Research and Development Roadmap 3.0

NATIONAL
OFFSHORE WIND
RESEARCH & DEVELOPMENT CONSORTIUM

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Acknowledgements

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Version History

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1 Background

1.1 Overview

The National Offshore Wind Research and Development Consortium (the Consortium), established in 2018 as a not-for-profit public-private partnership, focuses on advancing offshore wind technology in the United States through high-impact research projects and cost-effective, responsible development to maximize economic benefits. Current funding for the Consortium comes from the U.S. Department of Energy (DOE) and the New York State Energy Research and Development Authority (NYSERDA), each providing $20.5 million, as well as from the Commonwealths of Virginia and Massachusetts and the States of Maryland and Maine, for a total initial investment of approximately $47 million.

The Consortium is dedicated to managing industry-focused research and development of offshore wind to maximize economic benefits for the United States.

The Consortium seeks to help carry out a research agenda to accelerate the U.S. offshore wind industry in support of U.S. energy policy. The 2015 DOE Wind Vision modeled a scenario under which 86 gigawatts (GW) of offshore wind energy capacity is installed in the United States by 2050, which would account for approximately 7 percent of all U.S. electricity generation through large-scale project deployment in five offshore regions as shown in Figure 1 (DOE, 2015). This vision for offshore wind was used to develop the 2016 National Offshore Wind Strategy (the Strategy), a collaboration between the DOE and the U.S. Department of the Interior (DOI) (Gilman et al., 2016).

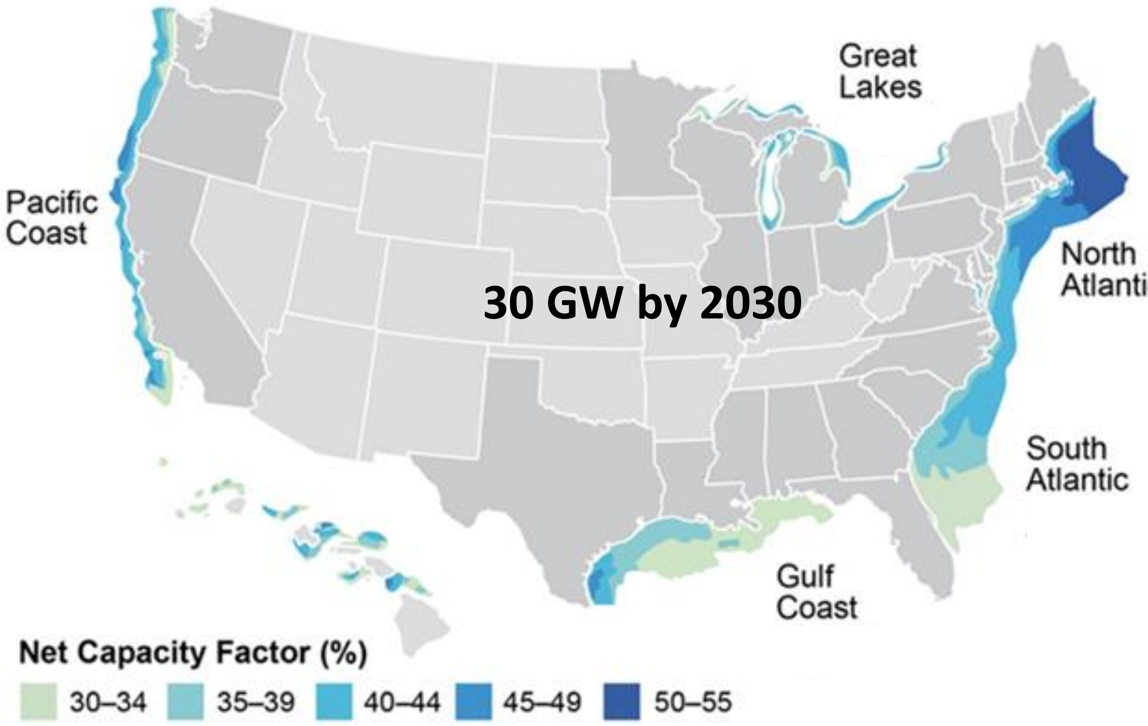

Figure 1. U.S. Offshore Wind Regions (Provided by NREL)

Recently, the Biden Administration strengthened the Wind Vision. On January 27, 2021, President Biden signed an Executive Order to double the capacity of offshore wind by 2035. Following this order, on March 29, 2021, the Biden Administration also released a detailed plan to "jump-start" offshore wind energy projects and create domestic jobs. The new plan identifies, for the first time, a U.S. deployment target, which calls for 30 GW of offshore wind in the United States by 2030. This aggressive target is achievable through appropriate coordination between the public and private sectors, and if met, will enable a longer-term target of 110 GW by 2050. Additionally, President Biden's proposed $2-trillion infrastructure plan will help enable the development of the U.S. offshore wind industry through the modernization of ports (Tankersley, 2021).

1.2 The Consortium's Research and Development Roadmap

The Consortium Roadmap serves as the overarching technical guidance document for the Consortium to advance offshore wind technology and drive wind innovation in the U.S. offshore wind industry. Specifically, it is focused on, but not limited to, technology advancement in each of three initial research pillars.[1] The Roadmap is regularly revised to adapt to changes in the U.S. offshore wind market, based on feedback received from the Consortium's members, Board, and Research and Development Advisory Group (RDAG). The Roadmap relies on expertise from the Consortium's internal technical team of offshore wind experts from DOE, the Carbon Trust, and the National Renewable Energy Laboratory (NREL). Roadmap revisions incorporate new research priorities and objectives as well as account for prior achieved research objectives. It has been approved by the Consortium's R&D Committee, who represent the intended end users of research activities, per the Consortium's principles of operation.

Pillar 1: Offshore Wind Farm Technology Advancement

This pillar focuses on technology advancements targeted at the major cost drivers of offshore wind. Accelerated innovation can reduce capital costs and development and deployment risks while increasing annual energy production, resulting in long-term levelized cost of energy (LCOE) reductions for fixed-bottom and floating offshore wind systems of 40 percent and 60 percent, respectively (relative to baseline LCOE figures presented in the Strategy). R&D conducted under Pillar 1 should also address the domestic physical siting challenges in wind turbine and wind farm technology (e.g., deep water, extreme conditions, freshwater ice, earthquakes, and hurricanes) as well as supply chain issues that may have unique U.S. solutions.

Pillar 2: Offshore Wind Power Resource and Physical Site Characterization

This pillar seeks improvements in offshore wind site characterization and site characterization technology that can drive significant cost reduction in U.S. offshore wind projects. R&D under Pillar 2 addresses lowering the time, cost, and/or uncertainty of wind resource assessment, geotechnical, and physical site characterization. Solutions may address cost reduction through increased annual energy production, reduced wind farm development timelines, greater certainty in the design environment, lower capital and operations and maintenance (O&M) costs, and lower project risk.

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[1] Generally, the Roadmap is informed by the three research pillars described in the original DOE funding opportunity announcement (DOE FOA 1767), summarized as follows (DOE, 2017).

Pillar 3: Installation, Operations and Maintenance, and Supply Chain

This pillar seeks technology improvements in wind farm installation, O&M, and supply chain issues related to the U.S. market, socioeconomic, and geophysical constraints. Installation costs, especially for methods that depend on high-capacity lift vessels and high levels of labor at sea, can drive up technology capital expenditures significantly. In addition, the estimated O&M costs for a fixed-bottom offshore wind farm in the United States, which range from $100 to $150 per kilowatt (kW) per year in 2015 U.S. dollars, can represent up to 30 percent of the total LCOE. Lowering these costs can lead to significant LCOE benefits. Finally, the immaturity of the U.S. supply chain may contribute to significant project cost and additional development risk. R&D under Pillar 3 should deliver technology solutions that will improve installation and O&M methodologies, reduce labor at sea, encourage domestic supply chain development, and subsequently, lower costs for offshore wind projects in U.S. waters. While Pillar 3 topics address some specific supply chain R&D areas, supply chain issues are central to the core objectives of the Consortium and consequently crosscut into all pillars of this Roadmap.

Although the Consortium may modify research objectives in future versions of the Roadmap, the Roadmap is expected to maintain an industry-focused offshore wind R&D agenda to help accelerate early U.S. offshore wind project development, LCOE reduction, and geographic industry expansion.

The first Consortium Roadmap was published in November 2018. Version 2.0 was published in October 2019, based on feedback from the Consortium’s R&D Committee and advisory groups and responses to the Consortium’s ongoing R&D solicitation.

Roadmap Version 3.0, building on the previous two versions, provides updates to all topic areas, which are revised regularly for clarity and better identification of specific project types. In some cases, topics areas were consolidated and new topic areas were added, in response to feedback.

New priority topics added or modified in Version 3.0 include:

- Industrialization of the Floating Supply Chain
- Workforce Development
- Floating Substructures
- Characterization of Atmospheric and Ocean Conditions at U.S. Wind Energy Areas (replacing Systematic Metocean Measurements in order to cover the required data, including of extreme events, more accurately)
- Floating Wind Operations and Maintenance

These updates are primarily driven by the continuous growth and evolution of offshore wind in the United States as defined by developer interests, individual state policy actions, and growing commitments to offshore wind globally.

There are now over 30 GW of U.S. policy commitments for offshore wind. Much of this expected deployment over the next decade will result from project activity already in the regulatory project pipeline or being considered for development as Call Areas (Figure 2).

