NATIONAL OFFSHORE WIND

RESEARCH & DEVELOPMENT CONSORTIUM

Research and Development Roadmap Version 2.0 | October 2019

CARBON TRUST

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NREL NATIONAL RENEWABLE ENERGY LABORATORY

rcg Renewables Consulting Group

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

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Acknowledgements

This Roadmap Version 2.0 for the National Offshore Wind Research and Development Consortium was prepared under the direction of Consortium Executive Director Carrie Hitt and produced by the Consortium's internal technical team comprised of offshore wind experts from the New York State Energy Research and Development Authority (NYSERDA), the United States Department of Energy (DOE), the Renewables Consulting Group (RCG), the National Renewable Energy Laboratory (NREL), and the Carbon Trust (CT). In addition, the Consortium's various advisory group members and offshore wind developers serving on the Consortium's Research and Development Committee provided extensive input. The primary authors are Walt Musial (NREL), Richard Bourgeois (NYSERDA), Gary Norton (DOE), Mike Derby (DOE), Emilie Reeve (RCG), Kimberly Peterson (RCG), Isabelle Bauman (RCG), Jan Matthiesen (CT), and Olivia Burke (CT).

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1 Background

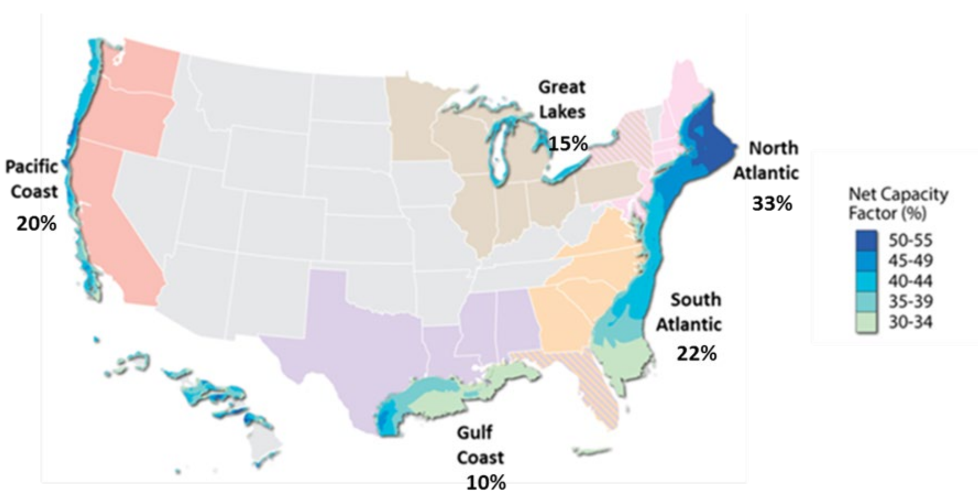
On June 15, 2018 the United States Department of Energy (DOE) announced its selection of the New York State Energy Research and Development Authority (NYSERDA), in partnership with the Renewables Consulting Group (RCG) and the Carbon Trust (CT), to lead the formation of a nationwide research and development consortium for the offshore wind industry. The National Offshore Wind Research and Development Consortium (the Consortium) is a nationally focused, independent, not-for-profit organization led by key offshore wind industry stakeholders and research institutions. 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 fulfill, in part, a long-term vision for offshore wind in the U.S. that is supported by current U.S. policy for an all-inclusive energy strategy. The 2015 DOE Wind Vision report modeled a viable scenario under which 86 gigawatts (GW) of offshore wind energy capacity is installed in the U.S. by 2050, accounting for 7% of all U.S. electricity generation annually through large-scale project deployment in five offshore regions as shown in Figure 1 (DOE, 2015). This vision for offshore wind was discussed in the 2016 National Offshore Wind Strategy (the Strategy), a collaboration between the DOE and the Department of the Interior (DOI).

To achieve this vision, the Strategy identifies technology innovations that will be needed to address the challenges in each of the five U.S. offshore regions and to lower the costs to allow offshore wind to compete in all regional electricity markets without subsidies. The necessary cost reductions can be realized in part through targeted research and development (R&D) funded under this Consortium that removes or reduces technological and supply chain barriers to deployment and lowers development risk to investors. The Consortium envisions this research could be conducted as desktop studies, design development, and computer analysis as well as hardware development with supporting demonstration and validation activities.

Figure 1. Offshore Wind Regions from Wind Vision

Showing percentages of the 86 GW scenario for each region. (Percentages indicate share of the prescribed 86 GW that each region contributes by 2050.)



1.1 The Consortium’s Research and Development Roadmap

This Consortium Roadmap complements, draws from, and builds on the National Offshore Wind Strategy. Its primary purpose is to serve 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 technology advancement in each of three research pillars. This Roadmap will be regularly revised to incorporate up-to-date stakeholder feedback and adapt to changes in the U.S. offshore wind market. Roadmap revisions are expected to incorporate new research priorities and objectives as well as to remove prior objectives that have been achieved.

The Consortium Roadmap expands on the broad topics discussed in the Strategy to enable targeted technical research in key areas important to the offshore wind industry in the U.S. The Consortium uses the Roadmap as its primary guide for developing competitive solicitations to distribute R&D funding. Specific topics and technical challenges solicited are prioritized by the Research and Development Committee of the Consortium’s board of directors (R&D Committee) and are subject to the requirements of the funding source(s) of each competitive solicitation. Therefore, at any given time only a portion of the topics identified in this Roadmap may be fundable under current solicitations. The intent of the Roadmap is to express the Consortium’s vison for a comprehensive list of research topics that need addressing, in present and future solicitations, in order to achieve its objective of reducing cost and removing barriers to the development of offshore wind in the U.S.

This Roadmap has been approved by the offshore wind project developers on the Consortium’s R&D Committee who represent the intended end users of research activities per the Consortium’s principles of operation. Input for this Roadmap was solicited from the Consortium’s R&D Committee and advisory groups. In addition, the Roadmap relies on expertise from the Consortium’s internal technical team comprised of offshore wind expert staff from NYSERDA, DOE, Renewables Consulting Group, the Carbon Trust, and the National Renewable Energy Laboratory.

Generally, the Consortium intends to distribute research funds through a series of open enrollment, competitive solicitations that mirror the three research pillars described in the original DOE funding opportunity announcement (DOE FOA 1767), summarized as follows (DOE, 2017).

