POWER-US
PARTNERSHIP FOR OFFSHORE WIND ENERGY RESEARCH

Reaching Convergence in United States Offshore Wind Energy Research:

A Multidisciplinary Framework for Innovation

A White Paper by the Massachusetts Research Partnership in Offshore Wind


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Reaching Convergence in United States Offshore Wind Energy Research: A Multidisciplinary Framework for Innovation

Synopsis

This white paper proposes a framework for offshore wind research and innovation in the United States which establishes the relationships, data, systems-level thinking, and strategic research approaches needed to advance the global offshore wind industry. As the nation enters a market that has matured substantially in Europe and is growing quickly in Asia, a well-coordinated, reliably funded approach to research can help secure U.S. stewardship of its natural resources and strengthen U.S. competitiveness in the global market. Successful large-scale research initiatives in infrastructure, ocean science, and manufacturing provide examples for how the nation can mobilize its research community to help set the long-term vision for an affordable and sustainable market in offshore wind.

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1. Introduction

The U.S. has enough offshore wind energy potential to meet its electricity demand several times over (Musial et al., 2016). During the development and writing of this white paper, affordable, commercial-scale offshore wind development has arrived on U.S. shores at costs lower than one could imagine even a few years ago (Massachusetts DOER 2018). As the U.S. retires aging oil, coal, and nuclear electricity-generation plants (ISO New England 2018), Europe works to mature the offshore wind industry (WindEurope 2018), and developers purchase wind energy area leases on the Outer Continental Shelf (BOEM 2018a), states along the East Coast have agreed to purchase enough offshore wind energy to bring this industry to the U.S. As a country, the U.S. faces critical decisions in the coming years regarding the role it wishes to play not only in the development of its own offshore wind energy resource but also in an emerging global market.

This white paper argues that domestic knowledge and innovation are critical to the successful long-term development of the U.S. offshore wind energy resource. It presents a vision for how the U.S. research community can help grow a sustainable domestic industry and a competitive global export market.

As this new heavy industry takes form, the U.S. has an opportunity to create a research framework that can support the development and communication of knowledge relevant to both near-term and long-term decisions and investments. In this white paper, the word “framework” refers to the collective intellectual, social, and physical structures necessary for identifying and meeting complex challenges that require expert engagement from multiple perspectives. A multidisciplinary research framework includes networks of experts from relevant physical, technological and social science disciplines; large-scale testing laboratories; ocean, atmospheric, and environmental monitoring arrays; regional energy markets; structured data repositories; computational platforms; codes and standards; and strong relationships among industry, government, and the research community, with connections to other key stakeholder groups.

Convergence Research

The title of this report refers to “Convergence Research,” which the National Science Foundation (NSF 2018) has identified as a priority for “solving vexing research problems, in particular, complex problems focusing on societal needs.” Integrating offshore wind energy into a transformed, power-electronic converter-based electrical grid for major population centers on U.S. coastlines is a complex challenge with large societal impacts. This white paper discusses the role of research in this endeavor, and recognizes that technical and social challenges are intertwined. According to NSF, Convergence Research has the following characteristics:

- *Research driven by a specific and compelling problem*

Convergence Research is generally inspired by the need to address a specific challenge or opportunity, whether it arises from deep scientific questions or pressing societal needs.

- *Deep integration across disciplines*

As experts from different disciplines pursue common research challenges, their knowledge, theories, methods, data, research communities, and languages become increasingly intermingled or integrated. New frameworks, paradigms, or even disciplines can form sustained interactions across multiple communities.

1. Introduction *(continued)*

The challenge of integrating offshore wind energy and other renewables into a revitalized electrical grid for major population centers on U.S. coastlines is complex and requires systems-level[1] thinking that spans multiple disciplines (see Figure 1). This richly integrated method of establishing goals, characterizing problems, and determining solutions reflects the transition we are now experiencing in our energy system.

The energy industry is vast, and it is not unusual to meet an "expert" in the field who may not have answers to even the simplest questions posed by a layperson. In offshore wind, the expert may be an engineer who understands the design of wind turbine blades, but not the birds that fly past them; a financier who understands the market and supply chain, but not the physical infrastructure required to stage construction; or an atmospheric scientist who understands the boundary layer above the ocean waters, but not the marine life and geology below. The idea of convergence, therefore, is critical, because the important breakthroughs related to integrating offshore wind into the U.S. energy supply on a large scale are most likely to come not from pure scientific insight but from direct dialogue among sectors (public, private, research); regions (Northeast, Mid-Atlantic, Southeast, Gulf, Great Lakes, West Coast); and disciplines (engineering, policy, economics, oceanography, atmospheric science, environmental science, business, construction). Reaching convergence involves committed and sustained efforts to communicate among sectors, regions, and disciplines in order to identify opportunities for innovation and to support decision-making about potentially competing public interests.

Global Offshore Wind by the Numbers (GWEC, 2018):

At the end of 2017: 18.8 GW of offshore wind installed world-wide

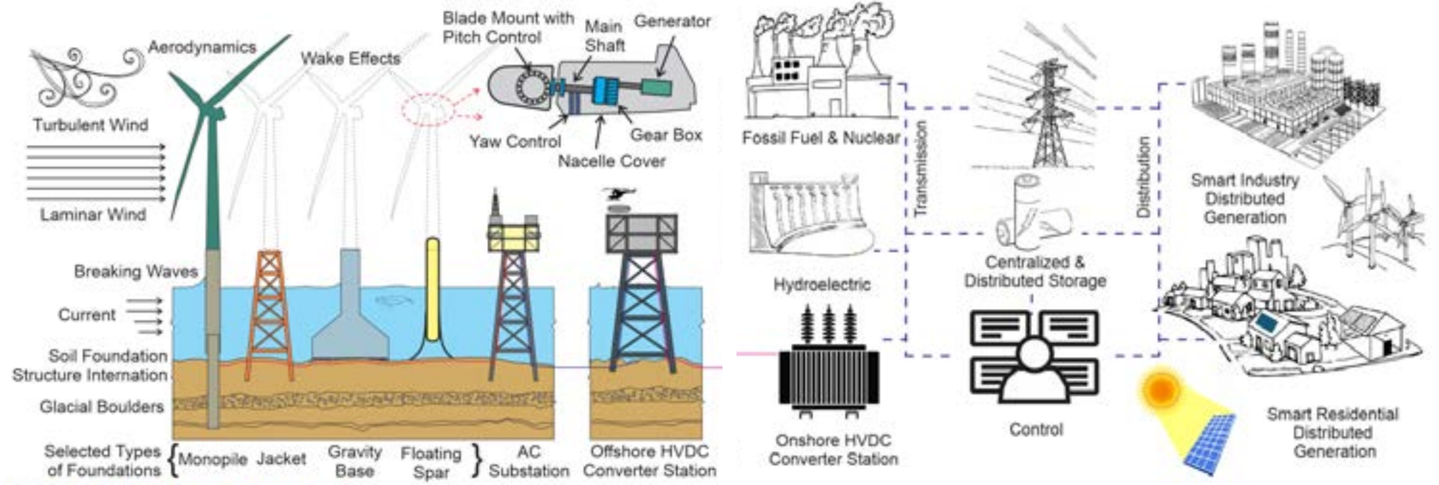
During 2017: 4.3 GW of new offshore wind power installed world-wide

At the end of 2017: 84% of offshore wind was deployed in nine European markets (36%, or 6.8 GW was in the UK). 30 MW was installed in the US.

Price for projects to be completed over the next 5 years will be reduced by ½ compared to those completed 5 years ago.

By the end of 2017, worldwide offshore wind plants were generating 4.5 times more electricity than in 2011.

Figure 1. Flow diagram of offshore wind infrastructure systems.



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[1] In this white paper, "systems-level" implies taking into consideration all elements of a system and how these individual elements interact with each other, the environment, and integral social systems to affect the function of the full system. The system could be an electro-mechanical system "device" such as an offshore wind plant or an organizational structure such as a research consortium. For an offshore wind plant, the system would include multiple wind turbines, towers, support structures, seabed geophysical conditions, ecosystem biology, metocean conditions, power transmission cables and electrical substations, and monitoring and control systems.

The Technology of Offshore Wind Energy — *J. F. Manwell*

Offshore wind energy has experienced remarkable growth over the last two decades, but there is reason to anticipate substantial advancement over the next several decades as well. Some of this advancement will be in the form of evolutionary refinement of existing technology. In other cases, there are some challenges that will require significant effort. In order to provide some context for considering these challenges, we provide a brief summary of offshore wind turbines below.

Offshore wind turbines are conceptually divided into two main subsystems: the rotor/nacelle assembly (RNA) and the support structure (see inset Figure 2). The RNA incorporates the blades, hub, rotating machinery, and most of the ancillary equipment. The support structure includes a tower, a substructure, and a foundation. For floating offshore wind turbines, a floating substructure is used and is held in place by mooring lines and anchors. Fixed bottom turbines are normally located in water depth of less than 60m. Floating offshore turbines are expected to become more widely used in waters of greater than 60m.

In principle, the concept of offshore wind is simple: take existing wind turbines, place them on suitable support structures in the ocean, and connect them electrically via submarine cables to the onshore electrical grid. In reality, the situation is more complicated. First of all, the support structures that are required are substantial in and of themselves—much more so than land-based towers and foundations. Second, the marine infrastructure that is required to install and maintain offshore wind turbines is significant and expensive.

Although much of the experience with land-based wind energy is applicable offshore, there are major differences. These differences may create new difficulties, but they also may provide opportunities. For example, the size of land-based turbines is constrained by transportation logistics. Such limitations do not apply in the ocean.

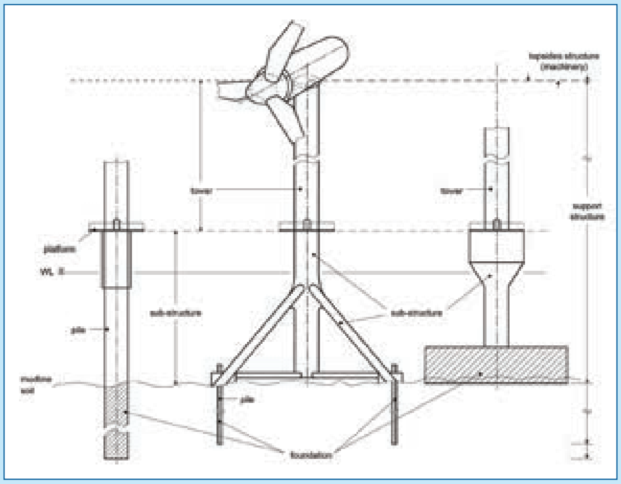


Figure 2. Subsystems and components of an offshore wind turbine. *(image credit: Kimon Argyriadis)*

Conventional wind turbines today typically have three blades, which are positioned upwind of the tower. For offshore applications, the rotor topologies could well be different, and this could result in advantages throughout the structure. Rotor diameters of offshore wind turbines are on the order of 150m, and it is likely that they will eventually exceed 250m. Such large rotors would be extremely heavy, with blade mass exceeding 100 tons. Designing such large rotors will be a challenge.

The spacing between wind turbines in offshore wind plants is nominally on the order of 5-10 rotor diameters. Such spacing is required in order to allow the recovery of wind speed and to minimize adverse effects on the turbines that are in wakes of others. This spacing is also generally preferred by the fishing industry. It is logistically and financially desirable to minimize spacing between turbines, so there is some tension between competing goals.

There is an intrinsic impetus to having large offshore wind plants. Accordingly, the electrical output is large. But it needs to be brought ashore in relatively few high-capacity submarine cables. As more offshore wind plants are built, the siting of multiple cables may become problematic, and the effect on the operation of the grid will become more significant. Appropriate grid management and possibly energy storage will need to be applied.

In addition to the obvious environmental benefit of reduced CO2 production with large offshore wind plants, there also could be a variety of adverse environmental impacts, the most obvious being on fisheries and marine mammals.

Designing support structures for large offshore wind turbines can take advantage of much of the experience of the offshore oil and gas industry, but there are important differences. In contrast to offshore oil and gas, offshore wind turbines will need to be constructed in serial production fashion with relatively many units. Additionally, design standards for offshore turbines and wind plants must evolve to facilitate mass production, while taking into account realistic reliability requirements for both the individual turbines and the overall energy system into which they will be connected.

Context for Offshore Wind Energy in the U.S.

States are the clean energy market-builders in the U.S., and energy policies in individual states depend upon a host of factors, including physical geography and political and economic history. A series of actions in Mid-Atlantic and Northeast states has created a highly visible commercial-scale offshore wind market in the U.S. for the first time (see Figure 3). Following the commissioning of the 30 MW Block Island offshore wind demonstration project in 2016 (see Figure 4) the Long Island Power Authority granted a 90 MW contract to Deepwater Wind. In 2017, the state of Maryland made Offshore Wind Renewable Energy Credit (OREC) awards to two offshore wind developers—Deepwater Wind and U.S. Wind—totaling 368 MW. In May 2018, Massachusetts awarded the largest commercial-scale contract to date for offshore wind energy in the country: an agreement with Vineyard Wind for an 800 MW wind plant, at a total levelized price of 6.5 cents/kilowatt hour in 2017 dollars (Massachusetts DOER 2018). Rhode Island simultaneously entered into contract negotiations with Deepwater Wind for a 400 MW wind plant.

Since Massachusetts made its legislative commitment in 2016 requiring utilities to purchase 1600 MW of offshore wind energy, New York has committed to purchase at least 800 MW through a procurement in the fourth quarter of 2018, with an overall goal of 2400 MW by 2030, and New Jersey has set a target of 3500 MW of offshore wind energy by the same year.

