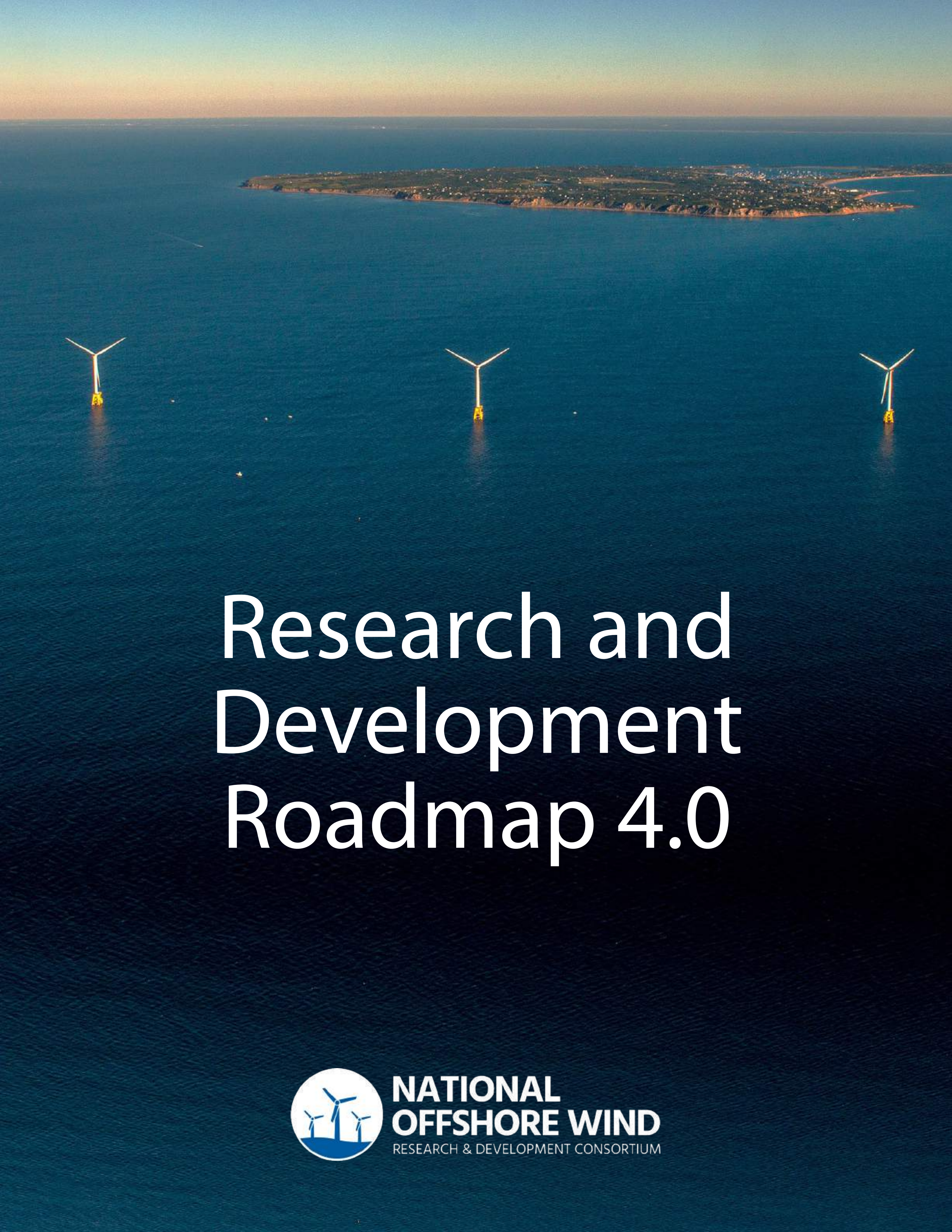

Research and Development Roadmap 4.0

NATIONAL OFFSHORE WIND
RESEARCH & DEVELOPMENT CONSORTIUM

TABLE OF CONTENTS

ACKNOWLEDGMENTS

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Version 2.0 .... October 2019
Version 3.0 .... June 2021
Version 4.0 .... April 2023

1 BACKGROUND

1.1 Industry 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 that enable cost-effective, responsible development and maximize economic benefits. Initial funding for the Consortium came from the U.S. Department of Energy (DOE) and the New York State Energy Research and Development Authority (NYSERDA), each providing $20.5 million, with additional funding from the Commonwealths of Virginia and Massachusetts and the States of California, Maine, Maryland, and New Jersey, for a total investment of approximately $53 million. The Consortium administers several committees, including the Research and Development Committee for members, the Research and Development Advisory Group for academia, and the State Action Network for state members.

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. This Roadmap serves to communicate that research agenda, taking into account recent industry progress and the changing geopolitical landscape that shapes the market.

Over the next few years, the offshore wind industry can expect more geographic global expansion, with Asian and North American development taking increasing global market shares. In the United States, there are only 42 megawatts (MW) of offshore wind energy deployed so far, but 932 MW of commercial projects are currently under construction. The number of countries in the offshore wind market is also increasing, with each country setting new offshore wind deployment targets. Several industry-leading countries like Denmark, the United Kingdom, and Germany have increased their offshore wind targets to gain energy independence from Russian fossil-fuel imports (Durakovic, 2022c; European Commission, 2022; Ferris, 2022; German Federal Ministry of Economic Affairs and Climate Action, 2022; Government of Belgium, 2022; Government of France, 2022; Government of the Netherlands, 2022).

There are now over 40 gigawatts (GW) of U.S. policy commitments for offshore wind deployment. The U.S. regulatory project pipeline is also growing rapidly. Recent Wind Energy Area (WEA) announcements have been made by the Bureau of Ocean Energy Management (BOEM) for leasing in the Gulf of Mexico and the Central Atlantic which, when included, will likely increase the U.S. pipeline to well over 70 GW. Figure 1 shows the project leasing activity in U.S. waters as of May 31, 2022.

In the United States, offshore wind energy deployment is driven by state policies, which seek climate and economic benefits as well as lower energy costs. A project's viability is greatly increased when both site control and offtake contract to sell the power are secured. Projects located where state policy provides a viable offtake mechanism have higher certainty of being built. There are 24 offtake agreements already in place for U.S. offshore wind energy. More recently, state policies have been strongly backed by the Biden Administration's deployment goals of 30 GW of offshore wind energy by 2030 (White House, 2021a). Public and private sector coordination, as well as proactive development of critical infrastructure, is needed to achieve the target. Achievement of this 2030 target also paves the way for a larger scale buildout of 110 GW by

2050. Recently passed legislation, such as the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA) of 2022, serve to support and incentivize the long-term development of offshore wind and the U.S. domestic supply chain (White House, 2022a and 2022b).

