



Offshore Wind Resource, Cost, and Economic Potential in the State of Maine

Walter Musial National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency & Renewable Energy Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report NREL/TP-5000-70907 February 2018

Contract No. DE-AC36-08GO28308



Offshore Wind Resource, Cost, and Economic Potential in the State of Maine

Walter Musial National Renewable Energy Laboratory

Suggested Citation

Musial, Walter 2018. Offshore Wind Resource, Cost, and Economic Potential in the State of Maine. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-70907. https://www.nrel.gov/docs/fy18osti/70907.pdf

NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency & Renewable Energy Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

National Renewable Energy Laboratory 15013 Denver West Parkway Golden, CO 80401 303-275-3000 • www.nrel.gov **Technical Report** NREL/TP-5000-70907 February 2018

Contract No. DE-AC36-08GO28308

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Available electronically at SciTech Connect http://www.osti.gov/scitech

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy Office of Scientific and Technical Information P.O. Box 62 Oak Ridge, TN 37831-0062 OSTI <u>http://www.osti.gov</u> Phone: 865.576.8401 Fax: 865.576.5728 Email: <u>reports@osti.gov</u>

Available for sale to the public, in paper, from:

U.S. Department of Commerce National Technical Information Service 5301 Shawnee Road Alexandria, VA 22312 NTIS <u>http://www.ntis.gov</u> Phone: 800.553.6847 or 703.605.6000 Fax: 703.605.6900 Email: <u>orders@ntis.gov</u>

Cover Photos by Dennis Schroeder: (left to right) NREL 26173, NREL 18302, NREL 19758, NREL 29642, NREL 19795.

Acknowledgments

This study was funded by the U.S. Department of Energy. The author would like to thank the many people who contributed to the content of this report from the National Renewable Energy Laboratory, including Philipp Beiter, Eric Lantz, Brian Smith and Suzanne Tegen. In addition, the contributions of Gary Norton, Dan Beals, Alana Duerr, and Patrick Gilman from the U.S. Department of Energy are greatly appreciated. Editing was provided by Sheri Anstedt (National Renewable Energy Laboratory). Any omissions are the sole responsibility of the author.

Abstract

This report provides information for decision-makers about floating offshore wind technologies in the state of Maine. It summarizes research efforts performed at the National Renewable Energy Laboratory between 2015 and 2017 to analyze the resource potential, cost of offshore wind, and economic potential of offshore wind from four primary reports: Musial et al. (2016); Beiter et al. (2016, 2017); and Moné et al. (unpublished).

From Musial et al. (2016), Maine's technical offshore wind resource potential ranked seventh in the nation overall with more than 411 terawatt-hours/year of offshore resource generating potential. Although 90% of this wind resource is greater than 9.0-meters-per-second average velocity, most of the resource is over deep water, where floating wind technology is needed. Levelized cost of energy and levelized avoided cost of energy were computed to estimate the unsubsidized "economic potential" for Maine in the year 2027 (Beiter et al. 2016, 2017). The studies found that Maine may have 65 gigawatts of economic potential by 2027, the highest of any U.S. state. Bottom-line costs for the Aqua Ventus project, which is part of the U.S. Department of Energy's Advanced Technology Demonstration project, were released from a proprietary report written by NREL in 2016 for the University of Maine (Moné et al. unpublished). The report findings were that economies of scale lowered the cost from \$300/megawatt-hour (MWh) for the two-turbine 12-megawatt (MW) Aqua Ventus 1 project, to \$126/MWh for the commercial-scale, 498-MW Aqua Ventus-2 project. Further cost reductions to \$77/MWh were found when new technology advancements were applied for the 1,000-MW Aqua Ventus-3 project in 2030. No new analysis was conducted for this report.

Table of Contents

Ac	knowledgments	iii			
1	Introduction 1				
2	Maine Offshore Wind Resource				
3	Maine Offshore Wind Cost of Energy and Economic Potential	4			
	3.1 Economic Potential Calculations	5			
	3.2 Offshore Wind Levelized Cost of Energy	6			
	3.3 Levelized Avoided Cost of Energy				
	3.4 Net Value and Economic Potential	9			
4	Aqua Ventus Cost Analysis				
5	5 Conclusions				
Re	erences				

List of Figures

Figure 1. Offshore wind technical energy potential by average wind speed for the state	
of Maine (Musial et al. 2016)	2
Figure 2. Offshore wind technical energy potential by state for water depths of greater	
than 60 m (red) and less than 60 m (blue) (Musial et al. 2016)	3
Figure 3. Levelized cost of energy for potential offshore wind projects from 2015 to 2030	
over the U.S. technical resource area	7
Figure 4. Atlantic Coast spatial LCOE distribution (2015–2027)	8
Figure 5. Atlantic Coast spatial LACE distribution (2015-2027)	8
Figure 6. Atlantic Coast spatial net value distribution (2015-2027)	10
Figure 7. Breakdown of capital expenditures for the 12-MW Aqua Ventus-I project	12
Figure 8. Breakdown of capital expenditures for a hypothetical 498-MW Aqua Ventus-II	
North Atlantic project (year 2022)	13

