–2024	Europe	Yes	No	Automation; robotics and big data analytics; cybersecurity; performance improvement; condition monitoring; minimized human interventions	
Offshore Wind Innovation Hub Roadmap	2023–2030[2]	United Kingdom	No	Yes	Automation; data engineering; sensing; control optimization; life	> 6 months

[1] For floating offshore, no related roadmaps dedicated to O&M available, so two project reports were included. As a result, timeline and updated intervals are not applicable.
[2] Most of activities covered by the Offshore Wind Innovation Hub roadmap end before 2030 with a few exceptions (e.g., automated data processing) forecasted to end by 2040.

Effort	Timeline	Targeted Market	Dedicated to O&M	Offshore Only	Key O&M Innovation-Related Topic Areas	Update Intervals
					management; monitoring; digital twins; smart maintenance planning; automated service; decommissioning	
Floating: Major Component Replacements by World Forum Offshore		World	Yes	Yes	Novel connect-disconnect solutions for mooring lines and dynamic cables for off-site service, as well as crane technologies to support on-site services	
Floating: COREWIND Identification of O&M Requirements and Monitoring Technologies		Europe	Yes	Yes	Floater motions not only impact accessibility but also workability of technicians; risk-based inspections, and subsea-resident, remotely operated vehicles are trending	
O&M Roadmap for U.S. Offshore Wind (Current Project)	2024–2035	United States	Yes	Yes	Not focused on logistics; R&D and technology-innovations-focused, including floating; fundamental to applied, higher risks, longer timeline	

1.3 Roadmap Development Process

This roadmap was developed in three phases. Phase 1 focused on semi-structured stakeholder interviews, mostly in one-on-one settings, to collect raw inputs around a few questions (see Appendix A) designed to serve the development of this roadmap. Additional questions were defined based on the interview input collected during Phase 1. Phase 2 leveraged opportunities at industry workshops or forums through interactive sessions surveying the audience and getting their responses to the questions defined during Phase 1. Phase 3 activities included literature reviews, specific documentation, and expert feedback collection on the draft roadmap before it was finalized.

In total, nearly two dozen interviews were conducted. They represent various sectors of the industry (e.g., original equipment manufacturers (both wind turbines and components), offshore wind plant developers or owners/operators, researchers, and consultants). These stakeholders are distributed roughly even as shown in Figure 2 (a). Also, 71% of them are from industry while 29% are from academia, as shown in Figure 2 (b).

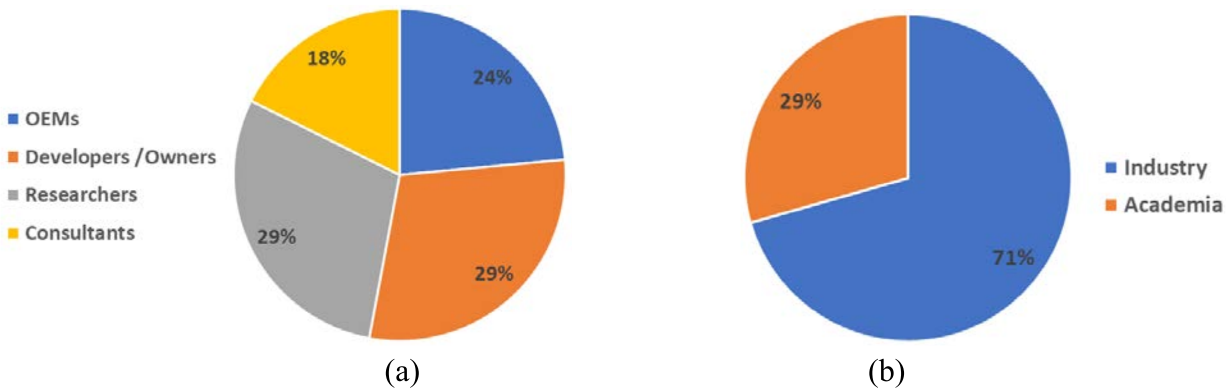

Figure 2. Entities represented by interviewees

Two interactive engagement sessions were organized. One was at DOE, the National Renewable Energy Laboratory, and Argonne National Laboratory annual drivetrain reliability workshop held in Golden, Colorado, in February 2023. There were about 170 attendees, roughly 90% from industry, most of whom are involved in O&M of land-based-wind plants. The other session was at the offshore wind O&M forum held in Berlin, Germany, in March 2023. There were about 45 attendees, representing different roles ranging from wind turbine manufacturers and offshore wind service providers to independent consultants or researchers, most of whom are involved in offshore wind plant O&M.

Feedback collected through all three phases was used to inform the topic areas identified in Sections 3 and 4, and recommended actions in Section 5 of this roadmap.

1.4 Top O&M Challenges

Findings from these stakeholder engagement activities conducted during Phases 1 and 2 were presented at the International Offshore Wind Partnering Forum hosted by the Business Network for Offshore Wind in Baltimore, Maryland, in March 2023. The project team organized a technical presentation and a panel discussion at the forum. The top O&M challenges identified for offshore wind energy in the U.S. market include the following:

- **Increase of component and wind turbine size at a fast pace:** Offshore wind turbines are getting bigger (e.g., 15-22 megawatts), with new turbine models introduced at a fast pace (e.g., every 2 to 3 years or less). As a result, a lot of newer offshore wind projects are built using turbine technologies that are not fully matured. This lack of maturity can lead to high finance, reliability (e.g., premature component failures), and safety risks. For the newest turbine technologies on the market, too few turbines may be installed and these may have limited time in operation, making it hard to identify reliability issues and solutions. As a result, there is a need to quantify uncertainty with new technologies to better support financial and O&M decision-making.
- **Unplanned maintenance:** Unplanned maintenance can lead to costs that are often not accounted for during the development stage of a wind energy project, and can also lead to

expensive repairs. As a result, there is a need to reduce the frequency of major component overhauls or replacements throughout a wind turbine's design life, and to consider maintainability as a metric during the turbine design or project development stage.

- **Inconsistent objectives for wind turbine manufacturers, wind plant developers, and wind plant owners:** Wind turbine manufacturers and wind plant developers are responding to market conditions driven by site suitability and financial conditions. This leads to a focus on production and development over a shorter time window (e.g., 5 years) with less consideration of O&M costs or risks throughout the entire life of the turbines or projects. Wind plant owners, on the other hand, need to minimize O&M costs and maximize turbine reliability and project revenue over a much longer time window (e.g., 20–25 years) or throughout the entire life of a project. Another factor making the dynamics among wind turbine manufacturers, developers, and owners more complex is warranty or service contract terms.
- **Low data processing efficiency, lack of standardization, and lack of confidence in models developed using data**: With many sensors and a large amount of data from offshore wind turbines and plants, there is a huge potential to use advanced digital and data analytics technologies to gain insight into asset performance and site conditions. However, there is a lack of standardized or recommended practices, which are important for improving data processing efficiency. In addition, various models developed using data (e.g., machine-learning algorithms) are challenged with gaining trust from end users due to the lack of explainable connections with the underlying physics that these models are supposed to describe.
- **Floating offshore wind technologies with more dynamic loading conditions and components:** In addition to wind turbines, attention also needs to be paid to floating offshore wind support structures. The whole system is subject to combined dynamic loads caused by both wind and wave conditions. Therefore, adding more components (e.g., mooring lines, dynamic cables, and active ballast systems) makes the O&M for floating offshore wind technologies more challenging. Although there are many lessons that can be learned from the oil-and-gas industry in this area, the economics of offshore wind are different, and this is reflected in lower O&M budgets.
- **Permitting, marketing, supply chain, and workforce challenges:** Permitting is an extensive but important process in ensuring compliance with worker health and safety and environmental regulations. Yet, requirements in different markets can add extra costs. For example, lack of service vessel availability can lead to high O&M costs. Limited and costly rare earth materials or parts can pose high supply chain risks. Finally, there is a limited workforce with little offshore wind O&M experience.

Please note this is not an extensive or fully inclusive list but rather the collective observations gathered from stakeholder engagements. This roadmap will focus on those challenges that can potentially be mitigated with innovative R&D activities and not the less technical topics (i.e., regulations, logistics, or workforce).

1.5 Roadmap Structure

This roadmap is organized as illustrated in Figure 3. Section 2 gives a brief overview of the future U.S. offshore wind market outlook. Section 3 provides additional information on major turbine components: blades, hub and nacelle, structure/foundation, and electrical. For each component, the discussion covers failure mode analysis and mitigation, monitoring/sensing and inspection, and maintenance execution using three subtopic areas. Within each subtopic area, the state of the current practices and technologies are briefly reviewed, as well as emerging technologies. Finally, challenges and needed research activities are briefly laid out. Section 4 follows the same structure as Section 3, but focuses on cross-cutting technologies, such as digitalization, standardization, and testing facilities. Sections 3 and 4 are mainly based on literature review or industry interviews. Section 5 presents recommended actions according to three different time frames (short, medium, and long term) based on the prioritized R&D areas from Sections 3 and 4 and using feedback collected through industry interviews and stakeholder engagements.

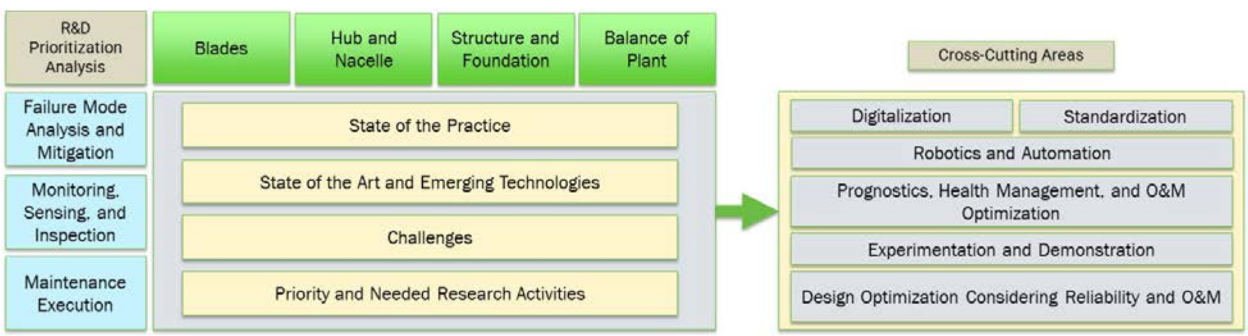

Figure 3. Structure for Sections 3 and 4

2 Development of Offshore Wind Energy in the United States

Buoyed by the Biden-Harris Administration's announcement of a national offshore wind energy target to install 30 GW by 2030 (The White House 2022), as well as state procurement targets, the offshore wind energy industry in United States is advancing quickly from its current nascent state of about 200 MW of installed capacity. This includes the 132-MW South Fork Wind, which was America's first fully built, commercial-scale offshore wind farm, and part of Vinyard Wind. Once fully operational, the 800-MW Vineyard Wind will increase the installed capacity in the United States to close to 1 GW.

Further federal support from the Inflation Reduction Act and the Floating Offshore Wind Shot™, along with a national target to deploy 15 GW of floating offshore wind by 2035 (DOE n.d.), together with increasing state targets, will see this growth continue. Currently, there are 232 MW of floating offshore wind in operation globally, with none in the United States (Janipour 2023). Independent forecasts developed by Bloomberg New Energy Finance and 4C Offshore estimate that offshore wind deployments will cumulatively reach between 30 and 52 GW by 2032 (Musial et al. 2023).

As the number of operational projects in the United States continues to grow, there is a need for increased focus on O&M considerations. With over 59 GW in global capacity from 293 operating projects (Musial et al. 2023), there are lessons learned and best practices that can be leveraged from more developed markets. However, advancements in offshore wind technologies and unique aspects of the U.S. market and environments will necessitate further R&D of innovative O&M technologies and approaches.

In the near term, it is expected that most of the offshore wind energy deployed in the United States will occur on the East Coast. However, floating offshore wind is also planned to be deployed in the Gulf of Mexico, West Coast, and possibly part of the Great Lakes. The Pacific has higher average waves and frequency of seismic events than the East Coast. The Gulf of Mexico has more frequent hurricanes. Locks of the Great Lakes St. Lawrence Seaway System limit the size of vessels that can reach the Great Lakes. These regions come with unique challenges that will influence O&M practices.

3 Components

Wind plants are composed of not only turbines but also balance-of-plant equipment to deliver power generated to the grid. All components require maintenance to ensure performance and reliability. A review of 15 publications on historical failure statistics showed the electrical, control, blades and hub, and pitch systems are the four most critical subassemblies for land-based wind turbines in terms of failure rates (Dao et al. 2019). These are also among the most critical components for offshore wind turbines. In terms of downtime, the gearbox, generator, blades and hub, and drivetrain are the four most critical subassemblies for both land-based and offshore wind turbines (Dao et al. 2019). The definition of drivetrain in Dao et al. (2019) is limited to shafts and bearings, primarily main shaft bearings and mechanical brakes, which is narrower in scope than what is referred to in this roadmap and typically includes the main bearing, shafts, gearboxes, and generator. Some of these components can be extremely costly to replace, as normally heavy-lift vessels are needed in addition to component material, labor, and lost revenue caused by associated downtime. This section discusses these major wind turbine components and balance-of-plant systems by grouping them into four categories: blades, hub and nacelle, structure/foundation, and balance of plant. For each component, failure modes and mitigation approaches, current O&M practices, emerging technologies, challenges, and prioritized R&D opportunities are summarized.

3.1 Blades

Wind turbine blades are among the largest composite structures in the world, with offshore variants now exceeding 130 meters (m) in length. They are also subject to hundreds of millions of fatigue cycles during a 20- to 40-year design life. Further, blades are subjected to environmental degradation from extreme heat or cold, rain, ice, and lightning, etc. (Veers et al. 2023).

3.1.1 Blade Failure Mode Analysis and Mitigation

Three main failure mechanisms are of concern for offshore wind blades, structural failure due to mechanical loads (often coinciding with manufacturing flaws), leading-edge erosion, and lightning strike damage (Katsaprakakis et al. 2021). These failure modes are the same as for land-based turbine blades; however, they may become more prevalent offshore due to scale and a more extreme environment, and the consequence from failure increases given the added difficulty of performing maintenance at sea.

3.1.1.1 State of the Practice

For structural failure, various design codes ranging from aeroelastic simulation to three-dimensional finite-element analysis are employed to evaluate the structural integrity of the wind blade structure under various design load cases (DLCs) and required resistances defined under International Electrotechnical Commission (IEC) standards 61400-1 (IEC 2019a), 61400-3-1 (IEC 2019b), 61400-3-2 (IEC 2019c), and 61400-5 (IEC 2020) to ensure safe operation of the structure over its lifetime and mitigate the chances of structural failure. Partial safety factors are used to account for uncertainty in loading, manufacturing, material properties, and modeling.