Pillar 1: Offshore Wind Plant Technology Advancement

This pillar focuses on technology advancements targeted at the major cost drivers of offshore wind energy levelized cost of energy (LCOE) in the U.S., which can be extended to global offshore wind markets. Accelerated innovation can reduce capital costs and development risk while increasing annual energy production, thus resulting in long-term LCOE reductions for fixed bottom and floating offshore wind systems of 40% and 60%, 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 plant technology (e.g., deep water, extreme conditions, freshwater ice, and hurricanes) as well as supply chain issues that may have unique U.S. solutions relative to European experience.

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, geo-technical, and physical site characterization. Solutions may address cost reduction through increased annual energy production, reduced wind plant development timelines, lower capital, and operations and maintenance (O&M) costs, and lower project risk.

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

This pillar seeks technology improvements in wind plant installation, O&M, and supply chain issues related to the U.S. specific market, socio-economic, and geo-physical constraints. Installation costs, especially for methods that depend on high-capacity lift vessels and high levels of labor at sea can drive up the cost of technology capital expenditures significantly. In addition, the estimated O&M costs for a fixed-bottom offshore wind plant in the U.S., which range from $100 per kilowatt (kW) per year to $150/kW/year (2015 U.S. dollars), can represent up to 30% 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 cost 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 may be cross-cutting into other pillars of this Roadmap.

1.2 Consortium Research Solicitations

This Roadmap elaborates on the broad guidance given by the research pillars in order to inform the Consortium's competitive solicitations, which may indicate specific priority technical topics. The Consortium's initial R&D solicitation was released in March 2019 and is administered by NYSERDA as Program Opportunity Notice (PON) 4124. PON 4124 is funded by NYSERDA and the U.S. DOE per the parameters of DOE FOA 1767 (NYSERDA 2019, DOE 2017).

All Consortium solicitations 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 U.S. Proposers of research topics already being addressed globally must explain why further research is necessary.
- 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. These topics may not be eligible to receive federal funding but may be addressed by the Consortium in the future.

- Proposals should provide benefits to multiple end users. 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.

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

In this document, a number of specific topic areas are described within each research pillar. The order in which topic areas are listed has no significance in terms of priority, timing, or importance. The Consortium's competitive research solicitations are intended to address the research needs identified in this Roadmap. It is important to note that while the competitive solicitation documents may reference or include topic areas described in this Roadmap, the Roadmap is not a governing document for any competitive solicitation unless specifically incorporated as such by the solicitation documents themselves.

1.2.1 Roadmap Version 2.0

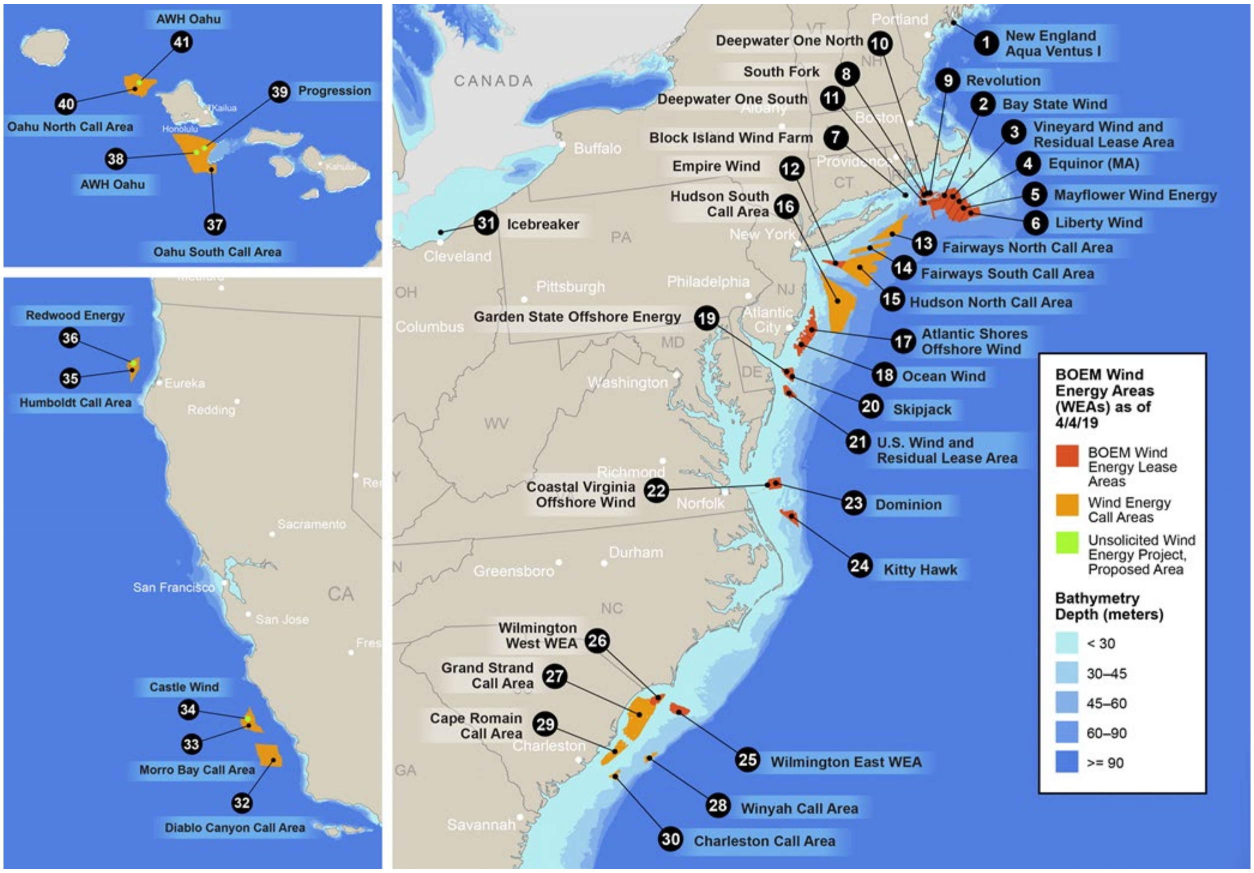
The first Consortium Roadmap, version 1.0, was published in November 2018. The present version 2.0 was developed based on feedback from the Consortium's R&D Committee and advisory groups, as well as the response to the Consortium's ongoing R&D solicitation.

Major changes in Roadmap Version 2.0 include the following:

- Updates regarding recent U.S. offshore wind market developments, including identification of several new lease and call areas.
- Updated descriptions of existing research topic areas.
- Addition of new topic areas:
  - Energy Storage Innovations and Integration
  - Regulations and Permitting—Radar Interference
- General formatting changes including more consistent numbering of topic areas.