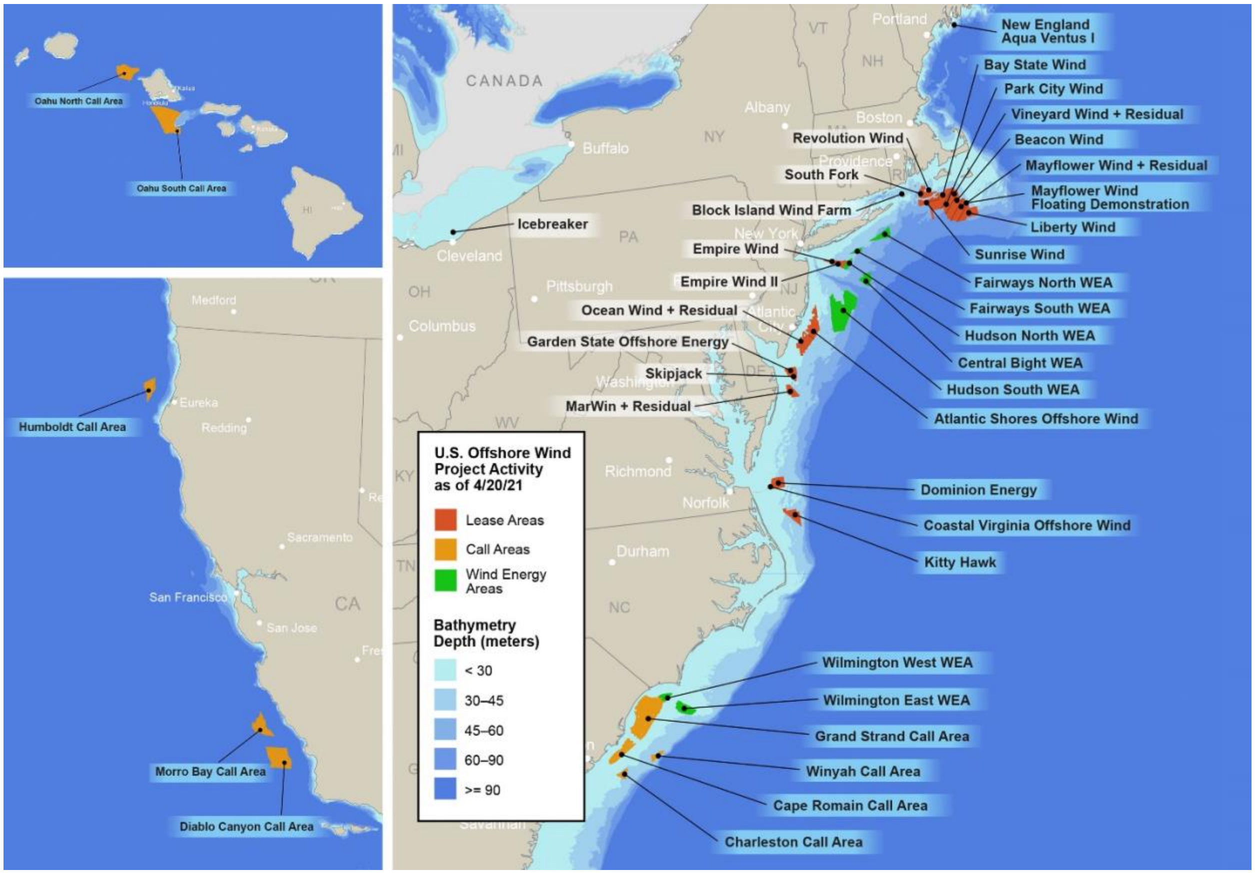

Figure 2. Locations of U.S. Offshore Wind Pipeline Activity and Call Areas, as of April 2021(Provided by NREL)

Consistent with the Consortium's policy of supporting the needs of the U.S. offshore wind industry, the Roadmap's primary focus is on technology solutions that can be realized in the near (zero to three years) to mid-term (four to seven years) time frame. These technology advancements are expected to deliver benefits of reduced risk and lower costs for ongoing and proposed development projects in all U.S. wind regions, as well as future lease and Call Areas.

1.3 Consortium Research Solicitations

The Consortium uses the Roadmap as a guide for developing competitive solicitations. Specific topics and technical challenges solicited are prioritized by its R&D Committee and may be limited by the requirements stipulated by the specific funding source(s) of each competitive solicitation. Therefore, only a portion of the topics identified in this Roadmap may be fundable under a given solicitation. The intent of the Roadmap is to express the Consortium's vison for a comprehensive list of research topics that need addressing.

The Consortium's initial R&D solicitation, released in March 2019, was administered by NYSERDA as Program Opportunity Notice (PON) 4124. PON 4124 was funded by NYSERDA and the U.S. DOE per the parameters of DOE FOA 1767 (NYSERDA 2019, DOE 2017). The Consortium's second solicitation, PON 4476 (Innovations in

Offshore Wind Solicitation 1.0), released August 4, 2020, was administered by the Consortium. In total, 40 research projects have been awarded, 20 from each solicitation. A complete list is included in Appendix A.

All Consortium solicited proposals are expected to adhere to the following general principles:

- Proposers should address issues essential for cost reduction, deployment, and industry expansion specific to offshore regions of the United States. Proposers of research topics that are already being addressed globally must explain why further research is necessary to adapt to U.S. conditions.
- Proposal topics will generally adhere to the three research pillars. Additionally, solicitations and project work supported by federal funding must adhere to DOE FOA 1767 guidelines and objectives. In some cases, this Roadmap includes important research areas that may be outside the scope of priorities indicated in DOE FOA 1767. They may not be eligible for federal funding but may receive support from the Consortium using alternative sources.
- Proposals should demonstrate that benefits to multiple end users are provided. R&D projects that benefit multiple end users are expected to have a greater impact toward achieving the Consortium's industry-wide cost reduction targets compared to R&D projects focused on a developer's specific commercial offshore wind project.

The Consortium's next solicitation may be informed by this Roadmap 3.0 and is expected to be released in 2021.

2 Pillar 1: Offshore Wind Farm Technology Advancement

2.1 Overview

Pillar 1 research focuses on technology advancements to the wind turbine and support structure system, as well as the entire wind farm, which have the potential to drive significant reductions in the LCOE for offshore wind in the United States. Pillar 1 includes both fixed-bottom and floating wind technologies with a focus on technology development that can address near-term and mid-term challenges for the initial phase of U.S. offshore wind projects.

2.2 Fixed-Bottom Technology

Fixed-bottom offshore wind technology is the primary platform architecture currently deployed, and designs reflect the collective experience from over 33 GW of global offshore wind projects. However, the physical and market conditions that determine development in U.S. waters can vary significantly from Europe and Asia. The following topics reflect U.S. research needs to advance wind farm technology.

2.2.1 Cost-Reducing Turbine Support Structures for U.S. Markets

Most fixed-bottom foundations installed to date have been designed for European offshore conditions and a 6 to 10 megawatt (MW) turbine class. With increasing offshore wind development in the United States and turbine growth to 15 MW, innovative products and solutions are required to reduce the overall LCOE by being more suited to U.S. offshore conditions, supply chain, vessel availability, and port facilities' requirements.

With more than 40 percent of the U.S. offshore wind resource located in water depths of 60 meters (m) or less, the use of fixed-bottom substructures offers the best near-term solution for the first phase of U.S. offshore wind projects taking place today in the northern and mid-Atlantic states. Available fixed-bottom turbine support structure designs may not be optimal for the near-term U.S. market due to differences in seabed characteristics, water depth, extreme weather conditions, environmental and regulatory siting constraints, availability of suitable installation vessels, and immaturity of the domestic supply chain. As the offshore wind industry continues to grow, there is a great opportunity to innovate, modify, and optimize offshore wind substructures for U.S. offshore conditions, and to adapt these structures for manufacture and installation by U.S.-based companies.

The support structure accounts for 20.1 percent of the capital expenditure for a fixed-bottom offshore wind farm (Stehly et al., 2020), and this percentage can increase with water depth, unfavorable seabed conditions, and varying capabilities of the local supply chain. There is the potential for innovative technologies to have a marked impact on reducing the capital expenditure for substructures and enable development at some sites where commonly used substructure technologies (e.g., monopiles) are not feasible.

Some examples of possible projects that may be considered under this topic are:

- Support structure design concepts that address unique siting challenges at U.S. offshore wind sites,
- Assessments of the suitability and reliability of existing available support structures for U.S. specific conditions,
- Advanced control systems and strategies to reduce fatigue and extreme loads on support structure technology,
- Innovations to improve reliability and lower maintenance costs,
- Design innovations that avoid conflicts with other ocean users or with the physical ocean environment (e.g., rocky soils and soft soils),
- Innovations that provide solutions to installation and infrastructure barriers such as vessel, port, and transmission constraints, and environmental constraints such as acoustic impacts,
- New solutions that enable lower cost installation with reduced risk,
- Development of advanced manufacturing and materials such as additive manufacturing, lightweight, high strength, corrosion resistant materials, and structural coatings that demonstrate increased reliability or lower cost.

2.2.2 Modeling of Array and Inter-Array Effects

Assessments are required to develop and improve understanding of how turbines behave within large arrays and how multiple arrays will impact regional energy production as well as lower maintenance costs. Five awards were made under this challenge area in the first two Consortium solicitations. That indicates the high importance that was originally placed on this area, but certain subtopics may not yet have been addressed. This topic has been updated to focus on new concerns with large-scale array modeling that have emerged.

As project sizes continue to grow and the number of lease areas on the outer continental shelf increases, new farm-wide design tools and control strategies are needed to understand the cumulative impacts of multi-turbine arrays and the industry’s ability to optimize regional energy capture. Recent evidence has emerged that the impact of multi-turbine arrays on downstream turbines and downstream arrays (inter-array effects) may be understated in some array wake models. It is important to quantify these cumulative impacts with the atmospheric conditions relevant to U.S. lease areas into the high fidelity and engineering array models (Nygaard et al., 2020).

In addition, while most array models focus on increasing energy capture, less attention has been given to deep array effects in terms of turbine maintenance and downtime. Preliminary research indicates that array optimization strategies can extend design life through load reductions of up to 50 percent for certain wind turbine components, which will reduce fatigue, hence turbine maintenance and O&M costs (Carbon Trust, 2017).

The following are examples of possible projects that may be considered under this topic:

- Models or methodologies to characterize the physical conditions of the U.S. lease areas, leading to better modeling of array blockage effects and cluster wakes,
- Studies to quantify the differences between U.S. and European wind conditions that can demonstrate improvements to the accuracy of wind farm system models used for U.S. offshore wind projects,

- Models that predict deep array loads and wake effects that lead to better turbine lifetime estimation,
- Methods and tools to improve deep array turbine reliability and reduce O&M costs.

2.3 Floating Offshore Wind Technology

2.3.1 Overview

Although almost all commercial offshore wind projects have been deployed in depths less than 50 m and use fixed-bottom substructures and foundations, approximately 1200 GW, or 58 percent, of the U.S. offshore wind technical resource area is in waters deeper than 60 m. The significance of the 60 m depth delineator is that water depths above 60 m are generally recognized as the frontier for nascent floating turbine support structures.[2] As additional near-shore sites in the Atlantic are developed, shallow water areas will become scarcer. Conflicts in near-shore siting, lease area density, and the need to find suitable interconnect locations may necessitate consideration of offshore wind sites greater than 60 m depth, which tend to be farther from shore (Musial et al., 2016). In the Gulf of Maine, shallow water sites, in general, are not available; floating wind will be needed to serve northern New England. University of Maine's Aqua Ventus 1 demonstration project, sponsored by the U.S. DOE under the Offshore Wind Advanced Technology Demonstration program and backed by Diamond Offshore Wind and RWE, is scheduled for commercial operations by 2023, and could become the first floating wind turbine project in the United States using a commercial scale wind turbine (U.S. DOE, 2021). This project promises to be the flagship for a robust floating wind industry in North America.