List of Tables

Table 1. Maine's Offshore Wind Characteristics	3
Table 2. Summary of Key Turbine Assumptions for the Spatial-Economic Assessment	5
Table 3. Available Capacity with Unsubsidized Economic Potential by State in 2027	9
Table 4. UMaine Floating Wind Energy Systems' LCOE Summary	. 11
Table 5. Key Assumptions for Future Cost-Reduction Potential	. 14

1 Introduction

The purpose of this report is to provide information for decision-makers about floating offshore wind technologies. It is a summary of several research efforts performed at the National Renewable Energy Laboratory (NREL) between 2015 and 2017 to analyze the resource potential, cost of offshore wind, and economic potential of offshore wind in the United States. For this report, the data and insights from primary research were summarized to focus on the state of Maine. The major conclusions, including data, graphics, and analyses, were derived primarily from the following reports:

- An Assessment of the Economic Potential of Offshore Wind in the United States from 2015 to 2030 (Beiter et al. 2017)
- A Spatial-Economic Cost Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030 (Beiter et al. 2016)
- Levelized Cost of Energy Analysis using a Floating Concrete Semisubmersible Foundation for the University of Maine (Moné et al. 2016 unpublished)
- Offshore Wind Energy Resource Assessment for the United States (Musial et al. 2016).

These studies focused on assessing the "technical" offshore wind resource potential (Musial et al. 2016), quantifying the variation in levelized cost of energy (LCOE) in major coastal areas of the United States (Beiter et al. 2016; Beiter et al. 2017), and estimating costs for the University of Maine's U.S. Department of Energy (DOE) Advanced Technology Demonstration project, Aqua Ventus (Moné et al. 2016). Beiter et al. (2016, 2017) also include an assessment of the economic potential of fixed-bottom and floating offshore wind technologies in major U.S. coastal areas. The assessment from Moné et al. (2016) includes case studies for both the two-turbine pilot project planned for the Monhegan Island demonstration site as well as two hypothetical commercial-scale projects; one using the current Aqua Ventus technology scaled to a 498-megawatt (MW) power plant size and another one using mature floating wind technology projected to be available in the 2030 timeframe. The relevant information pertaining to Maine was extracted from each report. Additional references and research detail can be found in each of these primary source documents. In drafting this report, text was added for context and readability, but no new analysis has been conducted.

2 Maine Offshore Wind Resource

Maine has a world-class offshore wind resource. It has high average wind speeds and a large quantity of resource in waters less than 1,000 meters (m) deep. Figure 1 shows that 90% of Maine's wind resource exceeds 9 meters per second (m/s).¹ In principle, Maine could use its offshore wind resource to supply offshore wind power to serve its in-state electric load as well as electricity markets in adjacent states such as New Hampshire and Massachusetts.



Figure 1. Offshore wind technical energy potential by average wind speed for the state of Maine (Musial et al. 2016)

A significant challenge in harnessing the most economically attractive offshore wind resource sites in Maine is water depth that is greater than 60 m, which is too deep for conventional fixed-bottom offshore wind technology (e.g., monopiles or jacket substructures).² To use its most economically viable offshore wind resource sites, Maine would need to deploy floating offshore wind technologies which, although they are advancing rapidly around the globe as described in NREL's *2016 Offshore Wind Technologies Market Report* (Musial et al. 2017), are currently in a pre-commercial stage of development.

Figure 2 shows the offshore wind technical resource potential for all offshore states in the United States (except Alaska) in rank order (Musial et al. 2016). The chart shows the quantity of resource in both deep and shallow water for potential offshore wind sites with wind speeds above 7 m/s and depths less than 1,000 m. This comparison is based on energy potential (terawatt-hours per year (TWh/yr), and Figure 2 shows that Maine ranks 7th in the nation in total offshore wind resource.

¹ Average wind speed is the most critical parameter that determines energy production potential and capacity factor.

 $^{^{2}}$ Most of the shallow resource <60 meters (m) is located very near shore and may be unsuitable for commercial offshore wind development because of conflicts with existing use and visual impacts.



Figure 2. Offshore wind technical energy potential by state for water depths of greater than 60 m (red) and less than 60 m (blue) (Musial et al. 2016)

Table 1 breaks down the quantity of offshore wind resource in Maine (gigawatt-hours/year [GWh/yr]) by water depth and regulatory jurisdiction (e.g., state waters versus federal waters).