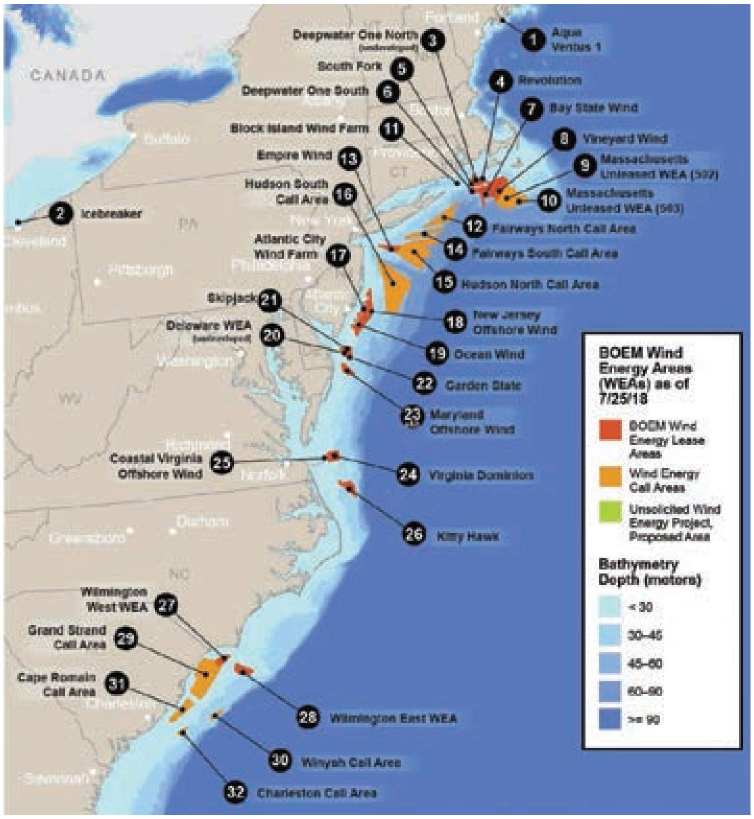


Figure 3: Atlantic Coast demand and resource coincide, projects are at early stage development and complexity requires convergent thinking. *(Image credit: U.S. DOE, Office of Energy Efficiency and Renewable Energy)*

In June 2018, Connecticut entered into contract negotiations with Deepwater Wind for a 200 MW wind plant. On August 9, 2018, Massachusetts enacted an energy bill authorizing the the Massachusetts Department of Energy Resources to mandate the procurement of an additional 1600 MW of offshore wind, which would bring the Massachusetts total capacity to 3200 MW. Radical changes in U.S. offshore wind energy in 2016 were further evident in the $42.5 million price tag for the federal wind energy lease area off the coast of New York. In January 2015, a substantially larger federal wind energy area off the coast of Massachusetts auctioned for less than $300,000. Two parcels in the Massachusetts area that went unleased in the 2015 auction are anticipated to be auctioned by BOEM in late 2018.

The focus on offshore wind at the state level was precipitated by changes in other areas of the energy market as well. For example, in 2017 New England's largest coal-fired power plant, Brayton Point (see Figure 5), retired, representing another milestone in the retirement of 16% of New England's electricity generation capacity by 2021 (ISO New England 2018).

Offshore wind presents an opportunity to create jobs in an industry that consists not only of the original equipment manufacturers (OEMs) who produce the turbines but also component manufacturers, developers, policy makers, financiers, engineers, lawyers, insurers, substructure fabricators, the construction and logistics industries, resource characterization experts, the operations and maintenance industry, electric utilities, cable manufacturers and installers, environmental experts, social scientists, and many other professions and trades that span the entire educational and socio-economic spectrum. The prospect of attracting new advanced manufacturing industries, construction jobs, and revitalizing port facilities to support growing regional supply chains are key motivators driving states' actions to enter the offshore wind market.

On the federal level, the Bureau of Ocean Energy Management (BOEM) has 12 active wind energy area leases in the Atlantic, at least one off every state from Massachusetts to North Carolina, with approximately 17 GW of potential capacity (BOEM 2018a). BOEM and several states have actively engaged in pre-permitting activities within these lease areas, including wildlife surveys and consistent engagement with fishing industry representatives. BOEM has also established formal partnerships with Denmark (2018), the Department of Defense (2012), the U.S. Coast Guard (2011), U.S. Department of Energy (2010), FERC (2009), and the U.S. Fish and Wildlife Service (2001-2014) (BOEM, 2018b). In 2015, DOE released its Wind Vision (USDOE, 2015), discussing the build-out of 86 GW of U.S. offshore wind by 2050.

In 2016, DOE and the Department of the Interior (DOI) jointly released their National Offshore Wind Strategy (USDOE, 2016). This successful partnership between the federal entities responsible for renewable energy leases on the Outer Continental Shelf and for energy technology development represents a significant federal investment in the success of the U.S. offshore wind industry. In December 2017, DOE released a Funding Opportunity Announcement (FOA) for administration of a U.S. Offshore Wind Research and Development (R&D) Consortium (USDOE 2017), which was awarded to the New York State Energy Research and Development Authority (NYSERDA) in June 2018. These actions laid the groundwork for a coordinated approach to public investment in research and development to support innovation and reduce development risk.

Figure 4. The 30 MW Block Island offshore wind demonstration project, developed by Deepwater Wind. *(Image Credit: MassCEC)*

As the first commercial-scale U.S. offshore wind projects advance in the development phase, the cost trajectory in the existing European market demonstrates that investment in R&D and strong market signals make an impact. In 2015, several U.K. publications expressed optimism about achieving Levelized Costs of Energy (LCoE) under £100/MWh (13.3¢/kWh) by 2020, also noting that LCoE is expected to be lower than the strike price. As soon as 2017, the market exceeded these expectations when DONG[2] Energy won the bid for the 1386 MW Hornsea Project 2 with a strike price of £57.5/MWh (7.6¢/kWh), which was 2.7 times lower than the 2014 £155/MWh (20.6¢/kWh) U.K. published strike price for renewables. Also in 2017, Germany awarded the world's first commercial-scale contracts for offshore wind without subsidies[3].

Unlike Europe, where energy policy and electricity markets are shaped at the national level, the success of this new energy industry in the U.S. requires collaboration among individual state initiatives and numerous federal entities. While the offshore wind industry is in its infancy in the U.S., states will continue to compete in the early race for investment and job creation. As the industry matures and confidence in the market builds, however, regional approaches to supporting industry growth will be essential to driving down costs, securing the public interest, and positioning the U.S. to compete in the global market.

[2] In an expression of its commitment to green energy, Danish Oil and Natural Gas (DONG) in 2017 changed its name to Ørsted, referencing the Danish Scientist, Hans Christian Ørsted (1777-1851) who is credited with the discovery of electromagnetism in 1820.

[3] Albeit without taking into account the cost of the electrical transmission system to the mainland, which was financed and constructed separately by the German utility.

Changing Tides

While the U.K. has developed the most offshore wind energy capacity to date, at more than 7 GW, Denmark leads the world in offshore wind energy technology development. Its largest offshore wind developer, Danish Oil and Natural Gas (DONG Energy), divested its upstream oil and gas production and changed its name to Ørsted on October 30, 2017.

> *2017 will be remembered as the year when offshore wind became cheaper than black energy, as demonstrated by the recent tenders for offshore wind in Germany and the U.K. It has never been more clear that it is possible to create a world that runs entirely on green energy. The time is right for us to change our name to demonstrate that we want to help create such a world.*

—Henrik Poulsen, CEO of Ørsted Energy (WindEurope, 2017)

Norway's largest petroleum developer (and the New York wind energy area leaseholder), Statoil, changed its name to Equinor on May 15, 2018.

> *The world is changing, and so is Statoil. The biggest transition our modern-day energy systems have ever seen is underway, and we aim to be at the forefront of this development. Our strategy remains firm. The name Equinor reflects ongoing changes and supports the always safe, high value and low carbon strategy we outlined last year.*

—Erik Reinhardsen, Chairman of the Board of Equinor (Equinor, 2018)

During the development of this white paper, some of the world's largest offshore energy companies, newer market entrants, and their supply chains established business centers in markets that are developing up and down the U.S. East Coast. The challenge now is this: as offshore wind energy development grows, how does the U.S. guide and encourage technical innovation, policies, and regulations that are consistent with the long-term public interest? New research holds the potential not only to help improve wind turbine and wind plant performance, but also to make the generation and transmission systems of our power grid more reliable and resilient, to create better understanding of the ocean and atmospheric environments, to understand and manage impacts on fishing and sensitive species, to guide investment in infrastructure that will sustain U.S. industry for decades to come, and to educate an energy-literate citizenry.

The development of cost-effective, environmentally responsible wind energy on the scale that Europe has experienced over the last 25 years has been built on a foundation of national and international research programs.

Levelized Cost of Energy Compared with Strike Price

—ORE Catapult, 2015

LCoE is the cost to produce electricity over the total lifetime (20-25 years) of the asset based on the expected MWh generated. It includes all costs to construct and to operate the asset but does not take into account:

- The cost of selling the electricity (including fees/risk margins deducted by the power purchase agreement (PPA) offtaker)
- Working capital costs to reflect the timing delay of revenues

The U.K. uses a Contract for Difference (CfD) mechanism to expand the market for offshore wind. Strike Prices are the amount paid to a generator for each MWh of electricity produced over a 15-year CfD term. Strike Prices are intended to produce a certain level of revenue and a reduced level of market risk in order to incentivize investment in offshore wind. After the 15-year term, the generator is reliant on the market electricity price only. Strike prices (over the 15-year term) are therefore expected to be higher than LCoE (over the 20-25 year term) for the following reasons:

- To allow the developer to recover an appropriate level of return over the life of the asset
- To cover the cost of selling the electricity in the market either through a Power Purchase Agreement (PPA) or by managing the electricity price risk
- To cover working capital costs incurred between generating electricity and receiving revenues

For example, the first offshore wind farm at Vindeby (Denmark) (Figure 6) also included three meteorological masts for research projects that were funded by various national programs. Germany funded similar work on the offshore research platforms FINO 1, 2 and 3 (Figure 7). Data from these platforms are made public to encourage participation and develop research directions. Europe has invested enormous resources in baseline investigations of marine ecology before, during, and after wind farm construction.

Figure 5. Brayton Point, New England's largest coal-fired electricity generation plan retired on June 1, 2017. Shown here are the last remnants of the facility's 680,000 ton coal pile in March 2017.

Figure 6. Orsted completed decommissioning of the Vindeby Wind farm in September 2017 after 25 years of service. *(Image Credit: MassCEC)*

European bodies, including the European Commission, have encouraged collaborative research across country borders by sponsoring a range of diverse research in offshore wind energy, such as resources, wakes, environment, access, technology, grid, and public opinion. Among other significant research investments, the U.K. has constructed £250 million in world-class testing and demonstration facilities utilized by the ORE Catapult. ORE Catapult is a leading, independent, cross-disciplined research and development platform serving utility companies, developers, manufacturers, and investors in new energy technologies. ORE Catapult encompasses a range of research, testing, and development capabilities such as wind turbine blade testing up to 100m (dual axis testing and blade erosion); drive train component and system testing on 1MW, 3MW, and 15MW test rigs; a 7MW demonstration turbine; and electrical infrastructure and materials research in ASTA-accredited laboratories. These investments have been credited with helping to reduce uncertainty and improve understanding and efficiency of large offshore wind plants, effectively cutting costs in half within 5-10 years.

The Massachusetts Research Partnership in Offshore Wind and the POWER-US Convening Initiative

Recognizing that strong relationships are the basis from which a multidisciplinary framework for offshore wind research can grow, several Massachusetts research institutions with complementary expertise worked with the Massachusetts Clean Energy Center (MassCEC) to form the Massachusetts Research Partnership in Offshore Wind (MRP) in the summer of 2016. Two factors that led to the creation of the MRP are the presence of important offshore wind research assets in Massachusetts—such as the Wind Technology Testing Center (Figure 8) (MassCEC 2018a, Hines and Ravindra, 2011)—and the timing of Massachusetts' emerging commercial-scale offshore wind market.

The MRP consists of seven Massachusetts research institutions: Northeastern University; Tufts University; the University of Massachusetts Amherst, Boston, Dartmouth, and Lowell; and the Woods Hole Oceanographic Institution. MassCEC provided funding to the MRP to consider and articulate the role of the research sector in achieving state and national clean energy goals, and to develop a *multidisciplinary framework for offshore wind energy reserach and innovation.*

In order to develop this vision for a multidisciplinary framework, the MRP engaged in discussions with colleagues throughout the United States, Europe, and Asia. The basis for this white paper is international experience with the offshore wind industry—including direct engagement in over a decade of pre-development activity in this country—U.S. experience in land-based wind, oil, and gas; civil infrastructure; ocean and atmospheric science; and fisheries, policy, and economics. Over the past two years, these discussions developed into the convening initiative known as the Partnership for Offshore Wind Energy Research (POWER-US), whose participants contributed to the development of this document.

Since March 2016, the MRP has convened nine international workshops:

- March 2016: The University of Massachusetts Lowell, Tufts University, NSF, and MassCEC hosted a conference in Lowell, MA, that resulted in the 2018 white paper: "Wind Energy Research: State-of-the-Art and Future Research Directions," (Willis et al. 2018).
- September 2016: Woods Hole Oceanographic Institution hosted a workshop on ocean, atmospheric, biologic, and geologic site characterization that resulted in the Ocean Test Bed concept.
- September 2016: Tufts University hosted an Interagency Workshop in Washington, D.C., including participation from BOEM, the Business Network for Offshore Wind (BNOW), DOE, Fraunhofer Institute for Wind Energy Systems (IWES), the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), NSF, and ORE Catapult.
- December 2016: The University of Massachusetts Amherst hosted a workshop with guest speakers from the National Renewable Energy Laboratory (NREL), ORE Catapult, Fraunhofer-IWES, and participants from more than 10 states. This workshop resulted in the convening of POWER-US.
- March 2017: The University of Massachusetts Lowell hosted a workshop that resulted in the POWER-US brand, website, and May 2017 Massachusetts legislative briefing.
- June 2017: Tufts University hosted a workshop that focused on discussions integrating technology and policy considerations.
- September 2017: The University of Massachusetts Dartmouth hosted a workshop on ocean science and fisheries that among academia, industry, and government targeting key aspects of stakeholder engagement.

Figure 7. Fino 1 platform. *(image credit: Gerrit Wolken-Möhlmann)*

Figure 8. MassCEC's Wind Technology Testing Center (WTTC). *(image credit: Chuck Choi 2011)*

- October 2017: National Renewable Energy Laboratory (with the MRP) hosted a workshop in Boulder, CO, that engaged participants from every major U.S. region and several international organizations.
- December 2017: Northeastern University hosted a workshop to review and discuss the first draft of this white paper

Also in December 2017, DOE issued Funding Opportunity Announcement (FOA) 0001767, soliciting proposals to administer a National Offshore Wind Research and Development Consortium. In March 2018, MassCEC and POWER-US jointly submitted a proposal in response to this FOA. The MassCEC/POWER-US team included an initial membership base of offshore wind industry leaders, states providing matching funds, top European research centers, and membership commitments by 30 public and private U.S. research institutions from 14 states, including two national laboratories.

The winter 2018 Consortium proposal development process provided a unique opportunity for POWER-US to successfully prototype the mechanics of convening multiple states, private entities, and research institutions with multidisciplinary expertise around specific challenges in offshore wind.

Lessons from this prototyping experience and the outcomes of the workshops described above inform the research themes and recommendations presented in this white paper.