Techno-economic cost models have shown that floating wind technology has the potential to achieve the same cost (or lower) as fixed-bottom offshore wind by 2030 (Beiter et al., 2016; Beiter et al., 2017; Gilman et al., 2016). As the market expands, learning curve effects and economies of scale can contribute to lowering floating offshore wind technology cost and achieving parity with fixed-bottom technology (Musial et al., 2020; Beiter et al., 2016).

In the Pacific region, where projects will be installed in water depths between 500 m and 1300 m, all installations will be required to be floating. In the Great Lakes, an additional 700 terawatt hours (TWh) per year of offshore wind resource, over waters deeper than 60 m, is potentially available. However, new ice resistant floating technology is needed to unlock this resource for future offshore wind development.

The Atlantic states have an abundance of possible shallow floating sites at depths between 60 m and 90 m (Figure 3). These sites, just beyond the current lease areas, may be the most accessible for future development, although there are significant technology challenges to mooring substructures at these shallow water depths. These challenges may be amplified as larger turbines are installed.

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[2] The depth range used to conduct U.S. floating wind energy resource assessments stops at 1300 m, which was recently extended from the previous limit of 1000 m.

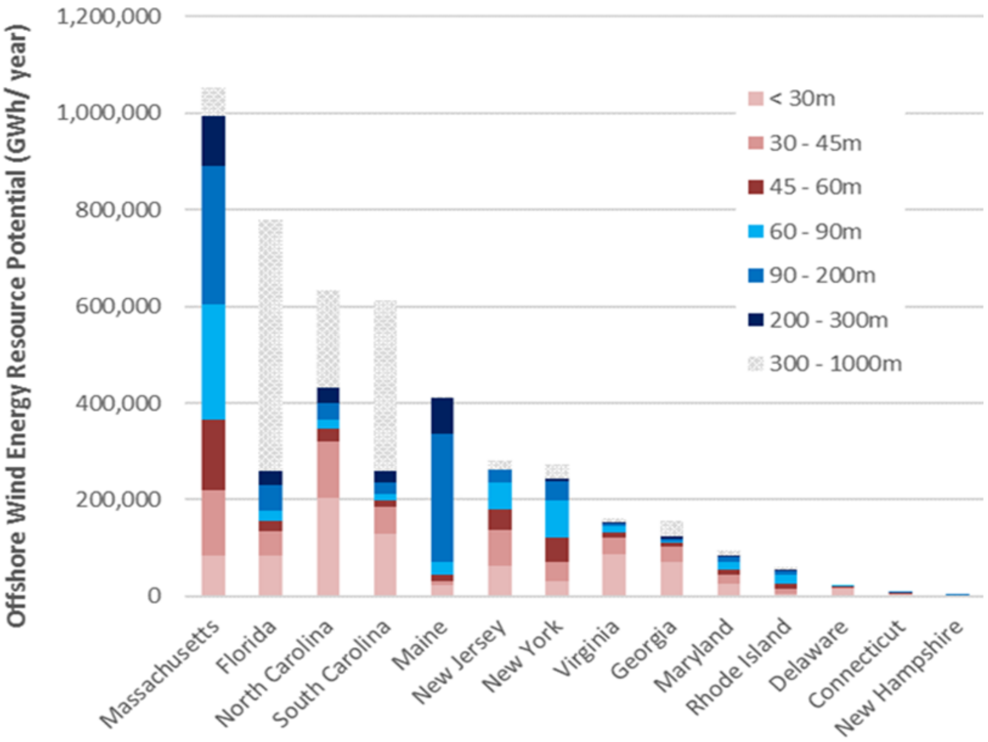

Figure 3. Water Depth Bands for U.S. Atlantic States Showing an Abundance of Resource from Depth of 60 to 90 Meters (Provided by NREL)

Technology is needed to reduce the cost of floating technology capital expenditures (CapEx) to achieve long-term cost targets at between $50 and $70 per megawatt hour (MWh) by 2030. This level of cost reduction is best achieved by implementation of multiple innovations within a complete system design. The spirit of innovation of floating wind technology in the United States is exemplified by the recent ARPA-E ATLANTIS program, which recently awarded $28 million in federal funding for high-risk, long-term floating control co-design of offshore wind projects that push the boundaries of innovation seeking breakthrough technologies that accelerate floating technology advancement (ARPA-E 2019).[3] The Consortium funding complements programs like ATLANTIS by targeting technology advancement on a near-term or mid-term scale that can be implemented at lower risk over the next seven years (ARPA-E 2021).

The following topics reflect floating wind technology priorities for this Roadmap.

2.3.2 Mooring Concepts for Floating Foundations

Although significant knowledge can be gleaned from the oil and gas (O&G) sector, floating offshore wind mooring concepts have unique challenges that require unique innovations and solutions. As the floating offshore wind industry grows, there is a considerable need to design, develop, and test mooring concepts that are fit for purpose.

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[3] ATLANTIS is an acronym for Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control.

At present, the global floating offshore wind industry — including its supply chain — is in its infancy. However, a significant global increase in the development and installation of floating offshore wind technology is predicted. With the considerable expertise that the United States already has through the O&G sector, there is the opportunity for O&G suppliers to diversify to floating wind and become global offshore wind supply chain leaders. Although significant strides have been made to develop suitable mooring concepts, greater efforts and technology innovations are needed to design, develop, and test a range of mooring concepts, components, materials, and installation methods that are suitable to different conditions.

Whether optimized for shallow regions or deep-water conditions, new mooring concepts should demonstrate feasibility using coupled dynamic mooring analysis to comply with International Electrotechnical Commission (IEC) design standards (e.g., IEC 61400-3-2), while achieving lower costs, verified using techno-economic system cost models. Concepts should also comply with other recommended practices for design, installation, and operations practices for floating systems in U.S. waters. Furthermore, consideration should be given to designing concepts that minimize conflicts with existing offshore activities and stakeholders, such as commercial fishing.

The Consortium has awarded seven mooring system projects under the first two solicitations, indicating that this challenge area is of major importance and has been addressed to some extent, but there may still be research gaps worth addressing.

2.3.2.1 Shallow-Water Mooring Concepts

Two projects have been awarded under the first two solicitations to address shallow water issues with catenary moorings. Current mooring systems (especially catenary mooring types) become more expensive at shallower water depths due to the need to avoid snap loading, anchor uplift forces, constrain watch circles to protect electric cables, and balance system natural frequencies with wave excitation. Large platform motions in storms can cause localized tension spikes (snap loads) in mooring lines when a line reengages after momentarily going slack (Hsu, 2018). Shallow water depths may also increase anchor loads and introduce unfavorable load vectors, requiring local seabed condition optimization. Alternative design configurations and mooring solutions are needed to address shallow water issues.

Examples of projects that may be considered include:

- Projects that manage loads transferred from mooring lines to substructures,
- Projects that optimize safety factors and introduce and test new materials without adding cost,
- Projects that address unique seabed conditions at representative U.S. shallow water sites,
- Projects that reduce footprints of mooring/anchors circle to minimize fishing conflicts,
- Design of active surveillance systems to detect mooring system health and status,
- Techno-economic studies to better understand the technical and financial parameters that define the water depth transition zone between fixed and floating wind.

2.3.2.2 Deep-Water Mooring Systems

The steep drop of the continental shelf off the Pacific coast, combined with requirements to minimize visual impact, tend to focus development areas off the Pacific coast into a narrow strip in relatively deep water. The five Pacific Call Areas all require floating wind technology. Projects in these areas will be sited in water exceeding 500 m depth. The deeper the water, the larger the anchor circle gets, which reduces the energy extraction potential for a given lease area. Alternative design configurations and mooring solutions are needed to address these deep-water conditions.

Examples of projects that may be considered include:

- More efficient designs for Pacific depths ranging from 500 to 1300 m,
- Concepts that reduce deep-water mooring system footprints for the California and Hawaii Bureau of Ocean Energy Management (BOEM) wind energy Call Areas,

- Mooring line and electric array cable configurations that can minimize impact on fishing activities and other existing ocean use activities,
- Assessments of mooring systems to minimize cost and maximize performance for various platform types,
- Advanced methods to automate/expedite anchor and mooring line installation,
- Optimized anchor designs and methods for installation in deep water and at sites prone to seismically induced soil liquefaction.

2.3.3 Floating Substructures

In a 2015 study by the Carbon Trust, scaling to larger substructure sizes was highlighted as the parameter that could deliver some of the greatest cost savings. However, there are significant challenges in upscaling, optimizing, and adapting the current substructure and system designs for serial production. While original equipment manufacturers (OEMs) reveal their plans for increasingly large turbines, the industry is preparing for commercialization of floating wind at utility scale. Considerable R&D is still required to design, develop, value engineer (cost minimization), and validate a range of floating substructures that can address turbine upscaling and overcome the necessary supply chain hurdles to produce and assemble full systems domestically. Technology innovation and optimization for the first generation of large commercial floating turbines is needed.

Floating wind substructures enable greater flexibility in supply chain industrialization (see Section 4.4.2) compared to bottom-fixed systems, but the maturity of the supply chain is at a lower readiness level. The evolution from single prototype subscale systems to full-size turbine demonstrator wind farms has proved the favorable scaling of floating substructures, with the larger turbines in demonstration projects reporting lower substructure mass increases relative to turbine capacity growth. However, upscaling of floating platforms may be constrained by other factors such as size and manufacturing capacity throughput limits, crane capacity limits in the assembly and installation of larger/heavier parts, increased complexity of system modeling, and size and capacity limits of ports and staging facilities. The modularity of many floating systems allows the manufacturing components in various facilities prior to marshaling and deployment from a single, or multiple port locations. A diverse and distributed supply chain will lower production risk. The TetraSpar floating platform for example, has been designed specifically around the manufacturing process and consists of modular components that can be transported by road and assembled at a suitable port within two days by means of a conventional dockside crane. Design solutions that consider holistically the U.S. environmental, economic, supply chain, and infrastructure landscape, as well as the generic physics of floating wind turbines are needed.

Examples of concepts that may be considered include:

- Analysis aimed at reducing the uncertainty in the characterization of external conditions of floating wind at potential U.S. sites,
- Working with designers to improve methods to lower the uncertainty of material fatigue properties in floating systems from load estimations using engineering system tools,
- Working with marine operations specialists on strategies to lower installation and assembly costs for floating offshore wind substructures integrated with large-scale turbines,
- Strategies and logistical approaches that facilitate greater port access or minimize port upgrade costs,
- Assessments that provide detailed methods and strategies (considering weights, clearances, substructure dimensions, draft, and assembly methods) to expand the field of U.S. suppliers and sites for floating wind,
- Working with substructure designers or suppliers on detailed studies that adapt single unit production to serial production at commercial production scale (e.g., 50 units per year), with emphasis on localization of manufacturing,
- Design innovations that facilitate the industrialization of the supply chain and demonstrate the potential for broader participation among domestic suppliers,
- Innovations that lower or eliminate total labor requirements for open ocean construction and/or reduce labor for maintenance at sea,

- Optimization strategies and methods demonstrating the full integration of floating systems (i.e., turbine, floater, mooring lines, anchors, and cables).