For leading-edge erosion, a combination of accelerated laboratory testing and simple analytical equations are used to assess the risk occurrence and ability of the protection system to adequately hold up during the design life of the turbine (DNV-GL 2020). The current practice for mitigation of erosion comes in various forms of coatings and tapes that can either be applied in the factory during manufacturing or in the field. However, these protection systems are costly as they may need to be applied periodically throughout the entire life cycle of the blades and can be subject to variability in their installation. Erosion is typically diagnosed based on visual inspection, with categories ranging from light (Category 1), where damage is limited to the protective coating only to severe (Category 5), where erosion has penetrated through the laminate. Repairs to the coatings and composite material are performed up-tower and usually only when damage has progressed to at least Category 3.

Damage from lightning strikes is the largest cause of catastrophic failure in land-based wind turbine blades and the most frequent insurance claim filed by wind farm owners (DNV 2023; Jou 2022). Lightning protection systems are designed in accordance with IEC 61400-24 (IEC 2019d). Offshore turbines are potentially more susceptible to increased lightning strikes due to open waters, increased annual frequency of lightning flashes, increased use of carbon-fiber spar caps, and direct exposure underneath a lightning storm (DNV 2023). However, current lightning protection system design requirements are the same for land-based and offshore installations, with only minor modifications of location factor used in estimating the annual number of lightning flashes to a single turbine and it can reflect relatively higher consequences from lightning strikes in offshore wind.

3.1.1.2 State-of-the-Art and Emerging Technologies

The current state of the art for failure mode analysis and mitigation for offshore wind turbine blades involves advanced analysis techniques and technologies to enable a condition-based maintenance approach, which includes identifying and prioritizing the level of risk associated with each component or system. It considers factors such as the likelihood and consequences of failure (e.g., cost of maintenance or repair). Once components or systems of high risks are identified, a reliability-centered maintenance analysis can be conducted to assign the most appropriate maintenance method.

The state of the art in failure analysis due to mechanical load involves progressive failure analysis. This type of analysis enables condition-based maintenance by allowing operators to assess the risk of failure of their wind blade structure in real time by incorporating inspection data with damage into their models.

State-of-the-art mitigation techniques specific to leading-edge erosion of wind blades include advanced leading-edge protection materials like metallic and ceramic leading edges, or polyurethane coatings that can better withstand the high-erosion-environment offshore. Also, the concept of operating the turbine in an "erosion safe mode" during high-erosion-potential events such as storms has been suggested as a potential mitigation strategy (Bech et al. 2018). While improvements in lightning protection systems for both land-based and offshore applications are ongoing, novel ideas like conductive coatings/paintings for blade protection (Lewke 2007; Arctura 2023), lightning diversion tape to increase lightning reception area and decrease damage to the blade,[3] and lightning monitoring systems to better understand lightning strikes, are all being developed and tested. Understanding lightning interactions with wind turbine blades and lightning strikes will advance the design and efficiency of lightning protection systems (Griffin 2023).

3.1.1.3 Challenges

Offshore wind blades are becoming longer at an ever-increasing rate. As offshore wind blades increase in size the primary failure mechanisms can change or may be exacerbated (Jensen et al. 2012). The time to market and speed with which wind blades are changing size mean that there is no historical data to effectively analyze failure rates and failure modes. Being able to identify, predict, and effectively mitigate these failure mechanisms and rates with our analysis tools from fundamental understanding of the physics as wind blades scale in size is key to effective O&M of offshore wind blades.

Wind blade repairs offer an additional challenge with analyzing failure modes and mitigating failures of offshore wind blades. Repairs are essential for mitigating failure of wind turbine blades. However, the combination of difficult accessibility and nonoptimal environment for composite repairs offers a difficult set of circumstances to ensure effective and high-quality repairs. Composite repairs have been shown to be sensitive to minor defects and variations in quality (Mishnaevsky 2022). Ensuring consistent and quality composite repairs is key to effective offshore wind blade O&M.

Offshore blades will be more susceptible to increased annual lightning strikes; however, that increase has not been quantified. While lightning protection systems exist, they fail frequently enough for lightning to continue to be the largest cause of unplanned downtime (DNV 2023; Jou 2022). Lightning protection systems (LPS) for land-based wind turbines, although designed by following international standard IEC 61400-24 (IEC 2019d), still encounter a variety of problems leading to these failures. Basic lightning physics interactions with wind turbine blades are still not well-understood, leading to concerns about LPS designed for land-based wind turbines according to IEC 61400-24 (IEC 2019d) being inappropriate for offshore installations. Current LPS systems are also inaccessible and difficult to test, requiring testing of sections individually rather than the entire system. The quality of the LPS for each design is usually unknown until problems arise.

[3] One lightning diversion tape example: Strike Tape (Weather Guard Lightning Tech n.d.).

3.1.1.4 Priorities and Needed Research Activities

There are several research needs for analyzing and mitigating failures in offshore wind turbine blades. Some of the key areas that require further investigation include predictive failure models for large blades and better composite repair methods. There are a few other areas needing further R&D:

- The size, location, and cost of offshore wind blades mean the consequences of failure are much higher than their land-based counterparts. This necessitates the need for better repairs of wind blades, approaching fatigue properties that are close to virgin material.
- Progressive failure analysis of wind blades requires using accurate predictive models of damage growth or progression in highly complex composite structures. Continued research into composite damage growth models that can adequately handle manufacturing and loading uncertainty is still needed.
- Leading-edge erosion will continue to be an issue for offshore turbines as they have higher tip speeds in general, which leads to exponentially higher damage rates. Erosion mitigation solutions such as speed reduction in erosive conditions and better leading-edge protection systems should be developed and implemented.
- Investigation into changes and understanding of lightning physics interactions with wind turbines offshore will allow for improved, more focused requirements for offshore lightning protection systems in a needed update to IEC 61400-24 (IEC 2019d). In addition, advanced lightning monitoring systems will provide detailed information on lightning strikes, both further advancing lightning protection system design and efficiency, reducing lightning damage and downtime. The need for an updated IEC standard is also voiced by DNV (Griffin 2023).

3.1.2 Blade Monitoring, Sensing, and Inspection

While structural health monitoring and sensing practices are inconsistent, inspection methods like drone and visual are widely used. Vast improvements are needed in all three areas to improve reliability and worker safety of offshore installations. Shortfalls currently exist around identification and repair of blade damage and defects due to ever-changing blade design, proprietary data, cost of poorly working systems, and shortage of experienced wind technicians. Data collected through monitoring, sensing, and inspection then suffers from varying interpretation throughout the industry, heavy reliance on artificial intelligence (AI), which are not fully validated and trustworthy (again due to lack of publicly available data), and from lack of expertise (Griffin 2023).

3.1.2.1 State of the Practice

Visual inspections are performed at regularly scheduled intervals to detect visible damage and defects on the surface of the blades and can identify surface cracks, leading-edge erosion, impact, and lightning damage. These inspections are typically carried out by drones with subsequent down-tower visuals via cameras and binoculars or up-tower via a rope technician. After the drone inspection damage is categorized, and repair schedules are planned around ratings and ideal downtimes based on yearly weather; however, inaccurate damage classification can lead to catastrophic failure. Lightning protection systems are inspected at regular intervals using simple connectivity tests.

Internal inspection of the blade can also be carried out via a camera deployed by a small robotic vehicle or up-tower blade technician. Rope technicians can also complete a nondestructive evaluation, typically an ultrasonic inspection, on the surface of the blade to learn about damage propagating within the blade.

Structural health monitoring and sensing techniques for blade health are not used consistently throughout industry although there are some employed for load sensing (Moynihan et al. 2022). One of the reasons is the relatively low annual failure frequencies and ease of access for maintenance to land-based turbines, which are different for offshore.

3.1.2.2 State of the Art and Emerging Technologies

Understanding the impacts of increased turbine scale as the industry moves offshore will be important and will help identify innovation pathways while reducing risk. This will allow for more instrumented blades, improved monitoring, and larger amounts of data. However, the right combination will need to be identified. Innovation of technologies is expensive but will help reduce risks and costs associated with ensuring human health and safety and downtime. The cost reduction is amplified in offshore installations where there is a higher concern for human risk due to unpredictable operating environments, and downtime due to unscheduled repairs, which can be significant due to waiting for weather windows.

Advanced robotic technologies for blades are rapidly evolving with commercial capabilities ranging from advanced inspection and automated repair for leading edges, to routine tasks like checking LPS continuity. These robots may also be equipped with instrumentation packages, thereby aiding in structural health monitoring, or future technologies to enable repairs of structural components like blades.

3.1.2.3 Challenges

Offshore weather conditions are less predictable and wind installations in some locations will see more frequent and higher intensity windstorms, icing, and lightning. Offshore wind turbines will generally have higher tip speeds, exacerbating erosion damage (DNV GL 2020). These conditions will increase the speed of wear on blades, which will increase needed inspection and repair, and drive innovation of monitoring, sensing, and inspection technologies. Choppy water conditions can cause trouble for drone or robot operators or make technicians who are traveling to the turbine sick and unable to perform tasks.

Lack of standardized wind blade technician training and consistent skill sets are problems that will extend to offshore installations. Sensors and monitoring, if implemented well, can more precisely guide actions, and make more efficient use of technician time. Currently, in the U.S. land-based wind energy industry, repairs are rarely monitored or checked for quality, which can lead to repeat failures. Importantly, knowledge sharing of repair effectiveness between owners and /operators is limited. Some operators are taking a fully preventative approach whereas others are more reactive, choosing to repair problems only when they reach an advanced state. Warranties for field repairs are quite short, and often end prior to deficiencies becoming apparent (Griffin 2023). Updated O&M standards combined with sharing case studies (e.g., by DOE and its national laboratories) for best practices will help mitigate these problems.

Current sensing and monitoring systems are in many cases expensive to install and operate and suffer from poor data quality. Data collection is also a challenge. There is a large amount of data that needs to be routed efficiently, often from a remote site to a responsible party who can process that information. Often accuracy is lacking in assessment of this data after inspection/collection, AI accuracy in damage categorization of drone images is not publicly shared but overly relied on, and blade expertise is not widespread (Griffin 2023).

3.1.2.4 Priorities and Needed Research Activities

The following research activities are recommended:

- Development and de-risking of advanced, reliable, and cost-effective sensors (e.g., inside blades) and structural health monitoring systems for wind turbine blades are needed for monitoring loads, damage initiation, and growth. Structural health and far-field sensing (i.e., digital image correlation) and monitoring will allow for collection of stress and strain data and aid in understanding dynamics, loads, and aeroelastic impacts of blades for floating offshore installations. While there will be more cost upfront, O&M costs will be reduced through a more comprehensive understanding of the condition and performance of blades, and industry will get better at predicting and preventing failures.
- Data outputs of these systems will need to be compatible with existing supervisory control and data acquisition (SCADA) systems. Case studies are needed for these systems to prove their technological abilities for operators to adopt them. Training and technician infrastructure will need to be set up to help close the gap in the lack of skilled blade technicians.
- Blade inspection and automated repair technology will also need to be developed to operate successfully and efficiently in the offshore environment. Novel automation solutions and repair techniques will help drive better detection and reaction to damage and defects, as well as reduce the time waiting for a follow-up inspection or repair crew to be deployed. The risk aspect of a rope technician will also be reduced due to decreased need for human intervention, and the quality/frequency of inspection and repair will be improved through advanced automation enabled by drones or robots.

- Advanced camera systems to take pictures to better monitor LPS and internal blade health are needed, especially for those making decisions on land and not present in the blade itself.

3.1.3 Blade Maintenance Execution

3.1.3.1 State of the Practice

The state of the practice in maintenance execution for offshore wind turbine blades involves a combination of preventive and corrective maintenance. Maintenance for offshore wind turbine blades includes visual inspection at regular intervals and repairs completed when damage above a certain threshold is found. Inspections are carried out either using a technician with binoculars or drones, in many cases. Internal inspections are done by technicians in the nacelle. Repair activities can include composite material (scarf) repairs for laminate cracks or delaminations, epoxy injections for bond line cracks, and sanding and replacing leading-edge protection when leading-edge erosion occurs. Wind blade repairs are done almost exclusively with technicians rappelling on ropes to access the wind blade structure.

3.1.3.2 State of the Art and Emerging Technologies

The state of the art in maintenance execution of wind blades is moving beyond preventive and corrective maintenance toward predictive maintenance. Predictive maintenance allows for the minimization of O&M activities which in turn reduces cost and risk.

State-of-the-art technologies of maintenance execution for offshore wind blades involves reducing risk and exposure of the technicians. Robotics and automation are increasingly being utilized for high-risk maintenance efforts such as inspection and repair. For example, multiple companies have recently come out with drone-robot combinations for leading-edge erosion repair execution (Bjerge 2023; Kuhlmeier 2023).

3.1.3.3 Challenges

While many routine maintenance activities such as leading-edge erosion detection and repair are well on their way to being fully automated, the inherent complexity in composite structural repairs makes it difficult to replace the human component. An additional challenge is large structural defects and failures, which in wind blades have historically necessitated the blade's removal from the wind turbine to repair on the ground. For offshore wind, removal of the wind blade from the turbine is logistically difficult and extremely costly once installed. Condition-based blade maintenance is expected to be economically beneficial, but it may impact safety margins should the frequency of maintenance be relatively reduced. Additionally, in the current state of the industry there is little to no data sharing of the blade design, manufacturing, or likely failure modes from the original equipment manufacturers (OEMs) with the owner/operators.

3.1.3.4 Priorities and Needed Research Activities

Two main areas of needed research in offshore wind blade maintenance execution are up-tower repair of large defects and damage, and increased automation of inspection and repair tasks.

- Currently, significant damages, such as extensive delamination in the root region or connecting bolt failures, often require removing the blade from the turbine. The process of blade removal is much more costly offshore, and developing procedures and techniques that enable up-tower repair of most damage sizes and locations on wind blades is essential for offshore wind energy to be economically more competitive, which is especially relevant for repairs near or at the root.
- The other key area for maintenance execution research for wind blades is continuing to develop automated solutions for inspection and repair. Currently, aerial drones assist wind turbine technicians in visually inspecting wind blades, speeding up inspections and increasing safety. Yet, research is needed to continue to support this trend and determine where drones and robots can be used to either physically replace or assist in the advanced inspection and repair of wind blades; and de-risking and improving the quality of the maintenance tasks.

3.2 Hub and Nacelle

There are various wind turbine components in the hub and throughout the nacelle, which typically include pitch systems, main shaft bearings, gearboxes, and generators in both geared and direct-drive turbines. As the offshore turbine rating increases, the weight and dimensions of these components also climb quickly. For example, for a 15-MW direct-drive turbine on a monopile, the hub and nacelle can weigh more than 800 metric tons (t), which includes a hub weight of about 200 t and the generator weight being about 350 t. In addition, the hub height for this turbine is about 150 m and the main bearing diameter is about 3 m (Gaertner et al. 2020). The reliability of these components is becoming increasingly critical as offshore turbines become bigger and are installed farther from shore, and their maintenance is much more costly than land-based wind turbines.