A Framework for Innovation, Strategic Research Themes and Next Steps

The following sections of this white paper introduce the concept of a research framework for offshore wind, strategic research themes, and next steps. These strategic themes and next steps are particular to the U.S. and can be understood as complementary to the research visions expressed by the European Wind Energy Academy, the Danish Research Consortium for Wind Energy, the U.K.'s Offshore Science and Innovation Audit, and ORE Catapult's (U.K.) Innovation Roadmaps (van Kuik et al. 2016, DFFV 2015, SIA 2017, ORE Catapult 2018a). The U.S. has considerable research assets that can be brought to bear on the offshore wind energy industry. In convening POWER-US, the U.S. academic sector has come together with key national laboratories, industry leaders, and experienced international partners in offshore wind research and development to consider an integrated approach for U.S offshore wind research. This network continues to engage in dialogue with multiple federal entities whose missions relate to science, engineering, energy, and the ocean and atmospheric environments.

Section 2 of this paper introduces the concept of a multidisciplinary framework for offshore wind energy innovation informed by large-scale U.S. research initiatives in infrastructure, ocean science, and manufacturing over the past two decades. Together, these initiatives represent more than $2 billion of research investment. Individually, each initiative is an effort by the U.S. to convene its top research assets and expertise in a given field for the purpose of setting investment strategies to achieve world-class research capabilities. Section 2 discusses the POWER-US convening initiative as a prototype for such a network, and it concludes by describing essential elements of an effective research framework.

Section 3 introduces five strategic research themes that have emerged in response to a wide range of experience in offshore wind energy over the past 25 years:

- Advancing near-term deployment and investing in long-term innovation
- Moving state-of-the-art to state-of-the-practice for resource characterization
- Planning long-term for ports, supply chain, and transmission
- Establishing a data-driven engineering paradigm for resilient infrastructure systems
- Pursuing the public interest and adapting to U.S. conditions

To develop a sustainable offshore wind industry, it will be necessary to support each of these themes and to cultivate a network of collaborators who can advance their integration.

Section 4 offers conclusions and suggests initial actions to build the network and move towards development of a shared framework for research and innovation.

Context for Research in Offshore Wind Energy: The Energy Transition

— J. F. Manwell

The Intergovernmental Panel on Climate Change has recommended that to avoid excessive adverse effects from climate change the overall global temperature rise should be limited to 2°C above pre-industrial levels (IPCC 2014). To accomplish this will require a nearly complete transition in the world's energy supply from fossil fuels to renewables. Technological advances over the past 50 years have made it apparent that such a transition is possible, although there is still much to do to make that transition a reality in a manner that is both timely and not excessively disruptive. The broad outlines of the transition are clear and have been succinctly laid out in a recent series of reports by the internationally accredited registrar and classification society DNV GL (DNV GL, 2017).

The world's total annual energy consumption is expected to level off over the next three decades and a broad transition is expected from solid and liquid fossil fuels to electricity derived from renewable energy sources, particularly solar photovoltaics and wind energy. It is projected that electricity as a fraction of the world's energy consumption will rise from 18% now to 40% in 2050. Moreover, 86% of that electricity will be generated from renewable resources, nearly all of which will come from wind energy (on land and offshore), solar photovoltaics, and hydropower. The manner of distributing and utilizing that energy will change as well: there will be extensive conversion of both transportation and heating to electricity. Generators and power converters of a wide range of sizes will be distributed throughout the electrical network, along with sensors, artificial intelligence devices, actuators, and energy-storage and load-management systems.

The DNV GL report summarizes the top-ten enablers for this transition:

- Continuing the growth of offshore wind
- Data analysis to optimize performance of wind, solar, grids, and their use
- Cyber security and investments to secure a robust electricity supply
- Flexibility, balancing, and cost-effective integration solutions
- Grids to facilitate growth of wind and solar
- Electrical vehicles
- Decarbonization of heat
- Strategic energy management
- Availability of subsidies
- Public acceptance

It is significant that offshore wind is the top enabler. Offshore wind energy has only emerged as a major contender in the world's energy supply in the last 25 years, but the potential resource area is enormous, and it will continue to grow as the technology to utilize deeper waters develops. It is anticipated that offshore wind will already contribute a third of wind energy's total by 2050. At a recent session of an International Energy Agency (IEA) advisory group, Technical Expert Meeting 89, it was decided to draft a "grand vision" for wind energy, much of which is focused on or directly relevant to offshore wind energy. Key focus areas include manufacturing and industrialization, design of very large turbines, atmospheric science and forecasting, plant control and operations, grid integration (including power electronic converters and energy storage), market design and geographic diversity in deployment, and fuel-production (based on electrolysis of water to hydrogen).

Within the field of offshore wind energy in particular, important topics to consider include opportunities for floating offshore wind turbines; industrialization of manufacturing and deployment comparable to that of shipbuilding during World War II; integrated systems-level, reliability based offshore wind plant design; and up-front consideration of social and environmental factors, including fisheries and other uses of the oceans.

The evolving renewables-based electrification of the world's energy supply is presently a focus of another IEA group, Task 25. According to the vision being developed, the electrical grid of the future will contain very few conventional thermal power plants. Consistent with the DNV GL report, Task 25 also expects that the primary source of electricity will be wind and solar photovoltaics, with some contribution from other renewable sources such as marine hydrokinetic devices.

With little synchronous rotating machinery in the system, frequency, voltage, and power quality in general will be maintained by power electronic converters. The matching of energy supply and demand will be mediated through a range of measures, including energy storage of various time scales, use of electricity for heating as well as cooling, and production of fuels such as hydrogen, ammonia, and synthetics. The transmission system itself with be modernized, taking increased advantage of high voltage direct current (HVDC) and high temperature superconductors. Increasingly, transmission lines will be installed underground and designed to facilitate distributed generation of a variety of scales and types. Closely connected to all these technical changes is the need to consider market design and coordination as well as the regulatory and institutional context in which these changes will take place. A detailed report summarizing the results of this assessment is expected later in 2018.

All these anticipated developments in the electrical system are, of course, relevant to more types of generators than offshore wind turbines, but the scale of offshore wind is particularly significant.

Education for an Offshore Wind Energy Industry — *J. F. Manwell*

As the offshore wind energy industry grows, so too must the work force. People at all levels will be required—tradespersons, field technicians, professionals, and university-trained researchers with advanced degrees. The offshore wind energy industry is similar in many ways to the land-based wind industry, but it has some significant differences. Given the scale of the undertaking, it is clear that the offshore wind industry will require a significant workforce of its own.

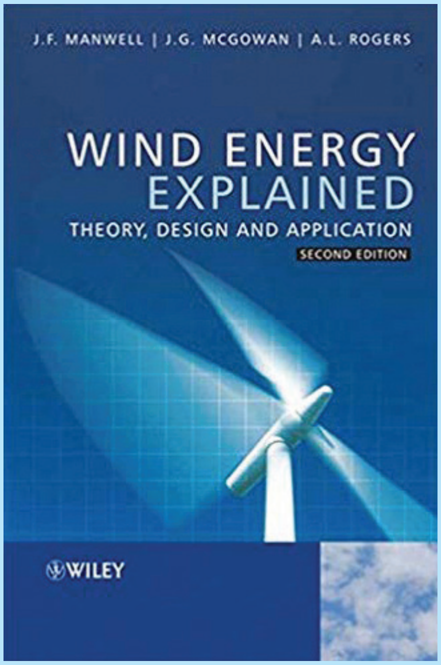
As summarized in a forthcoming white paper on graduate and undergraduate university programs in wind energy in the U.S. (Swift et al. 2019), it is estimated that the U.S. wind energy industry will need approximately 340,000 on-site and supply-chain jobs by 2050, including 85,000 jobs requiring a graduate-level education. Based on projections, the offshore wind energy sector will need at least a third of those jobs. To reach such numbers, there needs to be a substantial increase in the number, size, and capability of advanced-degree educational programs in the U.S.

Swift provides this summary:

"The workforce needs of the offshore wind energy sector are similar, but of a broader scope than the land-based wind energy sector. A wide variety of people with advanced skills is needed to help improve the technology, reduce its costs, and increase reliability, thus allowing ever-larger turbines to be placed cost effectively in progressively deeper water. In addition—and similar to the offshore oil and gas industry—technicians with many different types of skills will be needed to construct and maintain offshore projects. Most technicians will need practical knowledge of electricity, mechanics, and hydraulics, as well as an understanding of the basic principles of wind turbines. In addition, technicians will need courses in working at height and training in environmental health and safety. Furthermore, technicians will need more advanced training in their own areas of expertise. Typical examples include: operation of supply vessels, underwater welding, and support structure fabrication. As offshore wind energy technology evolves, there will be continual need to keep technician training up to date and to take field experience of

technicians into account in the design process."

As described in Manwell et al. (2015), the number of post-secondary institutions offering educational programs is presently limited. At the time of writing, there are 45 universities or colleges with courses in wind energy. Among those with undergraduate offerings, 22 had one undergraduate wind-related course, and eight had more than one. At the graduate level, 10 of the 17 offered only one wind-related graduate course, while seven offered more than one. Five of the wind energy courses were available on-line (three undergraduate and two graduate). Of the institutions with graduate programs, six offered a graduate certificate in wind energy.



Conversely, in Europe there is a range of educational programs supporting the expansion of the wind energy industry, including offshore. These include the European Academy of Wind Energy (EAWE) and the U.K. Industrial Doctoral Center for Offshore Renewable Energy (IDCORE) (PhD level); the Danish Technical University, with more than 200 faculty, staff, and PhD students devoted specifically to wind energy; the European Wind Energy Master program (MSc level); and the U.K.-based National Vocational Competencies program (technician level). The aforementioned study recommended educational initiatives that cover wind energy-related topics including business, policy, engineering, and environmental impacts, with a focus on professional education for both undergraduate and graduate students.

Here in the U.S., one promising development has been the creation of the North American Wind Energy Academy (NAWEA). Inspired by the example of the European Academy of Wind Energy, "NAWEA is composed of universities, research laboratories, and industry participants dedicated to coordinating wind energy research and education activities in order to advance the state of wind energy technology and to develop the next generation of wind energy engineers, researchers, scientists, and innovators" (NAWEA, 2018). NAWEA presently sponsors biannual conferences and maintains an education committee whose goal is to create coordinated and expanded university-level educational and research opportunities throughout the U.S. There is clearly a great potential for integrating NAWEA with the requirements of the offshore wind energy industry.

2. Multidisciplinary Framework for Offshore Wind Energy Research in the United States

According to the nine international workshops referenced in Section 1 and conversations with a wide range of European colleagues—cumulative European offshore wind research and development expenditures have exceeded $2 billion dollars to date. Through these investments in research—totaling approximately 3% of total European investment in offshore wind between 2010 and 2017 (Wind Europe 2018)—Europe has created a space for partnership among industry, governments, and the research community in which technology has advanced, infrastructure has improved, markets have become more competitive, and the cost of financing has been reduced in response to lower project investment risk.

From the European experience, it is clear that both public investment in research and strong connections between the research community and industry have helped advance offshore wind to its current state. It is also clear that the industry would have benefitted from earlier, more coordinated approaches to data, large-scale testing, modeling, and standards. The message, loud and clear over the past three years, has been that the U.S. has a unique opportunity to start fresh and do this right. While European investment and know-how may be sufficient to help launch the U.S. offshore wind industry, Europe will not ensure that we create jobs, set our own course toward energy innovation and security, establish a functioning and resilient infrastructure, and compete in the global market. In order to achieve these things, the U.S. must continue to make investments of its own.

Informed by the successes, challenges, and opportunities foreseen globally, the following vision for a U.S. offshore wind energy research framework is rooted in experience with large-scale U.S. scientific and engineering research initiatives over the past two decades. The offshore wind industry requires expertise in infrastructure, the ocean, and manufacturing. Coming together from backgrounds in each of these areas, the U.S. offshore wind research community brings experience from three major NSF and DOE initiatives that are relevant to a U.S. framework for offshore wind research:

- NSF's Network for Earthquake Engineering Simulation (NEES)
- NSF's Ocean Observatories Initiative (OOI)
- DOE's Institute for Advanced Composites Manufacturing Innovation (IACMI)

These initiatives share several common features: their temporal and geographic scales, the magnitude of their funding, and their sense of mission in bringing together a diverse research community to address complex, systems-level problems. Each of these initiatives has its own character, history, and mission, while providing unique insights into a vision for U.S. offshore wind research. Yes, the U.S. is joining the offshore wind industry 25 years into its development. But these initiatives represent the kind of world-class assets and experience that the U.S. can bring to the table in this emerging global market. This research experience, combined with intimate knowledge of and partnership with the U.S. offshore wind industry, has served as the motivating spirit behind the POWER-US convening initiative.

A National Network of Research Facilities and Expertise: The Network for Earthquake Engineering Simulation (NEES)

With funding through the National Science Foundation's (NSF) Major Research Equipment and Facilities Construction (MREFC) program, a 14-year $400 million research program was established in 1999 that included the design, construction, and enhancement of the 15 complimentary national testing laboratories shown in Figure 9 (EERI 1995, SRI 2001, NRC 2003, NRC 2011); a cyber-infrastructure for data archiving, visualization, and analysis (Hacker et al. 2011); a common open-access modeling platform (McKenna 2011); and a portfolio of research projects including large multi-institutional team science initiatives. This entity was the Network for Earthquake Engineering Simulation (NEES), which became operational in 2004 and developed into the world's leading systems-level approach to earthquake engineering research.

An International Network of Data Collection for Ocean Science: The Ocean Observatories Initiative (OOI)

The $1.4 billion Ocean Observatories Initiative (OOI 2018) was funded through NSF's MREFC program in 2009 to "dramatically alter ocean science by providing the means to collect unique, sustained, time-series data sets that will enable researchers to study complex, interlinked physical, chemical, biological, and geological processes operating throughout the global ocean." OOI is similar to NEES in its community-driven character, its establishment of standards for data and metadata, its attention to the state-of-the-art in data collection, and its committed relevance to stakeholder interests and social relevance (NSTC 2007, NSF 2009).

Using a combination of capital expenditures, commitment to maintenance, and research expenditures distributed through competitive solicitations, the OOI hosts the world's most advanced ocean observation networks (Figure 10) and provides measurements critical for interdisciplinary research on ocean, climate, and ecosystem behaviors that are relevant to pressing social issues.