These changes are primarily driven by the continuous growth and evolution of development scenarios for offshore wind in the U.S. as defined by developer interests, individual state policy actions, and the growing global offshore wind industry which surpassed 20 GW in 2019. According to the DOE 2018 Offshore Wind Technologies Market Report*,* published in August 2019, there are nearly 20 GW of U.S. state policy commitments for offshore wind by 2035. Much of this expected deployment over the next 15 years will result from project activity that is already in the regulatory project pipeline or is being considered for development as call areas (Figure 2).

Figure 2. Locations of U.S. Offshore Wind Pipeline Activity and Call Areas as of March 2019



Although there are no active projects in the regulatory pipeline for the Gulf of Mexico, several Gulf of Mexico projects have been proposed previously and new development activity is likely prior to 2035.

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 to mid-term timeframe. 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 that may be identified over the next several years.

2 Pillar 1: Offshore Wind Plant Technology Advancement

2.1 Overview

Pillar 1 research focuses on technology advancements to the wind turbine system or entire wind plant that have the potential to drive significant reductions in the levelized cost of energy (LCOE) for offshore wind in the U.S. 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 architecture currently deployed. It uses the experience from over 22 GW of global offshore wind projects. However, the physical and market conditions that determine development in U.S. waters can vary significantly from those in Europe and Asia. The following topics reflect U.S. research needs to advance wind plant technology.

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

Current fixed bottom foundations have primarily been designed for European offshore conditions. With increasing offshore wind development in the U.S., innovative products and solutions are required to reduce the overall LCOE by being more suited to U.S. offshore conditions, supply chain, and vessel availability.

Fixed-bottom turbine support structure designs originally developed for European sites may not be optimal for the U.S. market due to differences in seabed characteristics, extreme weather conditions, environmental and regulatory constraints, available installation vessels, and maturity of the domestic supply chain. With more than 40% of the U.S. offshore wind resource located in water depths of 60 meters (m) or less, the use of fixed-bottom substructures is feasible in many U.S. offshore locations (Musial, 2019) and offers the best near-term solution for the initial U.S. offshore wind projects. However, as the offshore wind industry continues to grow, there is a great opportunity to innovate, modify, and optimize offshore substructures to match U.S. offshore conditions, manufactured and installed by US-based companies. This was seen with the Block Island offshore wind project off Rhode Island, which was able to reduce the overall cost of the wind plant by using jacketed substructures fabricated by U.S. manufacturers in the Gulf of Mexico, as opposed to monopile structures fabricated in Europe.

Substructures and foundations account for 13.9% of the capital expenditure for a fixed-bottom offshore wind plant (Stehly, 2018), and this percentage can vary with water depth, bottom conditions, and the capability 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 existing substructure technology is not feasible. Assessments of the suitability and reliability of existing available support structures relative to U.S. specific conditions are required. Likewise, consideration should be given to improvements in control systems as advanced control systems can reduce fatigue and extreme loads on existing support structure technology, thereby improving reliability and reducing LCOE. Furthermore, consideration could also be given for a wide range of control techniques, including the use of structural damping devices, and advanced pitch control systems.

2.2.2 Enabling Large-Scale Offshore Wind Turbines

Turbine size has increased significantly over the past decade and is predicted to continue increasing. Assessments are required to understand the limits to upscaling as well as the impact of large turbine demand on the wider industry (e.g. manufacturing, testing, etc.).

Larger turbines have been shown to have a significant impact in lowering LCOE. Industry trends indicate wind turbines will grow to 15 megawatts (MW) by 2035 or sooner, with rotor diameters up to 250 m. Aside from the turbine scaling itself, this will create new technical challenges. These include understanding the impacts of larger turbines and their components on required vessel capacity, port infrastructure, test methods and facilities, installation (vessels and methods) and maintenance.

Solutions to adapt turbine designs, plant designs, and infrastructure may need to deviate from linear scaling assumptions in order to accommodate the larger turbine sizes. Comprehensive assessments and innovative solutions are needed to reduce risk in development, improve reliability, understand failure modes, and manage the costs of full-scale component validation tests. In addition, solutions are required that address all aspects of the supply chain and domestic offshore wind infrastructure.

Assessments of the system-wide impacts are needed to understand limits to scaling of large machine components and the demands of large machines on the wider industry including manufacturing, installation, testing (protocols and facilities), and transportation. Furthermore, the development, improvement, and validation of design and analysis tools to facilitate advancements and optimization of fixed and floating technology is beneficial. Innovative designs and solutions should be coordinated with national and global standards development.

2.2.3 Array Performance and Control Optimization

With offshore wind plants increasing in size, greater efforts are being made to increase the efficiency and energy capture across the whole wind plant. Assessments are required to develop and improve on array performance and control optimization tools.

As offshore turbines and projects become larger, new plant-wide design approaches and control strategies are needed to optimize energy capture, minimize turbine downtime, and reduce overall cost, based on an enhanced understanding of wake characteristics, wind profiles, and other atmospheric conditions at U.S. offshore wind sites.

Although a number of studies have been undertaken to understand atmospheric conditions, wake characteristics, and their effects on energy production at European offshore wind sites and on U.S. land-based wind sites, there is a need to better understand the atmospheric conditions at all U.S.

wind energy areas (Atlantic, Pacific, Gulf of Mexico, and Great Lakes). Understanding the differences between U.S. and European wind conditions is important as it will lead to improving the atmospheric models used to predict offshore wind plant loads and performance in the U.S. and inform how wind plant performance could be impacted.

Recent studies indicate that array performance and control optimization can improve lifetime economic performance through increased power production and reduced O&M costs, in addition to extending the lifetime of the asset. Moreover, the pitch and yaw-based control strategy estimates could result in a combined 0.5–3.5% increase in energy yield, and therefore, impact LCOE reduction. Furthermore, employing array optimization strategies could enable load reductions of up to 50% for certain wind turbine components, which will reduce fatigue and turbine maintenance and O&M costs (Carbon Trust, 2017). As the number and size of offshore wind plants built in U.S. waters increases, such methods and tools are needed to improve the wind plant annual energy production, increase reliability, and reduce O&M costs.

2.3 Floating Offshore Wind Technology

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 58%, or 1200 GW, of the U.S. offshore wind technical resource area is in waters greater than 60 m in depth. 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. As additional near-shore sites in the Atlantic are developed, shallow water areas will become scarcer. Conflicts in siting and landing power from wind plants may necessitate consideration of offshore wind sites greater than 60 m depth, which tend to be farther from shore (Musial et al. 2016).