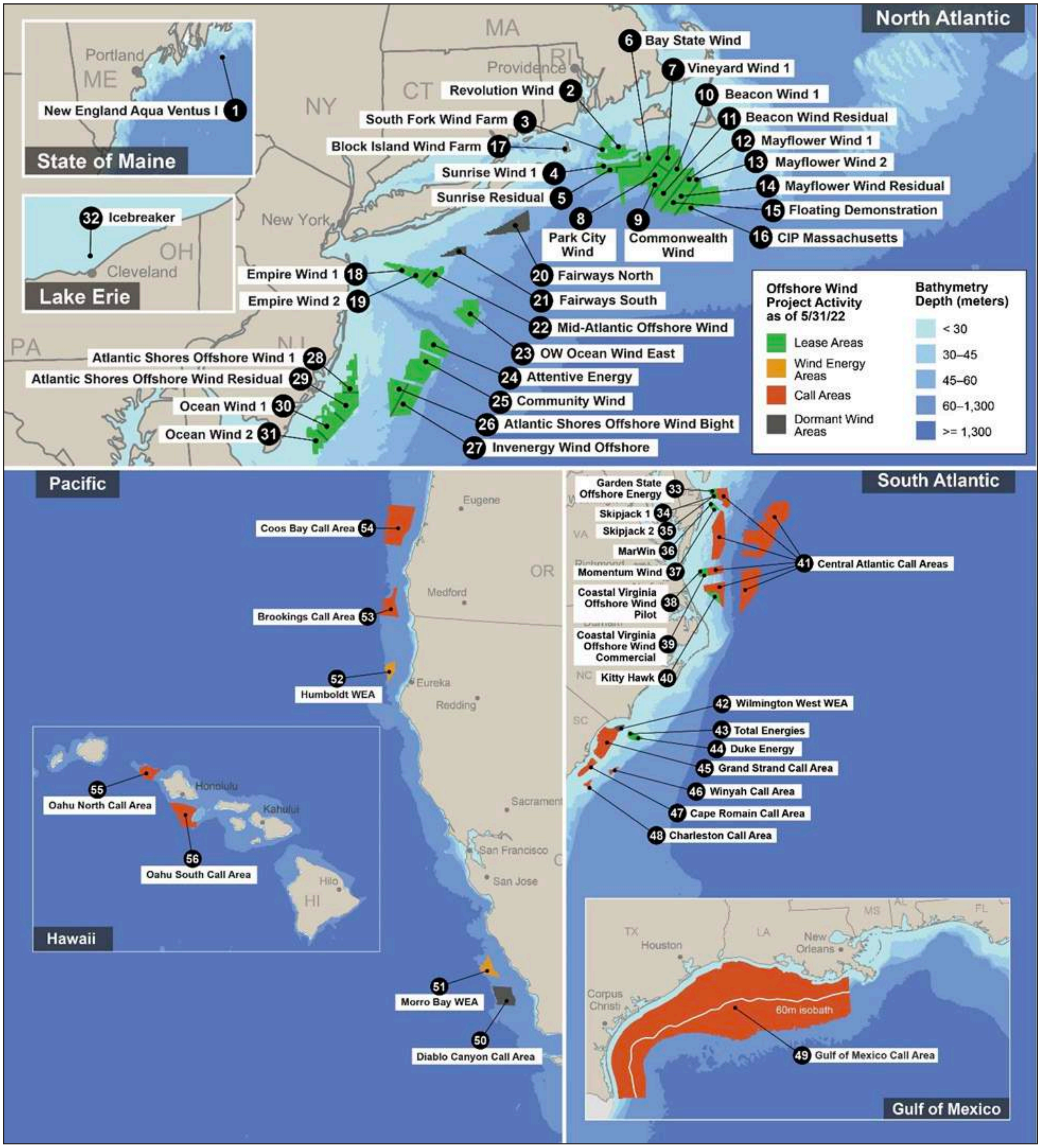

Figure 1. Locations of U.S. Offshore Wind Pipeline Activity and Call Areas, as of May 31, 2022 (Provided by NREL)

Another important federal action is the acceleration of offshore wind leasing by the Department of the Interior (DOI). In October 2021, the DOI announced their plan, "Offshore Wind Leasing Path Forward 2021–2025," illustrated in Figure 2. The plan calls for up to seven new lease auctions between 2021 and 2025. Three of those auctions have already occurred in the New York Bight, the Carolina Long Bay, and California's Morro Bay and Humboldt. (BOEM, 2021; BOEM, 2022a; BOEM, 2022b; BOEM, 2022c). In January 2023, the DOI also announced that it will publish revisions to the long-standing regulation for offshore wind energy development, Title 30 CFR 585, which promises to streamline the regulatory process and save developers over $1 billion.

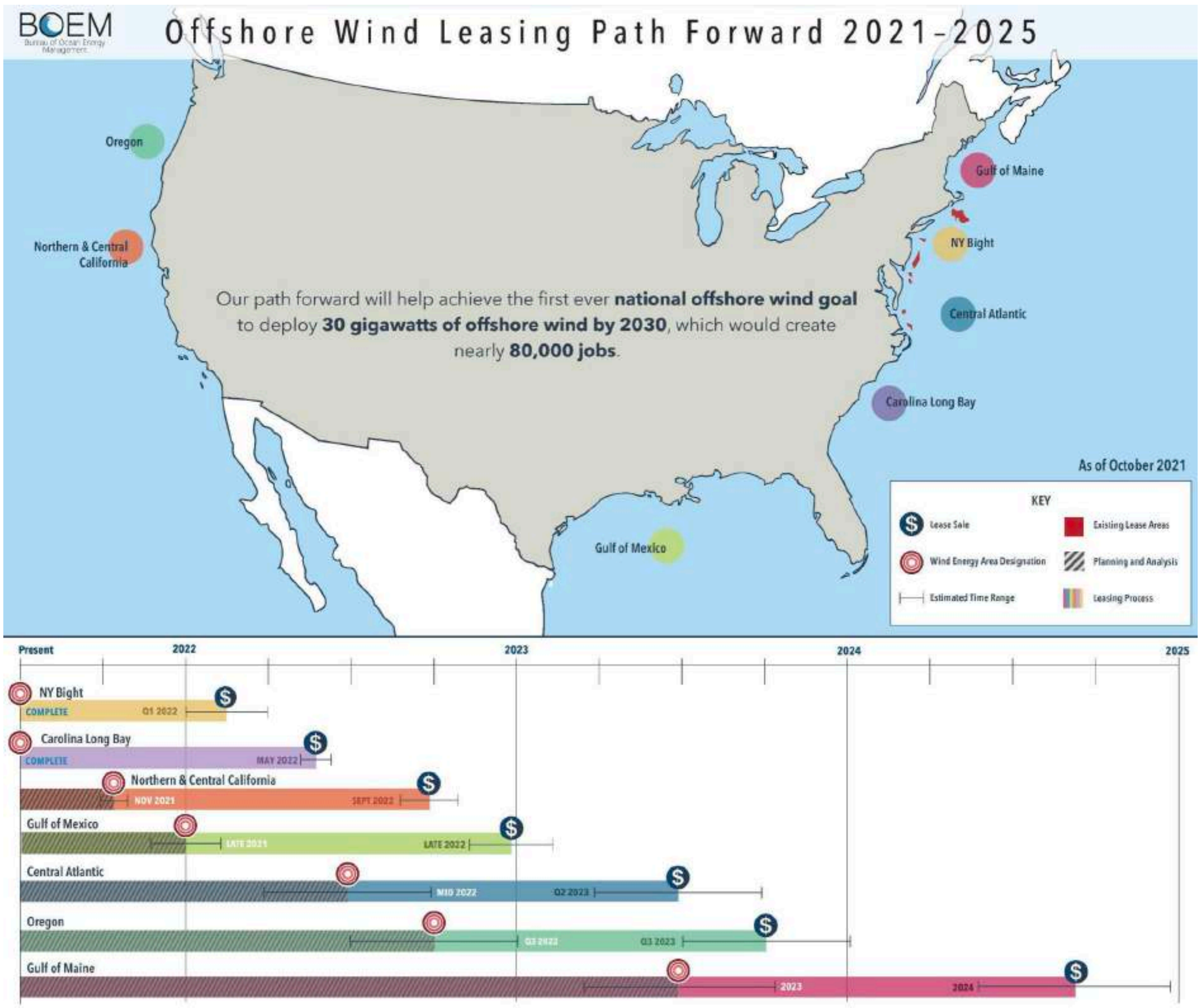

Figure 2. U.S. Offshore Wind Path Forward (Provided by BOEM)

As the United States electrifies transportation, buildings, and industrial sectors, demand for electricity will increase. The quantity of new generation needed is just now coming into focus. It is apparent that offshore wind will play a critical role in meeting energy demand. The map shown in Figure 1 may show only a fraction of the offshore wind sites needed for full decarbonization by 2050. Although this outlook is indeed a long-term goal, the technology advancement needed to scale renewable energy development must begin today.

Offshore wind buildout is necessary to enable grid-wide decarbonization targets. Offshore wind expansion will inevitably increase the urgency to accelerate the development of floating wind technology, as shallow sites become scarcer and offshore wind energy expands into regions with deeper oceans and lakes. Techno-economic cost models indicate that floating wind technology has the potential to eventually achieve the same (or lower) costs as fixed-bottom offshore wind (Beiter et al., 2016; Beiter et al., 2017; Gilman et al., 2016), but only if a commercial-scale industry can be achieved. To that end, in the 2021 DOI offshore leasing plan shown in Figure 2, five of the seven identified regions potentially have commercial floating wind areas (or a section suited for floating wind) and three of the regions (the Gulf of Maine, California, and Oregon) will use floating technology exclusively. Collectively, these five regions represent the beginning of the future U.S. offshore floating wind industry, including the first five commercial U.S. leases in the December 2022 auction in California, which sold for a total price of $757.1 million.

In September 2022, the Biden Administration announced “The Floating Offshore Wind Shot” (“Floating Shot”) initiative, which calls for a concerted nationwide effort to deploy 15 GW of floating offshore wind and to reduce the cost of floating offshore wind 70 percent by 2035 to a level of $45 per megawatt hour (MWh) (DOE, 2022). Technology innovation is needed to achieve these cost reductions. This level of cost reduction can be achieved by the simultaneous development and implementation of multiple innovations within the floating system design while also concentrating on volume production, standardization, industrialization of the supply chain, and reaping the benefits of global industry learnings. As the floating wind energy market expands, this industry experience and the economies-of-scale associated with market expansion can contribute to sizable reductions in floating offshore wind technology cost aligned with the Floating Shot (Musial et al., 2020; Beiter et al., 2016).

Consistent with the Consortium’s policy of supporting the technical needs of the U.S. offshore wind industry, the Roadmap’s primary focus is on technology solutions that can have an impact within the next seven years. These technology advancements are expected to deliver benefits of reduced risk and lower costs for development in all current and future U.S. offshore wind regions.

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]

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

Pillar 1: Offshore Wind Farm Technology Advancement

This research 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. 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 and enable significant cost reductions through industry learning.