3.2.1 Hub and Nacelle Failure Mode Analysis and Mitigation

For land-based wind turbines, the power electronics have been shown to be the most frequently failed components. They are typically inexpensive to fix, but this may change for offshore wind due to the increased challenge of accessibility. The annual fault rate of turbine electrical components including generators and power converters is high and they also have long downtimes, although the latter of which is still shorter than for gearboxes (Liang et al. 2022). Based on recent offshore wind operational experience in Europe, direct-drive turbines may have lower annual failure rates than geared turbines, but the operational expenses were similar based on jack-up vessel movement data analysis (Tobaben 2023). Industry experience has shown that most failure modes occurred to these components are the same between land-based and offshore due to the similarly adopted technologies.

Gearboxes are designed in accordance with IEC 61400-4 (IEC 2012), including International Standards Organization (ISO) 6336 gear rating and ISO 76, 281, and 16281 bearing rating standards (Nejad et al. 2022). Gearbox failures for land-based turbines are mainly related to bearings and the top failure mode appears to be axial cracking (Sheng 2014; Pulikollu et al. 2021), whereas rolling contact fatigue is not significant because it is sufficiently understood and accounted for in the design process. Some models still suffer gear failures in a few modes like bending fatigue, wear, and fracture (Pulikollu et al. 2021). Main shaft bearings are designed in accordance with IEC 61400-1 (IEC 2019a), with ISO 76, 281, and 16281 bearing rating standards (Nejad et al. 2022). They can also fail by axial cracking, as well as scuffing, pitting, cage fractures, and a few other failure modes (Hart et al. 2023).

Squirrel cage induction generators and doubly-fed induction generators are popular in legacy geared wind turbines and the main component failures occur are related to stator wedges, slip ring, rotor windings, wye ring, and generator bearings (Pulikollu et al. 2023). For new medium-speed and direct-drive offshore wind turbines, permanent-magnet synchronous generators are the most common type of failure. Among the most common permanent-magnet synchronous generator failure modes are cooling system failures (e.g., heat exchanger pipework, hoses, and motor failures), winding failures (e.g., insulation and connection failures and contamination), bearing failures (e.g., loss of lubrication; wear and failure of mechanical elements; and electrically induced failure), stator core failures (e.g., vibration, circulating current, and hot spot), and demagnetization (Freire et al. 2021).

Newer offshore direct-drive wind turbines employ integrated control systems with a full-scale converter for simultaneously improving power quality, reducing loads, damping mechanical resonances, and providing grid connection stability. A common failure mode of such converters is short-circuited wiring (Andreasen et al. 2021). A second common failure mode is direct current (DC)-link capacitor failure, which is mainly caused by material wear and dielectric breakdown at a high operational temperature.

Pitch systems can generally be grouped into electric and hydraulic types. Pitch system failure rates in some populations are over two times higher for offshore plants than land-based plants (Dao et al. 2019). For electric pitch systems, the top failed components are power electronics, battery packs, relays, and instrumentation. For hydraulic pitch systems, the top failed components are the hydraulic accumulator/oil tank, hydraulic valve, pitch cylinder, and instruments (Walgern et al. 2023). Both types suffer from pitch bearing failures. The failure rates tend to increase with rated turbine power.

3.2.1.1 State of the Practice

Mitigation of gearbox or main shaft bearing failures has been achieved because of improved materials as well as heat treatments, coatings, surface engineering, and advanced lubricants. Auto-lubrication has been explored on main shaft bearings and pitch systems. Another type of mitigation attempted by the industry is using an improved control valve in hydraulic pitch systems.

3.2.1.2 State of the Art and Emerging Technologies

For certain components, new bearing types are being explored. For example, hydrodynamic plain bearings in gearboxes are now widely available and a few manufacturers are performing bench-level testing and even developing commercial hydrodynamic plain bearings for use as the main bearing (Daido Metal n.d.; Waukesha Bearings n.d.). Geared and direct-drive turbines are both used in offshore. A recent trend is that geared drivetrains for offshore turbines are appearing to become more common (Durakovic 2021, 2023; Buljan 2021; Vestas n.d.).

For new generator technologies, there is ongoing work using superconducting technologies (General Electric Company 2021) or ferrites—an iron-rich ceramic—for magnets (Snieckus 2019). The superconducting technologies enable the wind turbine generator to produce more power in a smaller, lighter package using coils of superconducting wire that are made from an alloy of titanium and niobium (commonly used in steel) to produce the magnetic field.[Error! Bookmark not defined.] The ferrites option features a modular, multiple-stage design to save on cost and increase robustness. Both technologies can mitigate size constraint and supply chain challenges caused by the need for rare earth materials in conventional permanent-magnet generators. However, not much O&M information is available as both are still not commercialized and far from becoming state of the art.

3.2.1.3 Challenges

Direct-drive generators may become infeasible economically and physically if they grow too large. Traditional permanent-magnet generators face challenges with high cost and limited availability of rare earth materials, which could be a supply chain risk.

For almost any failure modes of interest, there are limited number of failed component samples with data that provides traceable failure progression and can be used to support needed research, unless specific considerations were made upfront under a project and dedicated data collection efforts were made. Each failure mode is often driven by various factors that are hard to single out and prioritize. This difficulty could be offset to some extent by collecting life cycle data on a bench-top test rig or performing accelerated life testing. Historically, even within one organization, the communications between project development and O&M teams are not fully transparent or adequately frequent which has hindered the potential to maximize the benefits from field operational experience.

Mitigation solutions typically take a long time to be accepted by the industry because the wind industry is not high risk-taking and slow to adopt new technology innovations. For example, there are many stakeholders to go through, from solution providers and component designers/manufacturers to wind turbine manufacturers and end users. In addition, there may be needed certifications for each stakeholder to show expected performance can be delivered by the introduced solution.

3.2.1.4 Priorities and Needed Research Activities

These components located in the hub throughout the nacelle can fail in various complex modes. In some of these failure modes, if not most, physics is not fully understood and cannot be appropriately accounted for during design. However, they may be prevalent in the field (e.g., bearing axial cracking). As a result, it is necessary to conduct systematic research to improve both inherent and operational reliability, identify drivers and root causes, and invest in mitigation solutions, with each step needing validation to be conducted as much as possible. Specific to offshore, expanding the inputs as needed to account for wind, wave, and overall system dynamics is required.

It is costly to conduct full-scale testing in either a dynamometer or field wind turbine. Sometimes the scale of the newly developed component is too large and there are no testing facilities available. Down-scale testing in a laboratory environment can be conducted to inform design and manufacturing reliability but cannot reflect actual operation conditions as the full-scale testing. There is an opportunity to leverage high-performance computing resources by developing models to simulate the physics or degradation process for certain failure modes. A prerequisite to creating these models is having a solid understanding of the physics, as well as boundary conditions and key drivers. These models could be used to evaluate various mitigation solutions, down select, and choose one or a few components for full-scale testing.

There is a need for some sectors of the industry to close the loop between O&M and material, manufacturing, and design, which can help improve performance of future products by incorporating some proved mitigation solutions or recommended practices.

3.2.2 Hub and Nacelle Monitoring, Sensing, and Inspection

The immediate goal of monitoring, sensing, and inspection is to detect turbine component faults early so cost-effective O&M can be practiced, and ultimately to identify root causes of component failure, which help improve future products.

3.2.2.1 State of the Practice

Regarding wind turbine components, the focus has been on main shaft bearings, gearboxes, and generator bearings. Normally, end users are the first to conduct performance monitoring or anomaly detection based on advanced analysis of SCADA data. The industry has also widely started practicing fault diagnostic and prognostic analysis based on dedicated condition monitoring technologies such as vibration or oil debris monitoring. Using multiple data streams and various technologies help cover a broader range of components and possible failure modes. The performance monitoring and component fault diagnosis/prognosis capabilities are enabled by various instruments which are permanently installed, and data are collected continuously.

For vibration analysis, raw signals are often preprocessed to extract features in either the time, frequency, or time-frequency domains. For the time domain, traditional statistical parameters (e.g., averages and root mean squares) can be extracted. The time series signals are also typically converted to frequency domain through Fourier transform as an example, or time-frequency domain through Wavelet analysis. Further analysis of these frequency or time-frequency domain signals can be used to detect various mechanical system problems, such as imbalance, misalignment, resonance, bearing or gear failures, looseness, etc. For bearings and gears, there are popular algorithms, such as enveloping analysis (or amplitude demodulation) or time-synchronous averaging, which have been shown to be effective for condition monitoring.

In terms of online oil debris monitoring, the sensors are typically based on magnetic field principles, which can detect debris size down to 30 ~ 40 microns. For oil cleanliness measurements, it is often based on optical approaches and can measure particle size down to 4 microns, and typically coded the results according to ISO 4406 (Noria Corporation 2012) into three bins: > 4 microns, > 6 microns, and >14 microns. The oil debris is typically used to monitor component damage and oil cleanliness is typically used to monitor contamination levels, which can be when the oil is received or during the gearbox operation, or control run-in of wind turbine gearboxes.

The industry is also practicing oil or grease sample analysis at certain time intervals, though it suffers from inconsistent sampling by technicians and variance caused by analysis procedures or techniques used by different laboratories. Of course, these analyses involve time needed for sampling, shipping, and reporting. One observation is that oil condition trending may not correlate with component damage well and therefore both need to be examined in the field.

Bore-scope inspections are often used periodically to check component conditions. They can also be triggered by analysis conducted based on either SCADA or dedicated condition monitoring system data. The outputs can be used to cross check these analysis results or inform maintenance decisions.

3.2.2.2 State of the Art and Emerging Technologies

For vibration analysis, a new wave of algorithms or models around cepstrum have been studied. Cepstrum is defined (Bogert et al. 1963) as the spectrum of the logarithmic power spectrum (i.e., in decibel amplitude form) and can be used as an effective way to represent repeated patterns in a spectrum (e.g., gear fault detection). In addition, it can consider both amplitude and phase information, be used to extract fault signals from noises, and explored further to help improve offshore wind turbine hub and nacelle component monitoring. Given there are multiple components of interest, an ensemble approach using various vibration signal and feature extraction methods is recommended. For oil-condition monitoring, beyond debris, the industry has also started trying various sensing principles (e.g., dielectric[4]) to continuously monitor changes in oil quality. In addition to traditional oil-sample analysis, filter-element analysis has also been conducted to identify which component might have been damaged by comparing the debris and a known alloy composition. The main obstacle with large main filtration loop filter

[4] Dielectrics are insulators and often used in the context of capacitors, wherein the material placed across the plates of a capacitor like a little nonconducting bridge is a dielectric (Elert 2024).

element analysis for wind turbines is cost, which can be mitigated to some extent by using a smaller side-stream filter element. In terms of sensing, edge computing[5] has enabled measurements from more sensing channels or a reduced amount of raw data transmission. Combining edge computing with the Internet of Things can play a significant role in handling future wind plant voluminous, heterogeneous data and distributed features under limited storage and processing capabilities (Nejad et al. 2022). Also, electric signature analysis based on dedicated instrumentation mainly for generator or converter condition monitoring is being explored, tested, or adopted at a smaller scale by industry. One new area of research is on virtual sensing, which infers unmeasurable variables (e.g., loads on the main shaft) from those that are measurable (e.g., tower accelerations).

3.2.2.3 Challenges

For vibration analysis, one main challenge is effective signal or feature extraction algorithms for gearboxes with multiple planetary stage configuration due to increased level of complexity or main bearings and direct-drive generators that rotate at a very low speed. For oil sample analysis, inconsistencies are caused by practices used in the field during sampling, and procedures used by various oil analysis laboratories. Most end users in the wind industry are concerned about costs due to the number of systems adopted that can easily reach hundreds if not thousands of dollars, and it can take years for new technologies to be tested or adopted in the field. Due to the accessibility challenges in the offshore wind environment, components with higher failure rates (e.g., power electronics) cannot be handled in the same manner as land-based anymore. It will be challenging to monitor components with high failure rates cost effectively and address new failure modes on large mechanical or structural components that are not yet well-accounted for. In addition, some components (e.g., planet bearings in a gearbox) are in locations that are challenging, if not completely impossible, to inspect.

3.2.2.4 Priorities and Needed Research Activities

There is a need for performance improvements in current monitoring solutions or development of novel cost-effective technologies including sensing for more complex gearbox configurations (e.g., multiple planetary stages) and low-speed rotational components (e.g., main shaft bearings in both geared and direct-drive wind turbines).

Technology demonstration and validation is another opportunity to potentially help shorten the adoption timeline for novel technologies by end users in offshore wind energy. Automation (e.g., oil sampling) has the potential to minimize variations from human operations in oil-sample or filter-element analysis. To gain more benefits from advanced vibration analysis, it is valuable for the modelers to have access to the needed component data during both the model development stage and monitoring data during the turbine operation stage, which may not be feasible in

[5] Edge computing is a distributed computing framework that brings enterprise applications closer to data sources. This proximity to data at its source can deliver strong business benefits, including faster insights, improved response times, and better bandwidth availability (IBM n.d.).

commercial operation but is encouraged for technology innovations in related topic areas. Like other industrial applications, wind turbine component failures happen but the number of records is limited. Therefore, it is necessary for stakeholders to collaborate and share component life data. One or a few centralized data repositories for various purposes (e.g., model development and validation, performance and reliability benchmarking) will be very valuable to evaluate novel technologies, identify opportunities for improvements, and speed adoption of standardized data collection or analysis practices. For monitoring solutions, new methodologies are needed to improve the effectiveness of vibration analysis for components with complex dynamics or low rotational speed, and electric signature analysis for generators. It is also beneficial to account for uncertainty, thereby showing increased confidence in recommendations from the models with lower missed detection or false alarm rates. As more sensors are deployed and become digitally connected, and the amount of data storage and transmission grows, it will be necessary to address cybersecurity risks with O&M of wind turbines, plants, and power transmission systems.

3.2.3 Hub and Nacelle Maintenance Execution

3.2.3.1 State of the Practice

Various types of maintenance (as shown in Table 1) can be carried out on hub and nacelle components. For example, scheduled maintenance can be accomplished based on either time or usage, or condition assessment, predictive, and prescriptive analysis. In addition to reactive and time- or usage-based preventative maintenance, increasingly more wind plants have started practicing condition-based maintenance (CBM) at land-based wind plants, and even more for offshore. For some turbine models, their gearbox high- or intermediate-speed-shaft components can be repaired up tower without using or moving a heavy-duty crane. However, if the damage is in the planetary stage of a gearbox, most likely a down-tower full gearbox replacement is needed, which typically requires a jack-up vessel that is equipped with a heavy-duty crane. Similar down-tower maintenance actions are typically needed for main shaft bearings, direct-drive generators, or pitch bearings. For offshore wind energy, due to the increased financial impact, it is more important to maximize scheduled or planned maintenance and minimize unscheduled maintenance than land-based wind plants.

3.2.3.2 State of the Art and Emerging Technologies

Predictive and prescriptive maintenance, enabled by advanced sensing techniques, novel and effective diagnostics and prognostics algorithms, and well-maintained databases for major mission-critical components, are emerging. To mitigate the financial burden from jack-up vessel service costs, some exploration of nacelle-mounted cranes or crawler cranes has started. Robotics are also being explored to conduct certain routine maintenance activities, such as oil sampling. Modularized design (e.g., splitting main shaft bearing housing from one to two pieces) is adopted for some large size components, and it can potentially enable up-tower maintenance of major mission-critical components.