The depth range used to conduct U.S. floating wind energy resource assessments stops at 1000 m, although some experts suggest this outer limit could be extended even deeper. 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 also contribute to lowering floating offshore wind technology cost and achieving parity with fixed-bottom technology (Musial 2019).

The Pacific region—where water depth will likely be between 500 m and 1000 m, requiring all installations to be floating—is expected to contribute 20% (17.2 GW) to the total U.S. offshore wind deployment (Figure 1). In the Great Lakes, an additional 700 terawatt-hours (TWh) per year of offshore wind resource that is over waters 60 m deep or more is potentially available. However, new ice-resistant floating technology is needed to unlock this resource for future development. In the Atlantic region, as shown in Figure 2, there is an abundance of possible sites at depths between 60 m and 90 m. Sites just beyond the current lease areas may be the most accessible for future development although there are significant technology challenges to mooring substructures in shallow water.

Technology is needed to reduce the cost of floating technology capital expenditures (CapEx) to achieve long-term cost targets at or below $60 per megawatt-hour (MWh) by 2030. This level of cost reduction is only achievable by multiple innovations within a complete system design. The following topics reflect floating wind technology priorities for this Roadmap.

2.3.1 Mooring Concepts for Floating Foundations

Although significant learnings can be taken from the Oil and Gas sector, floating offshore wind mooring concepts have unique challenges that require specific 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.

At present, the global floating offshore wind industry including its supply chain is in its infancy. However, global predictions demonstrate a significant increase in the development and installation of floating offshore wind technology. With the considerable expertise that the U.S. already has through the oil and gas (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 technological innovations are needed to design, develop and test an array of mooring concepts that are suitable to different conditions.

Whether optimized for shallow regions or deep-water conditions, new mooring concepts should demonstrate feasibility using dynamic mooring analysis for major International Electrotechnical Commission (IEC) design load cases and system cost models. Concepts should also comply with applicable recommended 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 commercial and recreational activities and stakeholders, such as commercial fishing groups.

2.3.2 Shallow Water Mooring Concepts

Current mooring systems (especially catenary mooring types) become more expensive at shallower water depths due to the need to avoid snap loading and anchor uplift forces; constrained watch circles; and the need to balance stiffer motion frequencies with wave excitation. Large platform motions in storms can cause localized tension spikes (snap loads) in mooring lines when a line re-engages after momentarily going slack (Hsu, 2017). 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, including load management solutions, optimized safety factors and new materials, without adding cost at sites representative of U.S. seabed conditions.

2.3.2.1 Deepwater Mooring Systems

The steep drop of the continental shelf off the Pacific coast, combined with requirements to minimize visual impact by locating projects far from shore, will likely lead to Pacific floating wind projects regularly sited in water exceeding 500 m depth. Assessments and innovative technology concepts are required to demonstrate mooring and anchoring system designs across a range of parameters including:

- Practical floating wind system depth limits
- Potential to exceed assumed practical limits (e.g., 1000 m maximum depth) for the Pacific coast and Hawaii
- Mooring line spread requirements—how they scale with depth for the California and Hawaii Bureau of Ocean Energy Management (BOEM) wind energy call areas, and how they can be optimized
- Mooring line and electric array cable configurations that can minimize impact on fishing activities and other existing use activities
- Potential of new mooring designs to minimize cost and maximize performance for various platform types
- Advanced mooring system designs including 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 Substructure Scaling

As the size of turbines increases to 15 MW and beyond, there is considerable R&D required to improve, design, develop, and test a range of floating substructures that can accommodate the upscaling of offshore wind turbines.

Hywind Scotland, the world's first commercial floating offshore wind farm, has deployed five 6 MW wind turbines mounted on spar-buoy floating foundations. These are currently the world's largest floating offshore wind turbines, but the WindFloat Atlantic project, due for completion 2019/2020 will deploy three 8.4 MW turbines on semi-submersible foundations. The evolution from single prototype to demonstrator-farm has proved the favorable scaling of floating substructures, with Wind Atlantic experiencing only a 75% increase in primary steel mass to gain a four-time increase in turbine capacity. Upscaling of floating platforms may be constrained by limits to manufacturing capacity; the assembly and installation of larger/heavier parts; numerical modelling with increased complexity; and inadequate regional ports and staging facilities. Floating platforms do however offer the ability to manufacture modular components in various facilities prior to marshalling and deployment from a single, or multiple port locations. 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 dock-side crane.

In a study by the Carbon Trust (Carbon Trust, 2015), scaling to larger substructure sizes was highlighted as the parameters that could deliver the greatest cost savings. Therefore, technology innovation to enable the upscaling and optimizing of floating substructures for 12 MW+ turbines is needed. Current leading substructure designs have all been designed and developed based on European offshore site conditions.

Assessments for the suitability of existing available support structures targeted for U.S. specific conditions are needed. The results of these assessments can be used to inform innovations that will ensure floating offshore wind is compatible with U.S. environmental conditions, supply chain, assembly port, and vessel availability. Furthermore, these upscaled systems are operating with different design loads than for fixed bottom sites and have higher levels of uncertainty. As such, further research is required aimed at reducing the uncertainty in the atmospheric characterization of floating wind sites combined with improved understanding of material fatigue characteristics and performance along with scale are necessary.

In addition, to achieve cost-effective floating wind structures, turbine and substructure systems will likely need to be assembled and commissioned at quayside in local or regional port facilities. Developing strategies to execute lower cost installation of floating offshore wind substructures with large turbines is a key technical challenge for project staging at U.S. port facilities. Conceptual methods and installation strategies that consider weights, clearances, substructure dimensions, water depth, assembly methods and so on may limit the number of U.S. suppliers and sites where these activities can be conducted. Cost trade-off studies are needed to identify viable port locations in the U.S. and the obstacles and barriers that must be overcome.

As the offshore wind industry continues to develop, the offshore wind industry and U.S. supply chain has the opportunity to innovate, upscale, and optimize floating offshore wind platforms to match U.S. offshore conditions, while utilizing local materials and stimulating local markets.

2.3.4 Control of Large Floating Arrays

At present there are no large-scale floating offshore wind plants installed globally. Therefore, there is limited understanding of the turbine or array scale dynamic behavior. Research is required to model and determine how floating turbines in an array behave under various atmospheric conditions and with different substructure types.