Pillar 2: Offshore Wind Power Resource and Physical Site Characterization

This research 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 and hazards assessment as well as geotechnical and metocean physical site characterization. Solutions may address cost reduction through increased annual energy production, reduced wind farm development timelines, greater certainty in understanding the design environment, lower capital and operations and maintenance (O&M) costs, and lower project risk.

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

This research 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-lift capacity vessels and large amounts 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 and may be necessary to achieve industry cost targets. Finally, the immaturity of the U.S. supply chain contributes to higher 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.

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, R&D Committee, and Research and Development Advisory Group (RDAG). The Roadmap relies on expertise from the Consortium's internal technical team of offshore wind experts from the DOE, the Carbon Trust, and the National Renewable Energy Laboratory (NREL).

As the industry evolves, the Consortium has modified and expanded its research pillars in subsequent versions of the Roadmap. Pillar 3 includes additional topics that are essential to the industry but may not match the original pillar descriptions (e.g., grid integration, mitigation of user conflicts, etc.).

The first Consortium Roadmap was published in November 2018. Based on feedback from the Consortium's R&D Committee, advisory groups, and responses to the Consortium's ongoing R&D solicitation, version 2.0 was published in October 2019. The Roadmap 3.0, building on the previous two versions and published in June 2021, provides updates to all topic areas.

In the Roadmap 4.0, topics were revised for clarity and better identification of specific project types. Topics areas were also consolidated in many cases and new topic areas were added in response to feedback to allow for a broader scope less constrained by the language in the original three pillars. Roadmap revisions incorporate new research priorities and objectives as well as account for prior achieved research objectives.

These updates are primarily driven by the continuous evolution of offshore wind in the United States as defined by developer interests, individual state policy actions, and experience gained from offshore wind globally. The Roadmap 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.

1.3 Consortium Research Solicitations

The Consortium uses the most recent 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 stipulations of 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 vision 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 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. The Consortium's third solicitation, PON 4584 (Innovations in Offshore Wind Solicitation 2.0), released October 2021, was also administered by the Consortium.

In total, 53 research projects have been awarded: 20 each from the first two solicitations and 13 from PON 4584. A complete list is included in the Appendix. Additional project background is available on NOWRDC's Project Database.

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.
- Solicitation topics will generally adhere to the three research pillars. In some cases, this Roadmap includes important research areas that may be outside the scope of priorities indicated in the original DOE FOA 1767. Generally, the solicitations are informed by the Roadmap, but the solicitation requirements supersede any guidance the Roadmap provides.

- 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 or where results cannot be publicly disclosed due to competitive interests.

The Consortium's next solicitation may be informed by the Roadmap 4.0 and is expected to be released in 2023.

2 PILLAR 1: OFFSHORE WIND FARM TECHNOLOGY ADVANCEMENT

2.1 Technology Overview

Pillar 1 research focuses primarily on technology advancements to the wind turbine and balance of system components which to a large extent drive the capital expenditures and are a primary focus for potential LCOE reductions. Pillar 1 includes both fixed-bottom and floating wind technologies, with an emphasis on technology development that can be deployed within the next seven years, for the initial phase of U.S. offshore wind projects.

In this Roadmap, major topic areas include floating wind station keeping, model development and validation, adaptations for new markets and expanding viable resource area, adaptations for 15 MW scale turbines, array design-optimization and control, electric infrastructure, and technology solutions to mitigate negative offshore wind impacts.

Long-term floating wind technology innovation in the United States is supported by the ARPA-E ATLANTIS (Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control) program (ARPA-E, 2019). The DOE intends to announce, as part of the Floating Shot, an additional $31 million for a second phase of ATLANTIS, scheduled to begin in 2023. The Consortium complements long-term research programs like ATLANTIS by targeting technology advancement on a near-term or mid-term scale that can be implemented at lower risk over a shorter time frame (ARPA-E, 2021). Consortium priorities address technology needs that will enable the first commercial floating projects.

While the floating wind markets emerge, another major near-term industry challenge is to adapt the technology, both fixed bottom and floating, to the new 15 MW turbine scale. Historically, the industry has taken several years to integrate and optimize the components so they can efficiently perform as a system. This process can be accelerated by the Consortium through targeted research. Adaptations and optimizations are also needed to make the current North Atlantic technology platform compatible with other emerging markets. Differing regional extremes in the external conditions can expand or contract the design load envelope or add new technology-specific requirements, such as in sites prone to hurricanes (e.g., the Gulf of Mexico) or surface ice floes (e.g., the Great Lakes). As the industry scales up, the engineering process is trending from single turbine impacts to array level impacts and strategies. A major area which the Consortium has addressed previously and will continue to support is opportunities for array design optimization and control. Additionally, as grid expansion is just beginning, offshore wind will play a major role in providing hardware systems to support grid function, reliability, and cost reduction. These topics are covered here.

2.2 System Adaptations for 15 MW Turbine Platform

2.2.1 Overview

Fixed-bottom offshore wind technology is the primary support structure architecture being deployed in the near-term market. Designs for U.S. projects currently build on lessons learned from the 57 GW of global offshore wind projects. As the U.S. market grows, the U.S. project design experience and the U.S.-specific physical and market conditions may drive some U.S.-specific innovations. The following topics reflect U.S. research needs to advance wind farm technology.

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

Most fixed-bottom foundations installed to date have been designed for European offshore conditions and the 6 to 10 MW turbine class. With increasing offshore wind development in the United States and turbine growth jumping to the 15 MW class, innovative substructure solutions may be required to adapt these systems to U.S. offshore geotechnical conditions, domestic supply chains, vessel availability, port facilities, and to ultimately achieve cost targets.

With most of the current 40 GW in the U.S. project pipeline located in water depths of 60 meters or less, the use of fixed-bottom substructures is the obvious near-term solution for the first phase of U.S. offshore wind projects. Available fixed-bottom turbine support structures, such as monopiles, may not always be optimal for this near-term U.S. market due to incompatible seabed characteristics, greater water depths in certain areas, extreme weather conditions, environmental and regulatory siting constraints (e.g., pile driving noise), availability of suitable installation vessels, geotechnical pile driving constraints (e.g., glauconite soils, boulders), incompatibility with the domestic supply chain (e.g., imported steel plate), and general supply chain risks associated with relying on one technology and limited suppliers. As the offshore wind industry continues to grow, there is a tremendous 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. These concepts may be even more important in regions where heavy-lift wind turbine installation vessels (WTIVs) are not available or even feasible, such as in the Great Lakes. Investments in this technology area can have a significant impact on lowering project risk and increasing competition in the supply chain. A recent study by Tufts University on concrete gravity-based foundations exemplifies the type of benefits sought through this topic area (Fried et al., 2022). The Consortium has already awarded several contracts to explore these innovations and will continue to support alternative substructures.

The support structure accounts for a significant fraction of the total capital expenditure for a fixed-bottom offshore wind farm (Stehly et al., 2020), and this percentage increases with water depth, unfavorable seabed conditions, and limitations of the supply chain. Innovative technology solutions could have a marked impact on reducing the capital expenditure for substructures by enabling development where commonly used substructure technologies are not feasible and by providing diversity to the supply chain.

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

- Support structure techno-economic feasibility studies that address unique siting challenges at U.S. offshore wind sites,
- Research that increases the suitability and reliability of existing available support structures for U.S. specific conditions,
- Float-out solutions that avoid heavy-lift WTIVs,
- Strategies to mitigate fatigue and extreme loads on support structure technology,
- Innovations to improve substructure reliability, extend design life, and/or lower maintenance costs,
- Design innovations that avoid conflicts with other ocean users or with the physical ocean environment (e.g., rocky and soft sediments),

- Innovations that provide solutions to installation and infrastructure barriers such as vessel, port, and transmission constraints, and environmental constraints such as construction noise,
- New solutions that enable lower cost installation with reduced risk,
- Development of advanced manufacturing and materials such as additive manufacturing, low carbon concrete, lightweight materials, high strength materials, corrosion resistant materials, and structural coatings that demonstrate increased reliability or lower cost.

2.2.3 Enabling Balance of System for Large-Scale Offshore Wind Turbines

Turbine rating is increasing significantly with nameplate capacities of up to 15 MW, and with rotor diameters up to 240 meters. These larger turbines will be the majority of what is deployed over the next decade. The 15 MW turbine platform is creating new technical challenges for the industry both domestically and globally, and is expected to be used for both fixed-bottom and floating wind turbines. The U.S. industry must address technical issues regarding the upscaling to 15 MW turbines and wind farm integration. Impacts of these larger turbines and their components on energy production, reliability, and the associated infrastructure need to be understood for recent cost reduction trends to continue.

While the global markets move to commercialize these larger turbines, reliability and systemic issues related to their U.S. 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 as machines get larger. Projects to mitigate technical 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 that might be considered 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,
- Designs to ease 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 national and regional 15 MW turbine supply chain requirements to avoid bottlenecks that may hinder industry growth at early stages,
- Projects to develop, improve, and validate the engineering design and analysis tools to facilitate advancements and optimization of 15 MW scale fixed and floating technology,

- Design solutions that address the coalescence of the natural frequency of large floating wind turbines rotational speed with fundamental tower system frequencies,
- Integration of 15 MW scale turbines with alternative substructure designs.