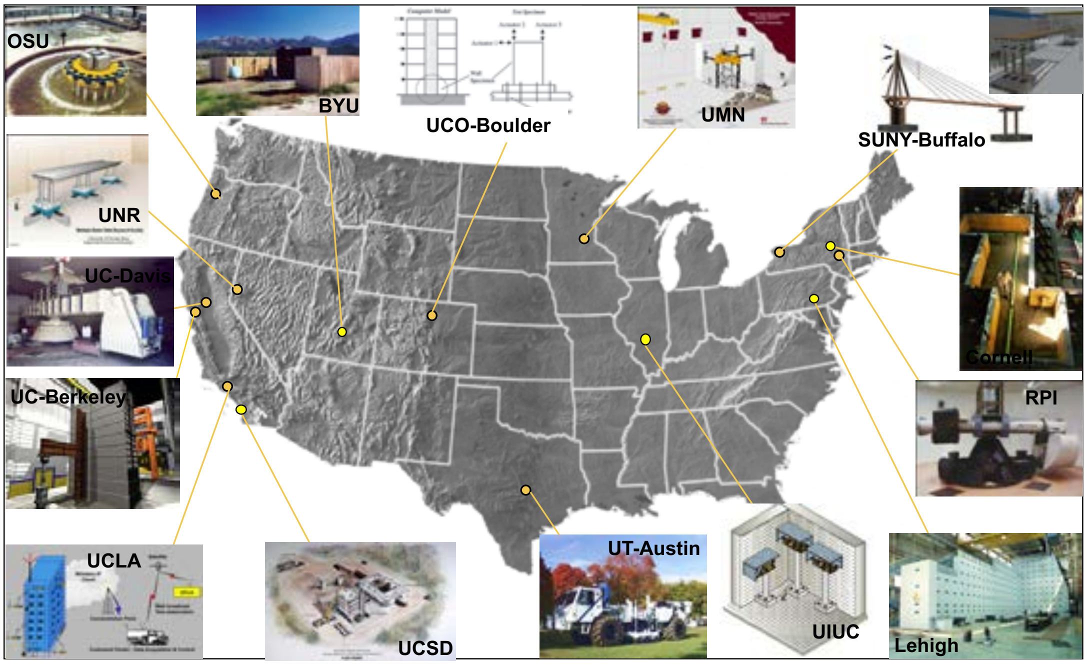


Figure 9: The National Science Foundation's NEES Network of Earthquake Engineering Laboratories and Cyberinfrastructure. *(image credit: NSF)*

A Collaborative Approach to Manufacturing Innovation: The Institute for Advanced Composites Manufacturing Innovation (IACMI)

Sponsored by the U.S. Department of Energy (DOE), IACMI is part of the National Network for Manufacturing Innovation (NNMI), which hosts several institutes supported by the Departments of Energy, Defense, and Commerce together with NASA, NSF, and the National Institute of Standards and Technology (NIST) (IACMI, 2018). IACMI shares several of the collaborative and networked characteristics of NEES and OOI, but its direct focus on manufacturing innovation and economic development give it a different character than the more scientifically oriented NSF initiatives.

Chief among these unique characteristics of IACMI and the other NNMI institutes are the relationships between public entities at the federal and state level (Figure 11), formal ties to industry and accompanying intellectual property agreements, and the importance of matching funds from participating state and industry partners. IACMI is an independent, membership-based 501(c)(3), which is funded with $70M of federal money from the DOE and $189M from other sources, such as state and industry members. The multiplication of federal funds by a factor of 2.7 speaks to the interest and commitment at the state level and within U.S. industry to work together to solve problems at scales that are too large to address independently.

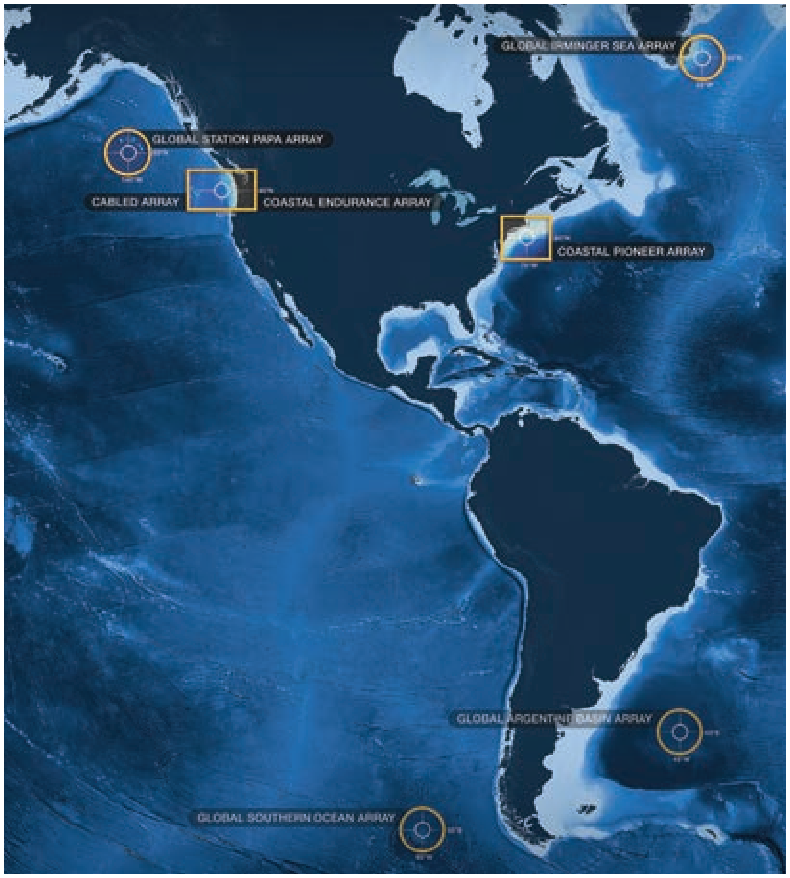
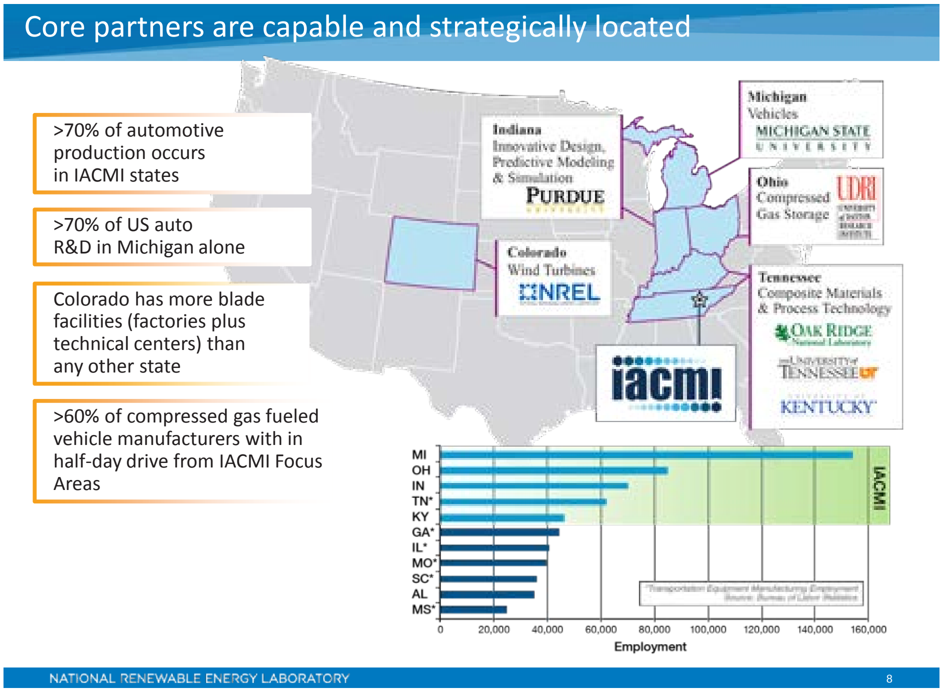


Figure 10: National Science Foundation's Oceans Observatories Initiative. *(image credit: NSF)*


Core partners are capable and strategically located

>70% of automotive production occurs in IACMI states

>70% of US auto R&D in Michigan alone

Colorado has more blade facilities (factories plus technical centers) than any other state

>60% of compressed gas fueled vehicle manufacturers with in half-day drive from IACMI Focus Areas

Figure 11: The IACMI Network of Charter Member States. *(image credit: IACMI)*

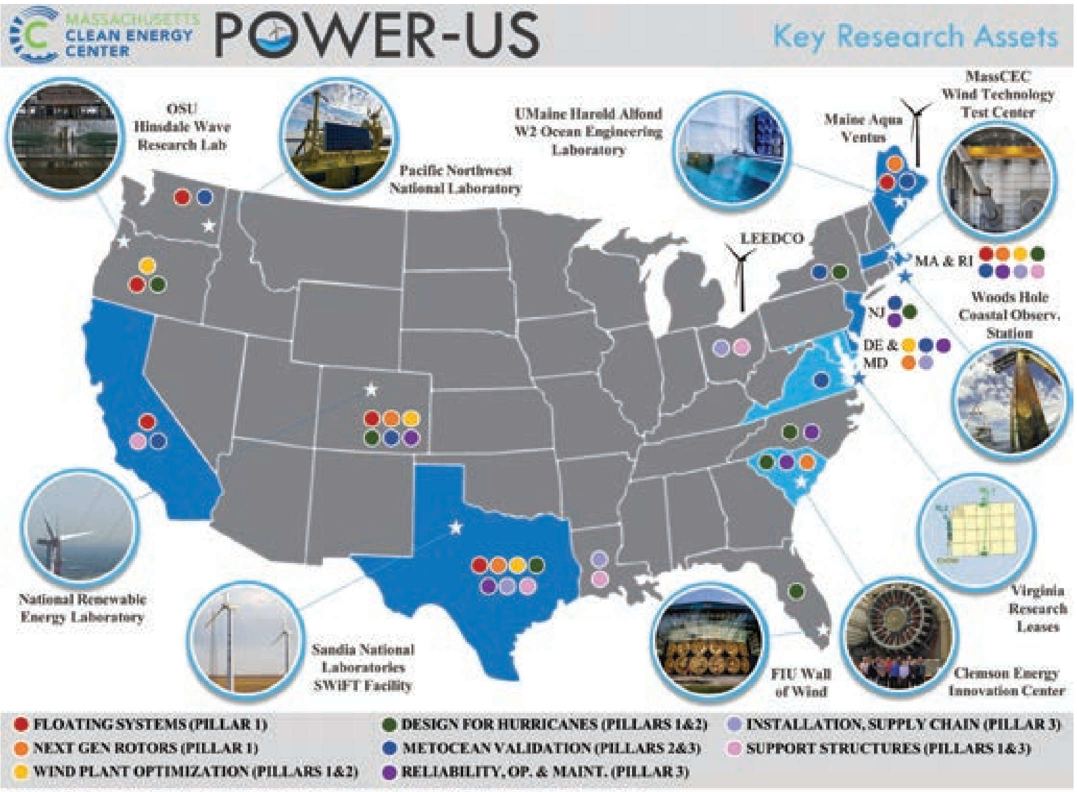
A Model for Offshore Wind Research Collaboration

Offshore wind energy is similar to earthquake engineering in its interdisciplinary nature, complexity, scale, reliance on large-scale testing, and need for sophisticated numerical modeling for design and for assessments of risk and reliability. It is similar to ocean and atmospheric science in the need for multi-disciplinary data sets formatted according to consistent standards for data and metadata. It is similar to composites manufacturing in its relevance to economic growth at the state and national levels, partnerships with industry, and the need to handle intellectual property with sophistication and sensitivity.

These features—coupled with hundreds of millions of dollars of existing U.S. federal research assets related to large-scale testing, ocean/atmospheric/environmental science, computational capacity, design expertise, policy and economics, and environmental advocacy—can create a similar network for advancing the development and operation of offshore wind energy systems not only in the U.S. but globally.

Figure 12 illustrates how a U.S. network of existing offshore wind research assets and expertise might appear. This figure was prepared in March 2018 as part of the MassCEC/POWER-US bid to administer the DOE Offshore Wind Research and Development Consortium. This initial network was conceived in response to a specific technology-focused, membership-based research funding opportunity, similar to DOE's IACMI Consortium.

Considering the scope of the opportunity for the U.S. to develop not only its own offshore wind resource but to contribute significantly to the global offshore wind market, a multidisciplinary framework for offshore wind energy research ought to include a wide array of federal entities such as: the DOE and its national laboratories, the DOI's Bureau of Ocean Energy Management (BOEM) and U.S. Geological Survey (USGS), the Department of Commerce's (DOC) National Oceanic and Atmospheric Administration (NOAA), the Department of Transportation's (DOT) Maritime Administration (MARAD), the NSF, the National Aeronautics and Space Administration (NASA), the Framework for Innovation in Offshore Wind Energy, the Office of Naval Research, the U.S. Army Corps of Engineers, and the U.S. Coast Guard.



*States colored in dark blue are prospective Charter Members. Discussions are ongoing with states colored in light blue.

Figure 12: POWER-US state-level engagement, technical expertise, and research assets.

Under joint sponsorship of such entities, the network imagined in Figure 12 could involve:

- Cultivating long-term relationships between industry and the research community for the purpose of developing trust and connecting research to reality
- Establishing connections among market-driving states, federal entities, and researchers that strengthen the basis for decision making and policy
- Convening research expertise from relevant disciplines and institutions to develop multidisciplinary approaches to problem solving
- Connecting together existing research assets with a cyberinfrastructure similar to the NEES network
- Including additional focus areas such as fisheries, geotechnical and geophysical site characterization, air and ocean environmental monitoring of affected species, systems-level reliability and resiliency, transmission and infrastructure, and policy, economics, and social sciences
- Adding ocean test beds, substructure and foundations testing facilities, and in-situ monitoring of U.S. offshore wind plants
- Supporting public/private/academic partnerships to develop and implement regional plans for transmission, infrastructure, and supply chain
- Providing a reliable long-term funding stream to support multidisciplinary research efforts that are more complex and far reaching than individual private sector entities are willing to pursue on their own

Coordinating existing U.S. research assets within a clearly defined multidisciplinary framework for offshore wind energy research would allow for both the identification of gaps in existing U.S. research capacity and for clear points of connection to international entities that may provide complementary assets and expertise.

What Does the U.S. Bring to the Offshore Wind Party? A View from Across the Pond

—*S. Wyatt, Offshore Renewable Energy (ORE) Catapult.*

With more than 15 GW already installed in Europe, you could be forgiven for thinking that the U.S. is a latecomer to the offshore wind party. But with ambitions for 30 GW by 2030 in the U.K. alone—and a global estimated potential of up to 350 GW—things are only just getting started, and the U.S. has a lot to offer this emerging sector.

As the U.K.'s innovation center of offshore wind (Figure 13), we see huge strength in collaborating with our colleagues in U.S. national labs and academia. And as our sector moves to larger turbines, there is still much to learn with regard to the reliability of the offshore plant. Shared research programs will help accelerate knowledge and further our collective understanding of longer-term performance in the field. Leading U.S. universities have many years of world-class research in areas such as structural analysis, composite design, and wind resource modeling. National labs such as NREL's wind technology center have a huge track record in wind energy and have been leading projects on the global stage for more than 40 years. Here at ORE Catapult, some of the testing protocols for our 100m blade tests have their roots in NREL research, and we expect to further progress representative testing through similar collaborations.