Applications for several large floating arrays, each in excess of 400 MW have already been submitted to BOEM for projects in Hawaii and California with proposed commercial operations dates around 2025; however, there are currently no large-scale arrays installed globally.

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. Currently, there is a poor understanding of how these additional platform motions will affect the performance and load response for both the single turbine and multiple turbine arrays. For example, wind turbine yaw behavior in air flows affected by wakes may be less predictable since the turbine can experience yaw drift from the platform in addition to its usual prescribed yaw position. Therefore, understanding the physics of how floating arrays behave under various atmospheric conditions, with six degrees of freedom and with different platform types is required. After which, advanced control systems and strategies will be needed at an individual turbine and array scale to optimize performance, minimize loading, and manage the dynamic interaction of multiple floating offshore wind turbines.

2.4 Technology for Both Fixed and Floating Offshore Wind

There are a number of challenges facing both fixed and floating offshore wind that innovative solutions could alleviate and greatly advance offshore wind in the U.S.

2.4.1 Hurricane Resilient Wind Systems

General understanding of the impact of tropical cyclones (hurricanes) on offshore wind turbines is limited. Research activities are required to increase understanding in terms of severity and probability at U.S. sites where wind turbines are likely to encounter hurricanes as well as to demonstrate turbine designs and survival strategies that withstand these hurricane conditions.

Hurricanes commonly occur along the entire Atlantic coast and Gulf of Mexico. Most hurricane prone proposed sites are limited to fixed-bottom substructures with the exception of Hawaii where floating turbine designs may need to be enhanced for hurricane conditions.

In the more northern latitudes, IEC Class 1 turbines are likely to have sufficient design margins to survive these storms, while substructure designs can be adapted 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 Class1 criteria, current turbine designs will have to be adapted to mitigate extreme loads and low-cycle fatigue. One of the challenges is understanding how often turbines will encounter these extreme conditions. The reference height and wind speed duration (10 m and 1-minute, respectively) used by the National Hurricane Center to classify the severity of hurricanes (e.g., Category 1-5) does not translate well to IEC design criteria (3 sec gusts measured at hub height). Therefore, it is difficult to determine how the severity of a hurricane at a given location in the U.S. relates to the IEC design conditions. In addition, the long duration and internal wind characteristics that a wind turbine is likely to experience during a hurricane passage (e.g., extreme gust factors, wind shear, veer, etc.) may not be sufficiently represented by the simple IEC 61400-01 3-second extreme load cases and models to increase the physical understanding of internal hurricane structures may be needed. These uncertainties can result in higher project risk (technical and financial) and greater insurance costs. The solutions to mitigate these risks have not yet been developed in detail and their associated costs are not known.

Technology innovations and research are required to reduce the risk for turbines operating in hurricane prone regions of the U.S. to approximately the same level as conventional offshore wind. It is expected that offshore wind projects proposed in hurricane prone areas, should anticipate increased capital costs of offshore wind system upgrades for hurricane design conditions. Research should also consider methods to minimize capital costs and technology risks, especially in BOEM Wind Energy Areas and areas where future wind farms might be sited (e.g., the Gulf of Mexico).

2.4.2 Floating and Fixed-Bottom Arrays in the Great Lakes

Despite the Great Lakes offering an opportunity for significant floating offshore wind development, there has been limited development of floating technologies of any kind that can survive freshwater ice. Considerable efforts are required to design, develop, test, and demonstrate survivability of floating wind turbine concepts that are suitable for deployment in the Great Lakes.

The Great Lakes have approximately 700 TWh/year of offshore wind resource with water depths of 60 m or greater which is nearly 10% of the total offshore wind resource of the U.S. This was excluded from the National Offshore Wind Resource Assessment conducted by NREL in 2016 because floating technology resilient to freshwater ice could not be identified (Musial et al 2016). However, the region is highly populated, which means that it is likely that large-scale deployment of offshore wind will be required to be further from shore resulting in the need for ice resistant floating wind technology. The design challenge is that ice loading can impart additional loads to the substructures and mooring systems under various wind conditions. Sheets of ice that move across the lake can apply large lateral forces that will drive the designs. Ice that freezes around the substructure can lock the hull and alter the dynamic characteristics of the system. These conditions are not currently well understood for wind turbines and need to be fully considered as part of the overall design.

Research is required to design, develop, and demonstrate new technology concepts that provide developers and original equipment manufacturers (OEM) with tools and design guidance to allow them to assess the viability of working in the deep-water regions of the Great Lakes. Furthermore, greater focus is required on the development of substructure and mooring system concepts that anticipate and resist ice loading. New technology solutions should demonstrate local knowledge of (1) statistical lake ice coverage and ice buildup at site locations where offshore wind technology is likely to be deployed and (2) constraints imposed by the narrow locks leading into the lakes from the Atlantic Ocean.

2.4.3 Power System Design and Innovation

The level of commitment from states to develop offshore wind has grown considerably; however, the rapid introduction of offshore wind to the current grid system will create a significant challenge. Greater research is required to understand the impact of offshore wind development on the grid as well as designing innovative approaches to minimize grid disruption and reduce overall costs.

The rapid deployment of offshore wind in the U.S. will create a significant challenge for utilities, developers, regulators, and policy makers who seek to introduce offshore wind with minimal grid disruptions and at the lowest cost. Transmission infrastructure typically accounts for 10–20% of offshore wind CapEx, of which 8–12% typically accounts for the cost of cable supply and installation (NREL 2017). In addition, European offshore wind plants have shown that cable-related incidents also account for 80% of insurance claims and approximately 60% relate directly to cable damage during construction (Carbon Trust, 2018).

The default scenario is for each wind project to deliver its power through individual export cable spur lines, which may not be feasible under multi-project, build-out scenarios. Greater research is required to understand the impact of offshore wind development on the grid as well as to design innovative approaches to minimize grid disruption and reduce costs. Collaborative power system R&D projects will financially enable the U.S. supply chain to develop innovative electrical infrastructure that would have otherwise been cost-prohibitive for them to design on their own. Furthermore, innovative cabling landfall and onshore cabling installation solutions need to be designed to minimize conflict with stakeholders, authorities, and landowners. 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 U.S., there is a considerable opportunity for tier 1 suppliers to develop supply lines in the states.

2.4.4 Energy Storage Integration

With the growing commitment to develop offshore wind and increase the use of renewable energy in the electricity mix, there is also a growing need to ensure energy security. Although there has been significant development in energy storage system design, greater efforts are needed to integrate innovative, fit for purpose energy systems with offshore wind.