2.2.4 Optimization Strategies for 15 MW Class Turbines

Most 15 MW turbines are built on a technology platform that can accommodate varying rotor and drivetrain sizes within a design envelope that enables engineers to develop turbines optimized for different sites. For example, in sites with slower wind speeds such as the South Atlantic and the Gulf of Mexico, significant energy gains and economic benefits can be realized through lowering the specific power (the ratio between the generator rating and the rotor swept area) to increase capacity factor. This trend is well documented for land-based turbines that have successfully entered many low windspeed markets (Wiser et al., 2022). The offshore wind industry has been focused on turbine MW upscaling but optimization of the current generation of 15 MW turbines for performance and load reduction has been compromised as a result. The Consortium does not envision direct support of new turbine development. Rather, acceleration of turbine optimization solutions in harmony with the needed industrialization and standardization of the supply chain would better serve U.S. development.

Projects under this topic area may include:

- Engineering studies to assess turbine optimization requirements mapped to different offshore wind regions,
- Solutions to increase rotor swept area in low wind regions,
- Design optimization strategies to reduce nacelle and rotor weight to facilitate installation and cost reduction,
- Analysis demonstrating weight and cost reduction for downwind rotors,
- Alternative horizontal axis configurations that can improve cost reductions but remain bankable.

2.2.5 Large Turbine and Substructure Testing Methods

The offshore wind industry's commitment to the new platform of nascent 15 MW class wind turbines may increase the value of full-scale laboratory testing. Advanced laboratory testing can help avoid costly, unanticipated field failures through validation of the 15 MW drivetrains, 120-meter blades, and floating support structures, prior to large-scale deployment. Design and manufacturing issues can be detected earlier in the laboratory before extensive serial production has occurred. This can lower operations costs significantly. For type certification, laboratory testing of major turbine components like blades and drivetrains is mandatory. However, testing methods and capabilities in U.S. facilities (and globally) find it difficult to keep up with the pace of offshore wind turbine growth. There is a limited number of facilities that are able to accommodate 15 MW turbine components. Therefore, test methods must be modified due to these capacity constraints, which increases uncertainty in the reliability of the component. Current test methods may not be sufficient to ensure the new turbines and their associated technology innovations are adequately verified prior to field deployment.

Current test methods provide some validation of reliable field performance by simulating the damage under field operating conditions and complying with type certification requirements. However, advances to improve the accuracy of these tests as the turbine scale increases can add enormous value to the laboratory testing and significantly reduce costly field failures. By simulating field conditions in a laboratory setting, accelerated lifetime testing and ultimate strength tests (at a component and subcomponent scale) can reveal critical manufacturing and design flaws during the prototype phase rather than learning from field test results after serial production.

Full-scale testing is also conducted on commercial components and subcomponents of a wind turbine to meet certification requirements or to validate design modification 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 and validations cannot be achieved if U.S. facilities are not upgraded.

For the larger blades (e.g., 100 meters or larger), it is difficult to conduct a single full blade test (as prescribed by IEC 61400-23 standards) that qualifies these large monolithic blade structures for field operation. Laboratory loading cannot accurately simulate the complex distributed field loading at all locations on the blade, potentially leaving this coming generation of turbines more vulnerable to field failures from undetected design and manufacturing flaws. This could lower reliability in the near-term unless capabilities and methods are developed to compensate for this increased uncertainty.

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

- Laboratory validation test methods that demonstrate greater accuracy or greater coverage of the validation range for major 15 MW turbine components,
- Methods to correlate laboratory results with field data and actual turbine response and/or possible linkages to avoid field failures,
- Alternative validation methods that achieve equivalent or higher accuracy through parallel subcomponent testing in smaller distributed laboratories to reduce the dependence on sparse, massive laboratory test facilities,
- Validation of virtual twin models complementing physical testing of innovative turbine technologies to expedite time to market of reliable offshore products,
- Innovations that can be implemented to improve the quality and accuracy of full-scale laboratory component validation tests,
- Methods to increase the utilization of existing facilities to adapt to 15 MW components,
- Blade and drivetrain test methods that extend the accepted validation methods beyond smaller component sizes and demonstrate applicability to the larger 15 MW size,
- Test methods to validate sediment/structure interactions for various foundation types including anchor placement, deploying fixed-bottom systems in various sediments, and pile driving constraints and risk mitigation,

- Test and instrumentation methodology to validate cyclic, transient, thermal, extreme, and long-term operation of direct drive generator systems.

2.3 Array Design, Optimization, and Control

2.3.1 Overview

This topic focuses on two areas: 1) the advancement of the accuracy and validation of the modeling tools used for full system evaluation of wind farm design and performance, and 2) wind farm system innovations to mitigate inter-array effects.

2.3.2 Array Design and Optimization Tools

Current turbine array models require better atmospheric inputs to reduce uncertainty in the calculations of energy losses due to wakes and blockage, fatigue loads, turbulence, and wake propagation. This uncertainty leads to imprecise decision-making in wind farm layouts, energy production estimating, 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 light detection and ranging (LIDAR) systems to provide more accurate turbulence measurements from both freestream and downstream wind turbine wakes for energy and load characterizations. Turbulence characterization is dependent on accurate understanding of atmosphere stability and wind shear over diurnal and seasonal periods. To meet the Consortium objectives on this topic, a high emphasis is placed on model validation using existing wind farm data or innovation of measurements made in similar environments.

Five awards were made under this challenge area in the first two Consortium solicitations. This topic has been updated in this Roadmap to focus on growing concerns with the accuracy of large-scale array modeling.

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

- 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,
- Methods to integrate atmospheric and oceanographic coupling on array and inter-array models,
- Methods to measure and quantify turbulence at the turbine scale,
- Models that predict deep array loads and wake effects leading to better turbine lifetime estimation,

- Models to understand 15 MW scale turbine wake behavior and possible ground effects, low level jets, power performance calculations, and other upscaling physical phenomena.

2.3.3 Mitigation of Offshore Wind Inter-Array Effects

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 more accurate atmospheric inputs relevant to U.S. lease areas using 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 increased turbine maintenance and downtime that may result from waked flow. 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:

- Quantification of flow control methods to mitigate inter-array wake effects and induce boundary layer mixing,
- Models or measurements to quantify variables that drive atmospheric stability conditions in order to improve modeled predictions of long-term energy and loads,
- Methods and tools to improve deep-array turbine reliability and reduce O&M costs,
- Innovative control strategies to increase offshore wind plant production or reduce the persistence of downstream cluster wakes.

2.3.4 Modeling Large Floating Arrays

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. Floating wind turbines 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, wake characteristics, 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 potentially 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 equipment 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,
- Quantitative assessments from models or field data that evaluate differences between floating and fixed arrays.

2.4 Mooring, Anchoring, and Station Keeping

2.4.1 Overview

Although significant knowledge can be gleaned from the oil and gas (O&G) sector, floating offshore wind mooring concepts have unique challenges that require innovative 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, 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 into floating wind and become global offshore wind supply chain leaders. Although significant strides have been made to develop suitable mooring concepts, additional efforts and technology innovations are needed to design, develop, and test a range of mooring concepts, components, materials, and installation methods that adapt to different U.S. conditions.

Whether optimized for shallow regions or deepwater 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 to date, indicating that this challenge area is of major importance, but as early commercial leasing has already ventured into deeper waters (e.g., California lease areas are as deep as 1,300 meters), the current knowledge base may still be insufficient. Water depth is the primary challenge, but new designs that mitigate stakeholder concerns often require solutions that have not yet been proven.

2.4.2 Deepwater Mooring Systems

The steep drop of the continental shelf off the Pacific coast, combined with requirements to minimize visual impact, have pushed development areas off the Pacific coast into a narrow strip in relatively deep water. The five California lease areas recently awarded all require floating wind technology with mooring systems in water exceeding a depth of 500 meters. The deeper the water, the larger the anchor circle, which reduces the energy extraction potential (array power density) for a given lease area. Alternative design configurations and mooring solutions are needed to address these deepwater conditions. In the Central Atlantic, new Call Areas with water depths up to 2,600 meters, over twice the depth of the California lease areas, were recently announced. At these depths, mooring, anchoring, and dynamic array cable protection will need more research, and the associated engineering model tools will need to keep pace.

Examples of projects that may be considered include:

- Integrated mooring and dynamic cable array designs for water depths between 600 and 3,000 meters,
- Models, analysis, and risk assessments for single point turret moorings and tension leg platform (TLP) anchors and tendons,
- Concepts that reduce deepwater mooring system footprints and mooring line lengths,
- 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 or expedite anchor and mooring line installation,
- Optimized anchor designs and methods for installation in deep water and at sites prone to seismically induced sediment liquefaction,
- Innovative solutions for dynamic export cable connections and floating substation station keeping challenges,
- Innovative solutions for quick disconnect of dynamic array cables and mooring lines for installation and service,
- Designs for efficient intra-array cable layouts that account for water depth and other ocean use activities,
- Large-scale array design tools that integrate dynamic array cables and mooring lines to enable cost-effective standardized approaches.