3.2.3.3 Challenges

Being able to conduct wind turbine repairs in the field and lessen component replacement time are critical. It is ideal for offshore wind plants to completely avoid down-tower full component replacements. For O&M optimization, it is necessary to consider availability of the type of vessel needed, wind and wave conditions, crew, and parts availability. For example, wave height can impact whether a technician can be safely transferred from a vessel to a wind turbine. These factors present some of the many challenges related to offshore wind maintenance planning. Also, the optimization objectives may not be limited to annual energy production or levelized cost of energy alone but can potentially add some conflicting objectives such as component loads, life, and electricity marketing prices. Like land-based wind turbines, there are many components that can fail in dramatically different ways. The physics of some of these failure modes is not well-understood. It also takes time or collaboration among multiple plants to establish a database with enough records to support predictive and prescriptive maintenance. Like other solutions, the adoption by end users is not easy; therefore, it is necessary to effectively demonstrate both the technology and benefits.

3.2.3.4 Priorities and Needed Research Activities

Due to the complexity and uncertainty of offshore wind energy O&M, it is important to perform maintenance that is based on thorough analysis and modeling, which can cover whole power plants, from wind turbine components and balance-of-plant systems to grid connection, and consider crew, spares, accessibility, vessels, costs, etc. Traditionally, optimization of O&M may target a single objective, which is often not realistic, and there is a need of research on multi-objective optimization. As a result, inputs from various sources should be considered, including turbine performance, component health condition and prediction, and appropriate handling of uncertainties (e.g., representation, quantification, propagation, and mitigation). Ideally, these models should also support project development and decommissioning O&M analysis needs.

3.3 Structure and Foundation

For fixed-bottom offshore wind turbines, structural components are like land-based but include both tower and substructure. For example, for a 15-MW direct-drive turbine on a monopile, the tower weighs about 850 t and the monopile with an embedment depth of about 45 m weighs more than 1,200 t (Gaertner et al. 2020). Mooring lines, anchors, and active ballast systems are also included within the list of structural components for floating offshore wind turbines.

3.3.1 Structure and Foundation Failure Mode Analysis and Mitigation

Traditional land-based wind turbine structural components (e.g., tower) do not fail often, but when they do, they can be catastrophic. It is therefore necessary to address any issues in a timely manner. For offshore wind applications, corrosion has shown to be a risk of failure and needs to be appropriately addressed (Price and Figueira 2017).

The failure mechanisms for the support structure of fixed-bottom offshore wind turbines are like those of land-based wind turbines. These include fatigue cracks in bolted and welded metallic connections, fatigue cracks in concrete, and corrosion of metal and metal-concrete interfaces. However, the failure probability of different mechanisms is altered because of the seawater and seabed. Most notably, the effects of scour—the erosion of the seafloor—can reduce the soil stiffness reacting to the turbine base and foundation, which reduces the natural frequency of the foundation. Scale model testing shows that the first natural frequency of the foundation can be reduced to less than one-eighth in extreme scour events (Prendergast, Gavin, and Doherty 2015). The reduction of natural frequency risks the foundation falling into the same natural frequency range as ocean waves, which could lead to resonance and resulting in a foundation sliding or tower buckling. Additionally, cyclic loading from more severe environmental loading in offshore environments causes heightened fatigue failure risk of these components compared to land-based environments, especially coupled with corrosion risk in the tidal and splash zones of the tower and foundation (Haselibozchaloee et al. 2022). Grouting and jacket joint failure are frequent failure modes due to the increased fatigue.

Watertight failure is the most common failure mechanism for floating platforms in the oil-and-gas industry. This failure is often due to human error; a weld defect, collapsed platform element (e.g., maintenance hole, vent) from mishandling; or a ship impact. Platforms are generally compartmentalized so that a failure will not result in the entire platform capsizing.

The transition piece between the tower and floating platform is also prone to cracking from extreme loads due to severe weather or from accumulated fatigue damage (Li, Diaz, and Guedes Soares 2021).

Floating structures could experience failure modes in the mooring system and are the most common failure event for floating support structures in the oil-and-gas industry. Historical data from the offshore oil-and-gas industry show mooring line failures occurring within 9 years of installation on average (Brown et al. 2005). This rate may be different for floating offshore wind due to their mass-produced nature and potentially different approaches to redundancy and safety factors. Mooring line or tendon failures typically occur due to either extreme weather events or fatigue. Failures from extreme weather occur from snap loading and out-of-plane bending, wherein failures typically occur at the end connection nodes of the mooring system, particularly the fairleads where tensions are greatest. Fatigue failure in chains occurs most frequently due to crack propagation in the chains or twist-induced fatigue. Crack propagation originates from manufacturing defects and is exacerbated by wear between chain links and corrosion on the chain in the marine environment. Twist-induced fatigue occurring between links is exacerbated by wind-wave misalignment, which could have a much greater effect on a wind energy mooring system than in offshore oil and gas due to the larger wind loads and more dynamic floating platform motions. In synthetic fiber ropes, failure can occur from extreme or fatigue loads, or from abrasion (with the seabed, with connection components, or internally due to ingress of sediment within the rope). Marine growth (biofouling) may increase the mass and roughness of mooring lines, reducing the fatigue life of the lines, and further contributing to mooring line failure for all line types.

Anchor failures have also been observed in the offshore oil-and-gas industry from torsion at the connection points during extreme loading events (Sharples, Smith, and Bea 2004). Anchor pullouts are uncommon for properly installed anchors, but soil degradation occurring from large deformation of the anchors in severe weather conditions increases the risk of failure due to pullout (Ward, Zhang, and Gilbert 2008). Anchor pullout from soil degradation is also of concern in offshore areas with substantial seismic activity, which may increase the risk of anchor pullouts due to sudden reductions in the strength of the soil.

3.3.1.1 State of the Practice

Failure mitigation of the structure and foundation components of offshore wind turbines has mainly been through compliance with various standards or guidelines. In the United States, current practice regarding proper offshore wind substructure design for failure mitigation is derived largely from various design codes maintained by the American Bureau of Shipping (American Bureau of Shipping 2020a), which are derived from and supplement the IEC 61400-3 (IEC 2019c) standards, and from standards of the American Petroleum Institute. European projects depend on standards published by DNV, as the American offshore wind industry is nascent and frequently leverages experience from the more established European industry. The DNV guidelines contained in DNVGL-ST-0126 and DNVGL-ST-0119 are often referenced as well. The American Bureau of Shipping design codes focus on assessing offshore floating systems, including specification for materials selection, environmental loading, structural design and fatigue assessment, and required geotechnical surveying (American Bureau of Shipping 2020b). The DNV requirements are similar, although they provide greater detail regarding manufacturing specifics and coating requirements. Existing standards approach failure mitigation via computational simulations of DLCs and survival load cases and finite-element analysis. Fatigue assessments are predicated on allowable stress design via S-N (stress – life cycle) or T-N (tension – life cycle) curves, fatigue design factors, and rainflow counting generated from time domain simulations. Survival load cases depend on a 50-year return period with significant wave conditions (considering wave spectrum parameters such as significant wave height and peak period), current conditions, and wind conditions, like land-based load cases. These standards are derived from knowledge and existing standards for land-based wind turbines and—particularly for floating offshore wind—offshore oil and gas.

For corrosion protection of structure and foundation components, the industry has been using cathodic protection and coating (Offshore Wind Design AS n.d.), both of which can have issues with high flow rates and seabed movement. Their design needs to consider a lot of factors, such as the weight and manageability of anodes for offshore installation, options for mounting the anodes, resistivity of the different layers (e.g., seawater, mud, clay), coating degradation, flow speed, the buildup of calcareous layers, simultaneous erosion/dissolution due to water currents and their sand load, and hydrogen evolution in a sealed environment (Mobiltex n.d.). Periodic inspections or continuous monitoring of cathodic protection and coating are necessary to ensure they are not breached, which could lead to subsequent corrosion on the offshore structure and foundation components.

3.3.1.2 State of the Art and Emerging Technologies

Insights from early experiences in offshore wind energy, primarily in Europe, indicate improvements in current design codes that would make failure mitigation more robust and can account for different levels of reliability. These improvements were obtained based on design codes derived from historic offshore oil-and-gas data (Hughes 2012). Various researchers have consolidated data from industry and recommended design standardization for probabilistically assessing seismic effects and cyclone impacts on a fixed foundation, which has previously not included explicit guidance outside of general geotechnical survey suggestions (Basack et al. 2022; American Bureau of Shipping 2020c). The SLIC project, created by a consortium of major stakeholders in the European offshore wind energy sector, identified improvements to standard suggestions for crack growth propagation in monopiles (Mehmanparast, Brennan, and Tavares 2017).

While many real-world lessons learned for floating offshore wind O&M are forthcoming, the first systematic review (Wang et al. 2022) of reliability assessment of offshore wind support structures revealed in recent research that there were design strategies using stochastic modeling. These modeling methods incorporate target reliability and consequence of failures to explicitly account for inherent uncertainties in hydrodynamic loading and soil properties (Wang et al. 2022). Ship impacts on reinforced concrete floating platforms—a structure largely unique to recent offshore wind platform designs —have been recently assessed to consider the differences between them and steel-based floating platforms, which could inform future design guidance for floating offshore wind platforms (Márquez, Le Sourne, and Rigo 2022). The *Floating Wind O&M Strategies Assessment* from the COREWIND project (Schwarzkopf et al. 2021) uses an O&M cost model to evaluate the effects of different O&M strategies on operating costs for floating offshore wind farms.

Given the impact corrosion and marine growth have on fatigue failures for the support structure of offshore wind turbines, recent research has explored mandating more detailed anticorrosive and antifouling coating specifications for foundations and tower interfaces. These specifications are adequate to minimize the corrosion and marine growth impacts on the support structure throughout the life spans of fixed-bottom offshore wind turbines. These changes were influenced by improvements in coatings research, particularly self-healing coatings (Alaneme and Bodunrin 2017).

3.3.1.3 Challenges

There are two prevailing challenges impeding effective failure analysis and mitigation for offshore wind: (1) lack of experience with offshore wind fatigue failures to formulate specific standards that could reduce O&M costs and challenges, and (2) difficulty monitoring underwater components (see Section 3.3.2). Scouring of fixed offshore wind farms in Europe has been generally overestimated in earlier years (Matutano, Negro, and López-Gutiérrez 2013), though higher rates of failure than expected have been observed for support structures overall. On the positive side, recent offshore wind turbines in Europe have experienced lower failure frequencies for blades and drivetrain components (Cevasco et al. 2022a). Lack of monitoring data regarding marine growth, soil-structure interactions, and higher-order wave loading makes generating accurate probability distributions challenging, which increases project risks and impedes the development of proactive maintenance strategies.

These challenges are even more apparent for floating offshore wind, as the industry is more nascent than fixed offshore wind. Furthermore, the industry is still at the knowledge gathering phase to identify differences between knowledge on floating offshore wind and oil-and-gas industries. In addition, soil-structure interactions for floating offshore wind components at the seabed (e.g., anchors, embedded parts of mooring lines) are not well-understood, let alone standardized.

3.3.1.4 Priorities and Needed Research Activities

The following research activities on failure mode analysis and mitigation for structure and foundation are recommended:

- Experimental testing to detail fatigue properties of offshore wind support structure components could be valuable to improve reliability of offshore wind systems and remove overengineering practices.
- Similarly, data acquisition and analysis of foundation and mooring failures from severe weather events would allow for more detailed assessment of failure probability due to low-cyclic loading events.
- In addition to the updates to design codes resulting from the previously mentioned research, standards should be assessed to determine whether they are properly accounting for out-of-plane bending and corrosion degradation effects on mooring systems for floating offshore wind systems.
- As with other components, the material characterization and application to digital twinning presents an inexpensive path forward to analyzing some of these unknown effects, especially as new materials continue to be applied to mooring systems, such as synthetic fiber ropes for deep-water installations and higher chain grades for shallow-water applications with harsh meteorological ocean conditions (Gordon, Brown, and Allen 2014). Existing knowledge of the fatigue characteristics of synthetic fiber ropes with less common materials or in less common loading regimes is limited and needs greater investigation.

3.3.2 Structure and Foundation Monitoring, Sensing, and Inspection

The tower and support structure must be monitored to prevent damage growth that could put the entire system at risk.

3.3.2.1 State of the Practice

Current practice for monitoring and inspecting offshore wind support structures largely depends on visual inspection of biofouling, corrosion, and foundation cracks, and on installed condition monitoring systems with sensors on the floating platform or mooring lines. While some early floating offshore wind farms in deeper water have demonstrated using ROVs (Fundingsland 2020), most fixed-bottom offshore wind farms still depend on sending divers from transport vessels due to the relatively lower operating cost. During visual inspection, the marine growth is removed to bare metal to assess any structural damage to the substructure, with care taken to minimize damage to any coatings.

Condition monitoring of the floating support structure can involve sensors built into the substructure or mooring lines. Some early floating offshore wind farms include load cells at the fairleads of the mooring lines to communicate tensions in real time, which could help track mooring system loads and fatigue damage, as well as detect mooring line failures (Kincardine Offshore Windfarm Ltd. 2019).

3.3.2.2 State of the Art and Emerging Technologies

As offshore wind farms continue to get larger, farther from port, and more numerous, industry is beginning to move toward nonhuman methods of monitoring and inspection. The recently installed Kincardine floating offshore wind farm includes platform motion detection with wireless communication to onshore, which issues an alert if the platform has drifted beyond expected values, which would indicate a mooring line failure (Kincardine Offshore Windfarm Ltd. 2019). ROVs become more economical as farms get larger and are being used more frequently (Khalid et al. 2022). Autonomous underwater robots have been recently presented for use for offshore wind visual inspection as well (Balmore Group 2023).

Nondestructive testing methods are being applied to offshore wind plant maintenance, with research demonstrating ultrasonic testing to detect corrosion and material defects (Thibbotuwa, Cortés, and Irizar et al. 2022) and acoustic testing for weld cavitation in grouted connections (Tziavos et al. 2020). As the floating offshore wind industry develops, ROVs with nondestructive testing capabilities used by the offshore oil-and-gas industry can be leveraged.

Novel sensors for measurements for offshore wind support structures are being demonstrated in research via the ROMEO project in the European Union, such as acoustic scour monitoring, hydrogen sulfide detectors for corrosion monitoring in confined submerged internal spaces, and waterproof inclinometers to detect underwater displacements (Kolios et al. 2018). Poor long-term reliability of load cells for floating offshore wind has prompted pursuit of other sensing approaches involving inclinometers, acoustic detection, or embedded fiber optics in synthetic ropes (Ford et al. 2020). One of the simplest and most common approaches explored in literature is to track the floating platform motions using GPS, possibly supplemented with inertial measurement unit readings. Feeding these motions into a digital twin or simpler anomaly detection method, failure or changes in the mooring system can be detected without requiring costly sensors (Cevasco et al. 2022b). The disadvantage of this approach is it is less accurate when estimating mooring loads and degradation that can be used to inform maintenance or predict failures. Structural health monitoring and digital twinning for floating offshore wind mooring systems is also being researched through the European Union's MooringSense project (MooringSense 2022).