With 16% of the world's onshore wind, the U.S. has been a leader in wind deployment. The hard-won lessons learned from onshore service models and the related approaches to data management and inspection regimes also will be highly relevant offshore. The operations and maintenance space is an area for which the industry knows it needs to raise its game. The U.S. can bring its world-class expertise in AI and digital technologies, as well as defense and autonomous systems, to bear on this area. U.S. wind plants could be operating more effectively sooner than their European counterparts, and we may well be looking over the Atlantic to the U.S. for examples of best practice in the future.

Figure 13. ORE Catapult's Levenmouth turbine

Much has been learned in Europe, and there is still more to learn with regard to using our rapidly growing industry as a means of economic development. Even at these early stages, it is clear that offshore wind in the U.S. must tick the dual boxes of clean, secure energy and economic growth if it is to gain support from key stakeholders. It is likely that U.S. coastal states will invest in port infrastructure and manufacturing capability, and perhaps we'll see bespoke designs for foundations and towers which are well suited to U.S. manufacture. There are win-win opportunities for U.S. companies to partner with U.K. companies in tackling market opportunity more effectively than they could on their own. In return, U.S. companies may bring new ideas, new efficiencies of scale, and new balance sheets to U.K. and European operations.

For organizations such as ORE Catapult, collaboration with the U.S. is an exciting opportunity, and sharing the cost and risk of developing this sector will enable both sides of the Atlantic to process faster and more efficiently than we have been able to previously. By collaborating in the research, testing, demonstration, and certification spaces, the U.S. and the U.K. stand to gain handsomely from the reduced insurance premiums and cost of capital that go with an industry that constantly seeks to "de-risk" itself. There will be significant opportunities to conduct parallel testing in U.S. and U.K. facilities that generate high-quality data and, by doing so, gain insights into asset performance in a faster, more efficient, and more detailed manner. Given that much of the EU Offshore Wind sector is underwritten and financed from London, it is in the U.S. offshore wind sector's interests to get as close as possible to this quite unique environment. A strong U.S./U.K. relationship greatly facilitates this.

Welcome to the offshore wind party, United States of America! We are excited to have you on board!

Elements of a Multidisciplinary Framework for Offshore Wind Energy Research in the U.S.

Key functional elements of NEES, OOI, IACMI, and entities such as U.S. National Laboratories, ORE Catapult in the U.K., Fraunhofer-IWES in Germany, and DTU in Denmark constitute the basis for a potential U.S. framework for offshore wind research. These elements include:

Integrated Community

Perhaps the most important contribution of the NEES program was to bring together researchers and stakeholders from diverse disciplines, private industry, and the public sector to form an integrated community of seismologists, geotechnical engineers, and structural engineers representing the standards community, state departments of transportation, insurers, model developers, and experimentalists. Convening the earthquake engineering community in this *integrated way* helped each group understand the many factors affecting the seismic performance of the built environment and the role of their expertise within a systems-level model for seismic resiliency. The breadth of disciplines and stakeholders in offshore wind is greater than those in the field of earthquake engineering, with an even greater need to build an integrated community.

Industry Relevance

Sustained conversation between industry and the research community requires clear communication and trust. The research community must respect the value of industry's direct experience within the context of specific projects and understanding of market realities, and industry must see value in providing researchers with access to project challenges and data for the purposes of developing effective studies. Reliable, sustained public funding for research that recognizes the importance of developing relationships over the course of years is a small investment compared to the long-term benefits of ensuring that research is relevant. These circumstances reflect the uniqueness of an industry that is just getting underway in the U.S. Now is the time to invest in building relationships so that they are well developed by the time the U.S. offshore wind industry begins to mature.

The U.S. offshore wind industry, however, is not generating the kind of revenue that can sustain the large-scale, collaborative, private investments that have become more common in the U.K. and Europe as offshore wind has matured. As an indicator of what the future could look like in U.S. offshore wind research, IACMI's success in pooling private research investments from the auto, compressed gas storage, and land-based wind energy industries demonstrates the importance of industry maturity for attracting private investment.

Test Facilities and Staffing

NEES included 13 nationally distributed testing laboratories and two mobile testing equipment systems. Nearly all of these NEES laboratories were previously existing university laboratories that were enhanced through NSF funding to provide new and advanced testing capabilities. All of these laboratories were national shared-use, in which the cost for testing (technicians plus equipment) was directly provided by NSF. With this approach, all researchers and industry had access to the latest laboratories provided they could obtain funding for their proposed test programs and research personnel.

The NEES network transformed the field of earthquake engineering from an aggregation of locally controlled, closely held research assets—available only to a few researchers—to a national system that had the capacity to support the most advanced large-scale testing capabilities in the world and a new generation of innovative and collaborative research teams.

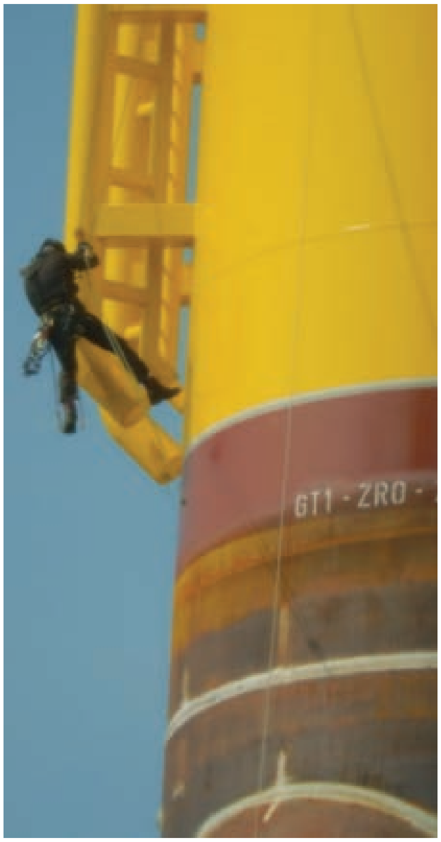
For offshore wind, the U.S. has already made substantial progress toward creating advanced testing laboratories, including those at Clemson University, the University of Maine, the Massachusetts Clean Energy Center, the National Renewable Energy Laboratory (NREL), and many others. There are important gaps in existing capabilities, however, and some of these could be filled by partnerships with existing U.S. laboratories, such as NSF's Wall of Wind at Florida International University and its Tsunami Wave Tank at Oregon State University, which were not created specifically for wind energy. Some can be filled by partnerships with international laboratories, and some can be filled by the construction of new purpose-built facilities.

Data Archives

In order to progress the state-of-the-art in earthquake engineering, it was necessary to have data and metadata from laboratory testing, site investigations, and the field performance of structures and systems. Similar progress in ocean observation requires measurement arrays distributed according to clearly identified regions with characteristics whose measurement holds promise for supporting fundamental advances in ocean science.

The required types and density of measurements in both NEES and OOI were governed by relevant attributes of component- and systems-level analytical and numerical models, so that these models could be fully developed, calibrated, and validated. Both NEES and OOI created a data cyberinfrastructure that could effectively archive, access, and visualize the data while protecting proprietary interests. Clearly established intellectual property policies in IACMI, ORE Catapult, Fraunhofer-IWES, and DTU, in coordination with relevant federal regulatory entities in the various countries, have formed the basis on which industry/government/research collaboration can flourish without damaging the business interests of industrial partners.

A major priority of a national research framework for offshore wind would be to convene the relevant stakeholders to broadly discuss the kinds of data that will most benefit the public through shared access—and that will use the kinds of data that must be protected in order to uphold the integrity of a competitive market. As discussed earlier, formal mechanisms of vetting and consensus are critical for the validation of new resource-characterization methods through proof-of-concept testing. This process requires publicly accessible data that represents the current industry gold standard against which new techniques and ideas can be tested, all for the purpose of making them bankable, insurable, and amenable to regulation.



Modeling Platform

An open-source modeling platform, OpenSEES (PEER 2018), was developed by researchers within the NEES network that enabled hundreds of researchers to expand upon modeling capabilities for different materials, loading regimes, and behavioral models. This platform is now used worldwide, with international workshops held to share skills and knowledge, and to build a large community that can advance the state of the art. Commercial software developers use these high-fidelity models to create design and analysis tools for industry. FAST, the open-source software platform created by NREL (NREL 2018), serves a similar role and can be enhanced to enable broader community contributions and model validation.

Conversations between the research community and industry thus far have highlighted several times that while industry has developed its own proprietary models, many of them were developed on the public platform created through publicly funded research. Furthermore, the individuals who work for industry to develop and refine their modeling techniques were educated within university and national laboratory environments that have proven critical to the long-term development of individual and national expertise. The availability and use of a consistent modeling platform that can evolve according to the needs and actions of the technical community will help ensure continuity and reliability of research over time. This platform will enable the community to develop analytical benchmarking standards, which, together with data benchmarking standards, form the basis of scientific consensus.

3. Strategic Research Themes

As commercial-scale offshore wind comes to the U.S., strategic public investments have the potential to adapt the European experience to our conditions in ways that increase domestic economic benefits and position U.S. research to drive technological innovation globally. This section introduces five strategic research themes that have emerged out of the nine workshops referenced in Section 1:

- Advancing near-term deployment and investing in long-term innovation
- Moving state-of-the-art to state-of-the-practice for resource characterization
- Planning long-term for ports, supply chain and transmission
- Establishing a data-driven engineering paradigm for resilient infrastructure systems
- Pursuing the public interest and adapting to U.S. conditions

The concepts of a long-term perspective, an organized approach to knowledge, and safeguarding the public interest resonate throughout this section. The first two themes detail how relationships and information sharing are essential to developing and implementing technical advancements that support healthy markets. The second two themes address the entire offshore wind energy system and its physical infrastructure, which require thoughtful cultivation in order to thrive. The final theme addresses the social infrastructure required for navigating the transition to a clean energy economy and the importance of its relationship to each technical theme.

During the development of this white paper, questions regarding the nature of research and its relationship to industry, markets, policy, and regulation have repeatedly come to the fore. Considering the multi-billion-dollar investment and substantial enabling infrastructure required to develop even a single commercial-scale project, it is unrealistic to expect a market to simply emerge. Nevertheless, the viability of offshore wind is predicated on a functioning market with competitive pricing. For these reasons, industry and government have engaged over decades in an iterative process to frame the marketplace in ways that stimulate healthy competition and signal the viability of long-term investments.

In this context of markets and pricing, research has value if it can measurably drive down cost and support regulatory decision making on time-frames of years and even months. Direct, short-term measurability of a single parameter, however, can belie the complexity of a long-term transition to clean energy which safeguards the public interest. Exclusive focus on short-term measurements of cost can bias public opinion toward an unrealistic understanding of science and technology. For instance, several workshops revealed commonly held fantasies: the scientific community has the measurements it needs to understand the atmospheric boundary layer; corrosion and fatigue science is already mature; an “app” exists to track right whales; industry developed its proprietary models from whole cloth.

In each of these cases, further discussion revealed the need for new understanding: the atmospheric boundary layer—and hence the wind resource—over the ocean requires fundamental scientific advancements based on high-quality measurements. The state-of-the-art in corrosion and fatigue is decades old and was not developed with modern offshore wind turbines in mind. Current right whale tracking depends on networks of measurement devices that are only beginning to be tested and installed in the ocean. These networks require years of further validation on real projects in order to receive and triangulate acoustic signals from the animals themselves, signals that exhibit a high degree of uncertainty.

Industry developed many of its proprietary models based on open-source platforms that were made possible through decades of public investment and research efforts. Furthermore, workshop discussions concluded that while expertise from different disciplines can be gathered together, it cannot be assembled into a functioning whole without deep collaboration and experience with real-world situations. Developing these collaborations and this experience requires both a mandate and enabling resources.

The research community's ability to understand offshore wind energy as a system, to make this understanding accessible and useful to industry and government, and to educate the next generation of professionals who will guide the world's transition to clean energy is essential to the long-term success of the U.S. offshore wind enterprise. Developing the U.S. offshore wind research community in order to achieve this level of depth, integration, and responsiveness to real-world issues is an ongoing project that requires a clear vision for the unique role that the research community can play in pursuing and protecting the public interest.

The U.S. research community is uniquely positioned to provide expertise, bandwidth, and an impartial, long-term perspective. Working with industry, which provides knowledge of particular markets and projects, and with governments, which provide policy and regulatory authority, the research community's role is to support decisions affecting the public interest with high-quality information and thinking.

3.1 Advancing Near-Term Deployment & Investing in Long-Term Innovation

Challenge Statement: Strong relationships between the offshore wind industry and the research community provide the context for project challenges to inspire research questions, and for systematic study over multiple projects to yield advancements at the systems level. Key to these relationships is an understanding of the multidisciplinary nature of offshore wind development, reliable funding, and sensible approaches to intellectual property and data sharing.

As the first commercial scale U.S. offshore wind projects advance, there is a window of opportunity to learn from early-stage developments through collaborations between industry and the research community. The essential challenge to successful collaboration, however, stems from the fact that industry and the research community develop and apply knowledge on different time scales. Through the process of planning and executing projects, industry encounters first hand the challenges that can generate compelling research questions. Industry is generally constrained, however, by the need to answer questions quickly and within the confines of a given project. It is not uncommon for questions to persist over multiple projects, or for cost-saving measures related to one part of the system to generate problems

in another part of the system. The research community has limited access to real-world problems and their context, and therefore must depend on the experience of industry to identify and articulate problems. However, having identified a relevant problem, the research community is well equipped to investigate the problem at a deeper level over the course of multiple projects.

Collaborations between industry and the research community are essential for developing trust, solidifying expertise, and educating the next generation of professionals who plan and execute offshore wind projects. European organizations and programs are helpful in highlighting the value of industry/government/research collaboration around applied research topics. In the U.K., the Offshore Renewable Energy Catapult offers a compelling example. ORE Catapult describes its industry engagement activities as follows:

> *We work with offshore renewable energy Owner/Operators and Original Equipment Manufacturers (OEMs) to add value to their activities and to support and influence the future of the industry.*
>
> *We are an independent partner able to convene the sector, with expertise and experience in reducing cost and risk associated with offshore renewable energy technology development and operations. We use our expertise in testing, validation, and demonstration to de-risk the introduction of new technologies.*
>
> *We are a solutions provider for OEMs—providing solutions to validate designs, manufacturing processes, and product reliability through innovative test set-ups and test methodologies. This enables clients to bring products to market earlier and with greater confidence. We can assist in validating OEM technologies, supporting incremental innovations and R&D programmes, setting challenges, and providing innovative solutions (ORE Catapult 2018b).*

Likewise, the Danish Research Consortium for Wind Energy “Wind

Energy Research Strategy" report (DFFV 2015) notes that engagement between industry and the research community has been a critical factor in the success of wind energy in Denmark:

> *Continuous feedback from industry and other end-users is crucial for the focus of and priority setting of the research. This is necessary for both development of new technologies and for the refinement of existing technologies towards more cost-effective solutions.*

Access to data is a substantial barrier to the systematic diagnosis and solution of persistent problems. Considering the importance of intellectual property (IP) to competitive advantage in the offshore wind market—along with the expense of collecting and archiving data—it is essential to develop an approach to data acquisition and archival that makes data collected for individual projects publicly available without compromising its IP value. The research community is dependent on data for a wide range of research topics including generating representative meteorology and oceanography (metocean) inputs for simulations as well as structural and performance response data for validating simulation models. In the U.K., various forms of data from offshore wind development are made public via the Crown Estate, with substantial resultant benefits to researchers.