2.4.3 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 (60 to 90 meters) 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 optimization for local seabed conditions. 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 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.

2.5 Adaptations for New Markets

2.5.1 Overview

This topic addresses the adaptation of offshore wind technology to allow deployment in new U.S. offshore regions previously considered technically or economically unviable. These adaptations include hurricane design augmentations for wind turbines in regions where major hurricanes (greater than Category 3) are frequent, mitigation of ice loads on floating wind turbines for Great Lakes environments, low wind speed turbines, and solutions to mitigate losses in the existing development areas.

2.5.2 Hurricane Resilient Wind Systems and Environmental Extremes

General understanding of the impact of tropical cyclones and hurricanes on offshore wind turbines is limited and design standards are based on simple extratropical storm extreme criteria, such as a 70 meters per second gust for three seconds. Hurricanes commonly occur along the entire U.S. Atlantic coast and the Gulf of Mexico, impacting over 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 and the Central Atlantic where floating turbine designs may be needed for hurricane conditions. Floating wind farms may also be developed in the South Atlantic and the Gulf of Mexico. 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. The state-of-the-art indicates that their substructures will be adapted for hurricane resilience using proven concepts and practices from the oil and gas industry (e.g., API RP-2A) and additional provisions may be included as needed based on recent IEC 61400-01 and IEC 61400-3-2 updates, such as battery backup for the yaw system in the event of loss of grid power and typhoon class blades and towers. As turbines are deployed in regions where extreme winds may exceed IEC Class 1 criteria, current turbine designs may have to be adapted further to mitigate extreme loads and low-cycle fatigue, but more work is needed to determine the proper design augmentations. One of the primary challenges is understanding the hurricane risk, or the frequency and severity of extreme hurricane conditions at specific locations. 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. Higher fidelity modeling of tropical cyclones may be needed to extract the relevant characteristics on a turbine scale that could affect the extreme loading. 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 due to offshore wind system upgrades needed 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:

- Improved physics-based risk models to quantify the understanding of location-specific hurricane severity and probability at U.S. offshore wind sites,
- Control system innovations that decrease extreme load conditions or increase strength reserves to protect existing or futures turbines from the impacts of extreme conditions wind, wave, or earthquake conditions,
- Methods to evaluate and mitigate the low-cycle fatigue accumulation during a single extreme event,
- Conceptual design solutions for bespoke hurricane turbine load minimization,
- Studies to determine the premium cost adders for current hurricane-class turbine upgrades and possible benefits of bespoke hurricane turbine designs,
- 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, precipitation, roll vorticity, and fatigue) to assess the adequacy of current IEC load cases and assumptions,
- Models that advance the accuracy of estimating combined extreme wind and wave load cases on an idling turbine or array,
- Design solutions that mitigate extreme earthquake loads in bottom-fixed and floating systems,
- Design solutions to extend the life of offshore wind components through corrosion resistance.

2.5.3 Overcoming Great Lakes Wind Design Constraints

The Great Lakes states produce about 25 percent of the total atmospheric carbon emissions, however the Lakes have over 10 percent of the total offshore wind resource potential of the United States, with a gross wind resource potential of 614 GW after excluding areas less than three miles from shore. This potential offers a significant opportunity to contribute to the decarbonization of this region. A 21 MW demonstration scale project is planned in the shallow waters of Lake Erie, seven nautical miles off the coast of Cleveland, but approximately 400 GW of the total Great Lake wind resource potential is in deep water (60 to 400 meters) more suited for floating wind. It is likely that large-scale Great Lakes wind farms will need to be sited farther from shore to avoid visual impacts, near-shore ice ridges and pileup, contaminated sediments, and avian/bat activity. This will necessitate a new class of ice resistant floating wind technology that can be installed and maintained with the marine equipment resident on these lakes, and which have customized substructures that minimize ice loading to protect their systems from the worst impacts of ice loading and scour. However, there has been limited development of floating technologies that can survive freshwater ice conditions. Considerable effort will be needed to design, develop, test, and demonstrate survivability of floating wind turbine concepts that are suitable for deployment under these conditions.

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

- 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,
- Geospatial ice models that predict ice ridge formation and magnitude,
- Ice models that estimate loading,
- Analyses that characterize extreme ice ridge technical risk to the turbines and cables,
- Floating substructure designs that minimize ice loading and protect dynamic cables,
- Vessel and crane strategies that enable 15 MW turbine installations for fixed and floating support structures,
- Great Lakes turbine design concepts or physical assessments that reduce uncertainty of possible damage or performance losses caused by potential ice accretion from lake spray,
- Design basis analyses of Great Lakes conditions,
- O&M innovations to mitigate barriers to Great Lakes access and service (e.g., helicopters).

2.6 Technology to Reduce Conflicts and Increase Coexistence with Ocean Users

2.6.1 Overview

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

2.6.2 Technology Solutions to Mitigate Wildlife Conflicts

Offshore wind arrays have relatively large structures 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. Technology solutions that can be integrated into the wind system design at a turbine or farm level and validated should be considered.

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

- Projects that consider mitigation of surface vessel collisions with marine life,

- New technologies that quantify and reduce avian species interactions with turbines,
- 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 remotely operated vehicles (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.

2.6.3 Solutions for Coexistence and Co-use with Other Ocean Users

The challenge is to maximize the use of offshore wind resources and ensure promoting coexistence with other ocean users. Wind energy is clean relative to burning hydrocarbons and nuclear energy, but it is also more diffuse, requiring a large amount of ocean area. With the expected expansion of offshore wind energy deployment, the industry needs new technologies and site selection methods to coexist with other ocean users in order to increase the number of viable sites and ensure they are developed efficiently while promoting coexistence with other ocean users. This means striving for the highest standards of stewardship of resources while meeting greenhouse gas targets. It is often taken for granted that there will be enough offshore wind resources to accomplish the decarbonization deployment goals, but the actual capacity of offshore wind resources can vary considerably, depending on a variety of technology and permitting constraints. Strategies that allow dual-use of the wind farm footprints and considerations to make those footprints as small as possible are needed.

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 and to inform improvements in the permitting processes with respect to multiple radar operators and other stakeholders. Many ocean users depend on radar for safety and navigation, including fishing and civilian vessels.

The Consortium is interested in technology solutions that increase wind resources, minimize negative impacts and risk, or allow co-use of the wind farm area.

Some examples specific to offshore wind development are:

- Technologies that expand access to wind farm areas for fishers and/or reduce the interference of floating or fixed-bottom wind projects with commercial fishing,
- Technologies that reduce downstream wake impacts allowing closer turbine and array spacing and reduced ocean space,
- Technologies that can be colocated at wind farms to increase public safety and security for U.S. coastal regions,
- Aquaculture feasibility studies that colocate food production using wind plant infrastructure.
- Wind farm structures that increase or protect habitat for ocean species,
- Cost-effective remote offshore wind hydrogen or alternative green fuel production, storage and transport that avoids export cable routing and expands resource area for green fuels,
- Technologies that tap into the expansive wind energy resources on the high seas to generate green fuels. (e.g., unmoored, roaming, and floating wind technology),
- Technologies for converter stations that facilitate mesh networks and improve grid flexibility,
- Studies to investigate sediment composition and behavior under offshore wind specific applications (e.g., glauconite sands and carbonates related to pile-sediment interaction),
- Solutions that reduce conflicts with landowners for export cable beach crossings and landside transitions.

2.7 Offshore Wind Electric Power Systems

2.7.1 Overview

This topic covers the capital equipment and systems associated with offshore wind farms in all regions including potentially remote installations and systems installed in areas where external conditions might harm the equipment (e.g., cable/ice interactions in the Great Lakes).

2.7.2 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 interconnection, which accounts for about 19 percent of the total offshore wind capital expenditure (CapEx) (Stehly et al., 2021). These cost percentages are expected to increase as projects are sited farther from shore, in deeper waters, project costs become integrated with ocean-based High Voltage Direct Current (HVDC) grids, 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 high voltage cable-related incidents account for 80 percent of insurance claims. 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 power system 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 ultracompact offshore HVDC stations,
- Projects seeking to improve seafloor cable cover designs, installation, and inspection methods,
- Detailed design solutions for floating substations resulting in cost-efficient floating substations,
- Certified designs for dynamic array cables at 132 kilovolt (kV) and/or dynamic export cables.

2.7.3 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 and the U.S. has set goals for carbon neutrality by 2050. 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 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 drive storage and/or capacity reserve requirements), and expanded operational envelopes to support the power system.

With the growing commitment to develop offshore wind, there is also an increasing need to ensure the security of the offshore wind energy supply. Therefore, cyber security is becoming a more urgent concern across the new energy grid.