3.3.2.3 Challenges

Current inspection practices for offshore wind farms are expensive, time-constrained, and often pose a risk to human life. These challenges become nearly unsustainable for floating offshore wind, as sending divers to more distant wind farms becomes difficult to schedule within weather windows and prohibitively expensive. Additionally, sending divers to the depths proposed for floating offshore wind farms requires special equipment, and poses health risks. Furthermore, operating in the thrash zone of mooring lines (where there is often the greatest wear) can be dangerous. Much like human-based manual blade inspection, assessing the severity of damage on support structure components is often subjective and inconsistent between divers (Brown et al. 2005). While ROVs are technologically mature and a viable substitute, they remain very expensive and still require local deployment.

Removing biofouling on subsea components (whether by diver or ROV) during inspection also degrades the anticorrosive coating on the components, even when care is taken, resulting in the components being at greater risk of damage due to corrosion and marine growth with every inspection.

The relative lack of sensors on substructural components means detailed data is scant, making structural health monitoring and predictive maintenance strategies nearly impossible at the current state of the art. Additionally, existing subsea sensors are prone to deterioration due to corrosion and marine growth, and are at risk of premature failure. There is a research gap in reliable methods to power certain sensors underwater, as most demonstrations rely on batteries that are not survivable in a marine environment for the 20+ year lifetime of an offshore wind farm.

In future floating offshore wind farms, the large quantity of mooring lines and power cables presents a new challenge in terms of the unprecedented scale of monitoring and inspection required. Monitoring and inspection methods need to be inexpensive at the scale of hundreds of these components within a given project.

3.3.2.4 Priorities and Needed Research Activities

Further research should prioritize developing inexpensive methods of uncrewed inspection, and in improving sensing and structural health monitoring capabilities.

In the near term, use of ROVs for visual inspection should become more widely adopted, and industry development should prioritize nondestructive testing and *in situ* maintenance capabilities to reduce dependency on divers. Longer term, research and industry should work toward developing fully autonomous vehicles that require no human intervention and can perform inspect-and-repair operations *in situ*. To help reach this state, research to improve condition monitoring is needed, as follows:

- Research into resilient sensors capable of providing real-time data on subsea component health should be paramount, including devices and methodologies capable of structural displacement, marine growth and corrosion detection, sea surface roughness, and intra-line sensors for mooring line wear and displacement. Improved battery technology and other methods of providing reliable, long-term power for sensors is also needed.
- New strategies for monitoring and inspecting large-scale floating offshore wind farms should be explored and evaluated to identify if new paradigms can more efficiently manage the large-scale needs of future projects. Economies of scale may be realized that enable new approaches to monitoring and inspection, such as having resident ROVs that are permanently stationed at a floating offshore wind farm and have a high use rate by virtue of the number of components needing inspection.
- Finally, digital technologies to improve structural health monitoring of support structures should be further researched so they can improve as more historical data are generated from an increase in sensor deployment. While fixed-bottom support structures are further along in development and can leverage monitoring techniques from land-based wind more readily, research into digital twins and artificial intelligence techniques used for land-based maintenance strategy (e.g., for gearbox and blade maintenance) should be areas of focus to develop monitoring systems for floating support structures that match the lifetimes and loading profiles of floating offshore wind installations expected in the coming years.

3.3.3 Structure and Foundation Maintenance Execution

Maintenance of the structure and support structure is required upon indication of damage from monitoring and inspection.

3.3.3.1 State of the Practice

Like other components, the support structures of most modern, fixed-bottom offshore wind turbines are typically maintained according to a preventative maintenance schedule. This process typically occurs simultaneously with routine inspection (via a diver or ROV) and involves removing marine growth from small sections of the tower/jacket structure and, if possible, the occasional reapplication of anticorrosive coating. The maintenance interval is based on years of service of a given wind turbine, with preventative maintenance becoming more frequent the older a turbine is. Corrective maintenance includes scour mitigation, bolt adjustments, or grout repair (Vieira et al. 2022). Due to relative lack of sensors, corrective maintenance fleets are sometimes sent out after extreme weather events under fear of damage, even if no faults are detected.

Typical maintenance execution for floating offshore wind turbines is not well-established due to the nascence of the industry, though early floating offshore wind farms and practices from offshore oil and gas can provide early insights. In the near term, preventative maintenance will likely be like offshore oil-and-gas platforms, with ROVs removing marine growth from mooring line connection points and scour protection near the anchors. Major corrective maintenance, such as in the case of mooring line failure or platform damage, will depend on the platform type. Semisubmersible platforms can be towed to port (Thomas 2023) without deconstruction of the turbine, allowing for platform maintenance at quayside and unobstructed mooring system maintenance on location. Spar platforms would either need to have the turbine removed before towing the platforms to shore or maintenance performed with the structure in place, with tugboats providing stability as needed (Ramachandran 2021).

3.3.3.2 State of the Art and Emerging Technologies

Much like other components, CBM strategies have been demonstrated for both foundation maintenance for fixed-bottom wind turbines (Lian et al. 2019) and mooring systems for floating turbines (Liu et al. 2020; Walker et al. 2021). These strategies also include potential to incorporate fault detection from other sensors currently under research, such as scour detection, mooring line failure detection via platform displacement, and mooring line wear. Predictive maintenance strategies have emerged for floating offshore wind farms via the European Union's FLOTANT project, which includes a methodology of risk assessment for the mooring system components and platform (Zhao, Thies, and Johanning 2021). Guidelines for structural health monitoring have been detailed for fixed-bottom offshore wind systems, including techno-economic analysis of the potential benefits of structural health monitoring (Martinez-Luengo and Shafiee 2019).

Several technologies to reduce the time requirements of offshore maintenance are undergoing active research. Several self-healing, anticorrosive coatings have been released to adhere to the life spans required by offshore wind, reducing the needs to reapply coating during maintenance (Price and Figueira 2017). For floating offshore wind, several quick-disconnect technologies for mooring lines are in development, which may significantly reduce both the time and vessel requirements for towing a platform back to shore for major repair (Apollo Engineering Consultants Ltd. 2023; Vogelsang 2022). Autonomous robots for maintenance of subsea components of fixed-bottom offshore wind farms are also in development (Ore-Catapult 2020).

3.3.3.3 Challenges

Much like other components, the most pressing challenge for maintenance of offshore wind support structures is the availability and cost of personnel and vessels. Maintenance for fixed-bottom support structures, whether via a diver or ROV, requires a support vessel and crew, which are subject to similar weather-window restrictions as for other components even if the maintenance is entirely subsurface. Maintenance often requires cleaning marine growth from the submerged component, which adds more time to the maintenance operation. Many mooring system repairs will require the platform to be disconnected from the mooring. Mooring line disconnection is a complicated and time-consuming process using current fairlead connections and requires multiple large vessels to provide stability to the platform during the disconnect. Even without vessel availability and weather-window concerns, disconnecting the platform can take several days by itself.

Floating offshore wind energy is also faced with a lack of a maintenance strategy for mooring systems given the current supply of required vessels. The scale of floating offshore wind projects in the planning stages already approaches the global supply of anchor handling tug supplies in operation. The lack of an existing maintenance strategy, particularly the research gap in predictive maintenance for mooring systems, could accentuate vessel shortages and increase downtime while waiting for vessel availability.

3.3.3.4 Priorities and Needed Research Activities

The following research activities on maintenance of structure and foundation are recommended:

- Research into maintenance for support structures should prioritize proactive maintenance strategies and technological development of robotic maintenance, which will build on the advances discussed in Section 1.3.2.4. Continued expansion of condition-based and/or predictive maintenance strategies could drastically reduce the number of unplanned maintenance visits, allowing for easier schedule coordination and cooperation for vessels and divers, which would reduce vessel and personnel delays, mitigating one of the largest causes for offshore wind turbine downtime. Similarly, further development in schedule optimization given vessel and port requirements for upcoming support structure maintenance tasks will enhance vessel coordination and availability, which will be necessary to support floating offshore wind farm maintenance.
- The scale of floating offshore wind farms and the corresponding quantity of mooring and cabling components may benefit new maintenance strategies that involve keeping an inventory of standardized replacement components for a given project. Offshore storage of replacement components should be explored to reduce onshore storage and vessel demands. Various options should be assessed and compared to determine what is most effective for future floating offshore wind farms.
- Further research on various technologies will also help reduce support structure maintenance time. Developing vessel designs that can tow and stabilize floating platforms with greater wind and wave resistance than anchor handling tug supplies will increase the range of acceptable weather windows and increase the number of vessels available to support floating offshore wind farms. Additionally, reducing the cost and

improving the reliability of rapid mooring line and power cable connect/disconnect technology would reduce mooring maintenance execution time by several days.

3.4 Balance of Plant

The scope under consideration includes everything from the wind turbine nacelle or pad-mount transformer, collection system, substation, and transmission lines to the grid, most of which are often treated as part of the balance of plant (Dvorak 2016), which is critical for delivering power generated at a wind plant to the marketplace. This balance of plant applies to both fixed-bottom and floating offshore wind turbine configurations. Diagrams of typical high-voltage alternating current (HVAC) and high-voltage direct current (HVDC)-interconnected wind power plants are shown in Figure 4 and Figure 5, respectively.

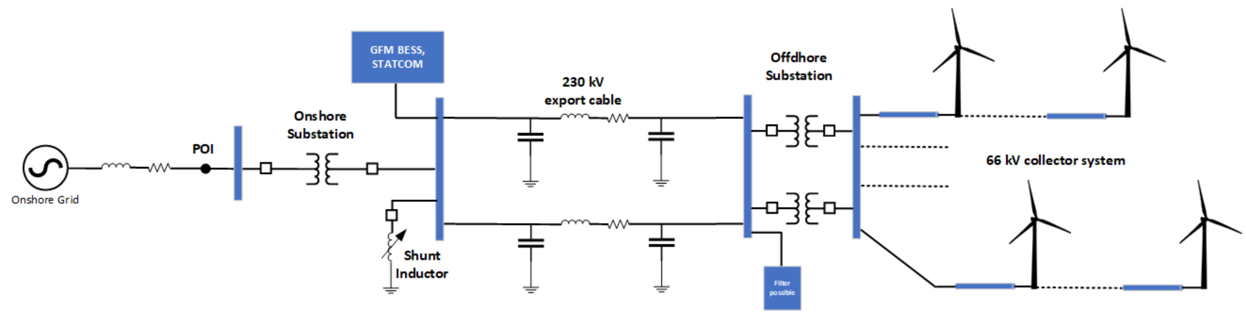

Figure 4. Typical HVAC-interconnected offshore wind power plant.

Note: POI = point of interconnection; kV = kilovolt; GFM = grid-forming; BESS = battery energy storage system

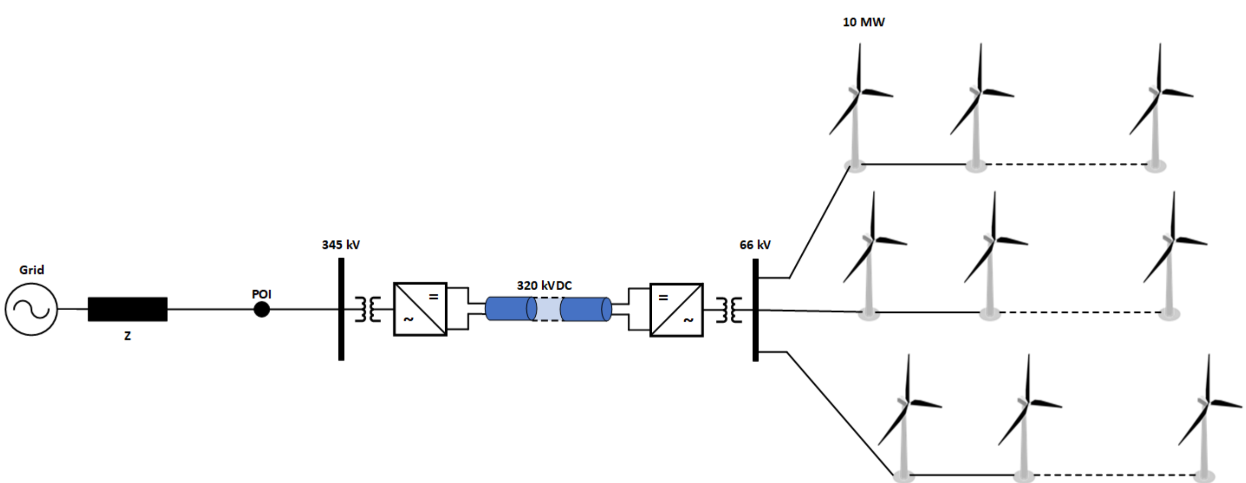

Figure 5. Typical HVDC-interconnected offshore wind power plant.

3.4.1 Balance-of-Plant Failure Mode Analysis and Mitigation

Each wind turbine typically has a nacelle- or pad-mounted transformer that takes the turbine electrical output and steps it up to the sub-transmission voltage level, typically 66 kilovolts (kV) or 69 kV, for efficient transmission through cables to the substation. They can be either oil filled or dry type. The transformers may have loose or damaged connections, which if not detected and fixed could pose a safety risk to personnel. Another common issue with oil-filled transformers is dissolved gas, which typically includes (Dvorak 2016) hydrogen, methane, acetylene, ethylene, and ethane. High dissolved gas concentrations can explode when a unit is switched in and out of service.

The cables include both array (between turbines and the substation offshore) and export (between the substation offshore/onshore and the grid, with a higher voltage between 220 kV and 360 kV) are typically undersea and covered by the seabed for fixed-bottom offshore turbines or include a dynamic portion above the seabed for floating offshore wind turbines. For floating, dynamic portions of cables are designed to accommodate floating platform motion with minimal loading on the cable. As a result, they typically take a curved shape, such as a “lazy wave,” that avoids large tensions or tight bending in the cable. These shapes are achieved by adding buoyancy modules on a section of the cable (the buoyancy section).

Depending on the transmission mode being either high-voltage AC or DC (Warnock et al. 2019), there can be converters between the substation on the water and the onshore substation before the electricity is being fed to the grid. The field data from both land-based and offshore turbines (Fischer et al. 2019) have shown that these power converters can fail at various locations, such as at the phase module (including insulated-gate bipolar transistor modules and corresponding driver boards, DC-link capacitors, and busbars), a power-converter control board, cooling system, main circuit breaker, grid-coupling contactor, and other power-converter components (e.g., electrical filter components, fuses, relays). Fischer et al. (2019) also found that environmental factors such as humidity and contamination as well as design and quality issues and human errors play an important part in the incidence of these failures. Thermal-mechanical fatigue is also an important issue in power converter failure, particularly with insulated baseplate power semiconductor modules and is not covered well by standards.