In order for the U.S. to learn from European experience, adapt this experience to U.S. conditions, and develop new technologies that will allow it to compete in the global offshore wind market, it is important to hold the following five near-term and long-term objectives in mind:

3.1.1 Foster cooperation between industry and the research community

Individual project budgets and time lines do not allow for the perspective and sustained conversation that are critical to advancing knowledge. Furthermore, it is not enough to advance knowledge on a scientific level; it is necessary for new knowledge to be bankable, insurable and amenable to regulation. Sustained conversation between industry and the research community requires clear communication and trust developed over long periods of time. If funding opportunities are made too competitive and short term, there will neither be sufficient opportunity to develop the critical relationships between industry and research nor to harvest the long-term benefits.

3.1.2 Establish effective standards for intellectual property, data acquisition, and data sharing

Essential to this approach is a dialogue that brings researchers together with developers, OEMs, financiers, regulators, and insurers to determine sensible practices for sharing data and respecting IP. The development of such practices will allow the research community to track the industry as a whole, delivering value to the private sector through higher confidence levels and clearer characterization of risk. Likewise, well-coordinated approaches to data collection, archival, and analysis will allow the research community to provide public-sector regulators and policy makers with scientific information as a basis for decision making. Regulators ought to consider placing a data-sharing requirement on the first or most-heavily subsidized wind farms. The offshore wind energy industry's obligation to the public and to the environment increases with the scale of development and the level of reliance on offshore wind for meeting the nation's electricity needs. While some data needs to be proprietary, a new paradigm is needed for both the sharing of data and the identification of what data is needed to improve operation and advance design practices.

This paradigm is not a mandate for industry to "provide all the data they collect" but a partnership among government, industry, and the research community to determine what data to collect and how to format and analyze this data to improve all aspects of design while protecting relevant IP. Although industry has been at the forefront of progress in offshore wind to date, collaboration with a well-organized research community will support an impartial and transparent approach to decision making. In addition to bankers, insurers, and regulators, key industry members have expressed interest in third-party validations of the decision-making data.

Figure 14. Floating concepts push technology development farther offshore. *(image credit: Josh Bauer, NREL).*

3.1.3 Support multidisciplinary research

Many research efforts critical to the advancement of offshore wind involve more than one discipline. For instance, accurate assessment of risk due to hurricanes and other extreme events requires engineers and atmospheric scientists to work together to determine the meteorological phenomena that are relevant to system level risk (Yu et al. 2012, Fraudenreich et al. 2014, Dibra et al. 2016, Kim et al. 2016, Hallowell et al. 2018).

Optimization of wind plant performance involves measurements and characterization of the atmospheric boundary layer within a wind farm as well as knowledge of options for layout and control accounting for turbulence (Martínez-Tossas et al. 2016, Ciri et al. 2017, Gebraad et al. 2017, Vasel-Be-Hagh and Archer 2017). Reliability and resiliency of the turbine system as a whole require not only well-established data from component testing but also reliable inspection methods, computational systems' identification, and knowledge of how different parts of the turbine system, plant, and transmission infrastructure interact.

3.1.4 Invest in transformational research

The academic community is well positioned to conduct research that may result in "step-change" impacts on offshore wind technologies, which can drive down costs and spark domestic innovation. For example, technically and economically viable floating offshore wind turbine systems are critical to the U.S. market, where 58% of the offshore wind resource is located in areas with seafloor depths greater than 60m (Figure 14). Such systems will require advanced controls, protection under extreme events, and rotors that are larger and lighter than the current industry standard (James and Costa 2015, Beiter et al. 2017, Peeters et al. 2017, Gaertner and Lackner 2018). U.S. development of such systems will position the nation to compete in the future global offshore wind market.

3.1.5 Develop sophisticated assessments of large-scale offshore wind development

The public sector must support the research community in asking critical questions related to the responsible and strategic long-term development of offshore wind, questions that would not be considered on a plant-by-plant basis. These assessments must consider environmental impact, fisheries compatibility, grid integration, and system reliability with development on the scale of hundreds of gigawatts. Finally, it is wise to consider the cumulative impacts of development at this scale before it happens, so that project-specific regulatory decisions can be made with reference to the nation's long-term interests.

If the U.S. wishes to innovate in the future, it is critical for the research community to work closely with industry to solve immediate needs and develop detailed domain knowledge. Without investment to support collaboration among academic institutions, national laboratories, and U.S.-based offshore wind industry members, the industry will grow by outsourcing technology, innovation, and jobs to European companies. However, with investment in U.S.-based industry/university/national laboratory partnerships, companies and researchers will generate an ecosystem that accelerates discovery, innovation, and job creation on a national level. Moreover, investment in research that is focused on the strategic deployment and operation of offshore wind—at large scales over many decades—will allow the U.S. to find global solutions that maximize public benefits while avoiding the haphazard risks of uncoordinated development.

3.2 Moving State-of-the-Art to State-of-the-Practice for Resource Characterization

Challenge Statement: Knowledge and technology must be bankable, insurable, and amenable to regulation in order to make a difference in the U.S. offshore wind industry. Scientific knowledge cannot be used as the basis for investment or decision making until it has been vetted according to established standards by an approved process. Ocean Test Beds (OTBs) will increase the technology readiness levels of new ideas by creating opportunities for proof-of-concept testing and demonstration to the wider community.

Detailed knowledge of the environment where offshore wind energy systems operate is a key element of the design, permitting, construction, and operation of a new wind plant. Environmental monitoring is needed not only to characterize the wind resource itself but the potential risks present within the construction and operation of a new project in an unfamiliar ocean. The current body of resource-characterization technologies utilized by both the European offshore and the U.S. onshore wind energy industries have recognized track records that provide a basis for accepted methodologies within the emerging U.S. offshore wind market. However, the landscape of applied ocean technology is rapidly changing, with forces of innovation emerging from basic ocean science research methodologies as well as onshore high-tech sectors that have the potential to jump-start the U.S. sector of this industry in a unique way.

Priorities for reducing costs and technological risks regarding site characterization have been identified through surveys of the strategic goals of the Wind Vision report (USDOE 2015), current best practices, the operation and monitoring efforts of European wind plant areas, the initial monitoring efforts at the Block Island offshore wind demonstration project, and present state-of-the-art methods. Representatives from a broad range of research, government, and industry groups made this assessment in order to characterize the challenges facing the industry and to determine what tools exist to meet those challenges. Summarized here, the results are fully described in a white paper that details both potential near-term, industry-changing advancements and that lays out the need for ocean test beds as research and development infrastructure (Kirincich et al. 2018). These physical and virtual facilities must be capable of driving innovative observations as well as the modeling and monitoring of the physical, biological, and use-characteristics present in offshore wind energy installation areas.

Today, with the rapid advancement of micro-computing, autonomous surface and underwater robotics, and physical and biological sensing technologies in the ocean science community, there exists a new and developing body of state-of-the-art technologies with the potential to revolutionize scientific understanding of the ocean characteristics critical to offshore wind systems. These technologies can enable the U.S. research community to:

3.2.1 Build an accurate estimate/forecast of the atmospheric boundary layer

Light detection and ranging (LIDAR)-based sampling of the atmospheric boundary layer and the potential wind energy resource available at the level of the turbines themselves are rapidly becoming the standard for static and historical site assessment. This represents a sizable cost savings and risk reduction over previous methods used to understand the historical potential for wind as the fuel for driving energy production. However, deficiencies exist in the application of these same methodologies to observe wind-based design conditions—for example, the turbulent loading of the turbine, wind shear characteristics, etc.—and to accurately predict the future and the near-future (10-60 minutes) winds present over an installed system (Sathe et al. 2015, Lundquist et al. 2017).

3.2.2 Enhance domain awareness and minimize impacts on critical marine mammal species

At its core, the objective of marine mammal monitoring is to find all the individuals of a protected or important species and guide offshore wind operations around them in order to minimize interactions and potential harmful effects. Thus, advanced sensing of protected marine species via networks of passive acoustic monitoring stations or mobile assets represent an attractive way, in parallel with aerial surveys, to ensure better data collection and more responsive and flexible site actions during construction and maintenance operations.

3.2.3 Develop infrastructure while preserving the marine ecosystem's goods and services

Of critical concern are efforts to manage the goods and services produced by the continental shelf such that they coexist synergistically with the physical structures and use characteristics of offshore wind. Mirroring this concern, a present goal of a National Academies of Sciences committee (NAS 2017) is to gather stakeholders who will identify and develop an operational framework for how to understand and assess the impact of individual projects on key species groups and the cumulative impact of multiple projects.

3.2.4 Advance geophysical and geotechnical knowledge of the sub-bottom environment

New research on and uses of sensing methods can provide more effective and more efficient geophysical surveys as well as advanced sensing of the sub-bottom environment. These methods are required to improve substructure and foundation design and to reduce construction risk within the unique U.S. Outer Continental Shelf conditions.

Applied to offshore wind energy as an industry, treating OTBs as innovation and testing centers would enable the advanced sensing of the sub-bottom, ocean, and atmosphere as well as numerical simulation techniques (Figure 15). The principal barrier to the widespread development and application of next-generation ocean technology is the "proof factor": these technologies, as promising as they are, require validation to support their full application within the regulatory, scientific, engineering, and investment communities. OTBs would provide the needed pathway to move innovations rapidly to implementation, to advance the permitting process through systematic technology validation, and to improve modeling, monitoring, and analysis in an open process by neutral third parties.

In summary, siting and permitting is a high-risk, high-cost aspect of offshore wind development. Solid scientific data on the design characteristics and consensus on the impacts of a wind plant on the marine environment are critical to reduce risk, advance public acceptance, and evolve the regulatory process. Factoring in the unique conditions present in the U.S. Outer Continental Shelf areas slated for offshore wind development, it is apparent that the offshore wind energy industry needs to examine the state-of-the-art methods within related fields for the next state-of-the-practice advancements. These advancements will address rapidly changing industry objectives, maintain competitiveness, and allow the industry to contribute toward the careful stewardship of the ocean as a common resource.

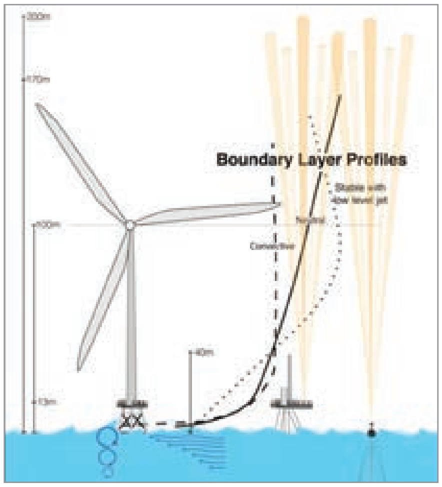


Figure 15. Ocean Test Bed sensing and measurements. *(image credit: Anthony Kirincich, WHOI)*

3.3 Planning Long-Term for Ports, Supply Chain, and Transmission

Challenge Statement: Investment in infrastructure and long-term planning are both necessary to transition U.S. offshore wind from an import industry to a domestic industry that can provide jobs and energy security. Planning for transmission, grid integration, ports, and an effective supply chain requires sensitivity and responsiveness to market signals as well as clear direction from the public sector. Thoughtful, impartial research engagement on the relationships between government decisions and market mechanisms can reduce market volatility and improve the yield on public investment in infrastructure.

Offshore wind energy plants are enabled by a physical infrastructure system that covers an enormous geographic extent, is regulated by multiple public entities, and has a measurable impact on the environment. This infrastructure system requires design that is sensitive to siting and market characteristics, accommodates multiple users, and functions largely in the public interest, even if certain components are not explicitly publicly owned. For example, substructures and foundations will be designed for local geotechnical and environmental conditions as well as with sensitivity to local port and supply chain considerations. And transmission grids and subsea cables may be designed and constructed to service multiple wind plants with different owners.

The entire offshore wind infrastructure system exists to serve the energy needs of society and the nation. It should be noted that construction and maintenance of this infrastructure system requires robust supply chains, and these supply chains rely in turn on other infrastructure systems such as road and rail transport networks.

Fisheries: Science and Stakeholder Engagement

—S. E. Lohrenz

The Bureau of Ocean Energy Management (BOEM) is obligated by federal law (30 CFR 585, BOEM 2018c) to ensure that activities related to offshore renewable energy development in the Outer Continental Shelf (OCS) are conducted in a manner that provides for “protection of the environment,” “conservation of natural resources of the OCS,” and “protection of the rights of other authorized users of the OCS.” Both commercial and recreational fisheries represent “authorized users,” so plans for offshore wind development must “avoid or minimize conflicts among users and maximize the economic and ecological benefits of the OCS, including multifaceted spatial planning efforts....”

BOEM is required to consult with the NOAA National Marine Fisheries Service (NMFS) and respond to findings related to the requirements of the Magnuson-Stevens Fishery Conservation and Management Act (MSA), as well as other federal statutes. A variety of efforts have been conducted or are underway to identify the potential impacts of offshore wind activities and infrastructure on fishing and fish populations and to develop plans and approaches to avoid or minimize negative impacts. Marine spatial planning efforts, such as the Northeast Ocean Plan (NOP 2016) and the Massachusetts Ocean Management Plan (MOP 2015), have been effective in gathering input from a variety of stakeholders and users of OCS resources. These efforts have also provided data and information for decision support through the Northeast Ocean Data Portal (NOD 2018).

Since 2009, BOEM has led an intergovernmental task force to seek input from federal agencies and from state, local, and tribal governments about offshore wind development throughout the lease process. This has included engagement with the Massachusetts Executive Office of Energy and Environmental Affairs and the Massachusetts Clean Energy Center (MassCEC). The Task Force has convened two working groups for fisheries and marine habitat issues. Since 2009, Massachusetts has held more than 100 public and stakeholder meetings to solicit input about offshore wind development. There have also been a series of four workshops and associated reports that have gathered input from state and federal agency representatives, fishing industry representatives, offshore wind developers, and fisheries research scientists from public, private, and non-governmental research organizations.