2.3.4 Large Floating Array Technology Issues

At present, there are no large-scale floating offshore wind farms installed globally. Therefore, there is limited understanding of the turbine or array scale issues and dynamic behavior within the array. Applications for several large floating arrays, each over 400 MW, have been submitted to BOEM for projects in Hawaii and California, with estimated commercial operations dates after 2026. Floating wind turbines differ from fixed-bottom turbines because their platforms allow six degrees of substructure motion, which can significantly influence the individual turbine's dynamic behavior, especially those subjected to downstream turbulence. The impact that these additional platform motions will have on the design, performance, and load response for both the single turbine and multiple turbine arrays is not understood. For example, a floating wind turbine's yaw behavior may be less predictable since the turbine's platform can drift rotationally in yaw, adding to its actively prescribed yaw position. This effect can be exacerbated in waked flow. Due to greater water depths, floating wind farm designs may also need different methods to protect cables and mooring systems and may have more apparatuses suspended in the water column.

Examples of projects that might be considered in this topic area include:

- Research to model and understand how floating turbines with six degrees of freedom in an array behave under various atmospheric conditions and with different substructure types,
- Advanced control systems and strategies at an individual turbine and array scale to optimize performance, minimize loading, and manage the dynamic interaction of multiple floating offshore wind turbines,
- Innovative solutions to export cable connections and floating substation challenges,
- Designs for efficient intra-array cable layouts that account for water depth and other ocean use activities,
- Detailed design solutions for floating substations resulting in cost-efficient floating substations,
- Certified designs for dynamic array cables at 132 kV and/or dynamic export cables.

2.4 Technology for Both Fixed and Floating Offshore Wind

There are several challenges facing both fixed and floating offshore wind that need to be addressed to advance offshore wind in the United States.

2.4.1 Enabling Large-Scale Offshore Wind Turbines

Turbine rating is increasing significantly with nameplate capacities of 12 MW to 15 MW available soon. With this growth rotational speeds are decreasing, with rotor sizes up to 240 m, soon to be sold by all major turbine manufacturers. Economic models have shown that larger turbines significantly lower offshore wind LCOE and are therefore likely to be adopted by all developers. These larger 12 MW to 15 MW turbine platforms are creating new technical challenges for the industry both domestically and globally, and these turbines are expected to be used for both fixed-bottom and floating wind turbines. The U.S. industry must address technical issues regarding large turbine scaling and wind farm integration as developers have already committed to using these turbines for near-term U.S. projects. Impacts of these larger turbines and their components on energy production, reliability, and the associated infrastructure need to be understood.

While the global markets move to commercialize these larger turbines, reliability and systemic issues related to their adoption must be addressed at the early production and full-scale qualification stages. In addition, large rotors may introduce new physical conditions related to wind farm wake interactions and dynamic resonance interactions between the slow rotating turbines and floating substructures, which are becoming increasingly difficult to avoid. Projects to mitigate issues with large turbines are envisioned via desktop assessments, component development, or hardware and testing systems implemented in the field or an existing laboratory, as appropriate.

Examples of innovative project solutions are:

- Technology design solutions to reduce project risk in implementation of large turbines in offshore project development and deployment,
- Innovative solutions that validate or demonstrate turbine reliability and reduce mean time between failures,
- Innovations that can be implemented to improve the quality and accuracy of full-scale component validation tests,
- Preliminary designs to inform the vessel and port requirements for specific locations where the marine operations will take place,
- Designs to adapt new offshore wind port facilities to minimize upgrade costs and/or streamline construction, assembly, and service operations,
- Studies that address all aspects of the large turbine supply chain and determine national and regional supply chain requirements to avoid bottlenecks that may hinder industry growth at early stages,
- Projects to develop, improve, and validate the design and analysis tools to facilitate advancements and optimization of fixed and floating technology,
- Models to understand 15 MW scale turbine wake behavior and possible ground effects, low level jets, power performance calculations, and other upscaling phenomena,
- Design solutions that address the coalescence of the natural frequency of large floating wind turbines rotational speed with fundamental tower system frequencies.

2.4.2 Hurricane Resilient Wind Systems and Environmental Extremes

General understanding of the impact of tropical cyclones and hurricanes on offshore wind turbines is limited. Hurricanes commonly occur along the entire Atlantic coast and the Gulf of Mexico and may impact approximately half of the total U.S. resource area. Most hurricane-prone sites will likely use fixed-bottom substructures, but BOEM Call Areas have already been established in Hawaii, where floating turbine designs may need to be enhanced for hurricane conditions. Floating wind farms may also be developed in the south Atlantic and the Gulf of Mexico, but because there is an abundance of shallow water in these regions, floating systems are less likely to be considered in the near- or mid-term. Technology developments under this topic area seek to reduce the risk for turbines operating in hurricane-prone regions of the United States.

In the northern latitudes of the Atlantic, IEC Class 1 turbines are more likely to have sufficient design margins in fixed-bottom and floating designs to survive tropical cyclones with reasonable precautions, while substructure designs can be adapted for hurricane resilience using proven concepts and practices from the oil and gas industry (e.g., API RP 2A). As turbines are deployed in regions where extreme winds may exceed IEC Class 1 criteria, current turbine designs will have to be adapted further to mitigate extreme loads and low-cycle fatigue. One of the primary challenges is understanding the frequency and severity of extreme hurricane conditions at specific locations. In addition, the reference height and wind speed duration (10 m and one minute) used by the National Hurricane Center to classify the severity of hurricanes (e.g., Saffir-Simpson Category 1-5) does not translate well to IEC wind turbine extreme wind design criteria (i.e., 70 m/s three-second gusts, measured at hub height). Therefore, it is difficult to compare the severity of a given hurricane at a given location to the IEC design conditions. Also, the long duration and internal wind extremes that a wind turbine is likely to experience during a hurricane passage (e.g., extreme gust factors, wind shear, and veer) may not be sufficiently characterized by the current IEC 61400-01 three-second extreme load cases and models. These design uncertainties can result in higher project risk (technical and financial) and greater insurance costs. It is also expected that offshore wind projects proposed in hurricane-prone areas should anticipate increased capital costs of offshore wind system upgrades for hurricane design conditions.

In addition to hurricanes, other environmental extremes such as earthquakes or corrosion may limit design life or increase risk to offshore wind installations, if not properly accounted for.

Examples of projects that might be considered in this topic area include:

- Research activities to quantify the understanding of location-specific hurricane severity and probability at U.S. offshore wind sites,
- Survival strategies for existing turbine designs that quantify, in terms of loads, strength reserves, and cost, a turbine's increased ability to withstand extreme conditions,
- Methods to evaluate the fatigue accumulation during a single extreme event,
- Cost studies to determine the premium for hurricane-class turbine upgrades,
- High-fidelity modeling to increase the physical understanding of IEC design limit-state hurricanes and their internal structures (e.g., gust factors, veer, shear, eye wall behavior, and fatigue) to assess the adequacy of current IEC load cases and assumptions,
- Studies that specifically investigate possible combined extreme wind and wave load cases on a turbine or array that may not be accounted for presently,
- Design solutions that demonstrate earthquake resistance in bottom-fixed and floating systems,
- Design solutions to extend the life of offshore wind components through corrosion resistance.

2.4.3 Floating and Fixed-Bottom Arrays in the Great Lakes

The Great Lakes offer a significant opportunity for offshore wind development with a gross wind resource potential of 519 GW. A 21 MW demonstration scale project is planned in the shallow waters of Lake Erie, 7 nm off the coast of Cleveland, but approximately 383 GW (over 700 TWh per year) of the total resource potential is above 60 m depth. This is equivalent to nearly 10 percent of the total offshore wind resource of the United States. However, there has been limited development of floating wind technologies that can survive freshwater ice conditions. Considerable efforts may be required to design, develop, test, and demonstrate survivability of floating wind turbine concepts that are suitable for deployment under these conditions. The Great Lakes region is highly populated, therefore it is likely that large-scale offshore wind farms will need to be sited farther from shore, necessitating ice resistant floating wind technology.

An example of projects that might be considered in this topic area:

- New technology concepts, tools, or design guidance that provide developers and original equipment manufacturers (OEMs) greater abilities to accelerate the development of floating offshore wind systems in the Great Lakes.

2.4.4 Offshore Power System Design and Innovation

The rapid deployment of offshore wind that is planned for the U.S. land-based grid in the North Atlantic creates significant challenges for utilities, developers, regulators, and policy makers to introduce this offshore wind energy to the existing infrastructure with minimal disruptions at the lowest cost. This topic area covers technical innovations that relate to the electrical infrastructure from the turbines to the land-based interconnect, which accounts for 18.7 percent of the total offshore wind CapEx (Stehly et al., 2020). These cost percentages are expected to increase as projects are sited farther from shore, in deeper waters, and the number of suitable land-based interconnection points become scarcer. As such, innovations in the electrical power system design can play a significant role in lowering system cost. The higher penetrations of offshore wind that the planned deployments will bring also puts increasing pressure on the offshore wind turbines and substations to provide more grid support services, in addition to electricity.

European offshore wind farms have shown that cable-related incidents account for 80 percent of insurance claims, and approximately 60 percent relate directly to cable damage during construction (Carbon Trust, 2018). In floating systems, dynamic electrical cable systems for individual turbines and their substations are still at an early stage of development and their cost and reliability must be demonstrated.

Collaborative power system projects for shared transmission will financially enable the U.S. offshore wind industry to develop electrical infrastructure that may otherwise be cost-prohibitive for a single project. Cabling landfall has been an issue of contention for past U.S. offshore wind projects. As most of the equipment is currently imported to the United States, there is a considerable opportunity for tier 1 suppliers to establish production and supply lines domestically.

Examples of projects that might be considered in this topic area include:

- Innovative solutions to cabling landfall and onshore cabling installation to minimize conflict with stakeholders, authorities, and landowners,
- Innovations to the array power distribution system and export cable system,
- Innovations to the offshore substation for lower cost and risk,
- Modeling hardware approaches to improve grid reliability for various grid solutions,
- Design and qualification of higher capacity dynamic power cables for floating wind turbines,
- Projects that minimize overall infrastructure cost through use of new technologies like solid-state transformers and ultra-compact offshore HVDC stations,
- Projects seeking to improve seafloor cable cover designs, installation, and inspection methods.