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., most 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's share of the grid generation mix increases, some 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-wires 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 time scales including long duration storage options,
- Projects that address offshore wind security in terms of physical or cyber threats.

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, validating analytical models, and data sets used for site characterization.

3.2 Metocean Research

3.2.1 Overview

The key topics under offshore wind power metocean research include validation of the metocean conditions and characterization of extreme external conditions that can drive the designs. The development of reference test sites is also a consideration. Through Consortium funding, Woods Hole Oceanographic Institution (WHOI) has successfully implemented a metocean reference station in the North Atlantic. However, atmospheric conditions that affect offshore wind characteristics such as wind shear and atmospheric stability vary considerably across U.S. regions. Other U.S. offshore wind regions may benefit from similar test sites developed in the North Atlantic to increase understanding of the regional physical phenomena, enable more accurate models, and validate observations.

3.2.2 Validation of Wind Resources and External Conditions

Wind resource assessments are essential to offshore wind planning decisions at the national, state, and project level. Offshore wind geospatial resource assessments have been conducted by public and private entities. These assessments are used to make major planning decisions such predicting energy output, estimating design envelopes, planning weather windows for construction and O&M, and setting insurance premiums. Each of these decisions impacts the cost and risk associated with U.S. offshore wind development.

The physics of modeling weather data is extremely complex. Most of these assessments initially rely on high-fidelity mesoscale modeling of the atmospheric boundary layer. Although science has evolved significantly over the past decade, the model set-up parameters are crucial. Additionally, modeled metocean data must be validated to understand the physics at a turbine scale and eliminate bias in the modeled data, and the models themselves need to be further tuned and upgraded.

Measurements made in situ at sea are the best way to validate these modeled data sets, but there are very few that are available relative to land-based sites due to the expense and difficulty of collecting data under these harsh conditions. The industry needs to be able to rely on the mesoscale models that are run with a variety of inputs, including, for example, reanalysis data and measured climate data (radiosonde, buoy, or land-based). Most publicly available data observations (i.e., measurements made in situ) are recorded from surface buoys at five meters height. When these measurements are extrapolated to hub height, uncertainty is increased due to lack of an accurate methodology that accounts for vertical variations in atmospheric stability, low-level jets, surface effects, seasonal and diurnal changes, and other atmospheric complexities. These biases can also exist in even the most advanced high-fidelity models and guidance to improve judgment in the modeling setup is lacking. In addition, these resource assessments do not account for the statistical variations due to climate change which will increase uncertainty in models based on hindcast data.

This topic area encourages the U.S. industry developers and scientific research institutions to work together to build validation and data sharing campaigns to lower uncertainty in critical metocean data sets and increase confidence in U.S. lease area energy production potential and to help increase certainty in the high-fidelity mesoscale weather models.

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

- New resource validation methods and extrapolation techniques using models, surface buoys, LIDAR, satellite data, or other existing data,
- Analysis of evolving or existing data sets not previously used for wind energy design or production estimates,
- 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,
- Data-driven models that quantitatively estimate the near- and far-term future impacts of climate change on the U.S. offshore wind resource,
- Analyses that inform weather research and forecasting model assumptions and lower uncertainty of future U.S. resource assessments through validations with measured field data.

3.2.3 Characterization of Extreme Conditions at U.S. Wind Energy Resource Areas

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. One of the most significant challenges is the characterization of extreme wind and wave loading on the offshore wind turbines and substructures. Models to assess extreme conditions, the resulting extreme loads, and the accuracy of predicting their frequency of occurrence are all subject to these investigations. In the Great Lakes, the extreme ice loads are thought to be defined by the occurrence of the 50-year extreme ice ridge that may exist during seasonal ice floes, but very little data exists to characterize these events which will vary dramatically as a function of lake, distance from shore, and effects from climate change. Additionally, it is not known how earthquakes will impact anchoring capacity in areas like the Pacific that are prone to seismic seabed movement, but investigations into the vulnerability of floating projects due to these conditions are warranted.

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

- Extreme wind/wave combinations and probability assessments at designated Wind Energy Areas,
- Studies to model and quantify extreme ice ridges in the Great Lakes,

- Geospatial assessments of extreme waves to reduce uncertainty in offshore wind turbine design basis,
- Studies for a foundation load design basis for fixed and floating substructures in the Great Lakes,
- Improved models for probabilistic quantification of extended periods of high and low temperatures and wind speeds to inform grid planning in all regions,
- 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,
- Analysis aimed at reducing the uncertainty in the characterization of external conditions of floating wind at potential U.S. sites.

3.2.4 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 supported an upgrade to the existing facility operated by WHOI. Since the core facility, including a fixed met tower, existed prior to this award it was eligible to receive funds from the Consortium. The WHOI metocean reference site may satisfy the regional needs near the Massachusetts Wind Energy Areas. However, since most wind speed conditions at hub height are measured with LIDAR systems that are privately owned, atmospheric scientists do not have access to this data and the industry is unable to acquire resource behavior intelligence in the necessary time frame. Additionally, LIDAR-based measurements, which are now the standard for wind resource assessments, do not accurately characterize other important physical phenomena such as turbulence and atmospheric stability. There may be a critical need to develop other U.S. metocean reference/research sites to serve Wind Energy Areas in the South Atlantic, the Gulf of Mexico, the Pacific, and the Great Lakes. These sites could increase the knowledge base outside the North Atlantic by improving understanding of the regional physical phenomena, enabling more accurate weather models, and validating observations.
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.

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),
- Methods to improve the characterization of critical weather phenomena in the high-fidelity weather models,
- Cost-effective test methods to improve developer observations within lease areas.

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 (WEAs) to support offshore wind development decision-making.

Currently, the assessment methods available to characterize the seabed sediments within the U.S. WEAs are insufficient to inform the necessary geophysical design data or to significantly reduce the effort needed to collect geotechnical seabed design data 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.

As commercial floating wind leasing has now begun, further consideration should also be given to methods for geotechnical and geophysical assessments needed for proper anchor placement under varying water depths and sediment conditions. These methods may differ significantly from oil and gas experience and from shallow fixed-bottom investigations where foundation location may be more precise.

Although extensive site-specific geotechnical data collection is beyond the scope of this Roadmap, a geospatial assessment of sediment 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 prefinance 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 (Fugro, 2022).

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 sediment types by aggregating regional databases and filling gaps,
- Geospatial assessments of sediment types correlated with support structure types,
- Assessments of proposed lease areas and draft Call Areas to help identify challenging geotechnical conditions in advance of lease auctions.

4 PILLAR 3: INSTALLATION, OPERATIONS AND MAINTENANCE, AND SUPPLY CHAIN

4.1 Overview

Research under Pillar 3 aims to reduce the risk to offshore wind by focusing on activities that lower the cost and time of U.S. offshore wind project fabrication, 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. These research activities will improve system reliability and maximize economic benefits through 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 Adapting Installation Strategies for U.S. Constraints

Heavy-lift wind turbine installation vessels (WTIVs) are generally used for all major bottom-fixed offshore wind farm construction activities, including installing wind rotor nacelles and support structure components at the offshore site. For the new 15 MW turbine class, weightlifting requirements are up to 900 tons for the nacelle components, and boom heights need to reach over 160 meters.

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 is 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 WTIVs with the capacity to install 15 MW turbines in time to prevent an industry slowdown. Additionally, to accommodate WTIVs, ports may need to be upgraded (e.g., additional dredging, wider access, and stronger quayside). At the 15 MW scale, there are only a few vessels worldwide that can perform these critical lifts, and there is only one vessel in the United States that is under construction that is capable.[2] If future turbine sizes increase significantly, this potential bottleneck will be exacerbated and could delay or stop deployment.

To avoid bottlenecks while maintaining Jones Act compliance, more creative installation strategies that use alternative vessels and innovative technologies may be needed. Solutions may include hybrid strategies using a combination of foreign flagged heavy-lift vessels and lower cost U.S. flagged barges, new vessel designs, the repurposing of U.S. flagged vessels from other industries, or adaptations of the turbine and support structure technology to avoid dependence on heavy-lift vessels. In general, vessel alternatives must be considered alongside turbine/foundation system design (fixed-bottom and floating).

[2] Construction of the first Jones Act compliant vessel is underway in Brownsville, Texas, to be operational in 2023, based out of Hampton Roads, Virginia. This will help the first few installations, but many more will be needed.

The Great Lakes pose a unique local challenge, as ships that are able to navigate through the locks of the St. Lawrence Seaway are too small to perform the normal operations of ocean-based wind farms. Wind turbine installation in the Great Lakes will require regionally specific solutions that may utilize ships already in the Great Lakes and locally fabricated substructures and components.

Floating wind solutions are mostly unproven for serial production, but this topic area would also address innovations that can be applied to nascent floating assembly areas and vessel strategies. This could reduce cost and facilitate efficient floating offshore wind assembly and on-site installation.