The major conclusions from a BOEM-funded study (Petruny-Parker et al. 2015) conducted by the Commercial Fisheries Research Foundation (CFRF) and the Cornell Cooperative Extension of Suffolk County Marine Program (CCE) were that there is currently a “lack of site-specific project data resulting in uncertainty and speculation” and a need for “robust baseline research and ongoing monitoring” to “evaluate impacts and determine mitigation measures.”

Concerns raised by the fishing industry include:

- Avoiding critical fishing habitat and migration routes
- Constraining the footprint of the offshore wind infrastructure to minimize interference with key species and ecological processes, and to reduce obstacles and hazards to navigation by other vessels
- Reducing potential disturbances due to noise and vibration
- Burying and regularly monitoring undersea cables to minimize electromagnetic field effects

Leaseholders in the MA WEA have hired fishing vessel owners to assist with assessment activities and engaged Fisheries Liaisons to work with the fishing community to address specific issues related to particular wind farm configurations and other concerns.

The infrastructure to support the manufacture and installation of offshore wind plants (Figure 16) is in its infancy in the U.S. While the U.S. can learn from European methods, the availability, size, and configuration of U.S. ports and market conditions will require the nation to adapt and innovate. New infrastructure is needed for all phases of project delivery: planning, construction, manufacturing, operation, maintenance, and the transmission and delivery of electricity into the grid.

The Massachusetts Clean Energy center completed the first of this new generation of ports in 2016 in New Bedford (MassCEC 2018b, Hines et al. 2017). Without the New Bedford Marine Commerce Terminal (shown in Figure 16) it would be extremely difficult to stage the first commercial-scale offshore wind farms on the tight timeframes required to ensure project affordability. The long-term risks of failing to move beyond a project-by-project approach in the development of offshore wind infrastructure in the U.S. are substantial and would result in an industry driven largely by external entities. Appropriately cast and implemented research and analysis can support world-class infrastructure development, efficiency, and appropriately scaled regional solutions. The Massachusetts Clean Energy Center's ports and infrastructure study has set a compelling example for how individual states can assess and communicate issues related to logistics and supply chain within a state (MassCEC 2018c). Further work in this spirit would extend to other states, combine supply chain and infrastructure studies, and integrate thinking within regions, considering how multiple states could work together.

Effective planning for U.S. offshore wind infrastructure will embrace issues of engineering and logistics, public policy, economics, energy market structures, and political realities. The research community, in partnership with industry, is in a position to provide a neutral third-party platform for analyzing the key issues that cross political boundaries and to suggest approaches that maximize economies of scale and public benefit by taking the following actions:

3.3.1 Consider supply chain, port infrastructure, and job creation as an ecosystem

The supply chain requires suitable land with appropriate shipping infrastructure in close proximity to the markets being served. Local, regional, and national strategies for port

Figure 16. The New Bedford Marine Terminal is a facility that supports Jones Act[1] compliant logistics by supporting the world's largest land-based cranes at the quayside. *(photo credit: MassCEC)*

and coastal infrastructure to support U.S. offshore wind, including the availability of coastal industrial land, must be evaluated from societal and political perspectives as land is repurposed. Environmental impact should be considered and balanced on a regional scale so that individual projects may be permitted within a larger constellation of projects. The redevelopment of existing infrastructure sites, including the environmental cleanup of coastal brownfields sites, require environmental technologies that allow for channel improvement to support industry vessels. Financing approaches that consider public and private investment models are key to establishing project viability and relationships with existing users of coastal land and infrastructure, including fisheries, shipping, and recreation.

Figure 17. offshore wind installation vessel

3.3.2 Develop infrastructure that is responsive to logistical realities

Europe has found that innovation in logistics and transportation drove the development of the infrastructure scheme that allowed the entire industry to flourish (Figure 17).

Infrastructure's reasonable evolution and expansion is premised on knowledge and innovation in logistics. Research on shipping methods, Jones Act[1] compliance, and new technologies for the transport of super-large components on land and over water can inform decision making at the policy level related to logistics issues.

3.3.3 Plan for effective transmission of electricity from offshore wind plants to the onshore grid

Power generated by offshore wind plants will need to be incorporated into the grid in a balanced and efficient manner. Grid layout and sequencing are key considerations for a new energy system with thousands of wind turbines constructed offshore. Weighing and discussing the benefits and challenges of offshore grid development vs. radial connections for individual projects should be engaged prior to making project design and regulatory decisions. For example, offshore wind plants could potentially be connected via an offshore transmission backbone, even though these projects will not be constructed simultaneously.

Therefore, phased transmission schemes will be needed for optimal integration through this shared infrastructure. It is important to consider and identify the business models that would optimize the

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[2] The Jones Act, Section 27 of the Merchant Marine Act of 1920, is named for Wesley R. Jones from Washington State and controls coastwise trade, or cabotage, in the United States. It prohibits foreign-flagged vessels from conducting domestic trade between domestic locations. For the U.S. offshore wind industry, this restriction means that foreign installation vessels equipped with heavy waterside cranes can install U.S. offshore wind farms, but they cannot carry components from a U.S. port to a U.S. wind farm. Therefore, in its nascent form, the U.S. offshore wind industry can receive components imported on foreign-flagged cargo vessels, arrange these components at a logistics port such as the New Bedford Marine Commerce Terminal, use landside cranes to load the components to U.S.-flagged barges (which are not equipped with heavy cranes), and transport these U.S.-flagged barges to the construction site.

public and private sector benefits of this approach. Science related to determining and mitigating the impacts of transmission components to the coastal and ocean environment, resources, and ecology should be the basis of policy. Grid and transmission financing along with grid development and integration can benefit from intensive dialogue among the research community, industry, and government. As multiple offshore wind plants come on line, significant public planning will be needed to ensure both ratepayer equity and power consistency.

3.4 Establishing a Data-Driven Engineering Paradigm for Resilient Infrastructure Systems

Challenge Statement: In order to be useful, data and computational power must be organized within a richly structured intellectual paradigm. Effective paradigms help engineers visualize and quantify the gaps and uncertainties in their knowledge. Proper understanding of uncertainty improves decision making about complex systems.

A data-driven, systems-level engineering paradigm will advance the design, development, operation, and repowering of U.S. offshore wind energy plants. This paradigm requires a rigorous numerical approach to uncertainty and recognition of the creative potential inherent in the breadth of design options, impact of decisions, and number of disciplines/communities involved in offshore wind energy generation. The importance of creating and maturing this paradigm will increase with the level of offshore wind energy development.

The current engineering paradigm is largely a linear process containing several coarse assumptions in the computational models and standards that are used for making design and operational decisions. Design is commonly done on a “plant-by-plant” basis. This approach cannot be sustained over the long-term. Considering individual plants in the context of a larger system is critical for determining and delivering:

- Suitable project lifespans
- Monitoring cumulative environmental, economic, and societal impacts
- Quantifying risks from extreme events
- Identifying uncertainties and opportunities for innovation
- Designing to an acceptable level of reliability
- Developing standards and models to support quality design decisions

Developing this paradigm will allow the U.S. to:

3.4.1 Introduce a fully probabilistic approach that considers uncertainty and reliability

Similar to other heavy infrastructure systems, the engineering paradigm for offshore wind energy should evolve into a systems-level approach that brings together all of the relevant disciplines and stakeholders and that expresses system- and component-level uncertainties in numerical terms. In other fields, such as earthquake engineering, the effective numerical treatment of uncertainty is referred to as a “fully probabilistic” paradigm. Key to this approach is the formal recognition that both the demands on systems and the capacities of systems and their components can vary. If this variation can be quantified, it becomes possible to assess system risk numerically.

Demands on offshore wind energy plants include electricity demand, corrosion and fatigue loads on structures and components, wind and wave loads from extreme events such as hurricanes and bomb cyclones, and demands on the marine environment due to construction and operation of offshore wind energy plants. Capacities represent the ability of the system and its components to resist demands. Since both demands and capacities can vary, developing numerical assessments of system risk requires the use of probabilistic methods to evaluate demand/capacity relationships under a wide range of possible scenarios.

3.4.2 Develop a workflow and decision-making process

Key factors that must be considered in design and operation of offshore wind plants include the loading (wind, waves, currents, and electricity demand), the capacity of each component resisting these loads (blades, nacelle, tower, substructure, foundation, seabed, and generation capacity), and the control algorithm that sets the pitch of the blades, yaw of the nacelle, and mechanical resistance of the gearbox or direct drive, effectively tuning the relationship between demands and capacities for specific conditions.

The tools used to design and operate offshore wind plants include the computational fluid-dynamics model; the surface characteristics of all components subjected to winds, waves, and currents; the structural models of all components; the geotechnical model of the seabed; and all of the standards and certification methods associated with each aspect of design and operation. An organized workflow and decision-making process would distill the core decision-making elements (demands and capacities) and the tools (modeling programs, standards, regulation) that are used in permitting, design, operation, inspection, repowering, and decommissioning.

Public organization and discussion of this process will facilitate an iterative engineering design process (Ask → Imagine →Plan →Test →Learn →Ask) and help identify opportunities for improvement with respect to the national value of offshore wind energy development.

3.4.3 Establish formal model development and validation procedures

High-quality data are central to the operation of this engineering paradigm. They are the basis for decision making, regulations, standards, and performance-based design; and they are essential to advancing basic science and the development and validation of high-fidelity and engineering computational tools. Shared data (Subsection 3.1) and effective benchmarking of data quality (Subsection 3.2) are central to the many disciplines and groups that need to work more closely together, including modelers and designers, regulators and insurers, developers and bankers, and engineers and operators. Sensitivity analyses using high-fidelity models from NREL and DOE and the engineering-level computational model from Danish Technical University (DTU) can be used to assess the impact of critical input parameter values and design selection on predicted performance, such as annual energy production (AEP), lifespan, and inspection requirements.

The identification of these impacts can serve as a basis for industry/government/research discussions aimed at allocating access to data based on decision-making responsibility. For instance, data relevant to regulation, insurance, policy, and opportunities for new players to enter the market should be considered for public access; whereas data relevant to a private entity's competitive position in the market, trade secrets, and privately funded performance studies should be respected as a privately held asset.

3.4.4 Improve electrical system reliability

The utility industry currently approaches the construction and allocation of a relatively small number of large generating plants through what is called Loss of Load Probability (LOLP) analysis. The LOLP approach is premised on the idea that generators use fuel that can be stored in large quantities and can be ordered well in advance of when it is needed. As the world transitions to renewable energy from wind and solar at scale, new relationships will develop between the reliability of multiple, spatially distributed, weather-dependent smaller generators and the overall energy supply. System reliability ought to be the overarching goal of the new clean energy industry. From that goal, various aspects of the design of individual generators and other components of the system should be evaluated.

For example, present wind turbine design standards utilize partial safety factors that are based on a certain reliability (or conversely, probability of failure) over a given time period—typically 50 years. Within the context of the overall energy supply, this approach could be either too conservative or not conservative enough, depending on the nature of the failure, the time required to repair the failure, and the alternatives available in the meantime.

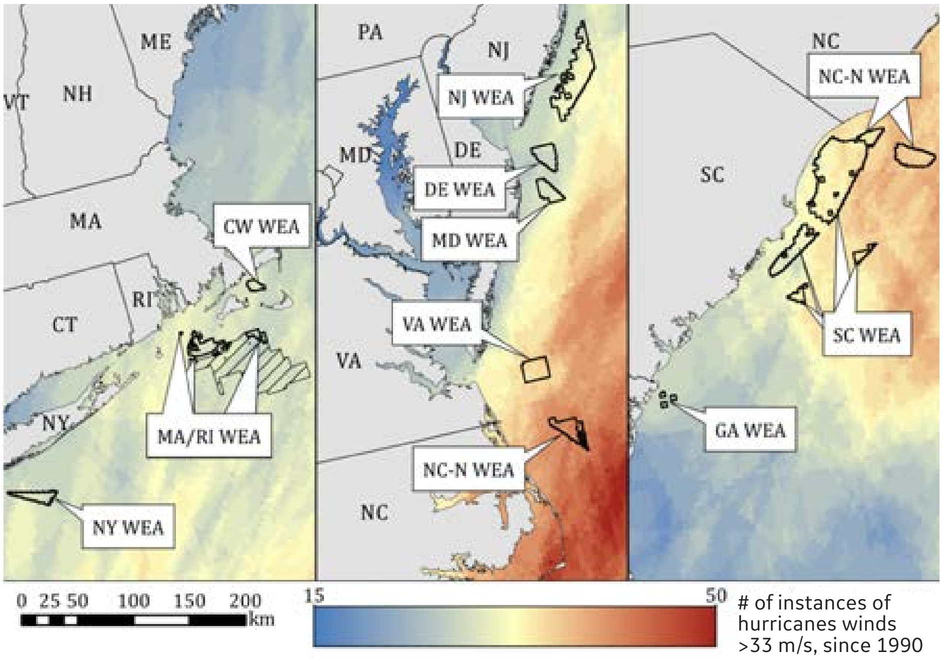


Figure 18. Historical hurricane records and East Coast wind farm areas. *(image credit: Spencer Hallowell)*

In the case of turbines designed for areas that are impacted by extremely intense systems (such as hurricanes, as shown in Figure 18, and "bomb cyclones"), the situation is further complicated by the nature, scales, and tracking of these intense atmospheric phenomena as opposed to large arrays of wind turbines that by their nature are distributed over a wide area. For example, the possibility of failure of a limited number of turbines due to a hurricane passing through a large array, in contrast to the low probability of failure of all the turbines due to the same event, needs to be assessed in the overall plan for the turbines and their installation.

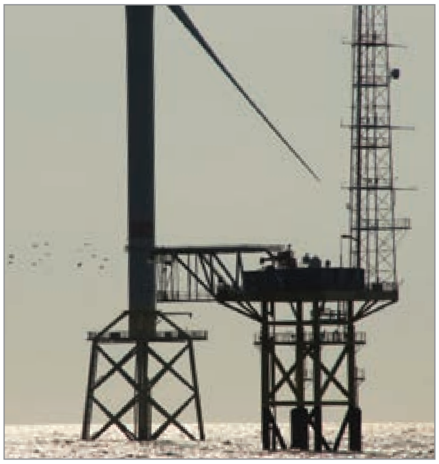
Research related to the incorporation of offshore wind into the grid provides both an opportunity to study the resilience of the grid itself and a potential for mitigative measures to be recast and improved. The fully probabilistic approach discussed in this subsection can be developed to offer predictions of generating-capacity outages caused by natural catastrophes.

3.4.5 Advance standards, guidelines and best practices

In the case of design standards, offshore wind turbine designs are a combination of class based (for the rotor nacelle assembly) and site specific (for the substructure and foundation). Class-based designs require less detailed site assessment than site-specific designs; it is simply necessary to ensure that the conditions at a site are no worse than those applicable to the class in question. Site-specific designs require a detailed site assessment before the design can be completed. Such an approach may result in a design better suited to the specific application but that will take longer than the class-based approach and may not yield meaningful savings or provide guaranteed reliability. When the alternatives are evaluated in the context of the reliability of the overall energy supply—while taking into account the total costs of the various approaches—it will become possible to make better decisions on the processes to follow.