Ocean Area with Minimum Average Wind Speeds of 7 m/s (Musial et al. 2016)			
State Waters	17,990 km²		
Federal Waters	108,304 km ²		
Total	126,294 km ²		
Net Technical Offshore Wind Energy Potential (Musial et al. 2016)			
Water Depth: 0–30 m	23,902 GWh/year	9,355 MW	
Water Depth: 31–60 m	20,120 GWh/year	14,772 MW	
Water Depth: 61–700 m	367,162 GWh/year	44,659 MW	
Total	411,184 GWh/year	94,498 MW	

Table 1. Maine's Offshore Wind Characteristics

Currently, offshore wind development activity in Maine is limited to the new technology proposed under the New England Aqua Ventus-I demonstration project that is participating in DOE's Advanced Technology Demonstration program (Musial et al. 2017).

3 Maine Offshore Wind Cost of Energy and Economic Potential

Techno-economic analysis detailed in Beiter et al. (2016, 2017) constitutes the primary reference source for characterizing over a broad area the economics of offshore wind for the state of Maine. These analyses were conducted using "NREL's Offshore Wind Cost Model". This model estimates the cost of offshore wind in the United States for hypothetical projects with commercial operation dates (CODs) between 2015 and 2027. Beiter et al. (2016, 2017) analyzed the impact of geospatial and temporal parameters across more than 7,000 U.S. coastal locations on LCOE. Beiter et al. (2017) also assessed in detail the economic potential of offshore wind in the United States. Economic potential is achieved when there is a positive "net value" which is calculated by subtracting the estimated LCOE from the estimated levelized avoided cost of energy (LACE) at a common location (see also Section 3.4). This section summarizes the relevant results from Beiter et al. (2016, 2017) for the Atlantic states and the state of Maine. It also offers insights into the available offshore wind resource in Maine at different levels of LCOE and assesses its present and future economic potential. Additional site-specific cost analysis for four conceptual projects off the coast of Maine are included in Section 4.³

In Beiter et al. (2016, 2017), estimates of offshore wind costs were calculated for three focus years corresponding to CODs⁴ of 2015, 2022, and 2027. In 2015, a baseline turbine rating of 3.4 MW was assumed as it reflected the average turbine size of installed offshore wind power projects globally in 2014 (Smith, Stehly, and Musial 2015), the last year of available data when the Smith et al. (2015) study was conducted. Informed by research on industry trends, turbine ratings of 6 MW and 10 MW were assumed to represent technologies for 2022 and 2027, respectively.⁵ Accordingly, the 6-MW turbine size proposed by the Aqua Ventus project corresponds with the turbine size assumptions for a 2022 COD in this analysis. Based on this assumed growth trajectory in turbine size as well as global industry maturation, a set of cost reductions and associated technology improvements were projected for 2015, 2022, and 2027. Estimated cost reductions were based on an assessment conducted by The Crown Estate, BVG Associates, and KIC InnoEnergy (The Crown Estate 2012; Valpy et al. 2014). The cost-reduction pathway used in Beiter et al. (2016, 2017) applies modeled cost reduction pathways derived from European projects from 2015 to 2027 and assumes that sufficient domestic deployment and maturing of the supply chain will occur in the United States to support these cost reductions. The turbine technology change indicated in Table 2 was assigned in the beginning of each focus year and held constant at all sites until the next focus year.

³ These analyses draw from many other relevant data sources and reports. Reviewing these documents is encouraged, including Moné et al. (2015), Energy Information Administration (EIA) *Annual Energy Outlook* 2014, Catapult (2015), E.C. Harris (2012), and The Crown Estate (2015).

⁴ All years reported in commercial operation date (COD), unless indicated otherwise.

⁵ The turbine size trajectory of 6 megawatts (MW) by 2022 and 10 MW by 2027 was informed by announced turbine supply agreements in 2015, indicating that by 2019/2020, the turbine size average would be between 6 and 8 MW and by 2027 turbine sizes of 10-12 MW will be available in Europe.

Financial Close	2013	2020	2025
Commercial Operation Date	2015	2022	2027
Turbine Rated Power (MW)	3.4	6	10
Power Plant Size (MW)	600	600	600
Turbine Hub Height (m)	85	100	125
Turbine Rotor Diameter (m)	115	155	205
Turbine Specific Power ^a (W/m ²)	327	318	303

Table 2. Summary of Key Turbine Assumptions for the Spatial-Economic Assessment

^a Specific power is the ratio of a wind turbine's nameplate capacity rating to its rotor-swept area. All else equal, a decline in specific power should lead to an increase in capacity factor.