The substation (Dvorak 2016) has a lot of components, such as transformers, breakers, switches, shunt compensation, and relays. These devices may experience failures at windings and bushings due to insulation deterioration, and there may also be failure modes unique to specific type of transformers (e.g., oil filled). The other three components may be prone to loose or damaged connections. The substation supporting structure can suffer from marine growth and corrosion failure modes, like on the wind turbine foundation or supporting structure. Therefore, component design, redesign, or testing under marine environments is an important issue.

3.4.1.1 State of the Practice

For static cables, there is a need to reduce failures and improve reliability through material, design, or manufacturing innovations. For dynamic cables in floating offshore wind, additional protections can include anchoring near where the cable touches the seabed and bend stiffeners at the platform connection or other joints to avoid sharp bends. For the substation, redundancy may be considered in addition to novel materials for critical components that are prone to failures.

3.4.1.2 State of the Art and Emerging Technologies

For cables, redundancy is occasionally adopted for export or inter-array cables (TÜV et al. 2014) but is not an industry standard practice yet.

3.4.1.3 Challenges

For HVDC converters, one of the challenges is to improve reliability yet keep costs down. There is a significant need for further R&D.

3.4.1.4 Priorities and Needed Research Activities

There is a need to develop new cable technologies that reduce failures. There is also a need to develop an automated repair system for large array and export cables (ETIPWind 2020c).

For converters, intelligent controls considering reliability or safety risks based on various artificial intelligence techniques, such as neural networks, are needed.

Advanced fault diagnosis methods are needed for offshore wind power electrical components. Such methods can be based on a modeling approach, data-driven machine-learning approach, and real-time measurements-based approach. For converter monitoring, the need for high-speed data collection becomes critical and is also an extension of some work that has been done (Penrose 2022) for land-based turbines.

3.4.2 Balance-of-Plant Monitoring, Sensing, and Inspection

3.4.2.1 State of the Practice

Typically, there are no dedicated sensors that are permanently installed on the electronic components under consideration in this section. Using a typical converter as an example, many sensors are included during design but are not integrated in implementation principally due to the high data rate requirements. As a result, regular inspections are recommended.

For nacelle- or pad-mounted transformers, regular inspections, typically by infrared, are recommended while online and under load, as well as oil sampling to monitor the dissolved gas level. Cost-effective sensing will be valuable for pad-mount transformers.

For cables, there are various offline inspections (Ikhennicheu et al. 2020) that can be used (e.g., visual, time-domain reflectometry, or partial discharge measurements) or online monitoring techniques (e.g., distributed temperature measurement system for fiber-optic wires embedded in the cable interstices).

Substations are subject to regulatory protocols and need to comply in terms of schedule and scope of inspections, which aim to ensure safety to personnel and equipment.

3.4.2.2 State of the Art and Emerging Technologies

Cable failures are costly to repair not only because of the cable cost but also the long downtime (at times, more than 3 months). It is critical to not only properly protect the cables but also monitor the cable system (Kurth et al. 2022). Recently, a holistic cable condition monitoring solution was introduced that employs distributed temperature, acoustic, electromechanical sensing, as well as partial discharge monitoring (Proserv n.d.).

3.4.2.3 Challenges

Dynamic cables in floating offshore wind turbines are even more challenging to inspect, monitor, and maintain due to their dynamics and varying load conditions.

3.4.2.4 Priorities and Needed Research Activities

Currently, there is not enough instrumentation on cables that technicians typically need for performing inspections and services. Due to the high failure rates and large insurance cost for cables, it is critical to install holistic cable monitoring systems and conduct predictive maintenance (El Mountassir and Strang-Moran 2018).

3.4.3 Balance-of-Plant Maintenance Execution

3.4.3.1 State of the Practice

Due to the typical practice of periodic inspections on almost all electronic components under consideration in this subsection, some of the maintenance can be planned. Often, it may end up being reactive after a failure has occurred and a loss of power is experienced.

3.4.3.2 State of the Art and Emerging Technologies

With the introduction of condition monitoring solutions for cables, some CBM can be conducted. To support floating offshore wind energy, attention needs to be paid to developing quick-connect and disconnect systems for mooring lines or inter-array cables (ETIPWind 2023).

3.4.3.3 Challenges

Complex factors leading to various cable failures (Gulski et al. 2021) are hard to appropriately address through one universal method. For dynamic cables in floating offshore wind, it is more challenging than fixed-bottom offshore wind and novel solutions are needed.

3.4.3.4 Priorities and Needed Research Activities

Like other wind turbine components, there is a need to minimize the O&M costs by reducing unplanned maintenance and increasing planned maintenance. To enable CBM of electrical components considered in this section, it is necessary to install dedicated instrumentation and conduct modeling analysis for fault detection, isolation, diagnostics, or prognostics.

4 Cross-Cutting Areas of Research and Development

To make offshore wind energy more cost-effective, there are areas of O&M research that are crosscutting. This section briefly reviews these topic areas, highlighting the state of the art and future R&D opportunities to meet offshore wind O&M needs. Figure 6 shows the topic areas identified throughout the stakeholder engagement activities during this roadmap development process that the U.S. offshore wind energy industry needs to address. The cross-cutting areas of R&D discussed in this section will cover most of these topics in depth (i.e., digitalization, robotics and automation, prognostics and health management and O&M optimization, experimentation and demonstration, standards and recommended practices, design optimization considering reliability, and O&M). The topics on workforce, logistics, regulations, and consortium are important for the U.S. offshore wind industry but will only be briefly discussed by highlighting innovative R&D activities due to the focus of this roadmap being on R&D.

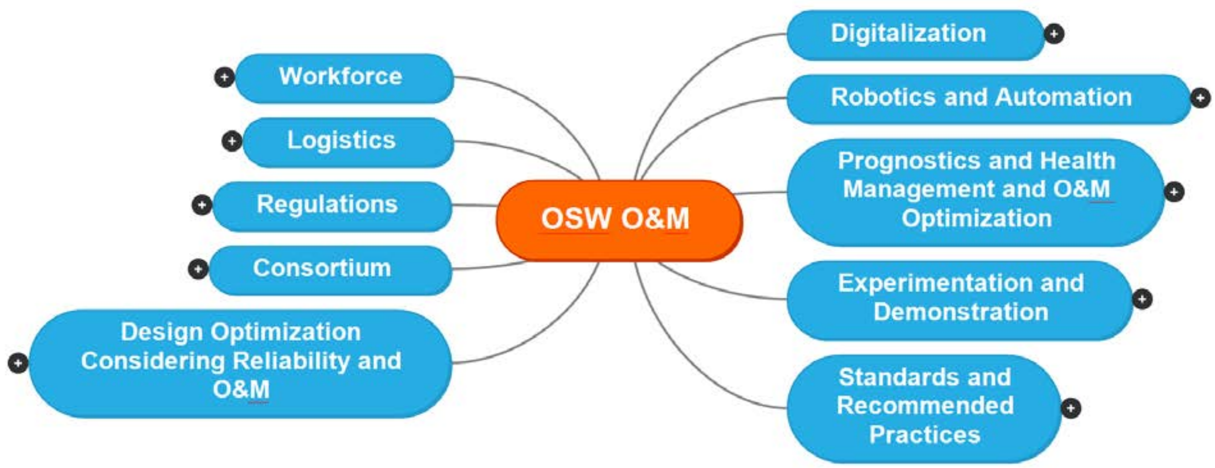

Figure 6. Offshore wind (OSW) O&M topic areas

For workforce, there is an industrywide awareness of limited engineers and certified technicians with enough experience to meet the fast development needs of the U.S. offshore wind industry. Some are available from other markets, but they may not be easily transferrable to the U.S. market. There is a need to develop the local workforce through knowledge transfer from other markets, although this takes time. Workforce development is an area where the government can play an active role, but out of scope for this current roadmap. For more information, please refer to the appropriate contents in *A Supply Chain Road Map for Offshore Wind Energy in the United States* (Shields et al. 2023).

It is worth noting that workforce and logistics are to some extent connected. There are not only wind power plants, but also marine logistics that need to be addressed. How can we mitigate accessibility challenges caused by weather and water conditions through new vessel technologies? Safety needs to be considered, and it is ideal to have a whole package of health and safety equipment for each subsystem with specified assessment processes and third-party certifications. Given the booming offshore wind energy development around the world, various markets are competing for vessels and other resources. When shipping goods, the Jones Act[6] needs to be followed.

During the first few years of U.S. offshore wind operation, the industry needs to work together to solve service issues across the board. To reach the current U.S. administration's net-zero greenhouse gas emissions target (The White House 2021) by 2050, it will be helpful to have innovative logistics solutions like green vessels powered by batteries or methanol (Offshore Engineering 2023), and advanced strategies to make better use of space at ports (e.g., coordinated port operations with vessel fueling, as fuel normally needs to be transported to the port). For green vessels and green crew transfer vessels especially, charging capabilities within the offshore wind plant are needed, as vessels may not have sufficient battery capacity for round trips to shore (e.g., hybrid systems combining wind with solar, battery storage, or hydrogen). Ports with adequate draft allowance and height clearance near areas of floating offshore wind development are also necessary to support tow-back maintenance of future floating offshore wind farms. For evaluating cost-effectiveness of O&M strategies, it is necessary to consider component transportation logistics and associated costs. Alternative opportunities, such as the redundancy of certain components (e.g., backup transformers at the substation) may be more beneficial in the long term. Also, it may be beneficial to group equipment (e.g., clustering of vessels and crane rentals) and mobilization of the crew. There are even opportunities for various projects to form a cluster, which can save costs by sharing logistical bases and developing a joint supply chain strategy. Given legal ownership of spare parts, a strategy like this probably requires a catalyst such as a neutral organization stepping in. To mitigate the pressure from supply chain issues, innovative methods to obtain spare components (e.g., three-dimensional printing) can be explored.

Regulations impact not only the deployment, but also the O&M of U.S. offshore wind. Crew rescue operations need to be considered early to guide the design of wind plants (e.g., a semiautonomous solution for retrieving casualties of crew members from water). Additionally, there is a lack of clear guidelines or policy on wind turbine and plant data ownership. New digital solutions need to comply with cybersecurity policies from the North American Electric Reliability Corporation and other regulatory agencies.

[6] The Jones Act is a federal law that regulates the transportation of merchandise between U.S. points is reserved for U.S.- built, owned, and documented vessels.

For the U.S. offshore wind energy industry, more collaborations are the best path forward (e.g., maximizing industrywide benefits by sharing resources). Coordinated activities might be the only feasible solution to reach the levels of deployment needed to meet national climate and energy goals (DOE 2023). For future consortiums to support offshore wind O&M, DOE national laboratories and universities can partner with industry, finding ways to work together, share experiences, and develop joint industry projects, so they do not duplicate efforts. It will be beneficial for any consortium to collaborate with stakeholders in Europe or other marketplaces. In the United Kingdom, ORE Catapult has an interesting model working with both the government and industry to advance innovative R&D. In Denmark, the Technical University of Denmark science park is another great model that joins industry and academia. In the United States, the National Offshore Wind R&D Consortium initially funded by DOE and the State of New York has been in operation for a few years with a broad range of funded projects at medium to high technology readiness levels (TRLs), with relatively shorter time to prototyping or commercialization.

4.1 Digitalization

Digitalization refers to the use of digital technologies (e.g., edge computing, cloud storage, data engineering, AI/ML modeling) to improve existing or enable new business processes, providing new revenue and value-producing opportunities (Clifton et al. 2023). As digital technologies advance, they have started changing almost every aspect of wind plant O&M, from sensing to modeling and decision-making. In terms of sensing, edge computing makes it possible for sensors to process raw data locally and downsize the amount to be transmitted and reduce the data transfer burden. Other novel sensing technologies enabled by digitalization can be explored to help improve wind turbine performance, reliability, and O&M. Wireless communication technologies (e.g., 5G or 6G), make not only technical tasks easier but also enrich technicians' life (e.g., access to videos or games) over the water. Hardware computational capability improvements (e.g., graphics processing unit) make big data mining and modeling that were not previously feasible more routine, at least at the R&D level.

Data access and sharing are issues faced by the wind energy industry. One of the reasons is that most data owners treat their data as business-sensitive, limiting exposure and putting them at a better position in a competitive market. Data sharing has improved over the years, but an industrywide effort serving multiple purposes, such as O&M, is needed. One industrywide gap exists between wind turbine OEMs and owners, and it needs to be filled to get a complete history of assets and optimize O&M. Among various data collection and sharing efforts, e.g., ReliaWind (European Commission n.d.-a), WInD-Pool (Fraunhofer IEE n.d.), industry-wide standardized practices or taxonomy are often not followed. There are a few recommended practices or standards, but it is difficult to have a greater impact if the adoption is voluntary or the value of return cannot be justified over the resources needed to adopt. For the United States, the North American Electric Reliability Corporation's GADS (NERC n.d.) offers mandatory data reporting for wind plants with a capacity bigger than 200 MW. However, the data reporting is not at the wind turbine or component level. When conducting an analysis, it is widely known that a lot of time is spent on data cleaning or tagging, and normalizing is needed due to the noisy (e.g., low signal-to-noise ratio) nature of wind energy data, and its various types and resolutions. As a result, a standardized pipeline based on widely adopted taxonomy will be very valuable. To encourage broader R&D and eventually a bigger impact to the industry, developing an open-source software framework like Open Operational Assessment (OpenOA) (Perr-Sauer et al. 2021) for assessing operational wind plant performance is an extremely valuable path to pursue.

In addition to analysis algorithms, traditional methods using statistics, spectrum, and time-frequency analysis to support digital resource assessment, performance analysis, or O&M solutions have become more refined and accurate. New R&D activities have been conducted based on AI and ML algorithms to benefit the wind energy industry throughout a plant's entire lifecycle (García Márquez and Peinado Gonzalo 2022 and Koukoura et al. 2018). These methods can leverage a large amount of data and represent individual features of wind turbines (e.g., turbine component-specific loads). They have been used for resource assessments, turbine or plant performance evaluation, component fault diagnostics, prognostics, and O&M decision-making, etc. Although AI and ML models are seeing an increased number of R&D activities, field deployment is limited. One challenge with wider adoption of AI and ML models in the field lies in its lack of interpretability and transferability, which can lead to increased skepticism by users.

In terms of modeling, a popular topic is digital twins, which has been a recent focus in academia and industry-funded projects (e.g., ROMEO). The focus to date has been on predicting failures of structural components like the tower, blades, or foundations. The twins needed for various project phases and purposes should be different, which makes its adaptation or periodic updates necessary. One challenge with wide adoption of digital twinning techniques that is like AI and ML models is the black box nature (e.g., no knowledge of model internal structure or parameters) and makes end users skeptical and lowers trust.

Another challenge faced by all models is validation as normally there is a lack of accessible data sets that can meet the needs. Model validation could be improved by providing performance benchmarking results as well as uncertainty based on independent datasets and metrics. To better serve the industry, it is necessary to develop and validate digital twining models (Branlard et al. 2023) by closing the gaps between the designer, manufacturer, and end users.