2.4.5 Energy Storage Integration Resilience and Reliability

Trends toward full decarbonization across all energy use sectors increase the need to make offshore wind more dispatchable and less subject to curtailment. This need has accelerated the demand for energy storage that is integrated on-site with offshore wind projects or at a system level with other combinations of generation and storage. In recent years, several states have adopted high-penetration renewable energy portfolio standards (RPS), including New York, California, Massachusetts, New Jersey, Rhode Island, Virginia, and Hawaii, where offshore wind is likely to be a major contributor. Due to the variability of renewable energy resources such as wind and solar, developing and integrating efficient energy storage is a key facet to achieving these states' long-term renewable energy targets. Energy storage will enable a more decentralized approach which will increase long-term energy security and system reliability. Although there has been significant development in energy storage system technology and design, greater efforts are needed to integrate innovative, fit-for-purpose energy systems with offshore wind.

There is also a need for improved understanding of high/low temperature extremes (which affect demand), extended periods of low or no wind (which could drive storage and/or capacity reserves), and the need for expanded operational envelopes to support the power system.

With the growing commitment to develop offshore wind is an increasing need to ensure the security of the offshore wind energy supply.

Another growing challenge is the need for black-start services. As conventional synchronous generating farms retire, and the supply of inverter-based power generators increase (e.g., wind turbines) the system becomes more vulnerable because grid-following inverter-based wind generation cannot form the power grid on its own and requires grid support for its operation (e.g., Texas statewide ERCOT grid event in February 2021). As offshore wind penetration increases, some of the offshore wind farms will need to be capable of carrying out system restoration services (i.e., black-start capability) instead of relying on thermal/gas power plants. Developing a grid-forming offshore wind turbine running in black-start mode is the first step to enabling black-start capability. Many distributed grid-forming wind turbines running in black-start mode must be centrally coordinated and sequentially energized. Technology innovation is needed to develop black-start capability for the offshore wind turbines, and further system integration is needed for power restoration to the inverter-based generation.

Examples of projects that might be considered in this topic area include:

- Development and demonstration of methods and tools for integrating storage with offshore wind systems using data and analytical modeling at the turbine, wind farm, or system level,
- Offshore wind storage options that demonstrate and quantify the value to the grid through increased dispatchability to meet peak demand, or demonstrate increased ability to provide capacity, flexibility, or other grid services,
- Solutions that supply grid essential reliability services (such as voltage control and frequency response) and increase system reliability,
- New turbine designs capable of black-start and grid forming,
- Grid forming solutions that can be implemented system-wide using turbines with black-start capabilities,
- No-wire alternatives for green hydrogen production at scale,
- Alternatives to battery storage, such as hydrogen, thermal storage, or pumped hydro storage for specific applications that address a full range of timescales including long duration storage options,
- Projects that address offshore wind security in terms of physical or cyber threats.

2.4.6 Decommissioning, Life Extension, and Infrastructure Repowering

A typical offshore wind project today is expected to last 25 to 30 years, but project life expectancy continues to increase as more projects approach their theoretical end of life. Typically, projects will be decommissioned and the parts removed from the ocean and salvaged. For most projects, this logic is used for the turbines that are subject to high load cycles over many years, but the remaining infrastructure that comprises the subsea cables, support structure, substations, and land-based grid may have many more years of useful life. Significant cost benefits may be available if developers can repower or repurpose much of the remaining infrastructure. Similarly, the wind turbine may have residual life after its life expectancy or lease period has expired. Life extensions can be engineered into wind farm systems to enable longer lives (and lower LCOE), for example, with part replacements and upgrades that maintain safe operation.

Examples of projects that may be considered under this topic area include:

- Studies that assess the component lifetime of key infrastructure systems and calculate LCOE alternatives to decommissioning,
- Studies that assess cost impacts of decommissioning for different substructure types,
- Innovations and wind farm alternatives that deliberately design for life extension and repowering beyond traditional lifetime windows,
- Studies that offer recycling options for large wind turbine blades,
- Studies that repurpose oil and gas infrastructure for hydrogen production and storage.

3 Pillar 2: Offshore Wind Power Resource and Physical Site Characterization

3.1 Overview

Pillar 2 research aims to reduce the risk of offshore wind, focusing on activities that lower the cost, time, and uncertainty of site characterization for offshore wind developers on the U.S. outer continental shelf. Metocean and physical site characterization activities will focus on data collection and validation, improving site characterization modeling and measurement methodologies, and validating analytical models and data sets used for site characterization.

3.2 Metocean Research

The following topics reflect the Pillar 2 offshore wind power resource and physical site characterization priorities.

3.2.1 Comprehensive Wind Resource Assessment

Wind resource assessments are essential to offshore wind planning decisions at the national, state, and project level. Offshore wind geospatial resource assessments are used by public and private entities to make major planning decisions that impact the U.S. offshore wind industry. Based on the relative lack of measured wind data offshore, as well as the time and expense associated with new on-site measurement campaigns, the industry relies on mesoscale models that are run with a variety of inputs, including, for example, reanalysis data and measured climate data (radiosonde, buoy, or land-based). Current resource assessments do not include full validation of modeled data due to lack of observations at hub height or changes to the resource due to climate change.

Most publicly available data observations have been recorded from surface buoys at 5 m height, which have high uncertainty when extrapolated to hub height because an accurate methodology that accounts for vertical variations in atmospheric stability, low-level jets, surface effects, seasonal and diurnal changes, and other atmospheric complexities has not yet been developed.

Examples of projects that may be considered under this topic area include:

- Resource validation methods and extrapolation techniques using models, surface buoys, LIDAR, satellite data, or other existing data,
- Studies or models that quantitatively estimate the near and far term future impacts of climate change on the U.S. offshore wind resource,
- Studies that inform Weather Research and Forecasting model assumptions and lower uncertainty of future U.S. resource assessments.

3.2.2 Characterization of Atmospheric and Ocean Conditions at U.S. Wind Energy Areas

Current turbine array models require better atmospheric inputs to reduce uncertainty in the calculations of energy loss, fatigue loads, turbulence, and wake propagation. This uncertainty leads to imprecise decision-making in wind farm layouts, energy production reporting, wind energy area lease delineations, and wind energy area placement. An enhanced understanding of array wake characteristics, wind profiles, low-level jets, wake surface effects, seasonal and diurnal variability, and other atmospheric conditions at U.S. offshore wind sites is needed at all U.S. Wind Energy Areas (Atlantic, Pacific, Gulf of Mexico, and Great Lakes). Characterizing key environmental and operational variables for offshore wind turbines at a multitude of spatial and temporal scales can greatly improve the modeling accuracy. More work is needed to supplement LIDAR systems to provide more accurate turbulence data from both freestream and downstream wind turbine induced sources for energy and load characterizations. Turbulence characterization is dependent on accurate understanding of atmosphere stability and wind shear over diurnal and seasonal periods.

Extreme weather events can also drive designs, and it is important to understand the characteristics, frequency, and severity of extreme wind and waves at sites where offshore wind turbines may be sited.

Examples of projects that may be considered under this topic area include:

- Methods to measure and quantify turbulence at the turbine scale,
- Models or measurements to quantify atmospheric stability to improve the predictions for long-term energy and load assessments,
- Extreme wind/wave combinations and probability assessments at designated wind energy areas,

- Studies for a foundation load design basis for fixed and floating substructures in the Great Lakes,
- Collaborations to gather, compile, process, calibrate existing metocean data collected near U.S. wind energy areas that enables the reduction of uncertainty in modeling the resource, including wind-wave-wake interactions,
- Improved models for probabilistic quantification of extended periods of high and low temperatures and wind speeds to inform grid planning,
- Assessments of earthquake impacts on bottom-fixed and floating wind arrays and anchors systems,
- New technology assessments of extreme lake ice coverage, buildup, lock-in, and ridge thicknesses.

3.2.3 Development of a Metocean Reference Site

To date, the Consortium has funded the development of one reference site in U.S. waters off the coast of Martha's Vineyard in Massachusetts that can support key industry requirements including floating LIDAR validation and metocean data reference points. This project supports an upgrade to the existing facility operated by Woods Hole Oceanographic Institute (WHOI). Since the core facility, including a fixed met tower, existed prior to this award it was eligible to receive funds from the Consortium.

Technologies that are used to perform resource assessments, which may include improved floating and scanning LIDAR systems, large-area scanning systems, remote temperature profiling, and wave height measurements can be verified and validated against standard, vetted observations within the controlled reference test area. Transparent methods for assessing individual methods/sensors, open to the industry at large, may also be performed to develop and verify best practices and standards and to ensure the quality and consistency of testing and validation practices.

The WHOI metocean reference site may satisfy the regional needs near the Massachusetts wind energy areas. However, there may be an additional need to develop another metocean reference site to serve other BOEM Wind Energy Areas.

Examples of projects that may be considered under this topic area include:

- Proposals to expand facilities at additional reference sites in other geographic regions where offshore wind is being considered (e.g., repurposing existing oil rigs).

3.3 Physical Site Characterization

3.3.1 Seabed Survey Methods, Geophysical, and Geotechnical Database

There is currently limited detailed understanding and data on the national offshore seabed characteristics. Greater assessment is required to improve understanding of seabed characteristics for current and future Wind Energy Areas to support offshore wind development decision-making.

Currently, the assessment methods available to characterize the seabed soils within the U.S. Wind Energy Areas are insufficient to gather the necessary geophysical design data to conduct efficient geotechnical seabed surveys for wind farms. Consideration needs to be given to seabed interfaces, including ground modeling, cable routing, identification and mitigation of geohazards, site investigations to determine substructure type and suitability of foundation options, environmental and jurisdictional issues, and design guidance for project life calculation.

Although extensive site-specific geotechnical data collection is beyond the scope of this Roadmap, a geospatial assessment of soil type is critical for a first order assessment of substructure types, new lease area evaluation and selection, and local and regional cost estimates for state and federal planning.

Research and innovative methods should aim to serve U.S. offshore wind developers to provide up-to-date information on the geotechnical and geophysical conditions that can aid the permitting process and lower development costs during the pre-finance phase of development for fixed and floating offshore wind. Note that a similar topic area was recently part of a BOEM Broad Agency Announcement (BAA) solicitation 140M0121R0006 for Proposed Safety and Technology Verification Research Projects.

Examples of projects that may be considered under this topic area include:

- Research to define the minimum requirements for site development,
- Proposals to provide a central national database of geophysical and geotechnical data that documents soil types by aggregating regional databases and filling gaps,
- Geospatial assessments of soil types correlated with support structure types.

4 Pillar 3: Installation, Operations and Maintenance, and Supply Chain

4.1 Overview

Research under Pillar 3 aims to reduce the risk of offshore wind by focusing on activities that lower the cost and time of U.S. offshore wind project construction, installation, and operation and maintenance costs through the development of innovative deployment strategies, logistics,

machine reliability, advanced maintenance strategies, and critical supply chain elements. Research activities will improve system reliability through the advancement of large component test methods, and the development of strategies to increase local content and mitigate cost increases due to U.S. Jones Act regulations, lack of sufficient port facilities, immature supply chain and manufacturing, and dependence on increasingly large heavy-lift vessels. The following topics reflect the Pillar 3 offshore wind installation, operations and maintenance, and supply chain priorities.