In recent years several U.S. states have adopted high-penetration renewable energy portfolio standards (RPS), including several principal offshore wind states including New York, California, Massachusetts, New Jersey, and Hawaii, for which offshore wind is likely to make up a major proportion of the RPS in these states. According to the International Energy Agency (IEA) annual energy outlook, the price of battery storage has dropped to almost $1,300/kW, decreasing over 15% in the past year and continues to decrease. 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' renewable energy targets. Energy storage will enable a more decentralized approach which will increase long-term energy security and system reliability.

Significant R&D is required to develop and demonstrate methods for integrating storage with offshore wind systems using data and analytical modeling at the turbine, wind plant, or system level. Offshore wind storage options should demonstrate value to the grid through increased dispatchability to meet peak demand, supplying grid essential reliability services (such as voltage control and frequency response), increased system reliability, system restoration capability (i.e., black start), or otherwise demonstrating the value in helping to meet a state's RPS targets. Alternatives to battery storage, such as thermal storage, should be considered. Identifying synergies with the growing market for electric vehicles is encouraged.

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 measurement methodologies, validating analytical models used for site characterization.

3.2 Metocean Research

The following topics reflect the Pillar 2 offshore wind power resource and physical site characterization priorities from the first Consortium Roadmap (Version 1.0).

3.2.1 Comprehensive Wind Resource Assessment

Wind resource assessments have been key to major public and private offshore wind planning decisions. Although some strategic work has been undertaken to present the national offshore wind energy resource, far greater efforts are required to present a comprehensive, fully validated wind resource assessments at multiple time scales.

Currently, the most comprehensive wind resource assessment of U.S. offshore territory is a 2016 assessment conducted by the National Renewable Energy Laboratory (NREL), with inputs from multiple models. However, the assessment has several key limitations, and has not been fully validated against existing measured data. Further efforts are needed to assess the wind resource within the U.S. exclusive economic zone that better quantify the resource and its uncertainty at multiple heights where turbines operate, with a time-varying component and are specifically in the offshore marine environment in order to enable more accurate modeling of power output, operational costs, and grid integration.

Offshore wind geo-spatial resource assessments have been 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 historical measured wind data offshore, as well as the time and expense associated with new on-site measurement campaigns, the industry frequently 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). Existing turbine wake models may require revision to account for decision-making at the wind farm level rather than individual turbine level. These models can be improved by better understanding, characterizing, and probabilistically forecasting key environmental and operational variables for offshore wind turbines (including wind and ocean variables) at a multitude of spatial and temporal scales to assist in uncertainty decision-making.

A significant limitation is that the 2016 NREL resource assessment is averaged over a typical meteorological year, but it does not provide a temporal component, which is necessary for proper characterization of the resource and grid integration factors. Furthermore, the resource assessment presents wind speeds only at a hub height of 90 m, while future offshore wind turbines are expected to be erected with hub heights 120 m or higher, and with maximum tip heights exceeding 200 m. Finally, consideration could be given to the benefits of a higher spatial resolution to allow for more in-depth planning. Further overall efforts are required to increase the offshore wind resource assessment knowledge base specific to U.S. waters.

3.2.2 Systematic Metocean Measurements

At present the existing modeled metocean data is poorly validated due to insufficient long-term measurements near designated BOEM Wind Energy Areas. Further data are needed to reduce the uncertainty and increase the confidence in metocean measurements.

Assessments of the offshore wind energy resource on the U.S. Outer Continental Shelf is highly dependent on the accuracy of state-of-the-art mesoscale weather models used to generate high resolution data over multiple time scales and a wide geographic area. The data generated by these models needs to be validated, as the uncertainty is too high for uses including power curve validation, grid integrations, and other applications. The existing modeled data is poorly validated as few long-term measurements exist, especially near BOEM Wind Energy Areas or at wind turbine hub height.

Most available data observations have been recorded on surface buoys at 5 m height which provide poor assessments at hub height. The extrapolation from 5 m to hub height adds significant uncertainty because an accepted methodology that takes into account variations in atmospheric stability, low-level jets, surface effects, seasonal and diurnal changes, and other atmospheric complexities has not yet been developed. The lack of credible metocean observations drives uncertainty higher for the national resource assessments and in most Wind Energy Areas, which can increase project risk and raise financing costs. Data is needed to reduce the high uncertainty in modeling the resource including wind-wave-wake interactions. Any new data collected should look to include high-frequency measurements to enable validation of turbulence models at BOEM Wind Energy Areas. Data measurement campaigns should demonstrate the ability to deliver interim reports to meet urgent short-term needs but strive for highly credible long-term records.

3.2.3 Development of a Metocean Reference Site

At present there is no suitable metocean reference site in U.S. waters that can support the rapid growth of the industry. The development of a fit for purpose metocean reference site is required to support a number of key industry requirements including floating LIDAR validation and metocean data reference points.

The U.S. offshore wind industry is poised for rapid growth in the coming years, with multiple gigawatts under development and increasing areas of the U.S. outer continental shelf identified as suitable for future developments. To realize the industry's full potential, accurate information is needed about the resource characteristics and external design conditions of both the atmospheric and subsea environments at heights and depths relevant to wind turbines and their associated structures.

Technologies that are used to perform resource assessments, which may include improved floating and scanning LiDAR systems, large-area scanning systems, remote temperature profiling, wave height measurementsetc., need to be verified and validated against standard, vetted observations within a controlled reference test area. Transparent methods for assessing individual methods/sensors, open to the industry at large, are also needed, as are best practices and standards for ensuring that the quality and consistency of testing and validation practices meet the high standards necessary for building confidence in new technology and facilitating growth in a dynamic, capital-intensive market.

To achieve this end, the development of one or more metocean reference sites, akin to the FINO (Forschungsplattformen In Nord- und Ostsee) reference stations in northern Europe, is needed in an open ocean location representative of the existing BOEM Wind Energy Areas. This metocean reference site can be used to support the testing and validation of innovative methods in wind resource observations and site characterization. Furthermore, a complementary land-based reference station may also be needed where more detailed fixed met mast measurements can be conducted at higher elevations for ground-truth assessments. These met mast reference stations can provide much needed information on turbulence and stability measurement methods and calibration techniques.

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 Wind Energy Areas and possible 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 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.

In general, there is no central national database of geotechnical data that documents the estimated soil types and aggregates the various regional data that have been collected and documented. Although extensive site-specific geotechnical data collection is beyond the scope of this Roadmap, a geo-spatial 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 geo-physical conditions that can serve to speed up the permitting process and lower development costs during the pre-finance phase of development for fixed and floating offshore wind. Research should define the minimum information requirements for successful development practices.