In addition to specific turbine technology advancements described in Table 2, other future advancements were assumed to drive cost reductions in total capital expenditures (CapEx) (e.g., turbine, substructures, electrical infrastructure), operational expenditures (OpEx), and financing. Factors that increase the annual energy output of offshore wind plants were also included.

3.1 Economic Potential Calculations

LCOE reflects the total cost of generating a unit of electricity and is commonly expressed in dollars per megawatt-hour (\$/MWh). LCOE is typically calculated for the expected lifetime of the offshore wind electricity-generating plant. LCOE varies by location because of geographic factors that affect energy production (e.g., average wind speed variations) and CapEx (e.g., varying sea states, distance from shore, water depth, soil and substructure suitability, and availability of critical infrastructure).

LCOE alone is generally not sufficient to assess economic viability because it does not capture the electric system value that can be attributed to a particular generation source operating in a specific location. To calculate economic potential, Beiter et al. (2016, 2017) needed to estimate the LACE for each offshore location. LACE is a metric used to approximate the electric system value of a generation technology operating in a given location over its expected lifetime and commonly expressed in \$/MWh. Electric system value, as assessed by Beiter et al. (2016, 2017), is defined as the revenue that an offshore wind generator can earn (reflecting its marginal economic value) without considering subsidies. The system value of offshore wind is affected by unique technology-specific features including the location (i.e., coincidence with load patterns and available transmission), uncertainty (i.e., forecasting errors), and variability (i.e., generation profile) (Hirth 2013). LACE also varies by location because of differences in the system value of new electricity, which are determined by a range of factors, including the cost of competing generation technologies, the existing resource mix, demand patterns, and transmission constraints (Beiter et al. 2017).

As a metric to determine the value of new generation projects, LACE was developed to complement the well-established LCOE metric (e.g., Energy Information Administration [EIA] 2015; Namovicz 2013; EIA 2013). These metrics are complementary in the sense that LCOE comprises a measure for revenue requirements (based on the cost required to generate electricity), whereas LACE captures the revenues available to that generating source. Therefore, the two metrics can be compared to provide an indicator of economic attractiveness (EIA 2013).

The difference between LCOE and LACE at a given location is defined as "net value," and is used to define economic potential, which is the subset of sites with a given capacity (in MW) within the technical resource potential resource area (Musial et al. 2016), in which "net value" is greater than zero.

As such, "net value" at a given site, i, is defined in Equation 1:

Net value
$$(\%/MWh)_i = LACE - LCOE$$
 (1)

For a given offshore wind site to have economic potential, LACE must be greater than LCOE. A more detailed description of how LACE was determined for Maine and for various sites around the United States is provided in Beiter et al. (2017).

3.2 Offshore Wind Levelized Cost of Energy

The shaded grey area in Figure 3 shows the variance of LCOE estimated by the NREL Offshore Wind Cost model across all U.S. coastal sites (indicated by the vertical blue two-way arrow) and over time (along the horizontal time axis). The lower edge of the LCOE shaded area (the very best offshore wind sites) shows a cost decline from \$130/MWh⁶ in 2015 to approximately \$60/MWh in 2030. Figure 3 also includes two offshore wind cost-reduction reference sites; one for the fixed-bottom technology and one for the floating technology, respectively. The characteristics of these generic reference sites are specified in Beiter et al. (2016)⁷ but their site conditions are generally intended to represent typical spatial conditions for the existing Bureau of Ocean Energy Management lease areas already auctioned on the U.S. outer continental shelf. Although these reference sites are intended to represent the average of many Bureau of Ocean Energy Management lease areas, they do not represent a specific location or power plant site. The two reference site curves follow the same general cost-reduction trends shown in the overall data from Figure 3. The two curves show that although the LCOE for floating technology is significantly higher in 2015, fixed-bottom and floating technology costs are predicted to converge over time. This is an important aspect to understand the cost estimations for the state of Maine, which will likely depend on floating technology.

Some of the drivers that lead to lower LCOE in general include:

- Stronger wind resources, ranging from 8.5 to 10 m/s, which result in net capacity factors between 40% and 60%
- Closer proximity to the land-based grid interconnect, which minimizes the electrical infrastructure and maintenance costs
- Proximity to an inshore assembly area
- Proximity to shore-based port facilities, which minimizes installation, maintenance, and export system costs
- Shallower water depths, which minimize substructure costs.

⁶ All dollars reported in \$2015, unless indicated otherwise.

⁷ The fixed-bottom cost-reduction scenario site assumes a water depth of 30 m and a distance from shore of 30 kilometers (km). The floating cost-reduction scenario site assumes a water depth of 100 m and a distance from shore of 30 km.



Figure 3. Levelized cost of energy for potential offshore wind projects from 2015 to 2030 over the U.S. technical resource area

Source: Beiter et al. (2016)

Note: Fixed-bottom and floating scenarios are represented by exponential curve fits through the modeled LCOE values in 2015, 2022, and 2027.