4.2 Robotics and Automation

Robotics and automation will likely play an important and increasing role in offshore wind O&M due to difficulties in accessibility, increased cost of failures, and concerns with worker safety. Currently, aerial drones are widely used in the wind industry for blade inspections and crawling robots are used for both inspection and erosion repairs for land-based and offshore wind (e.g., Blade Bug, Clobotics, Wind Robots). Underwater robots are also used to inspect platforms and electrical infrastructure (European Commission n.d.-b). With growth in wind turbine sizes and deployment, offshore wind presents additional opportunities for inspection and repair. Systems that are not economical for a 5- to 10-MW platform can be cost-effective for larger sizes as they represent greater investment and risk. Thus, it is likely that robots and automation will greatly expand. Increasingly complicated structural repairs of blades might be accomplished by robots that grind and apply laminates or repair patches. Routine maintenance tasks, such as lubrication replacements, bolt tension checks, and cleaning, may offer opportunities for further development of robotics technologies. Underwater infrastructure inspections, operations, and repair will also likely increase in number and scope due to the cost and worker safety implications of using divers.

Logistics is another application where use of autonomous vehicles will grow as offshore wind expands. Uncrewed supply and maintenance vessels can be used to move components to remote locations, stage inspections, and repair robots. Autonomous platforms can also be used for collecting data on a wind turbine's operational conditions as well as impacts on marine life. There may also be opportunities for automation during permitting and financing processes, such as survey of wind and wave resources, or subsea conditions.

Most current efforts in this area around the globe are at the prototype or demonstration stage on specific wind turbine platforms. The needed R&D includes developing new capabilities to meet specific needs in offshore wind, transferability from one turbine platform to another, and adding artificial intelligence to handle unexpected situations and self-training capabilities. When multiple robotic agents are deployed at a typical offshore wind plant, there is a need to optimize their deployment based on internal communications and through intelligent planning.

4.3 Prognostics and Health Management, and O&M Optimization

Various maintenance strategies were introduced in Section 1.2.1 and referred to in the maintenance execution sections under various components in Section 3. Different monitoring, sensing, and inspection techniques for major offshore wind turbine and plant components were discussed in respective parts of Section 3. Although the connections between them might not be explicitly stated, they can be better understood from a prognostics and health management (PHM) perspective. PHM is an approach to system life cycle support that seeks to reduce or eliminate inspections and time-based maintenance through accurate monitoring, incipient fault detection, and prediction of impending faults (Jouin et al. 2013) and has been used in various applications (e.g., aviation, electronics, and nuclear power plants). The connections can be visually demonstrated through a reference architecture for PHM process as shown in Figure 7 (Jouin et al. 2013). It has seven layers, which are grouped into three stages: observe, model/analyze, and decide. The maintenance strategies correspond to the observe stage, whereas monitoring, sensing, and inspection techniques correspond to the observe and model/analyze stages. Zooming in further, most industry practices correspond to layers 2 to 4 with prognostics, and layer 5, which is becoming an active area of research in recent years. In terms of R&D activities, they span all three stages and need to be carried into future years to maximize the potential benefits from various PHM techniques to offshore wind O&M. The outputs from PHM can be used to optimize O&M, a decision-making-under-uncertainty process in which the expected maintenance effort should be balanced against the expected costs of failure. For offshore wind energy, O&M decision-making research is very active and needs to be continued (Pinciroli et al. 2022). PHM and O&M optimization combined offers a pathway for significant reduction in offshore wind O&M costs by minimizing both the number of maintenance actions needed and the expected number of failures over a wind farm's lifetime.

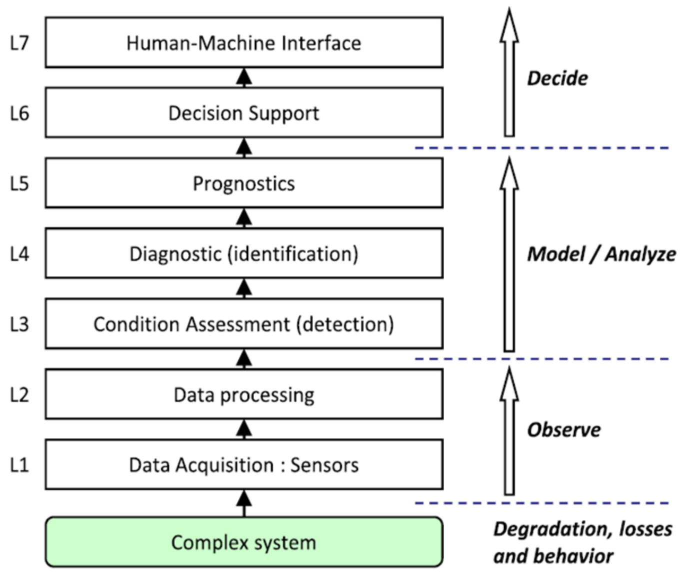

Figure 7. A reference architecture for the PHM process

With the advanced development of various sensing, monitoring, or inspection technologies, every component at an offshore wind plant can be surveyed periodically or monitored continuously. Corresponding to the observe stage, the R&D gap to fill includes developing cost-effective monitoring solutions including sensing for blades, towers, converters, transformers, fixed-bottom foundations, floating support structures, mooring lines, anchors, and dynamic cables. Please note for each subsystem/component, the needed sensing technologies and best-performing monitoring solutions may differ. The subsequent challenge is how to synergize the various data streams for useful information or knowledge extraction, and maximize the benefits from PHM for wind plant O&M. These monitoring solutions, from sensing to outputs, most likely will suffer from errors or power loss events, so determining how to ensure the outputs from them are trustworthy is another challenge.

Moving to the model/analyze stage, for high-frequency time series data, various advanced signal processing, feature extraction, or modeling algorithms need to be researched to improve their effectiveness for anomaly detection, fault diagnostics, and prognostics. This is especially needed for components not traditionally targeted (e.g., power electronics and pitch) or new failure modes. It is challenging to synchronize different data types, including maintenance records, through one centralized platform to maximize efficiency and extract valuable insights from the data. Predicting the future is always challenging, which is the same for wind turbine component faults. One expected output is estimating the remaining useful life, for which effective and trustworthy modeling techniques that can extend the prediction horizon are needed. The need for effective prognostic techniques also applies to land-based wind plants. The core models should also be able to assess reliability and integrity throughout the life of a wind turbine component to support repowering, life extension, and decommissioning needs.

O&M optimization has the potential to drastically lower the levelized cost of energy of offshore wind energy. In Europe, there have already been significant efforts to develop O&M optimization methods specific to offshore wind (Morato et al. 2022). While there has been a lot of academic work researching the optimal methods for O&M of a wind farm, there have been limited studies conducted in the real world (Sperstad et al. 2017). Finally, research into optimal O&M of wind turbines tends to focus on a single component rather than consider the interdependencies between components and their maintenance and failures (Rinaldi et al. 2021). Challenges and research opportunities for O&M optimization of offshore wind energy include real-world comparison and validation of optimal O&M strategies and developing methods and frameworks for O&M optimization that identify and account for the interdependencies between the various components of a wind turbine and wind farm.

A few example activities for PHM and O&M optimization R&D include the following:

- A planning tool to support project development by considering O&M costs and risk factors based on reliability projection of components and carbon footprint throughout the plant's life cycle (e.g., material use, and decarbonization of vessels).
- Optimizing control and O&M for a specific turbine or wind plant by balancing between power production and component loads and reliability.
- Research into more accurate, realistic, deployable, and fully validated models with appropriate uncertainty handling to support an offshore wind plant's operation stage and decision-making by considering all factors possible (e.g., different business scenarios and uncertainty levels, or even wind turbine models and technologies).
- Developing optimized asset management strategies, wherein condition monitoring and advanced data analytics, like machine learning, play an important role in service planning and parts management (removing humans from the decision-making process and minimizing technician visits).

4.4 Experimentation and Demonstration Facilities

Novel technologies can be prototyped, validated, further developed, and demonstrated based on both testing facilities and pilot projects. Testing of wind turbine components is necessary to ensure reliability of a wind plant over its lifetime. Because of the massive size of offshore wind turbines, the places where the components can be tested and certified are limited. In the United States, there is the capability to test wind blades up to 90 m in length (e.g., the Massachusetts Clean Energy Center's Wind Technology Testing Center [MassCEC n.d.]) and drivetrains up to 15 MW (Dominion Energy Innovation Center [Clemson n.d.]). In Europe, there are facilities at gearbox manufacturers in a back-to-back configuration rated to 30 MW (ZF n.d.), and at other institutes a 25-MW dynamometer (LORC n.d.).

Testing for mooring lines and anchors can leverage load testing facilities used for the oil-and-gas industry, with U.S. mooring line testing for proof and cyclic loading up to 1,500 t (DCL Mooring & Rigging 2023) and 50-g (force of gravity, g = 9.8 m/s^2) geotechnical centrifuge testing and 405-kilonewton dynamic pullout testing for anchor installations, allowing testing at a reasonable Froude scale for wind applications (University of California 2023). For interactions between the soil and foundation, the new testing capabilities and a hybrid simulation approach to be developed at the Offshore Wind Hybrid Simulation Facility (Lehigh University n.d.) for both fixed-bottom and floating offshore wind turbines can be used to perform pilot projects simulating U.S.-specific environments.

For blade testing, the WTTC recently finished testing the GE Haliade-X 107-m wind blade, but it necessitated cutting off the tip of the blade for full testing. Although the WTTC was capable of testing General Electric's current offshore wind turbine blade, the rate at which offshore turbines are growing may make exiting capabilities of the WTTC inadequate for future turbine designs, such as the recently announced CSSC Haizhuang H260-18MW, which will have 128-m blades (Wind Power Monthly 2023). There are, however, preliminary plans to expand the WTTC to accommodate up to 150-m blades (Schoenberg 2022). If the planned expansion of the WTTC does not happen, the next generation of offshore wind blades will have to be tested outside the United States, such as at the Fraunhofer wind blade testing facility in Germany, which has the capability of testing wind turbine blades at sizes above 120 m (Fraunhofer 2022).

O&M test facilities are needed to accelerate the development of new technology. Such facilities are beginning to be developed in Europe (ORE-Catapult n.d.-a, n.d.-b), but have not so far been constructed in the United States. From the interviews conducted as part of this roadmap, interviewees saw value in an offshore facility where new O&M strategies could be implemented and benchmarked against existing solutions. This facility could solve the new technology adoption issue of needing operational data and a real-world demonstration before owner/operators implement new technologies. Additionally, the site could be used for validating new and existing O&M optimization strategies.

One of the benefits of using test facilities is that the test article can be over-instrumented for validation. Attention needs to be paid to both wind-turbine-level responses and component-level reliability. If possible, the uniqueness of offshore operational environments should be considered.

Pilot projects can benefit from public sector funding support and leveraged to shorten time to market for O&M technology innovations (e.g., demonstration for autonomous vessels, robots, or drones for surveillance or cargo shipment, and monitoring solutions). Due to the share of funds from the public sector, some data from pilot projects can potentially be made available to enable advanced R&D. From the insurance perspective, normally 1 year of operational data for a new turbine model is required to get a reasonable premium, and the data need can potentially be met through relevant pilot projects. The additional value from combining OEM and owner O&M data can also be demonstrated based on pilot projects.

4.5 Standards and Recommended Practices

Standards for wind energy systems have existed for four decades now, with offshore-wind-specific versions in existence for almost 20 years. Notably, the American National Standards Institute/American Clean Power Association OCRP-1-2022 covers design, manufacturing, installation, commissioning, operation and service, decommissioning, and repowering. IEC 61400-3-1 (IEC 2019b) and IEC/TS 61400-3-2 (IEC 2019c) specify the design requirements for fixed-bottom and floating offshore wind turbines, respectively. Additionally, DNV-ST-0437 and DNV-ST-0119 address design requirements for fixed-bottom and floating offshore wind turbines. These standards, in general, are highly focused on the lifetime design for components and plants, with relatively little attention on O&M. Specific O&M standards for components have been started by first focusing on blades (IEC n.d.), which will be published within the next 5 years. These O&M standards may be proposed for other major turbine components and published in the next decade. This is an area with significant potential to improve and homogenize O&M practices.

In addition to standardization are best practices (e.g., data collection for various business needs may be different and can be better defined). Recommendations are needed on interpreting standards under local laws (e.g., product adaptation for specific markets). Also needed is recommended standardization of key performance indicators and evaluation practices for IEC conformity assessment. It will also be beneficial for the industry to adopt standardized components with the same specifications but provided by multiple suppliers.

4.6 Design Optimization Considering Reliability and O&M

The wind industry and related research have historically focused on reducing capital costs and increasing power production to make wind cost competitive with other energy industries. Many of these gains have come by reducing margins and redundancy in design. However, with maintenance and consequence of failure costs being significantly higher for offshore wind than land-based wind, more attention needs to be placed on designing and optimizing wind turbines and farms with greater reliability to reduce needed maintenance actions and decrease the probability of catastrophic failure. Because there are many challenges related to reliability-based design optimization (RBDO) for offshore wind energy systems research is needed to better understand or solve those issues. First, in a RBDO framework the uncertainty in modeling and variation is accounted for by treating design inputs as stochastic variables. Because of how new the offshore wind industry is in the United States, there is currently not enough data to accurately create the required probability distributions needed for inputs in a RBDO. It will be extremely valuable to explore potential data-sharing opportunities from other markets (e.g., Europe or Asia).

While there have been many publications on RBDO, they all focus on a single component and single failure mechanism (Li et al. 2017; Hu et al. 2016; Stieng and Muskulus 2020). Research is needed to understand the full system effects (e.g., both turbine and supporting structure in floating offshore wind) of using RBDO as well as investigation into how to account for multiple failure mechanisms rigorously and efficiently. Research to enable these advances is needed in advanced algorithms that can avoid or overcome the curse of dimensionality (e.g., with one more dimension added to a dataset, the volume of space the dataset represents increases exponentially) that occurs when trying to account for many different variables.

Reliability can also be enhanced by improving the design process in terms of advancing the tools used to enable design, and the design standards (covered in Section 4.5) and associated design basis. Improving and validating the physics-based models used in numerical design tools is the focus of second challenge identified by the grand challenges of wind energy in (Veers et al. 2019). Better understanding of the meteorological ocean conditions where offshore wind turbines will be installed, including inflow characterization, air-sea interaction, and farm-level wake effects, will lead to improved system reliability because the accuracy of design tools is tied to the inputs being used.

During the design process, various site-specific environmental conditions and hazards (e.g., earthquakes, wave heights) are considered. The O&M experience from the field on impacts from extreme weather conditions like lightning strikes, typhoons, hurricanes, storms, and tsunamis gained through post-event inspections; influences from wildlife (e.g., fish and whales); and new failure modes caused by environments (e.g., high salinity); can be fed into the design phase, leading to improved products going forward.

5 Recommended Actions

The recommended actions in this section are compiled based on observations from the reviews of both literature and recent industrial advancements from Sections 3 and 4, inputs from individual industry interviews, and stakeholder engagement events organized by the project team. They are grouped into different topic areas that include some example activities. The time horizon in this roadmap goes up to 2035 and these activities are presented in three phases: short term (now to 3 years), medium term (4 to 7 years), and long term (through 2035). To conduct these activities, close collaboration between the public and private sectors is needed. This collaboration will enable advanced O&M technology and process innovations and help speed their adoptions in the field to help the U.S. offshore wind energy industry succeed. There are appropriate roles for the public and the private sectors to play as suggested in Table 3. It could be beneficial to have a third party (e.g., consulting firm or university) lead a forum between industry and government to provide a neutral assessment of the R&D activities and help determine the steps needed to achieve the short- and long-term goals.