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 mitigate cost increases due to U.S. regulations regarding transporting merchandise and reducing 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 Conflicts

Offshore wind development has to work in balance with other marine users and wildlife, aiming for minimal disturbance. Improved techniques and innovative technologies are required to help reduce potential siting conflicts and turbine interactions with wildlife at U.S. offshore wind installations.

Offshore wind arrays have relatively large statures and footprints, and therefore can have significant impacts on wildlife and other ocean users during the construction and operation phases if not properly addressed. Proactively mitigating siting conflicts can have long-term benefits by shortening development timelines (and hence cost), minimizing curtailments, and strengthening community relationships. This is especially important in areas where endangered species, such as Atlantic right whales, are active. Current techniques 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, taking into account 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. Examples of potential siting conflicts during construction or operation include, collisions of surface vessels with marine mammals, avian species interactions, interference with fishing, and the impact of noise on marine mammals from underwater pile-driving.

4.2.2 Installation Strategies for Large Turbines

As turbine size increases, heavy-lift vessels that are typically used to install offshore wind foundations and turbines are becoming more in demand. Without an available regulation-compliant heavy-lift vessel in the U.S., installation strategies and innovative technologies are required to support the development of the U.S. offshore wind pipeline.

Heavy-lift vessels are generally used for all major offshore wind plant construction activities, including installing wind rotor nacelles and support structure components at the offshore site. Weightlifting capacity and boom height tend to drive vessel costs up rapidly, and therefore, the ability to install the forecasted larger size turbines may be limited if the lift capacity of available vessels cannot increase accordingly.

Furthermore, the Merchant Marine Act, 1920 (also known as the Jones Act) requires any vessel that is transporting merchandise between two points in the U.S. to be U.S. built, U.S.-flagged, and U.S.-owned. As U.S. offshore wind plants are sited in U.S. waters, any vessel transporting components to or from an offshore wind plant would be required to comply with this law. Although there are a number of U.S. vessels that can support the construction of an offshore wind plant in U.S. waters, there are currently no Jones Act compliant heavy-lift vessels with the capacity to install the heavier turbine components (e.g., the nacelle) at the heights required. Additionally, to accommodate larger heavy-lift vessels, ports may need to be upgraded (e.g., additional dredging, wider access, stronger quayside, etc.).

The Great Lakes pose a local challenge as even moderate size ships may not be able to navigate through the locks. Wind turbines installations on the Great Lake may require very 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 U.S. may not be the only, or the best, way to meet the installation requirements for, ever increasing, ultra-large wind turbines. This is an opportunity for the U.S. industry to develop alternative, innovative solutions for offshore heavy-lift works such as new ship 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.

4.3 Operation and Maintenance

4.3.1 Offshore Wind Digitization through Advanced Analytics

Managing component damage or failure in an offshore wind plant has to date been reactive. 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, system reliability is likely to become a growing concern. In an offshore environment, the cost of component damage/failure or operations and maintenance (O&M) is significantly more expensive to manage because accessibility and logistics are far more complicated. Managing these issues on a reactive basis has proven to be 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 reduce the levelized cost of energy (LCOE).

At present there is a considerable amount of data being collected across offshore wind plants, mostly through turbine and plant level Supervisory Control and Data Acquisition (SCADA) systems. The SCADA system acts as a central “nerve center” for the wind plant connecting individual turbines, the substation and meteorological stations to a central computer. SCADA systems are predominantly used to support analyses on the productivity of the wind plant and therefore focus primarily on collecting data to monitor the turbines’ operating status, health condition, real-time and long-term performance, as well as efficiency (e.g., orientation, yaw, etc.). Comparatively little data is being collected to monitor the health of other components that make up the offshore wind plant, such as foundations and electrical cables etc., 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 or industry standards) and may only be identified once the damage has progressed to a more serious (expensive) state.

There is the opportunity to not only considerably improve and increase the technology used to capture component status data, but also develop a holistic integrated system that can collect, analyze, and interpret all component level data and make O&M decisions remotely. This would allow for fault detection during construction as well as facilitating better O&M planning leading to a more efficient and cost-effective maintenance process, including a reduced need for expensive offshore labor.

4.3.2 Testing Methods and Infrastructure

As advances are made to improve and increase the size of turbines and other components, testing is required to ensure the components are meeting relevant standards and performance criteria. Current testing methods and facilities are unable to match the pace of offshore wind innovation. Increased efforts are required to ensure state-of-the-art technology is appropriately tested and can be applied with confidence.

Full-scale drivetrain and blade testing are conducted on commercial components of a wind turbine to meet certification requirements and to increase system reliability and lower field failures. By simulating field conditions in a laboratory setting, accelerated lifetime testing and ultimate strength tests can reveal critical manufacturing and design flaws earlier than they would arise under field operating conditions. Test apparatus and methods must keep pace with new innovations and turbine upscaling trends toward 15-MW turbines over the next decade. As turbines grow, test methods may need to be revised to accurately simulate the damage caused by field operating conditions.

As components get larger, it also becomes increasingly more difficult to conduct a single test (as prescribed by IEC 61400-23 standards) that qualifies a 100-m+ blade structure for field operation. At the same time, current test facilities are becoming outgrown, whereas the next generation of turbine components cannot be adequately validated due to test facility capacity constraints. As a result, next generation turbines of the 12-MW to 15-MW scale may be more vulnerable to serial field failures and elevated maintenance leading to higher operational costs unless test facilities upgrade their capabilities and methods to meet this challenge. The utility of the existing U.S. large-scale component test facilities needs to be maximized in order to address wind turbine growth to 15-MW generators and 120-m blade lengths or more.

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. Greater research is required to identify, design, develop and test innovative approaches that enable the safe transfer of technicians to the turbine in higher sea-states, thus increasing the available O&M window.

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 the 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.

4.3.4 O&M Strategies and Tools

To date O&M strategies and tools have been developed based on European conditions. These approaches and tools may not be fit for purpose for the range of U.S. conditions. Further improvements and innovations are required to develop strategies and technologies that meet U.S. offshore wind O&M requirements and reduce the overall LCOE.