In Figure 4, heat maps of the LCOE for the Atlantic Coast are presented. In 2015, LCOE was estimated to range from approximately \$125–\$270/MWh in the Northeast⁸ and \$145–\$315/MWh in the mid-Atlantic regions⁹ to \$150–\$385/MWh in the Southeast.¹⁰. These ranges decrease to \$95–\$180/MWh (Northeast), \$110–\$210/MWh (mid-Atlantic), and \$115–\$260/MWh (Southeast) by 2022. By 2027, the LCOE range in the Northeast was estimated to decline to \$80–\$130/MWh (Northeast), \$85–\$150/MWh (mid-Atlantic), and \$90–\$185/MWh (Southeast).

The Atlantic Coast was found to have some of the lowest LCOE sites in any of the U.S. coastal areas. Low-cost sites are generally near shore and in relatively shallow waters. Some of the lowest-cost sites are located in Maine, Massachusetts, Rhode Island, and New York. As shown in Figure 4, areas of relatively low LCOE extend far from shore in Maine, New Hampshire, Massachusetts, and Rhode Island, mostly because of high average wind speeds (see Musial et al. 2016).

⁸ The Northeast region includes Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, and New York.

⁹ The mid-Atlantic region includes Delaware, Maryland, Virginia, North Carolina, and South Carolina.

¹⁰ The Southeast region includes Georgia and Florida.



Figure 4. Atlantic Coast spatial LCOE distribution (2015–2027)

3.3 Levelized Avoided Cost of Energy

The LACE for the Atlantic coastal states is shown in Figure 5 as heat maps for the three target years: 2015, 2022, and 2027.



Figure 5. Atlantic Coast spatial LACE distribution (2015–2027)

The variance in LACE is relatively high in the Atlantic Coast region than the other coastal regions. These differences can be observed in detail in Beiter et al. (2017). The highest levels of LACE are generally found off the coast of Virginia, Connecticut, Rhode Island, Massachusetts, and Maine, primarily because of comparatively high electricity price levels. Comparatively low levels of LACE were found on the Southeast Coast along Florida, North Carolina, and South Carolina where electricity price levels are generally lower. LACE increases incrementally from

2015 to 2027 as shown by the increasingly dark color scheme in Figure 5 and estimated by EIA's *Annual Energy Outlook* generation price forecasts (EIA 2014).

3.4 Net Value and Economic Potential

Figure 6 shows a heat map of the "net value" estimated for the Atlantic Coast for 2015, 2022, and 2027. The data show that by 2027, coastal areas in the Northeast and the eastern shore of Virginia (southern part of the Delmarva Peninsula) begin to have a positive net value, indicating there is economic potential for offshore wind in these regions (shown in yellow and green).

The model suggests that economic potential for offshore wind exists in the following states (listed in descending order by the amount of economic potential): Maine, Massachusetts, Rhode Island, Virginia, New Hampshire, New York, and Connecticut. Quantitative estimates of economic potential are shown in Table 3.

State	Economic Potential (Nameplate Capacity in Gigawatts)	
Maine	65	
Massachusetts	55	
Rhode Island	16	
Virginia	4	
New Hampshire	2	
New York	1	
Connecticut	1	

Table 3. Available Capacity with Unsubsidized Economic Potential by State in 2027

Source: Beiter et al. (2017)

In these areas, relatively low LCOE values coincide with relatively high LACE values. By 2027, this combination creates favorable economic conditions for offshore wind in these regions even in the absence of state or federal subsidies. There is also a subset of sites (approximately 9 gigawatts (GW) of economic potential) in Massachusetts and Rhode Island where the net value was found to be greater than \$15/MWh in 2027. Although 9 GW comprises less than 1% of the total resource estimated for the Atlantic Coast region, it exceeds the combined capacity of landbased wind and photovoltaics currently installed in the northeast as of 2015 (Beiter and Tian 2016). These sites are predicted to have the highest net value in the United States. A considerable band of coastal areas with a net value between -\$50/MWh and \$0/MWh in 2027 spans from far distance locations off the coast of New England states down to the coast of Virginia. This suggests that there is potential for a much greater area to move to positive net value and contribute to the total economic potential as the industry matures over time and with greater rates of technology innovation and cost reduction.





4 Aqua Ventus Cost Analysis

This analysis was conducted by NREL under contract with the University of Maine (UMaine)¹¹ in the late 2015/early 2016 timeframe (Moné et al. 2016). The purpose of this work was to inform the evaluation of the total cost of the different offshore wind project scenarios using UMaine's semisubmersible concrete substructure in the Atlantic, including capital investment costs (e.g., equipment and its installation), operation and maintenance costs, finance costs, and estimated energy production.