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 hybrid solutions that enable cost-effective regulatory compliant use of foreign flagged heavy-lift vessels,
- Alternative regulatory compliant vessel solutions that improve the efficiency and lower cost of cable installation and maintenance,
- Innovative floating installation vessel concepts that address key issues with platform stability during assembly and tow out, anchor installations, mooring system connect/disconnect, or large component repairs,
- 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 towers, nacelles, and blades without the need for large cranes.

4.3 Operation and Maintenance Innovations

4.3.1 Overview

Over 30 percent of the cost of offshore wind energy can be attributed to O&M and it is imperative that these costs be addressed at the design stage. The subtopics are data driven and aim to drive cost reductions through increased reliability and reduced worker hours at sea.

4.3.2 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 just seven to hundreds in just a few years, system reliability will be a growing challenge. Compared to onshore wind, the cost of component damage/failure or O&M is significantly more expensive to manage offshore because accessibility and logistics that 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 and operate in potentially dangerous conditions, which ultimately would reduce 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 a 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, and 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 with 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 a comprehensive 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.

4.3.3 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 30 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. Many United States offshore Wind Energy Areas have significantly different weather and physical siting conditions than offshore wind farms in Europe. In addition to the surge of development in the Northeast, the icy waters in the Great Lakes region and the deep water of the Pacific and Central Atlantic may necessitate the adaptation of O&M technology for floating wind technology (Dewan, 2017).

One service issue that affects turbine accessibility and availability is the safe transfer of offshore wind technicians during high-sea states. Offshore wind sites in the Pacific Ocean have higher average sea states than other U.S. regions which may increase the cost of repairs, increase machine downtime, and increase construction cost and risk. New solutions to widen construction and O&M weather windows without lowering safety to crew are needed.

Additionally, the first generation of 15 MW turbines that will comprise the U.S. offshore wind fleet will not yet have an established track record for service and performance, and it is likely that many of the maintenance systems for these turbines will be developed and proven in U.S. waters. The implementation of innovative O&M strategies and technologies can contribute significantly to increased power generation, timely maintenance, higher wind turbine reliability, and lower cost.

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 and technology innovations 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, which include airborne drone inspection, blade repair robots, underwater drones, and automation and artificial intelligence,
- Advancements in autonomous technologies for wind data collection, monitoring and diagnosing 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,
- 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 Floating Wind Operations and Maintenance

Floating wind is on the rise globally, but only about 200 MW have been deployed so far. The small fleet of installed floating turbines have generally demonstrated stable, safe operation and excellent performance, but the track record for operations and maintenance is insufficient to quantify reliability or predict maintenance costs. In the nascent fleet, 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 developers using semisubmersible substructures (80 percent of all proposed floating wind farms) plan 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 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 benefit coming from the experience of the existing offshore wind 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 deepwater 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,
- Methods to facilitate the safe and expedient connection and disconnection of moorings and dynamic cables,
- 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 Overview

The development of the supply chain for offshore wind is critical to ensure economic benefits come to the United States, but also to ensure long-term cost reductions are realized. Particular attention is given to floating wind, which is still at a higher cost. Expectations are that accelerated supply chain development would help the industry achieve rapid cost reductions and increase the pace of commercialization and deployment. As lowering cost is a central theme for the Consortium, these solutions should provide pretext for all areas of this Roadmap.

4.4.2 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 U.S. manufacturing and supply capabilities. However, the overall U.S. industrial base is robust and has most of the necessary capabilities to contribute to all aspects of the offshore wind supply chain. One of the primary goals of the Consortium is to fund research that helps ensure that the economic benefits of U.S. offshore wind development are maximized. This topic area is also a high priority for the U.S. Department of Energy, which has launched the FLoating Offshore Wind ReadINess (FLOWIN) Prize (see section 4.4.3).

As the industry begins 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 and investments that favor domestic content. This would include investments to adapt U.S. factories to manufacture major components such as blades, towers, nacelles, cables, and substructures. Infrastructure investments should include U.S. flagged vessels, accelerated upgrades to ports and the electric grid, and enhancements to marine operations capacity. Solutions to this challenge area will support the realization of offshore wind economic benefits for developers, ratepayers, and state governments.

Although the United States has a strong supply chain for the land-based wind industry, the adaptation to offshore wind will require significant retooling and retraining, as the physical size of the land-based components is much smaller than the requirement for 15 MW class offshore wind turbine systems. The wind industry competency, much of which is geographically located in the central United States, needs to expand to coastal areas.

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

- Projects that bring designers and fabricators together to address the need for accelerated domestic production of a specific component,
- Design studies that assess the logistics, tooling, and cost to adapt a prototype design fabrication concept to full-scale serial production,
- Innovations that leverage existing U.S. supply chain manufacturing capabilities to de-risk factory conversions and incentivize larger supply chain investments,
- Design studies that assess the conversion and cost of existing fabrication facilities for specific offshore component serial production.

4.4.3 Industrialization of the Floating Supply Chain

To achieve the $45 per MWh by 2035 cost reduction goals set by the Biden Administration, the current generation of prototype floating substructures must evolve quickly from single-unit production to full-scale serial production as the industry enters the commercial phase. There are significant challenges in upscaling, optimizing, and adapting the current substructure and system designs for serial production. Floating wind substructures enable greater flexibility in supply chain industrialization compared to bottom-fixed systems due to their increased site independence, but the maturity of the supply chain is at a lower readiness level.

This topic area has been identified broadly through the industry as a critical step in the development of floating wind and is at the center of the "Floating Offshore Wind Shot." As part of the Floating Shot initiative, the DOE announced the FLOWIN Prize. This is a three-phase, $6.85-million investment designed to pave the way for cost-effective domestic manufacturing and deployment of commercial-scale floating offshore wind energy technologies in U.S. waters. Projects under this topic would be required to complement the FLOWIN Prize (DOE, 2022a).

The greatest cost-savings that can be realized for floating wind is likely through economies of scale, which can be accelerated through research done under the Consortium. Projects ideally would be coordinated with the development of new port infrastructure and the designers of the next generation of substructures, and then integrated into the system optimization with the wind turbine. The industrialization of the supply chain for floating wind substructures will address the fundamental challenges facing ports to enable tier 1 component manufacturing domestically, ports that can conduct heavy-lift operations and quayside assembly of the turbine and support structure, load-out of fully commissioned systems to site, and large component maintenance of 15 MW scale systems. The number of suitable ports that can accommodate commercial offshore wind will be greatly expanded if, through industrialization, design and logistics can come together to standardize and repurpose existing ports and production facilities. The goal would be to simplify the manufacturing process to provide greater competition and streamlining of subcomponent production to increase throughput (e.g., increases 10x relative current capacity). The emphasis on simplification and standardization of the supply chain is intended, in addition to lowering costs, to ensure that new floating designs increase the use of domestic supply chain options.

Modularization of floating systems can allow the expanded and parallel manufacturing of components in multiple facilities prior to marshaling and deployment from respective marshaling port locations. A diverse and broadly distributed supply chain will lower production risk. The TetraSpar floating platform, for example, has been designed specifically around this manufacturing strategy, consisting of simple standardized modular components that can be transported by road and assembled at a suitable port 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 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 (e.g., lower water draft or overhead clearance limits) 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,
- 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).

4.4.4 Decommissioning, Life Extension, and Infrastructure Repowering

A typical offshore wind project today is designed for a 25-year life, but project design life continues to increase as confidence grows from experience that turbines can operate longer. Extending the life of a project is also an important lever in reducing life cycle costs. Typically, projects will be decommissioned and the parts removed from the ocean and salvaged at the end of their service life. For most projects, some major components like the turbines that are subject to high-load cycles over many years may need replacement, but some of the remaining infrastructure such as the subsea cables, support structures, substations, and land-based grid could potentially have many more years of useful life. Significant cost benefits may be available if developers can repower or repurpose the primary components and infrastructure. Similarly, the wind turbine or its subcomponents may have residual life after its design life is reached or its lease period has expired. Life extensions can be engineered into wind farm systems to enable longer lives (and lower LCOE) with, for example, 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 advance recycling options for large wind turbine blades,
- Studies that repurpose oil and gas infrastructure for hydrogen production and storage.

4.5 Accelerating U.S. Offshore Wind Infrastructure

4.5.1 Overview

This topic addresses the technology solutions to accelerate offshore wind infrastructure to prevent bottlenecks that may arise from inaction or delayed planning. This topic looks at grid, transmission, ports, and workforce development, each of which can delay or disrupt long-term deployment if not addressed as part of the initial phase.