4.2 Installation

4.2.1 Technology to Reduce Siting, Construction, and Operating Conflicts

Offshore wind development must work in balance with other marine users and wildlife, aiming for minimal disturbance. Improved techniques and innovative technologies may help reduce potential siting conflicts, turbine interactions with wildlife, and lower construction and operating costs at U.S. offshore wind installations.

Offshore wind arrays have relatively large statures and footprints, and therefore may have significant impacts on wildlife and other ocean users during the construction, operation, and decommissioning phases if not properly addressed. Proactively mitigating siting conflicts can have long-term benefits to developers by shortening development timelines (hence cost), minimizing curtailments, and strengthening community relationships. Understanding species presence during construction and operation, as well as potential risk mitigation options, is especially important in areas where endangered species, such as North Atlantic right whales, are active. Currently, techniques available to protect wildlife through curtailment of operations may excessively restrict construction windows and significantly increase installation costs.

New technology is needed to reduce risk to wildlife and to increase construction windows, considering U.S. regulations and development experience to date. Validated technology solutions that can be integrated into the wind system design at a turbine or farm level should be considered.

Spinning wind turbine rotors also have the potential to interfere with high-frequency radar signals used by the U.S. Coast Guard to monitor ocean currents in real time. Long-term efforts to address interactions between land-based turbines and radars are beginning to result in better understanding of the technical problem and potential solutions. Similarly, new technology is needed to minimize interference between offshore turbines and radar systems as well as to inform improvements in the permitting processes with respect to multiple radar operators and other stakeholders. Fishing and civilian vessels also depend on radar for navigation.

Examples of projects that may be considered under this topic area include:

- Projects that consider mitigation of surface vessel collisions with marine mammals,
- New technologies that quantify and reduce avian species interactions with turbines,
- New technologies that reduce the interference of floating or fixed-bottom wind projects with commercial fishing,
- Technology concepts that reduce the impact of underwater pile-driving noise on marine mammals,
- Mooring line sensors for detection of secondary entanglement, marine growth, and line failure,
- Adaptation of ROVs for protection/detection of wildlife and underwater hazards,
- Radar interference mitigation technologies and measures that may resolve siting issues that affect permitting,
- Radar solutions that aid in safe navigation and vessel operation for commercial and recreational fishing vessels,
- Technology solutions that mitigate and reduce interactions with federally managed, protected, and endangered species and their habitats,
- Technology solutions to characterize surface sediments leading to reduced interactions with federally managed species,
- Solutions that reduce conflicts with landowners for export cable beach crossings and land-side transitions.

4.2.2 Installation Strategies for Large Turbines

Heavy-lift vessels are generally used for all major offshore wind farm construction activities, including installing wind rotor nacelles and support structure components at the offshore site. Weightlifting capacity (e.g., 600 tons) and boom height (e.g., 160 m) tend to drive vessel costs up rapidly, and therefore, the ability to install larger size turbines up to 15 MW may be limited if the lift capacity of available vessels cannot increase accordingly. As turbine size increases, these heavy-lift vessels are becoming more scarce.

The Merchant Marine Act of 1920 (also known as the Jones Act) requires any vessel transporting merchandise between two points in the United States be U.S.-built, U.S.-flagged, and U.S.-owned. As offshore wind is sited in U.S. waters, any vessel transporting components to or from an offshore wind farm would be required to comply with this law. Although several U.S. vessels can support the construction of an offshore wind farm in U.S. waters, there may not be enough Jones Act–compliant heavy-lift vessels with the capacity to install the heavier turbine components (e.g., the nacelle) at the heights required in time to prevent an industry slowdown. Additionally, to accommodate larger heavy-lift vessels, ports may need to be upgraded (e.g., additional dredging, wider access, and stronger quayside). Floating wind may provide a way to deal with the limited availability of Jones Act–compliant large heavy-lift vessels if the wind turbines can be erected on floaters quayside, therefore only requiring available Jones Act–compliant tugs and anchor handlers to perform the offshore installation.

Jones Act compliance may require installation strategies that may use alternative vessels and innovative technologies to support the development of U.S. offshore wind projects. Solutions may include the participation of some foreign flagged vessels in compliance with the Jones Act, the repurposing of U.S. flagged vessels from other industries, and adaptations of the turbine and support structure technology to avoid the expense and uncertainty of heavy-lift vessels.

The Great Lakes pose a local challenge as even moderate-size ships may not be able to navigate through the locks. Wind turbine installation in the Great Lakes may require unique solutions that utilize ships already in the Lakes and locally fabricated substructures and components. The continuous upscaling or manufacturing of Jones Act–compliant heavy-lift vessels in the United States may not be the only, or the best, way to meet the installation requirements for the 12 MW to 15 MW wind turbines.

This topic area provides an opportunity for the U.S. industry to develop alternative, innovative solutions for offshore heavy-lift works such as new vessel designs, the repurposing of existing U.S.-flagged vessels, or new, efficient lifting techniques for specific components. Vessel alternatives must be considered alongside turbine/foundation system design (fixed-bottom and floating) to enable cost-effective and efficient assembly and installation of ever larger wind turbines, in compliance with the Jones Act, and with the potential for deployment throughout the world.

Examples of projects that may be considered under this topic area include:

- Technology concepts for repurposing existing Jones Act–compliant vessels for fixed-bottom or floating installations,
- Float-out turbine/foundation concepts that eliminate the need for heavy lift vessels,
- Alternative logistics solutions that reduce the uncertainty and cost of heavy lift vessels,
- Alternative regulatory compliant vessel solutions that improve the efficiency and lower cost of cable installation,
- Dynamically compensating crane and lifting strategies to enable non-jack-up installation vessels in deeper water,
- Climbing cranes and other lifting appliances enabling erection of wind tower, nacelle, and blades without the need for large cranes.

4.3 Operation and Maintenance

4.3.1 Offshore Wind Digitization Through Advanced Analytics

Managing component damage or failure in an offshore wind farm has to date been reactive, with response to failures as they occur. With general global advances in analytics and technologies, there is an opportunity to develop innovative solutions and technologies that will enable predictive operations and maintenance, while also reducing the overall cost, risk, and safety concerns.

With the number of offshore wind turbines installed in U.S. waters set to increase from seven to hundreds in just a few years, system reliability will be a growing concern. Compared to onshore wind, the cost of component damage/failure or operations and maintenance (O&M) is significantly more expensive to manage offshore because accessibility and logistics are far more complicated. Managing these issues on a reactive basis is expensive and inefficient. However, with current advances in analytics and technology, there is the opportunity through intelligent advanced data analysis to optimize O&M strategies, reducing the need for technicians to go offshore, operate in potentially dangerous conditions, and ultimately reducing the levelized cost of energy (LCOE).

At present, there is a considerable amount of data being collected across offshore wind farms, mostly through turbine and farm level Supervisory Control and Data Acquisition (SCADA) systems. The SCADA system acts as a "central nerve center" for the wind farm, connecting individual turbines, the substation, and meteorological stations to a central computer. SCADA systems are used to assess the wind farm focusing primarily on monitoring the turbines' operating status, health condition, real-time and long-term performance, as well as efficiency (e.g., orientation and yaw). Comparatively little data is being collected to monitor the health of other components that make up the offshore wind farm, such as foundations and electrical cables to assess damage or likelihood of failure. Issues on these components are usually identified during physical component inspections (for which there is currently little guidance and few industry standards) and may only be identified once the damage has progressed to a more serious (and expensive) state. Partnerships with turbine OEMs or developers with operating wind farms are highly encouraged in this topic area.

There is an opportunity to not only considerably improve and increase the technology used to capture component status data, but also to include fault detection during construction. This topic encourages facilitating better O&M planning, leading to a more efficient and cost-effective maintenance process, including a reduced need for expensive offshore labor.

Examples of projects that may be considered under this topic area include:

- Strategies to use existing data to remotely determine health status of critical components,
- Holistic integrated systems that can collect, analyze, and interpret all component level data and make O&M decisions remotely,
- Analysis tools that mine large SCADA data volumes for component or systems anomalies,
- Methods to extend SCADA and remote health monitoring systems to support structure and subsea cables,
- Development and maintenance of an equipment reliability database specific to the U.S. offshore wind industry,
- Innovations on the concept of digital twins to improve reliability and extend life,
- Offshore wind digitalization collaboratives for data transfer between turbine OEMs and operators for efficient monitoring.

4.3.2 Large Turbine and Substructure Testing Methods

The advanced testing and validation of the next generation of 15 MW drivetrains, 120 m blades, and floating support structures, prior to large-scale deployment, has the potential to avoid a costly wave of unanticipated field failures. Design and manufacturing issues detected early in the laboratory can lower operations costs by orders of magnitude. For major turbine components like blades and drivetrains, laboratory testing prior to serial production is mandatory to ensure reliable field operation. Current testing methods and facilities in the United States have been unable to keep up with the pace of offshore wind turbine growth. The current capacities of the test facilities located in Boston, MA, (Blades) and Charlestown, NC, (Drivetrains) are too small to accommodate the coming 15 MW generation of turbine components, so test methods must be modified due to these test facility capacity constraints, which introduces uncertainty in the reliability of the component. Greater efforts are required to ensure new 12 MW to 15 MW turbines and technology innovations are adequately tested and verified prior to field deployment.

Current test methods may provide some validation of reliable field performance by simulating the damage under field operating conditions. However, advances to improve the accuracy of these tests as the size of turbines increases are required. By simulating field conditions in a laboratory setting, accelerated lifetime testing and ultimate strength tests can reveal critical manufacturing and design flaws earlier than under field operating conditions.

Full-scale drivetrain and blade testing are also conducted on commercial components of a wind turbine to meet certification requirements and to increase system reliability and lower field failures. Testing is conducted to ensure that component designs comply with relevant testing standards (e.g., IEC 61400-23 and IEC 61400-04). However, full compliance cannot be achieved if the facilities are not upgraded.

As blades get larger, it becomes increasingly more difficult to conduct a single test (as prescribed by IEC 61400-23 standards) that qualifies a 100 m or larger monolithic blade structure for field operation. Laboratory loading cannot simulate the correct field loading at all locations on the blade, leaving the next generation turbines of the 12 MW to 15 MW scale more vulnerable to serial field failures and elevated maintenance due to undetected design and manufacturing flaws. This could lead to poor reliability unless test facilities upgrade their capabilities and methods to meet this challenge.