Table 3. Roles for Public and Private Sectors

Public Sector	Private Sector
Focus on fundamental research, technology development, and proof-of-concept demonstrations	Focus on technology evaluation, demonstration, and commercialization
Conduct lower TRL research and development to move technologies to a medium or high TRL	Conduct higher-TRL activities that help transfer R&D conducted by the public sector to market
Lead consortiums with a broad range of stakeholders from designers to owners and operators	Provide guidance on industry needs and filling in needed gaps (e.g., data access or testing site for technology demonstration)
Develop testing facilities and pilot projects, and perform experiments and demonstrations	Become customers/partners of test facilities and pilot projects
Conduct analyses to inform investments and policies to improve O&M (e.g., reliability, vessels, spares, workforce, recyclability)	Provide input to analysis efforts to improve relevancy and accuracy

There are four common themes that were identified as being beneficial through all three phases of this roadmap's targeted timeline (shown in Table 4).

Table 4. Common Themes Across All Timelines

Theme	Examples
De-risk O&M innovation through validation	• Novel repair techniques • Lightning protection solutions • Blade erosion mitigation • Full-scale dynamometer testing • Field testing (full and subscale) • Pilot projects (government and industry) • Robotic inspection and repair
Consider comprehensive life cycle costs	• Wind turbine (e.g., blades, drivetrain, support structure) • Balance of plant • Logistics • Vessels and crew • Parts availability • Environmental conditions (e.g., wind, wave, extreme weather, marine growth)
Close the gap between design, manufacturing, and O&M in the field	• Modular/repairable designs (e.g., medium-speed drivetrain, multistage direct-drive generator) • Improved repair techniques and self-healing materials
Develop industry standards for offshore wind energy applications	• Design conditions • Component reliability • O&M

Finally, the recommendations in the upcoming sections are organized by topic area, as follows:

- **Failure analysis and mitigation:** This topic area includes investigating and characterizing fundamental material properties that govern degradation processes for mission-critical wind turbine or balance-of-plant components and can be used in component design, prognostic operations, and end-of-life decision support (e.g., decommission, life extension, or recycling). The topic area also includes modeling and analysis research that considers component reliability degradation, potential repairs or prevention methods, as well as developing and validating various methodologies and tools.
- **Monitoring, sensing, and inspection:** This topic area includes either continuous data acquisition using permanent instrumentation on the wind turbine and balance of plant, or periodical data acquisition using anything from turbine-mounted sensors to a full suite of monitoring or inspection solutions.
- **Maintenance execution:** This topic area involves various activities that enable wind plant maintenance, which is determined based on wind turbine or balance-of-plant component conditions. Also included are training or R&D activities to help address future workforce or logistics needs for performing maintenance. This topic area also covers analyzing, evaluating, and implementing various maintenance strategies that are based on

inspections, monitoring, modeling, and analysis to minimize costs and maximize safety, performance, and reliability.

- **Design optimization considering reliability and O&M:** This topic area includes the methodologies and tools needed for new offshore wind turbine or plant design by considering reliability, O&M needs, and comprehensive costs (e.g., parts, labor, and vessels) throughout the entire lifecycle of the wind turbine or plant. Based on historical experience of certain turbines or balance-of-plant components, new solutions can be developed with improved performance and maintainability at a lower cost. One critical piece for this topic area to be successful is the feedback loop from the field to the wind turbine or component designers and manufacturers so that quality of future products they deliver to the industry can be improved.
- **Prognostics, health management, and O&M optimization:** By targeting mission-critical components (e.g., blades, drivetrains, towers, and support structures), this topic area focuses on modeling and analysis for anomaly detection, fault diagnostics, prognostics, O&M optimization, and decision-making to support O&M needs during both project development and operations.
- **Digitalization, robotics, and automation:** This topic area includes the use of digital technologies to improve existing or enable new business processes; provide opportunities to increase project value and revenue; employ robotics for wind plant O&M; and automate tasks traditionally done by people to reduce technician health and safety risks.
- **Standards and recommended best practices:** This topic area covers industry standards and recommended best practices that are needed for offshore wind O&M.
- **Experimentation and demonstration:** This topic area includes various scales of wind turbine or plant testing, from the lab and prototype to full scale. These activities are extremely valuable in helping reduce risks with O&M innovations through validation.

5.1 Short Term (Now–3 Years)

It is expected that in the short term, U.S. offshore wind will focus mainly on fixed-bottom wind turbines on the East Coast. The projects will be mostly new, and most reliability challenges are expected to be related to serial defects, design issues, or manufacturing defects. Most of the developers have O&M experience from other international offshore wind markets, and there is a huge opportunity for knowledge transfer to benefit the U.S. offshore wind industry. One effective and critical activity is to leverage lessons learned from other markets, and seek collaboration opportunities accessing established resources, including knowledge/expertise, vessels, crew, and data.

Table 5. Short-Term Recommended Actions

Topic Area	Recommended Actions
Failure Analysis and Mitigation	Increase accuracy in design tools for characterizing loads experienced by turbine components, supporting structures, and balance-of-plant equipment

Topic Area	Recommended Actions
	Develop probabilistic progressive failure models for structural components
	Standardize failure modes and classifications
Monitoring, Sensing, and Inspection	Investigate embedded and smart sensing of critical structural components above and below water
	Develop cost-effective structural health monitoring solutions for blades, towers, and support structures
Maintenance Execution	Develop training programs and certifications for technicians and engineers
	Develop and demonstrate advanced technologies (e.g., virtual reality) for technician training
	Validate blade repair methods through testing, field data, and inspection methods
	Develop new technologies to support crane-less operations, including both installation and maintenance
	Research innovative vessels (e.g., service operation vessels, crew transfer vessels) or other transportation solutions (e.g., cargo or human drones)
	Research solutions for maximizing efficiency at port and at sea by considering vessel availability, accessibility, etc.
	Evaluate cost-effectiveness between *in situ* and tow-back strategies for various floating offshore wind scenarios, specific to U.S. regions
	Develop enabling technologies for tow-back services for floating offshore wind (e.g., connect and disconnect systems for mooring lines or inter-array cables)
	Develop innovative solutions for floating-to-floating transfer of crews or equipment by considering safety for floating offshore wind
Design Optimization Considering Reliability and O&M	Research reliability-based optimized design methods for offshore wind turbines and plants based on improved understanding of loads and environmental impacts
	Evaluate reliability and financial risks for wind turbine up-scaling and determine the optimized turbine rating or integrated turbine and supporting structure design for floating offshore wind
	Improve reliability and maintainability of major turbine components (e.g., generators, gears, bearings, and pitch bearing) through novel design, manufacturing, and validation
	Develop new mooring lines, marine anchors, and dynamic cable solutions for floating offshore wind
Prognostics and Health Management and O&M Optimization	Develop a practical and deployable project development optimization tool based on costs, reliability prediction, installation, transportation, etc.
	Organize collaborations or develop a platform that supports benchmarking of modeling methodologies based on independent datasets and metrics
	Evaluate and validate novel CBM technologies or O&M models against field operational experience
Digitalization, Robotics, and Automation	Model and evaluate interactions between weather, ocean, marine life, electricity demand, and grid, and their impacts on O&M, and investigate mitigation solutions
	Organize collaborative activities or develop platforms to benchmark turbine and plant performance, downtime, and supply chain including delivery and costs
	Develop a digital ecosystem that harmonizes various types and resolution of data that are based on a standardized taxonomy or ontology, with demonstrated use cases (e.g., data engineering, fault diagnostics) to show additional value from digitalization
	Develop AI/ML algorithms to model individual turbine behaviors, extract knowledge (e.g., large language models), survey the health of turbine components, and make O&M decisions
	Build digital twins of the wind turbine, plant, and substation to support entire life cycle needs (e.g., evaluating turbine performance/reliability, effects from component scaling, and troubleshooting)

Topic Area	Recommended Actions
	Research mitigation technologies for cybersecurity risks associated with digital O&M
	Develop and demonstrate remote monitoring, inspection, and maintenance technologies that minimize crew visits
Standards and Recommended Practices	Support offshore wind O&M standard development, both domestic and international, including floating plants and extreme environmental events
	Evaluate data collection and modeling/analysis efforts, recommend best practices, and demonstrate through implementation.
	Develop industrywide taxonomy/ontology
Experimentation and Demonstration	Develop sub and full-scale testing facilities
	Identify specially permitted sites to demonstrate robotics and automation solutions
	Establish pilot projects with widespread data access to enable further R&D

5.2 Medium Term (~4−7 Years)

More offshore wind projects, including floating projects, are expected to become a reality in the U.S. offshore market in the medium term. Some of the fixed-bottom projects built earlier will reach a point of transition from under warranty with turbine manufactures to out of warranty. The O&M efforts can be conducted by either the project owner or a third party. This approach can help validate higher TRL research and development in the field that may not be feasible when turbines are still under warranty.

Most of the topic areas identified in Section 5.1 can be continued through the medium term as needed. A few new areas that will need attention are presented in Table 6.

Table 6. Medium-Term Recommended Actions

Topic Areas	Recommended Actions
Failure Analysis and Mitigation	Conduct experiments to understand wind turbine lightning physics
	Collect operational failure data to improve designs
	Develop composite damage growth models that include manufacturing and loading uncertainty
Monitoring, Sensing, and Inspection	Design built-in infrastructure for residential drones or robots on turbines or substation
	Develop technologies enabling smart sensing and intelligent situation evaluation and prediction
Maintenance Execution	Develop climber cranes to mitigate large component replacement burden on jack-up vessels
	Develop improved composite repair methods
Design Optimization Considering Reliability and O&M	Research new materials for wind turbine or balance-of-plant systems that can help improve O&M (e.g., self-healing or smart materials for blades)
	Fully validate floating offshore design against field experience including all components: the turbine, floating platform, mooring lines, anchors, and dynamic cables
	Research novel design concepts for floating offshore wind
Prognostics and Health Management	Research advanced multivariable and multi-objective optimization methods to account for all possible factors affecting O&M

Topic Areas	Recommended Actions
and O&M Optimization	Develop algorithms for intelligent decision-making by leveraging an increased amount of O&M data from the U.S. offshore wind energy fleet
	Research new modeling methods for predicting component degradation, based on an increased amount of O&M data
	Research plant-level optimization methodologies to minimize costs and maximize component service life by linking controls with production and loads
Digitalization, Robotics, and Automation	Establish accessible data sources to support novel R&D, including failure data, time series, work orders, etc.
	Investigate automated maintenance based on residential robots
	Research automated decision-making that minimizes human involvement
Standards and Recommended Practices	Support revision of industry standards or updated best practices
	Develop a consortium to support data sharing, O&M issues exchange, and investigation of mitigation methods, which can help align resources to benefit the industry
	Establish key metrics widely accepted by industry

5.3 Long Term (~8–12 years)

By 2035, some offshore wind energy projects in the United States have accumulated close to ten years operational experience and consideration of upcoming repowering projects could be a hot topic. More wind turbine components (e.g., blades) are expected to be replaced as the fleet ages. Floating offshore wind plants will most likely have accumulated some experience to provide data to evaluate on-site versus tow-back maintenance for major component replacements or turbine overhauls. More operational experience will be gained by offshore wind plant owners, who normally are more willing to share information to either pursue O&M technology innovations themselves or push wind turbine manufacturers to advance.

Most of the topic areas identified in Sections 5.1 and 5.2 can be continued as needed, with a few new subjects that can be explored, as shown in Table 7.

Table 7. Long-Term Recommended Actions

Topic Areas	Recommended Actions
Failure Analysis and Mitigation	Facilitate data sharing from component manufacturing
	Improve progressive failure models based on operational experience
Monitoring, Sensing, and Inspection	Implement fully autonomous monitoring of underwater components
Maintenance Execution	Develop novel vessel solutions, port-charging infrastructure, and offshore charging capabilities that account for decarbonization needs
Design Optimization Considering Reliability and O&M	Research novel turbine or system design with improved performance, reliability, and maintainability (e.g., more modularization) that can be maintained without heavy-duty cranes or vessels
	Research new turbine or plant component materials supporting reclamation
	Optimize designs to reduce redundancy in wind turbines or the plant
	Optimize project designs that consider emissions, wastes, and circular economy throughout the project life cycle
Prognostics and Health Management and O&M Optimization	Develop reliability models to support repowering, lifetime extension, and decommissioning
	Research optimized O&M strategies for co-operation of multiple technologies (e.g., wind, solar, and hydrogen)
Digitalization, Robotics, and Automation	Develop sensing to modeling and analysis technologies that improve wind turbine intelligence and enable self-awareness of performance and health
	Develop fully autonomous inspections and interventions solutions for components both above and below water

6 Conclusion

The purpose of this roadmap is to identify the primary operations and maintenance research activities needed if the 30-GW-by-2030 (offshore wind) and the 15-GW-by-2035 (floating offshore wind) deployment targets are to be met. These activities require effort from national and private research laboratories, academia, and industry to be successful. The roadmap indicates specific targets in several categories and over short-, medium- and long-term time frames. These targets all point toward the major topics of 1) de-risking O&M innovation through validation, 2) considering comprehensive life cycle costs, 3) reducing gaps between design, manufacturing, and O&M in the field, and 4) developing industry standards for offshore wind energy applications. Through dedicated efforts in the areas described, the U.S. offshore wind energy fleet can become more cost-effective and sustainable with enhanced performance, reliability, and lifespan.

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Appendix A. Guiding Interview Questions

1. **What are the top three offshore wind O&M challenges?** (e.g., wind turbine, balance of plant, accessibility, or supply chain)
    a. **What factors have you considered in this ranking?** (e.g., production loss, downtime, failure rates)
    b. **What subsystems you are most concerned about?** (e.g., blades, gearboxes, generators, foundation, cables)
2. In terms of knowledge transfer:
    a. **What lessons in terms of O&M from other markets do you think can be transferred to the U.S. market?**
    b. **What unique needs must be addressed to succeed in the U.S. offshore wind market?**
    c. **What unique challenges do you see with floating offshore wind in terms of O&M**?
3. To address these challenges, **what R&D areas you would recommend focusing on?**
    a. **What factors have you considered in identifying these topic areas?**
        i. **Among these, what are more appropriate for the public sector like DOE and its national laboratories to take on?**
    b. **If you could rank these, what are the top three opportunities for three different time horizons: short term (e.g., ~1–3 years), medium term (e.g., ~4–7 years), and long term (e.g., ~8–12 years)?**
4. **What do you think about digitalization (e.g., data standardization or artificial intelligence and machine learning) and automation (e.g., robots, uncrewed vehicles underwater or drones) technologies in support of offshore wind O&M?**
5. **What environmental impacts should we be concerned about for OSW O&M?**

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