4.5.2 Grid Access, Expansion, and Transmission Upgrades

The Biden Administration has set targets for 30 GW of offshore wind development by 2030. With northeastern U.S. states already making policy commitments for over 40 GW by 2035, this target appears to be achievable, provided infrastructure development including grid upgrades keeps pace (Musial et al., 2022). All regions of the United States have unique challenges in integrating offshore wind to the grid and significant additional technical, economic, and regulatory challenges for transmission. There is great concern that offshore wind deployment could be delayed if the pace of grid infrastructure expansion does not keep pace. 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 near-term U.S. offshore wind projects plan to utilize the most accessible grid points of interconnection to simplify development and lower cost, but it is likely that extensive new transmission upgrades will be unavoidable for longer-term development in the eastern United States. According to the "Building a Better Grid Initiative," published by the DOE in January 2022, high priority areas will be prioritized to enhance transmission planning (DOE, 2022b). 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 offtake alternatives to building new transmission.

4.5.3 Grid Integration and Market Impacts

The growing number of state policy commitments for offshore wind energy that now exceeds 40 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 and future regions where the commercial industry is evolving. 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 independent system operators (ISOs) and regional transmission operators (RTOs) on these grid reliability issues. This information is essential for developers, regulators, and state energy planners to mitigate adverse grid impacts and 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, plant 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 offshore wind into transmission systems,
- Development and deployment of operational forecasting systems for grid operators.

4.5.4 Feasibility Studies and Bases of Design for Port Upgrades

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 all coasts. 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. Ports will need to be built or upgraded to the required specifications for both bottom-fixed arrays 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, the Great Lakes, and the Gulf of Mexico. Feasibility studies must take into account vessel requirements and load-out restrictions. All upgrades must consider the requirements and specifications for deploying 15 MW class offshore wind turbines and 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 to assess the port development requirements in terms of capacity and proximity to Wind Energy Areas for various scenarios on a regional basis. Projects should work with stakeholders and developers to optimize requirements and location selection,
- 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,
- Assessments of ship emissions under various port utilization scenarios and green vessel conversions.

4.5.5 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 offshore wind regions to meet workforce demand. This topic provides an opportunity to develop training centers and create new ways of training technicians (e.g., offshore, electrical, mechanical, and welding) and managers to master the execution and operation of an offshore wind plants 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 at heights, working at sea, and evacuation).

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APPENDIX: LIST OF AWARDED PROJECTS

	Awardee	Project Title	Technical Focus Area
1	National Renewable Energy Laboratory (NREL)	Development of Advanced Methods for Evaluating Grid Stability Impacts	Electrical Power Systems
2	Pacific Northwest National Laboratory (PNNL)	An Offshore Wind Energy Development Strategy to Maximize Electrical System Benefits in Southern Oregon and Northern California	Electrical Power Systems
3	GE Research	DC Collection and Transmission for Offshore Wind Farms	Electrical Power Systems
4	Tufts University	Transmission Expansion Planning Models for Offshore Wind Energy	Electrical Power Systems
5	Offshore Wind Consultants	Shared Landfall and Onshore Cable Infrastructure for Cable Colocation Feasibility Study	Electrical Power Systems
6	ThayerMahan	Transmission and Export Cable Fault Detection and Prevention Using Synthetic Aperture Sonar	Electrical Power Systems
7	University of Michigan	Robust Stabilization of Subsea Power Cables Using Nonlinear Energy Sinks	Electrical Power Systems
8	Clarkson University	Atlantic Seaboard Offshore Stability Risk Evaluation and Service	Electrical Power Systems
9	Rutgers University	AIRU-WRF: AI-Powered Physics-Based Tool for OSW Forecasting and Grid Integration	Electrical Power Systems
10	CODAR Ocean Sensors	Oceanographic HF Radar Data Preservation in Wind Turbine Interference Mitigation	Environmental and Conflicting Use
11	Advisian	Technology Development Priorities for Scientifically Robust and Operationally Compatible Wildlife Monitoring and Adaptive Management	Environmental and Conflicting Use
12	Cornell University	Right Wind: Resolving Protected Species Space-Use Conflicts in Wind Energy Areas	Environmental and Conflicting Use

	Awardee	Project Title	Technical Focus Area
13	Saildrone	Renewable Powered, Uncrewed Mobile Assets to Monitor Protected Marine Mammals	Environmental and Conflicting Use
14	NREL	Co-Design Solutions for U.S. Floating Offshore Wind and Fishing Compatibility	Environmental and Conflicting Use
15	RCAM Technologies	A Low-Cost Modular Concrete Support Structure and Heavy Lift Vessel Alternative	Fixed Structure Engineering
16	ESTEYCO	Self-Installing Concrete Gravity-Base Substructure Sizing for 15 MW Turbine	Fixed Structure Engineering
17	Texas A&M University	Vibratory-Installed Bucket Foundation for Fixed Foundation Offshore Wind Towers	Fixed Structure Engineering
18	Keystone Tower Systems	Tapered Spiral Welding for U.S. Offshore Wind Turbine Towers	Fixed Structure Engineering
19	DEME Offshore US, LLC	Tri-Suction Pile Caisson Foundation Concept	Fixed Structure Engineering
20	Deep Reach Technology	Application of Novel Offshore Oil and Gas Platforms to Large Wind Turbines	Fixed Structure Engineering
21	Stony Brook University	Computational Control Co-Design Approach for Offshore Wind Farm Optimization	Fixed Structure Engineering
22	NREL	Wind Farm Control and Layout Optimization for U.S. Offshore Wind Farms	Fixed Structure Engineering
23	PCCI, Inc.	Quarter Scale Testing of the Intelligent Mooring System for FOWT Platforms	Floating Structure Engineering
24	ESTEYCO	Evolved Spar Concrete Subconstruction for Floating Offshore Wind U.S.-Based Design	Floating Structure Engineering
25	NREL	Shared Mooring Systems for Deepwater Floating Wind Farms	Floating Structure Engineering

	Awardee	Project Title	Technical Focus Area
26	Principle Power, Inc.	Innovative Deepwater Mooring Systems for Floating Wind Farms (DeepFarm)	Floating Structure Engineering
27	Principle Power, Inc.	Demonstration of Shallow-Water Mooring Components for FOWTs (ShallowFloat)	Floating Structure Engineering
28	UMass Amherst	Techno-Economic Mooring Configuration and Design for Floating Offshore Wind	Floating Structure Engineering
29	Virginia Tech	Dual-Functional Tuned Inerter Damper for Enhanced Semi-Sub Offshore Wind Turbine	Floating Structure Engineering
30	Triton Systems, Inc.	Innovative Anchoring System for Floating Offshore Wind	Floating Structure Engineering
31	University of Maine	Design and Certification of Taut-Synthetic Moorings for Floating Wind Turbines	Floating Structure Engineering
32	GE Research	Autonomous Vessel-Based Multi-Sensing System for Inspection and Monitoring	O&M and Safety
33	UMass Lowell	A Novel Structural Health Monitoring System for Offshore Wind Turbine	O&M and Safety
34	Dive Technologies	Fully Autonomous Subsea Asset Inspection by a Shore-Launched AUV	O&M and Safety
35	ULC Robotics	UAS to Transform Offshore Wind	O&M and Safety
36	GE Renewable Energy	Self-Positioning Single Blade Installation Tool	O&M and Safety
37	Tagup Inc.	Survival Modeling for Offshore Wind Prognostics	O&M and Safety
38	GE Research	Enabling Condition Based Maintenance for Offshore Wind	O&M and Safety

	Awardee	Project Title	Technical Focus Area
39	GE Research	Radar Based Wake Optimization of Offshore Wind Farms	O&M and Safety
40	Tufts University	Physics Based Digital Twins for Optimal Asset Management	O&M and Safety
41	GE Renewable Energy	Weld Assembly of Large Castings	Supply and Logistics
42	NREL	Standardized Scalable Mooring Solutions Optimized for the U.S. Supply Chain	Supply and Logistics
43	Electric Power Research Institute (EPRI)	Verifying OSW Turbine Blade Integrity During Manufacture	Supply and Logistics
44	Business Network for Offshore Wind (BNOW) and NREL	30 GW by 2030: Supply Chain Roadmap for Offshore Wind in the U.S.	Supply and Logistics
45	Crowley	Technical Validation of Existing U.S. Flagged Barges as a “Feeder” Solution for the U.S. Offshore Wind Industry	Supply and Logistics
46	Exmar Offshore Company	Feasibility of a Jones Act Compliant WTIV Conversion	Supply and Logistics
47	MARIN USA	Comparative Operability of Floating Feeder Solutions	Supply and Logistics
48	NREL	A Validated National Offshore Wind Resource Dataset with Uncertainty Quantification	Wind Resource and Site Characterization
49	GE Research	Impact of Low-Level Jets on Atlantic Coast Offshore Wind Farm Performance	Wind Resource and Site Characterization
50	Cornell University	Reducing LCOE from Offshore Wind by Multiscale Wake Modeling	Wind Resource and Site Characterization
51	Woods Hole Oceanographic Institution (WHOI)	Development of a Metocean Reference Site near the MA and RI Wind Energy Areas	Wind Resource and Site Characterization
52	Northeastern University	Ensuring Long-Term Availability and Bankability of Offshore Wind Through Hurricane Risk Assessment and Mitigation	Wind Resource and Site Characterization