Examples of projects that may be considered under this topic area include:

- Blade and drivetrain test methods that extend the accepted validation methods beyond current standards and practices,
- Validation test methods that demonstrate greater accuracy or greater coverage of the validation range for major components,
- Methods to correlate laboratory results with likely field failures,
- Alternative validation methods that achieve higher accuracy through parallel subcomponent testing in smaller distributed laboratories,
- Test methods to validate soil/structure interactions for various foundations types including anchors and fixed-bottom systems,
- Test and instrumentation methodology to validate cyclic, transient, extreme, and long-term operation of direct drive generator systems,
- Virtual smart testing models complementing physical testing of innovative turbine technologies to expedite time to market of reliable offshore products.

4.3.3 High Sea State Technician Transfer Solutions

Offshore wind technicians are often unable to work during high sea states due to risks involved with transferring to the turbine.

Offshore wind sites in the Pacific Ocean, including California, Hawaii, Oregon, and Washington, have higher average sea states than the Atlantic, North Sea, Great Lakes, or Gulf of Mexico. As a result, the expected availability for operating systems will be lower due to smaller O&M weather windows, which may prevent timely repairs and will likely increase machine downtime. Similarly, construction cost and risk may increase. Cost effective offshore wind development in these areas may depend on new solutions to widen these construction and O&M weather windows without lowering safety to crew or increasing overall project risk.

Examples of projects that may be considered under this topic area include:

- Research to identify, design, develop and test innovative approaches that enable the safe transfer of technicians to the turbine in higher sea states.

4.3.4 Operations and Maintenance Strategies and Tools

To date, most O&M strategies and tools have been developed on European offshore wind farms where, collectively, over 25 GW has been installed. This European O&M experience and the tools developed may need to be adapted for U.S. environmental and regulatory conditions, as well as geospatial constraints due to vessel, supply chain, and port access. The global offshore wind operation and maintenance market is expected to grow annually by 17 percent to more than $12 billion by 2028 (Yang et al., 2021). Offshore wind farms are remote, and often inaccessible in harsh weather conditions. The United States experiences significantly different weather conditions and has different bathymetry than offshore wind farms in Europe. In addition to the surge of development in the Northeast, the icy waters in the Great Lakes region pose unique challenges, and the deep water in the Pacific necessitate the deployment of floating wind technology (Dewan, 2017). Each of these conditions, as well as unique service port limitations, require the customization of O&M service systems. Finally, the first generation of turbines that will comprise the U.S. offshore wind fleet will be the newly developed 12 MW to 15 MW class machines, with a limited track record for service and performance. It is likely that many of the maintenance systems for these units will be developed and proven for the first time in U.S. waters. The implementation of innovative O&M strategies and technologies can contribute significantly to increased power generation, cost effectiveness, timely maintenance, and longevity of the wind turbines.

Examples of projects that may be considered under this topic area include:

- Improvements and innovations for strategies and technologies that address unique U.S. offshore wind O&M requirements and demonstrate reduced LCOE,
- Strategies that reduce requirements for labor at sea,
- Specific logistical strategies and technology innovations that optimize vessel availability, crew transport and training, scheduled maintenance, and remote monitoring and diagnostics,
- Advancements beyond the state-of-the-art in new promising technologies for O&M include drone inspection, blade repair robots, underwater drones, and automation and artificial intelligence,
- Advancements in autonomous technologies for wind data collection, monitoring turbine condition, and performing maintenance on turbines,
- Studies that investigate the long-term effects of corrosion and how it affects the fatigue of support structures to optimize the design life and reliability in U.S. environmental conditions.

4.3.5 Floating Wind Operations and Maintenance

Floating wind is on the rise globally, but less than 100 MW have been deployed so far. The industry has demonstrated stable and safe operation as well as excellent performance, but the nascent track record for operations and maintenance is insufficient to quantify reliability or maintenance costs. Floating offshore wind systems use the same turbines as bottom-fixed offshore wind systems, but control modifications are necessary to manage loads and structural modifications are often needed to tune system dynamic responses. Floating substructures require different accommodations for personnel access. The marine operations needed for large component replacement (e.g., blades, hubs, gearboxes, and generators) are also quite different, as most semisubmersible substructures (90 percent of all proposed floating wind farms) expect to disconnect their mooring lines and tow the turbine and substructure assembly into a suitable, sheltered service port, where the nacelle can be accessed by a high-capacity crane at quayside. Whether at sea or at quayside, crane operability and functionality is impacted by the platform motion, which complicates the lifting strategy and may call for innovations to compensate for relative motion between the floating turbine and the crane hook.

Many of the floating wind system components are also not found on bottom-fixed systems at all. Components such as the moorings and anchors, buoyant substructures, passive and active ballast systems, mechanical damping systems, floating specific instrumentation and controls, dynamic cables, and dynamic substations must all be maintained with little prior experience coming from the existing offshore industry.

Examples of projects that may be considered under this topic area include:

- Comprehensive studies that assess floating operations and maintenance costs and cost trade-offs for a range of substructure types,
- Reliability and cost assessments for the development of efficient inspection, monitoring, and repair of dynamic cables, mooring lines, and anchors in shallow, mid-depth, and deep-water installations,
- Reliability and cost assessments for the development of efficient inspection, monitoring, and repair of substructures above and below the waterline,
- Engineering assessments of the long-term degradation and repair requirements due to corrosion and fatigue damage for steel substructures,
- Innovative ocean engineering and logistics-based assessments of cost and labor trade-offs between catenary mooring disconnect and tow-in versus at-sea crane repairs for large component repair and replacements,
- Assessments of safe personnel transfer and access for different platform types and sea states,
- Innovative solutions that enable cost-efficient and safe exchange of major components, such as blades, gearboxes, bearings, generators, and converters while at sea.

4.4 Supply Chain

4.4.1 Technology Solutions to Accelerate U.S. Supply Chain

Many of the components, subcomponents, and infrastructure for the initial phase of commercial offshore wind projects in the United States will be imported due to lack of qualified U.S. manufacturing and supply capabilities. However, the U.S. industrial base is robust and has most of the necessary capabilities to contribute to all aspects of the offshore wind supply chain.

As the industry emerges to install the first wave of offshore wind projects, there is an opportunity to accelerate the maturation of the U.S. offshore wind supply chain. This can be done through technology innovations that favor domestic content (e.g., concrete substructures), investments in U.S. flagged vessels, accelerated upgrades to ports and harbor infrastructure, enhancements to marine operations capacity, and adaptation of the existing manufacturing sector to accommodate offshore wind components (e.g., support structures and blades). Attention to this challenge area will ensure that the expected economic benefits are actually realized by developers, ratepayers, and state governments.

The first demonstration projects have relied on imported turbines. While the Block Island Wind Farm used European-assembled turbines and a foreign-flagged installation vessel, it also invested in U.S.-produced steel jacket substructures supplied by fabricators from the Gulf of Mexico's oil and gas industry. Although the United States also has a strong supply chain for the land-based wind industry, the adaptation to offshore is not an easy task, as much of that competency is geographically located in the inland United States, and the physical size of the land-based components is much smaller than the requirement for 12 MW to 15 MW offshore wind turbine systems.

Examples of projects that may be considered under this topic area include:

- Projects that bring designers and fabricators together to address the accelerated domestic production of a specific component,
- Design studies that assess the logistics, tooling, and cost to adapt a prototype concept to full-scale serial production,
- Innovations that capitalize on existing U.S. supply chain infrastructure to avoid imports,
- Design studies that assess the conversion and cost of existing fabrication facilities for specific offshore component serial production.

4.4.2 Industrialization of the Floating Supply Chain

The cost of floating offshore wind is expected to continue dropping at a rapid rate and may soon compare in cost to bottom-fixed offshore wind systems. To achieve cost parity with bottom-fixed technology, the current generation of prototype floating substructures must evolve from single unit production to full-scale serial production as it enters the commercial phase. This important cost-saving step can be accelerated through the Consortium. Projects ideally would be coordinated with the development of new port infrastructure, the designers of the next generation of substructures, and integrated into the system optimization with the wind turbine. The industrialization of the supply chain for floating wind substructures will address a fundamental challenge of finding suitable ports that can facilitate domestic manufacturing, assembly, load-out, and service of 15 MW scale systems. The number of suitable ports that can accommodate commercial offshore wind assembly and load-out will be greatly expanded if, through industrialization, design implementation can rely on more standardized existing production facilities that are more distributed and can allow for the disaggregation and streamlining of production and assembly to increase throughput (e.g., 10x increases relative current capacity). This industrialization task will emphasize simplification and standardization of the supply chain to ensure that new designs for this nascent industry make full use of domestic supply chain options.

Examples of projects that may be considered under this topic area include:

- Design and cost studies of proven floating offshore prototype substructures that adapt prototype assembly methods to serial production through value engineering approaches, demonstrating highly increased production volume and lower cost,
- Substructure design innovations that allow relaxed port and infrastructure assembly and manufacturing requirements and increased domestic content,
- Projects that adapt domestic supply chain infrastructure or manufacturing facilities to address floating system components for mass production or rapid deployment,
- Adaptive designs that enable commercial-scale production of concrete substructures and components for floating wind systems.

4.4.3 Grid Access, Expansion, and Transmission Upgrades

The Biden Administration has set targets for 30 GW of offshore wind development by 2030. With northeastern states already making policy commitments for over 30 GW by 2035, this target appears to be achievable, provided there are sufficient grid connections (Musial et al., 2020). Connecting offshore wind to the grid in all regions of the United States presents unique technical, economic, and regulatory challenges for transmission planning and grid system operations. Ultimately, the deployment of offshore wind in the United States depends on grid infrastructure available and ability to transmit the electricity generated. But there is great concern that offshore wind deployment might be limited by the pace of grid infrastructure expansion because the planning and execution of large grid expansion projects takes longer than offshore wind farms in many cases. The impacts of offshore wind deployment need to be better understood at local, regional, and national levels, and the costs and benefits associated with different transmission upgrades strategies need to be characterized to enable decision making for investments in grid expansion.

The first few offshore wind projects will prefer the most accessible grid points of interconnection. It is likely that extensive new transmission upgrades will be unavoidable for longer-term development in the eastern United States. These longer-term upgrades will increase project cost and could significantly delay development timelines if not addressed at an early stage. Several alternative solutions have been proposed to aggregate power among multiple wind farms or to develop offshore grids and HVDC backbones to distribute power along the coast, but a general lack of information about grid interconnect options make state and regional planning more difficult.

Examples of projects that may be considered under this topic area include:

- Capacity expansion modeling and analysis to study regional growth scenarios and their impacts for high penetration renewable scenarios,
- Methods to maintain operational reliability as the grid system adapts to higher offshore wind penetrations,
- Temporal and geographical studies to assess the capacity limits of the current land-based grid to accept offshore wind deployment, including the role that storage might play,
- Studies to determine lowest cost solutions for infrastructure and technology requirement to most effectively incorporate offshore wind into the transmission grid,
- Comprehensive modeling and analysis to determine the costs of transmission system upgrades and the best location (i.e., prioritization) for transmission upgrades,
- Analysis of static and dynamic behavior of the onshore grid at various levels of wind integration to determine grid support required using technologies like Flexible AC Transmission Systems (FACTS), Phase Shifting Transformers, and other “no wire” alternative solutions,
- Studies to model and assess storage and local off-take alternatives to building new transmission (see Section 2.4.4).