The focus of this proprietary report is the 12-MW offshore wind project—Aqua Ventus-I—which is planned to be installed off the coast of Monhegan Island in southern Maine. The two-turbine 12-MW project is the next phase of UMaine's VolturnUS prototype, which was a 1:8 scale concrete semisubmersible hull, composite tower, and wind turbine that was in Penobscot Bay for a 1.5-year test program in 2013/2014. This initial effort served to collect data and demonstrate the first offshore grid-connected wind turbine in the United States. To provide a better understanding of the potential viability of the technology at demonstration and commercial scales, an LCOE analysis was performed for three floating wind concepts using Aqua Ventus technology: 1) a 12-MW demonstration, 2) a 498-MW commercial scale array with current technology, and 3) a 1,000-MW commercial scale array with 2030 technology. LCOE numbers in Table 4 provide a summary of costs and energy production related to offshore wind projects relevant to the UMaine floating wind technology (UMaine 2018). The information used in this analysis came from NREL's internal Offshore Wind Database, multiple economic models, and Aqua Ventus-I supplier quotes.

Description	Aqua Ventus-I (12-MW) (US\$ ₂₀₁₅ /MWh)	Aqua Ventus-II Atlantic 498-MW Project 2022 COD (US\$ ₂₀₁₅ /MWh)	Aqua Ventus-III Atlantic Floating 1,000- MW Project 2030 COD (US\$ ₂₀₁₅ /MWh)
Turbine Capital Cost*	59	38	***
Balance of System*	181	57	***
Financial Costs*	10	16	***
Operation and Maintenance Cost**	50	15	***
Total System LCOE	300	126	77

Table 4. UMaine Floating Wind Energy Systems' LCOE Summary

(Source: Moné et al. 2016)

*These categories are multiplied by the discount rate, and insurance, warrantee, and fees to obtain LCOE

**This category is considered tax deductible

*** Data not available

The site parameters for this analysis were representative of conditions at Monhegan Island (column 2) and the Massachusetts wind energy areas (columns 3 and 4) (Musial 2013). It was also assumed that federal or state policy incentives were not available (e.g., the investment or production tax credits); that is, no subsidies exist. For the two-turbine (12-MW) Aqua Ventus-1

¹¹ Funding from the University of Maine was awarded to UMaine by DOE under a cooperative agreement as part of the Advanced Technology Demonstration funding opportunity.

demonstration project, the \$40 million DOE grant money is included in the LCOE calculation. This is shown in column 2 of Table 4. In column 3, a 498-MW commercial-scale wind power plant using current technology (e.g., 6-MW turbines, semisubmersible concrete hull) is estimated, and is considered representative for the states of Maine or Massachusetts for projects built in the 2020/2022 timeframe. Note the costs for the demonstration project is \$300/MWh, which is relatively high due to the small project scale. In contrast, the large-scale commercial project, using UMaine's Aqua Ventus technology, is summarized in column 3 and has an estimated LCOE of \$126/MWh. The LCOE reduction was achieved by upscaling the project to a commercial size to capture economies of scale.

Some of these LCOE scaling differences can be attributed to the change in the capital cost distribution shown in Figure 7 and Figure 8 (Moné et al. 2015). Figure 7 illustrates the estimated cost breakdown of Capex for the Aqua Ventus-I 12-MW project. By comparison, Figure 8 shows the cost breakdown for the hypothetical 498-MW commercial-scale project in the Atlantic. In each figure, the turbine costs are highlighted in green, the balance of plant is highlighted in blue, and the financial costs are highlighted in purple.



Figure 7. Breakdown of capital expenditures for the 12-MW Aqua Ventus-I project



Figure 8. Breakdown of capital expenditures for a hypothetical 498-MW Aqua Ventus-II North Atlantic project (year 2022)

Although the costs for the smaller two-turbine project are generally higher in all cost categories as a result of lower volume and reduced leverage in purchasing components, the percentages attributed to the balance of plant are also much greater for the smaller-scale project. This higher BOS percentage results because many of the plant-wide costs, which are in some cases fixed and independent of project size, are distributed over fewer turbines (i.e., two turbines for the demonstration project compared to 83 turbines for the commercial-scale project).

Another cost influence that may have an impact on LCOE similar to project upscaling is the impact of future technology and industry maturity. Just as the industry has seen rapid cost declines in fixed-bottom offshore wind technology (Musial et al 2017), NREL cost models predict similar (or greater) cost declines for floating technology due to technology advancement and industry learning (Figure 3).