The global offshore wind operation and maintenance market is expected to grow annually by 17% to more than $12 billion by 2028 (Wood Mackenzie, 2019). Offshore wind farms are remote, and often inaccessible in harsh weather conditions. The U.S. experiences significantly different weather conditions and bathymetry than offshore wind farms in Europe, with icy waters in the Great Lakes region and deep water in the Pacific that necessitate the deployment of floating wind technology (Dewan, 2017). Each of these conditions, as well as service port restrictions, require customized O&M servicing. Further research is needed to improve and develop specific logistical strategies and technology innovation to optimize vessel availability, crew transport and training, scheduled maintenance, and remote monitoring and diagnostics.

Current technologies being developed for O&M include drone inspection, blade maintenance robots, underwater drones, and automation and artificial intelligence. Further research into advanced and autonomous technology is also required for wind data collection, monitoring turbine condition, and performing maintenance on turbines. In addition, the long-term effects of corrosion and how it affects the fatigue of support structures is required in order to optimize the design life and reliability in U.S. environmental conditions. The application of innovative strategies and technologies promises increased power generation, cost-effectiveness, timely maintenance, and longevity of the wind turbines.

4.4 Supply Chain

4.4.1 Technology Solutions to Accelerate U.S. Supply Chain

The current U.S. offshore wind supply chain is limited requiring many of the components to be imported. It is desirable to build on the unique offshore characteristics of the existing U.S. domestic supply chain to support the development of offshore wind nationally. Increased U.S. development of innovation and concepts will support the acceleration of the U.S. offshore wind supply chain.

Many of the components, subcomponents, and infrastructure for the initial phase of commercial offshore wind projects in the U.S. will be imported due to lack of qualified U.S. manufacturing and supply capabilities. There is an opportunity to accelerate the maturation of the U.S. supply chain through technology solutions involving ports and harbor infrastructure, manufacturing sector growth, and enhanced marine operations capabilities, with benefits realized by developers, ratepayers, and state governments.

Proposed demonstration projects have relied on imported turbines. For example, the first U.S. offshore wind farm off Block Island was assembled using European-built turbines and a foreign-flagged installation vessel. However, the Block Island project has also shown the potential for U.S. produced and installed components, with steel jacket substructures supplied by fabricators from the Gulf of Mexico's oil and gas industry. While the U.S. 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 U.S., where the scale of components is much smaller than the requirement for offshore wind. This poses logistical challenges for existing land-based manufacturing facilities in transportation of large components to coastal sites and in the upscaling of factories.

Significant job opportunities in the fabrication and construction of offshore wind plants exist along the eastern seaboard, which has resulted in the implementation of some training programs throughout the region, but 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, welders, etc.) and managers to master the execution and operation of an offshore wind turbine in compliance with U.S. safety and regulatory requirements.

4.4.2 Grid Access, Reliability, Expansion, and Transmission Upgrades

The large pipeline of state policy commitments for offshore wind energy has raised concerns that the current grid and transmission system may not be able to handle the increased inflow of energy. Studies and assessments are required to identify the potential future risks and solutions to support electric grid and transmission system decision-making.

The U.S. DOE Wind Vision report forecasts 86 GW of offshore wind power capacity in operation by 2050. In the near term, approximately 20 GW of offshore wind development has been committed by U.S. states along the East Coast by 2035 (Musial et al. 2019). Connecting 20 GW of offshore wind to the grid presents unique technical, economic, and regulatory challenges for transmission planning and grid system operations. Ultimately, the deployment of offshore wind in the U.S. depends on the infrastructure available and ability to transmit the power generated.

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. Some earlier studies have begun to assess the impacts of offshore wind on the U.S. grid (ABB. 2014); however, there have been no comprehensive offshore wind integration studies recently that policymakers and system operators can reference when making decisions regarding the buildout of offshore wind relative to the existing transmission grid infrastructure in areas where offshore wind is deployed. Without regional or national plans for offshore transmission expansion and integration, individual projects will have difficulty running radial export cables from their wind energy areas as the number of viable near-shore connection points is limited. The first few offshore wind projects will take the easily accessible grid connections and extensive new transmission upgrades will be unavoidable for the second phase of development. These upgrades will increase project cost for the later projects and could require significantly delayed development timelines. Several alternative solutions have been proposed to aggregate power among multiple wind plants or develop offshore grids and backbones to distribute power along the coast, but a general lack of information about grid interconnect options make state and regional planning more problematic.

Research is required to explore the integration of the first 20 GW of offshore wind power capacity into the eastern U.S. electricity system considering key variables such as injection location, transmission expansion requirements, system reliability, capacity value, load growth, the future use of energy storage, plant retirements, and penetration of other complementary renewables. All of which will provide developers, regulators, and state energy planners information that can be used to anticipate future grid requirements for offshore development before offshore capacity exceeds known interconnect options.

Research is needed to address impacts at a regional level and examine (1) infrastructure and technology advancements that are available to most effectively incorporate offshore wind into the transmission grid, (2) the costs of system upgrades, and (3) location of transmission upgrades. Research should assess system resiliency under extreme events and consider the impacts of key variables such as load growth, the future use of energy storage, plant retirements, and penetration of other complementary renewables.

4.4.3 Detailed Ports and Harbor Study

Understanding the specifications for deploying 15-MW offshore wind turbines and the corresponding capabilities and characteristics of the nation's existing ports and harbors is vital for determining project feasibility and LCOE. Assessments are required to identify the ports and harbors that are most suited to support the construction of offshore wind projects and to evaluate the cost of upgrades.

The development of critical infrastructure, such as ports and harbors, needs to precede both floating and fixed offshore development, since it may determine project feasibility and cost. Port and harbor development must be planned in conjunction with vessel development to assess the necessary access and project support capabilities unique to floating wind and fixed offshore wind. Yet, publicly available information about detailed U.S. port specifications is limited. Detailed design information is needed to inform the port selection and upgrade requirements for U.S. offshore wind port facilities in the Atlantic, Pacific Coast, Great Lakes, and Gulf of Mexico.

Regional assessments are required that narrow down and characterize potential ports for collective use by the industry. There is a considerable need for a national live 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 need to consider the costs of conceptual plans that may accelerate the development of port facilities for deployment of future upscaled offshore turbines, installation vessels, and floating turbine assembly areas. In some regions the needed ports may not exist, in which case surveys are needed to identify possible new ports locations.

4.4.4 Regulations and Permitting—Radar Interference

Land-based wind turbines have been observed to affect with weather and military radar signals, creating a source of contention with radar owners and users. In the U.S. outer continental shelf and Great Lakes regions, radar interference mitigation technology and measures need to be developed to resolve issues that may affect permitting.

Spinning wind turbine rotors 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 in respect to multiple radar operators and other stakeholders.

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