4.4.4 Grid Integration and Market Impacts

The growing pipeline of state policy commitments for offshore wind energy that now exceeds 30 GW has raised concerns about potential risks to the land-based grid in maintaining reliability as high penetrations of offshore wind are integrated. Without accurate regional and national information of the impact of offshore wind expansion and integration, policy makers will not have enough data to act appropriately on necessary grid infrastructure investments.

Research is required to explore the integration of the first 30 GW of offshore wind power capacity into the eastern U.S. electricity system, as well as future regions where the commercial industry is evolving, such as California. Research should consider key variables such as power injection location, transmission expansion requirements, system reliability, capacity credit, capacity value, load growth, energy storage, thermal plant retirements, and penetration of other renewables. Where appropriate, researchers should work closely with the ISOs and RTOs on these grid reliability issues. This information is essential for developers, regulators, and state energy planners to mitigate adverse grid impacts and to anticipate future grid requirements for offshore development at an early enough stage to avoid grid capacity becoming a barrier. The Consortium has awarded several projects on grid integration and system planning, though additional studies and planning will be needed.

Examples of projects that may be considered under this topic area include:

- Power flow modeling at key injection points,
- Assessments of system resiliency under extreme events (extreme sustained heat, low wind periods, system-wide blackouts, turbine black-start options, and extreme cold),
- Mitigation strategies for avoidance of system-wide impacts and costs due to key variables such as (but not limited to) load growth, energy storage, farm retirements, extreme weather and climate changes, and penetration of other renewables,
- Impact of offshore wind on electricity prices and strategies to minimize electricity costs,
- System optimization studies for assessing infrastructure investments (e.g., HVDC backbones, shared offshore transmission options, and critical onshore transmission build trade-offs),
- Integrated offshore and onshore planning studies, with the aim of reducing the number of landing points, to optimize both the onshore and offshore infrastructure,
- Collaborations to coordinate planning across ISOs for integration of OSW into transmission systems,
- Development and deployment of operational forecasting systems for grid operators.

4.4.5 Detailed Port Designs and Cost Studies

Multiple marshaling ports are needed as part of the critical infrastructure for offshore wind to support the manufacture, assembly, load-out, and service of over 30 GW of offshore wind turbines on the Atlantic coast. These ports need to provide ship access with no overhead restrictions to the open ocean, adequate acreage for component storage and assembly, and deep draft channels wide enough to bring large turbine installation vessels and/or floating substructures in and out. In addition, marshaling ports are needed for future projects off the West coast, Hawaii, and in the Great Lakes. The Gulf of Mexico has existing port facilities adequate for oil and gas deployments, however the existing port infrastructure is inadequate to support the scale of deployment planned by the offshore wind industry.

Multiple offshore wind ports need to be built or upgraded to the required specifications for both bottom-fixed arrays (near-term) and floating arrays. Detailed design information is needed to inform the port selection and upgrade requirements for U.S. offshore wind port facilities in the Atlantic coast, Pacific coast, Great Lakes, and Gulf of Mexico. Specific port development and upgrades must be planned in conjunction with vessel requirements and load-out restrictions to assess the necessary access and project support capabilities. These upgrades must consider the requirements and specifications for deploying offshore wind turbines at least 15 MW in size but should also consider allowing headroom for further turbine growth.

Examples of projects that may be considered under this topic area include:

- Creation of a national database of information on individual ports and the factors determining suitability for the various marine activities related to offshore wind including fabrication, installation, and operations,
- Studies that develop conceptual plans and cost estimates to upgrade existing ports for deployment of bottom-fixed or floating offshore wind,
- Studies for brown-field development of new port facilities where no suitable ports exist for upgrade,
- Supply chain studies to determine the capacity of the port infrastructure and assess the industry's ability to reach its targets,
- Assessments to enable coexistence of wind industry activities with other port and infrastructure users to mitigate port space use conflicts.

4.4.6 Workforce Development

Significant job opportunities in the fabrication, construction, and service of offshore wind farms exist along the eastern seaboard, which has resulted in the implementation of training programs throughout the region. It is vital that the setup and development of these training programs is accelerated in different regions to meet workforce demand. This is an opportunity to develop training centers and create new ways of training technicians (offshore, electrical, mechanical, and welders) and managers to master the execution and operation of an offshore wind turbine in compliance with U.S. safety and regulatory requirements. In addition, training programs need information and curricula to ensure that the workforce is well qualified. This requirement extends to the research community of scientists and engineers that will be required to develop and maintain future generations of offshore wind turbines.

Examples of projects that may be considered under this topic area include:

- Plans to implement regional training centers as part of existing academic institutions,
- Technical solutions for improving worker certifications for offshore wind jobs in marine operations and work at sea,
- Development of concepts and requirements for training centers for practical training of offshore technicians (e.g., training working at heights, working at sea, and evacuation).

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Appendix A – List of Awarded Projects, as of March 29, 2021

Pillar	Technical Challenge Area	Proposal Title	Lead Proposer
Pillar 1: Offshore Wind (OSW) Farm Technology Advancement	1.1: Array Performance and Control Optimization	Computational Control Co-design Approach for Offshore Wind Farm Optimization	Stony Brook University
		Impact of Low-Level Jets on Atlantic Coast Offshore Wind Farm Performance	General Electric
		Reducing LCOE from Offshore Wind by Multiscale Wake Modeling	Cornell University
		Wind Farm Control and Layout Optimization for U.S. Offshore Wind Farms	NREL
	1.2: Cost-Reducing Turbine Support Structures for U.S. Markets	A Low-Cost Modular Concrete Support Structure and Heavy Left Vessel Alternative	RCAM Technologies
	1.3: Floating Structure Mooring Concepts for Shallow and Deep Waters	Demonstration of Shallow-Water Mooring Components for FOWTs (ShallowFloat)	Principle Power, Inc.
		Design and Certification of Taut-Synthetic Moorings for Floating Wind Turbines	University of Maine
		Dual-Functional Tuned Inerter Damper for Enhanced Semi-Sub Offshore Wind Turbine	Virginia Tech
		Innovative Anchoring System for Floating Offshore Wind	Triton Systems, Inc.
		Innovative Deepwater Mooring Systems for Floating Wind Farms (DeepFarm)	Principle Power, Inc.
		Shared Mooring Systems for Deep-Water Floating Wind Farms	NREL
		Techno-Economic Mooring Configuration and Design for Floating Offshore Wind	UMass Amherst
	1.4: Power System Design and Innovation Challenge Statement	Development of Advanced Methods for Evaluating Grid Stability Impacts	NREL
Pillar 2: OSW Power Resource	2.1: Comprehensive Wind Resource Assessment	A Validated National Offshore Wind Resource Dataset with Uncertainty Quantification	NREL

and Physical Site Characterization	2.2: Development of a Metocean Reference Site	Development of a Metocean Reference Site near the MA and RI Wind Energy Areas	WHOI
Pillar 3: Installation, O&M, and Supply Chain Solutions	3.2: Offshore Wind Digitization Through Advanced Analytics	Enabling Condition Based Maintenance for Offshore Wind	General Electric
		Physics Based Digital Twins for Optimal Asset Management	Tufts University
		Radar-Based Wake Optimization of Offshore Wind Farms	General Electric
		Survival Modeling for Offshore Wind Prognostics	Tagup, Inc.
	3.3: Technology Solutions to Accelerate U.S. Supply Chain	30GW by 2035: Supply Chain Roadmap for Offshore Wind in the U.S.	NREL
PON4476 - Innovations in Offshore Wind Solicitation 1.0			
Round 1: Enabling Large-Scale Wind Turbines	Challenge Area 1.1	Self-Installing Concrete Gravity-Base Substructure Sizing for 15MW Turbine	ESTEYCO SL
		Vibratory-Installed Bucket Foundation for Fixed Foundation Offshore Wind Towers	Texas A&M
	Challenge Area 1.2	Technical Validation of Existing U.S. Flagged Barges as a "Feeder" Solution for the U.S. Offshore Wind Industry	Crowley Marine Services
		Feasibility of a Jones Act–Compliant WTIV Conversion	Exmar Offshore Company
		Comparative Operability of Floating Feeder Solutions	MARIN USA
Round 2: Support Structure Innovation; Supply Chain Development	2.1: Support Structure Solutions to Reduce Impact and Cost of Fixed and Floating Arrays	Evolved Spar Concrete Subconstructure for Floating Offshore Wind US-Based Design	ESTEYCO SL
		Tri-Suction Pile Caisson Foundation Concept	DEME Offshore US LLC
		Application of Novel Offshore Oil & Gas Platforms to Large Wind Turbines	Deep Reach Technology
		Quarter Scale Testing of the Intelligent Mooring System for Floating Offshore Wind Turbine Platforms	PCCI, Inc.
	2.2: U.S. Supply Chain Development Through Innovation	Tapered Spiral Welding for US Offshore Wind Turbine Towers	Keystone Tower Systems
	2.3: Solutions to O&M Challenges	Unmanned Aircraft System to Transform Offshore Wind	ULC Robotics
	2.4: Safety System Innovation	Self-Positioning Single Blade Installation Tool	GE Renewable Energy

Round 3: Electrical Systems and Innovation	3.1: Submarine Cable Innovations to Reduce Failures, Electrical Losses and Cost	Transmission and Export Cable Fault Detection and Prevention Using Synthetic Aperture Sonar	ThayerMahan
	3.2: Innovation in Transmission Hardware and Transmission Options to Reduce Interconnection Costs	DC Collection and Transmission for Offshore Wind Farms	GE Research
		Shared Landfall and Onshore Cable Infrastructure for Cable Colocation Feasibility Study	OWC Consultants
	3.3: Innovation or Strategies to Mitigate Grid System Impacts	Transmission Expansion Planning Models for Offshore Wind Energy	Tufts University
		An Offshore Wind Energy Development Strategy to Maximize Electrical System Benefits in Southern Oregon and Northern California	Battelle Memorial Insitute (PNNL)
	3.4: Technology Solutions to Mitigate Use Conflicts	Technology Development Priorities for Scientifically Robust and Operationally Compatible Wildlife Monitoring and Adaptive Management	Worley
		Right Wind: Resolving Protected Species Space-Use Conflicts in Wind Energy Areas	Cornell University
		Oceanographic HF Radar Data Preservation in Wind Turbine Interference Mitigation	CODAR Ocean Sensors LTD