The future cost-reduction potential for floating wind, including the Aqua Ventus technology, was estimated in column 4 of Table 4 using NREL's Offshore Wind Cost Model. This approach resulted in an estimated cost reduction for floating wind technology with an LCOE of \$77/MWh for the 2030 timeframe. In this future scenario, a larger 1,000-MW project sited in the Massachusetts wind energy area was assumed.¹² Table 5 shows the key assumptions driving the LCOE reduction between 2015 and 2030 COD from this additional cost scenario.

¹² This is the same Massachusetts site as the 498-MW Aqua Ventus-II utility-scale project summarized in column 3 of Table 4. However, as shown in Table 5, we do anticipate an increase in net capacity factor even at this same site as a result of advancements in turbine technology and plant operations, which increase energy extracted per unit of installed capacity and reduce overall plant losses.

Offshore Wind Turbine Specifications	2022 Aqua Ventus-II Baseline	2030 Aqua Ventus-III Advanced Technology
Turbine Rated Power	6.0 MW	10 MW
Net Capacity Factor	46.7%	54%
Power Plant Size	498 MW	1,000 MW
Plant Resources	9.3 m/s at 100 m	9.3 m/s at 100 m
Water Depth/Distance from Shore	100 m/52 km	100 m/52 km
Substructure Foundation	Semisubmersible	Semisubmersible

Table 5. Key Assumptions for Future Cost-Reduction Potential

The estimated reductions in LCOE for floating technology between today's technology (e.g., 6-MW turbines, immature supply chains, and limited deployment experience) and future technology (e.g., larger project and turbine scale, mature supply chains, higher capacity factors) are also shown by major cost categories in the waterfall plot in Figure 9. These results can be generally used to approximate floating wind technology trends (using semisubmersible substructures). Beiter et al. (2017) assumes the industry will develop a wide array of technology innovations and a robust regional supply chain that does not rely entirely on projects originating in Maine.



Figure 9. Floating offshore waterfall for 2015–2030 (COD) UMaine LCOE reduction

5 Conclusions

This summary report includes detail on the resource and economic potential for offshore wind in Maine. Specific project cost estimates reported were assessed for coastal sites in Maine and Massachusetts between 2015 and 2030. Data presented in this report draw from several previously published sources, as well as one proprietary report written by NREL for UMaine in April 2016. The assessments include heat maps of LCOE, LACE, and net value.

These data show that by 2027, significant economic potential is estimated to grow in many northeast states, with the highest economic potential found in Maine. Based on assumptions from NREL's Offshore Wind Economic Model, 65 GW of economic potential is estimated to develop in the state of Maine by 2027. This economic potential occurs mostly in water depths greater than 60 m but is the most economic potential of any state in 2027. Moreover, the number of sites with a positive net value (or a value close to a positive net value) may continue to increase with time as a result of falling offshore wind costs and incrementally increasing avoided costs of energy.

The analyses reviewed for this summary report also showed that economies of scale and future technology advancements are likely to play a large role in reducing the cost of floating offshore wind. As shown, the cost of energy for the Aqua Ventus technology was estimated to decrease from \$300/MWh for a two-turbine project to \$126/MWh for a 498-MW commercial-scale project. When expected advances in floating wind technology were applied (e.g., 10-MW turbine sizes), the estimated LCOE by 2030 was calculated to be \$77/MWh. To achieve these cost levels, further technology improvements are needed in deep-water floating wind, which is currently in a nascent stage of development. UMaine has been a major contributor to the global advancement of floating technology through the DOE Advanced Technology Demonstration program (Musial et al. 2017).

Limitations of these analyses and corresponding caveats are discussed in detail in the source reports; however, here are some of the most important caveats to keep in mind:

- To achieve the modeled cost reductions, continued investments in technology innovation, development, and the market visibility of a robust domestic supply chain must be established and maintained during the analysis period from 2015 to 2027 (Navigant [2012]; European Commission [2016]).
- This analysis does not consider competition among technologies, dynamic feedback from increasing renewable deployment on wholesale electricity prices, export or import situations, or the alleviation of electricity system constraints (e.g., transmission constraints) over time; along with net value, these factors are critical in making future power generation procurement decisions.
- LACE was estimated based on annual averages of marginal generation prices and a constant capacity value. This specification does not consider the subhourly, hourly, or seasonal coincidence of offshore wind generation profiles with marginal generation prices or capacity value.
- LACE, as applied here, does not include possible policy-related factors or subsidies, either nationally or in individual states, such as renewable energy support mechanisms (e.g., the

production tax credit, carbon pollution and other greenhouse gas regulations, state renewable portfolio standards, and loan guarantee programs), energy sector and environmental regulations, or benefits from portfolio diversification.