3.5 Pursuing the Public Interest and Adapting to U.S. Conditions

Challenge Statement: U.S. Offshore wind technology will be deployed over the long term in a social, political, economic and environmental context that is unique to this country. This includes regulatory and market structures; political and cultural dynamics; and community values that not only differ from the leading European offshore wind markets, but also reflect significant variation from region to region. Understanding, communicating and adapting to the specific attributes of these multiple social systems is essential to supporting effective innovation aimed at advancing the domestic offshore wind industry.



Achieving the significant potential benefits of developing this transformative new energy sector will require thoughtful examination of a multitude of sometimes conflicting public interests, including: the economic health of existing ocean industries, navigation, the cost of energy, climate change mitigation, new job creation and economic development and environmental/human health and aesthetics. Of foundational importance is a well-constructed framework for assessing the benefits and risks of different industry-development strategies, weighing these against diverse community values and engaging a broad range of stakeholders in the process.

Advances in engineering and natural sciences are vital to the opportunities for offshore wind in the U.S., however, the transmission of new knowledge or technical innovation from the lab or field to practical application will be crucial to ensure industry relevance, and will frequently require adaptation of regulatory, electricity delivery or business systems. Effectively managing the necessary changes will require robust, diverse stakeholder engagement, impartial analysis of economic costs and benefits, and examination of related tradeoffs in public values.

In response to complex challenges and opportunities about issues of sustainability, a traditional approach has been to assemble a team or network of subject-matter experts, including those in engineering, physics, marine sciences, geology – to evaluate problems and suggest technical options. While such an approach is an important part of the process, it is critical to strengthen the effort by more fully and equally integrating social science expertise from the start, so that issues of risk, equity, long-term impacts, as well as market costs and benefits - along with their distributions - can mutually inform the findings of natural science and engineering analysis. Inadequate or late inclusion of social science research in the process of technology deployment can lead to unintended consequences, disparate negative impacts or foregone opportunities. Several decades of research now underscore the successful deployment

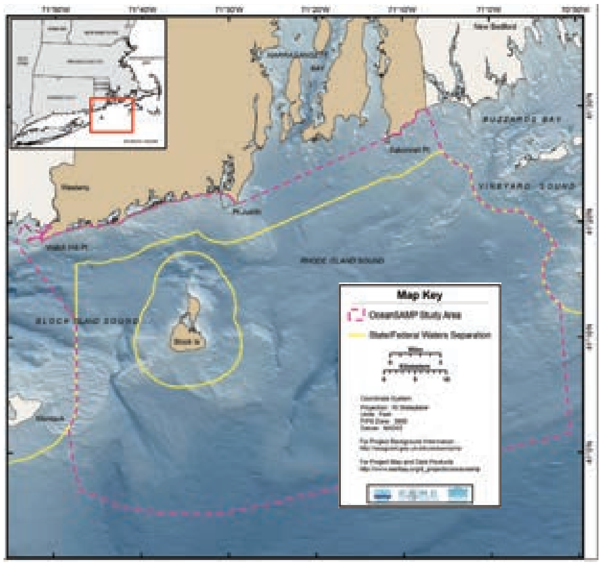


Figure 19. Extent of the Special Area Management Plan established by Rhode Island. *(image: RI Coastal Resource Management Council)*

of new transformative technologies with the rigorous integration of social science research and assessment in conjunction with engineering and hard sciences research from the inception of the process (Clark et al., 2016) Also crucial is the deeper recognition that stakeholder engagement and the inclusion of multiple perspectives and data sources is fundamental to improving the salience, credibility and legitimacy of such efforts (Matson et al., 2016, Cash et al., 2003).

One particularly relevant example of the effective integration of multiple technical and social science disciplines, combined with the robust engagement of stakeholders – the Rhode Island Ocean Special Area Management Plan (SAMP) – is shown in Figure 19 and described in the call out on the following page.

Deployment of offshore wind at the scale and speed outlined in the Department of Energy's 2015 Wind Vision (US DOE, 2015) and the NREL Renewable Energy Futures report (Hand et al., 2012) will capture a range of public and private interests, risks and rewards. A successful industry development strategy will require public policy innovation in a number of areas. To properly navigate this range of issues, the research community should partner with the public sector, industry and a multitude of stakeholder groups to combine state-of-the art *collaborative knowledge management and decision-making processes with* innovative *approaches* to utility business models, supply chain logistics, and market mechanisms and other systems as discussed below.

3.5.1 Apply innovative community and decision-making to the offshore wind siting and permitting process

Advance robust, data-driven, participatory approaches to analyzing tradeoffs among varying industry and community considerations; for example, SeaSketch (SeaSketch, 2018) and Structured Decision Making (Gregory, 2012). Develop new tools to analyze data from early projects to support collaborative development of equitable environmental and user mitigation strategies and cumulative impact assessment. Translate complex science (e.g. fisheries) to support effective engagement of key stakeholder groups. Create model community benefit agreements to balance impacts and create opportunity at the local level.

3.5.2 Develop new business models/market mechanisms to address the economic benefits and opportunities of offshore wind at scale

Develop alternative business models for utility operation to address large-scale integration of renewables into the grid, including cost analysis, electricity pricing and contracting structures. Use the emergent offshore wind market to prototype innovation. Create incentives to allow both developers and utilities to see revenue opportunities in offshore wind deployment. Analyze regional grid impacts and develop options for integrating state-based market development approaches. Advance new analytic tools to appropriately value less-quantifiable gains like systems flexibility and resilience.

3.5.3 Model alternative supply chain and maritime infrastructure development approaches to increase efficiency, cost-competitiveness and sustainable economic development benefit

Consider the efficacy of tying state-level economic benefits tests to market mechanisms for individual projects. Develop alternative approaches to best support the transition to a more integrated, regional supply chain/

infrastructure, including transmission, to maximize both industry and public benefit. Determine the right time in the industry-deployment timeline to incentivize this shift.

Numerous policy and social drivers, including renewable energy targets, job creation opportunities and retirement of traditional energy sources, have created a context in which the U.S. can pursue offshore wind as a potentially transformative energy source. The opportunity for significant positive impact in several regions of the country is well documented (Hand et al., 2012, US DOE, 2015). Achieving the positive impact of the technological innovation called for in the four preceding research themes will depend on the integration of discrete social science disciplines in the design of research questions, as well as an overarching commitment to collaborative strategies, outreach to a wide range of stakeholders who represent unique and relevant market perspectives and, as highlighted in Strategic Theme 1, a view to the long-term social acceptance and economic sustainability of the industry.

Ocean SAMP Celebrates 5 Years, Reveals New Findings

—Excerpted from: (Smythe et al. 2016).

The Rhode Island Ocean Special Area Management Plan (Ocean SAMP), a marine spatial plan that is among the first in the U.S., laid the groundwork for the siting and permitting of the nation's first offshore wind farm, a five-turbine, 30MW project off Block Island.

This case study provides us with two meaningful narratives. The first is about preparing a marine spatial plan for an area which will be shaped by numerous interests and resources crucial to Rhode Islanders: commercial and recreational fishing, commercial shipping, recreational boating and sailing, marine resources and habitats, and—potentially—offshore wind energy development. The second narrative is about the long process of locating and permitting the U.S.'s first offshore wind energy project. Of course, these two stories are interwoven, and that is how they unfolded over time. Yet it is important to emphasize that the Ocean SAMP was launched, prepared, and adopted as a comprehensive ecosystem-based marine spatial plan and not as a renewable energy facility-siting plan.

The SAMP's combined research-and-stakeholder approach was as much a social process as a planning exercise, turning a diverse array of participants into Managing Successful Programs practitioners. Ocean SAMP participants included not only the lead planning agency but other state and federal agencies, commercial and recreational fishermen, boaters, divers, renewable energy developers, environmental organizations, the Narragansett Indian Tribe, and private citizens, including residents of Block Island and other adjacent coastal communities. Each made unique contributions to the Ocean SAMP development, bringing their individual skills and expertise to the process.

Many noted that the data and policies contained in the Ocean SAMP document are seen as highly credible and meaningful precisely because of the social process that generated them, a process that brought together a wide array of stakeholders, researchers, and government agencies to jointly learn, ask questions, reflect, and see things from each other's points of view. These technical, planning, and social benefits are all tightly entwined.

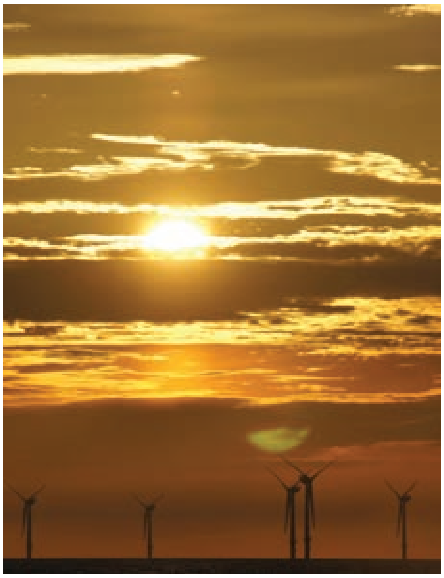
As Ocean SAMP stakeholder chair Ken Payne summed it up, the Ocean SAMP "took a situation that was potentially highly tense and converted what could have been a battleground and contested space into a space of developing shared understanding. That's huge.... Very simply, it replaced a battle over impacts with a shared effort and social order. From battle to learning. That's what marine spatial planning can do."

4. Conclusions and Next Steps

This white paper recognizes the emergent offshore wind industry as a significant opportunity to meet regional energy needs, advance renewable energy goals, catalyze job creation, and invest in advanced manufacturing, port facilities and other infrastructure systems. It also illustrates the scope of the challenge in deploying this technology at scale, and the need for innovation and adaptation of thinking about marine planning, infrastructure, engineering, policy and other disciplines.

Offshore wind continues to advance because it has proven to be a tremendous market opportunity, worthy of investment by the private sector. The public sectors in this country and globally continue to provide financial and policy support as the anticipated public interest benefits prove to be real. Industry is at the center of technology innovation: R&D investment by the private sector, often including public co-funding, continues to drive cost reduction and problem-solving. This white paper makes the case for building on industry efforts through public investment in accessible, large-scale research and testing facilities; continued support for engagement by academic and other private research institutions and systematic training of next generation professionals. These investments will be essential to addressing pivotal questions that are too complex or too long-term for individual companies to address on their own, including those of overarching public significance.

The suggested approach to advancing research and innovation in the U.S. offshore wind sector - collaborative, networked, convergent and systems-based - reflects successful experience in other nationally significant technology and infrastructure development challenges discussed in Section 2. Strategic early investment in bridging disciplines - developing robust platforms for facilitating partnership, knowledge dissemination, international exchange and ongoing consideration of the full spectrum of industry, public sector and community perspectives, will encourage efficiency in problem solving, groundbreaking innovation and more sustainable results.



Section 2 outlines five key features of the approach, and suggests some initial steps (some of which are already underway) toward creating a *national framework for offshore wind research and innovation*:

1. **An Integrated Community.** Convening the overall U.S. offshore wind research community – including universities, research institutions, the national labs, state programs, federal agencies and international partners - is ongoing and a fundamental objective and success of the POWER-US initiative. Based on discussions thus far, initial next steps in advancing this effort include:

- Launch a discussion among leaders of the country's major offshore wind-related testing facilities, including existing assets that are not currently engaged in offshore wind R&D but, to explore capabilities, shared challenges and consider a long-term vision for networking.

- Work with relevant federal entities such as BOEM, DOE, NOAA, NSF and others listed in this paper to discuss a coordinated approach to a sustained, long-term funding stream, for offshore wind research.

- Develop an effective platform for on-going discussion among market-driving states to support co-funding for shared research challenges, particularly those with regional implications, such as transmission, supply chain, port infrastructure development, and cumulative economic and environmental effects of offshore wind development.

2. **Industry Relevance.** Federal agencies, offshore wind industry leaders and the research community are engaged in on-going and emerging collaborations which are poised to contribute significantly to industry priorities.

- DOE's partnership with NYSERDA in establishing an industry-led $41 million *National Offshore Wind Research & Development Consortium*, informed by the U.K. Carbon Trust's Offshore Wind Accelerator, provides an immediate, tangible opportunity for developing best practices in collaborative research initiatives.

- An initiative led by NREL and the American Wind Energy Association (AWEA) and supported by BNOW is underway to update AWEA's 2012 "Offshore Wind Compliance Recommended Practices: for design, deployment and operation of offshore wind turbines in the United States" to cover the additional topics of floating foundations and cables.

3. **Test Facilities and Staffing**. DOE's Office of Energy Efficiency and Renewable Energy (EERE)'s Wind Energy Technology Office (WETO) is to be commended for a recently issued RFI seeking information on U.S. offshore wind R&D testing facilities, including existing capabilities, opportunities for enhancement, and recommendations for new facilities. The data gathered will provide a basis for considering a long-term vision for research infrastructure in this country, as suggested in this white paper.

- Develop a long-term funding strategy to enable the necessary facility enhancements and sustained research community engagement, considering the approaches of NEES and OOI outlined in Section 2.

4. **Data Archives**. Consistent cyber infrastructure and data archiving for multi-disciplinary offshore wind research, with standards for meta-data, format and reporting should be developed with a long-term perspective that recognizes the primacy of domain knowledge over computer system design. Data standards and norms should develop iteratively over time, recognizing the complexity and difficulty of this task, and with emphasis on dialogue between the needs of specific projects and the drive towards a consistent architecture. Catalyzing this process can begin by:

- Establishing specific project examples by prototyping data management systems as key features of funded projects in a variety of disciplines.

- Support ongoing communities of interest to compare and vet these prototypes in an effort to evolve consistent norms over the long term. Engage industry in discussions about archiving private data in a way that makes it available for research while protecting intellectual property.

5. **Modeling Platform**. The development of open-source modeling platforms will enable integrated structural, mechanical and electrical systems models that can be linked, via hybrid simulation, to the testing facilities.

- Provide resources and review for benchmarking studies that set the standard for approaches to system-level modeling.

- Develop a protocol for updating benchmarking studies as system-level modeling improves, and support the technical community in evaluating and maintaining high-quality benchmarks.

Section 3 introduces 5 strategic research themes that emerged from the study and workshop discussions that informed this white paper. In combination with the concept of a tangible multidisciplinary, collaborative and system-based network described above, these ideas provide a basis for on-going conversation among government, industry, key stakeholders and the research community about how to leverage the best of U.S. research expertise in support of the domestic offshore wind industry.

The authors intend to continue this conversation, and invite feedback, suggestions and questions.

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