- Economic potential is not a measure of project-specific profitability.
- The Crown Estate (2012) report was the primary foundation for the NREL Offshore Wind Cost Model. As such, it is important to be aware that more recent cost declines indicated by European offshore wind auctions in 2016 and 2017 were not considered in writing this report (Musial et al. 2017). The documented 65% decline in fixed-bottom European winning tender prices may indicate that some of the costs assessed by Beiter et al. (2016, 2017) could be conservative given that U.S. costs for floating wind are likely to be influenced by European market factors. Although floating technology may not follow the same cost trajectory as seen in Europe's fixed-bottom auctions, the relative cost differences between the Aqua Ventus 12-MW pilot project and larger commercial-scale projects (Table 4) are expected to remain proportionally comparable, because these project differences are predominately a function of project scale and future technology advancements rather than foundation type.

References

Beiter, P., W. Musial, A. Smith, L. Kilcher, R. Damiani, M. Maness, S. Sirnivas, T. Stehly, V. Gevorgian, M. Mooney, and G. Scott. 2016. *A Spatial-Economic Cost Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030* (Technical Report). NREL/TP-6A20-66579. National Renewable Energy Laboratory (NREL), Golden, CO (US). www.nrel.gov/docs/fy16/66579.pdf.

Beiter, P., and T. Tian. 2016. 2015 Renewable Energy Data Book. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Accessed December 2016. www.nrel.gov/docs/fy17osti/66591.pdf.

Beiter P., W. Musial, L. Kilcher, M. Maness, A. Smith. 2017. An Assessment of the Economic Potential of Offshore Wind in the United States from 2015 to 2030 (Technical Report). NREL/TP-6A20-67675. NREL, Golden, CO (US). <u>http://www.nrel.gov/docs/fy17osti/67675.pdf</u>.

Catapult. 2015. Cost Reduction Monitoring Framework 2015. Qualitative Summary Report to the Offshore Wind Programme Board. Swindon, U.K.: Innovate UK Technology Strategy Board. Accessed May 2016. <u>https://ore.catapult.org.uk/wp-content/uploads/2016/05/Cost-Reduction-Monitoring-Framework-2015.-Qualitative-report.pdf</u>.

The Crown Estate. 2012. *Offshore Wind Cost Reduction Pathways Study*. London, U.K. <u>http://www.thecrownestate.co.uk/media/5493/ei-offshore-wind-cost-reduction-pathways-study.pdf</u>.

The Crown Estate. 2015. *Cost Reduction Monitoring Framework: Summary Report to the Offshore Wind Programme Board*. Glasgow: Catapult Offshore Renewable Energy. <u>https://ore.catapult.org.uk/documents/10619/110659/ORE+Catapult+report+to+the+OWPB/a8c7</u> <u>3f4e-ba84-493c-8562-acc87b0c2d76.</u>

E.C. Harris. 2012. *Offshore Wind Cost Reduction Pathways: Supply Chain Work Stream*. London, U.K.: The Crowne Estate. <u>http://www.thecrownestate.co.uk/media/5614/ei-echarris-owcrp-supply-chain-workstream.pdf</u>.

Energy Information Administration (EIA). 2013. "Levelized Cost of Electricity and Levelized Avoided Cost of Electricity Methodology Supplement." Presented at the Workshop on Assessing the Economic Value of New Utility-Scale Renewable Generation Projects Using Levelized Cost of Electricity and Levelized Avoided Cost of Electricity, Washington, D.C. July 25. Accessed May 2016. <u>http://www.eia.gov/renewable/workshop/gencosts/pdf/methodology_supplement.pdf</u>.

EIA. 2014. *EIA Annual Energy Outlook 2014*. Washington, D.C.: Energy Information Administration. Accessed May 2015. <u>http://www.eia.gov/forecasts/aeo/pdf/0383(2014).pdf</u>.

EIA. 2015. *Annual Energy Outlook 2015 with Projections to 2040* (Technical Report, DOE/EIA-0383(2015). Washington, D.C. Accessed July 2015. http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf. EIA. 2016. "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2015." Washington, D.C. Accessed March 2016. https://www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf.

European Commission. 2016. "SET-Plan—Declaration on Strategic Targets in the Context of an Initiative for Global Leadership in Offshore Wind." Paper presented by the SET Plan Secretariat, Brussels, Belgium, January 20. Accessed June 2016. https://setis.ec.europa.eu/system/files/declaration of intent offshore wind.pdf.

Hirth, L. 2013. "The Market Value of Variable Renewables: The Effect of Solar Wind Power Variability on their Relative Price." *Energy Economics* 38:218–236. doi:10.1016/j.eneco.2013.02.004.

Moné, C., T. Stehly, B. Maples, and E. Settle. 2015. 2014 Cost of Wind Energy Review (Technical Report). NREL/TP-6A20-64281. National Renewable Energy Laboratory (NREL), Golden, CO (US). <u>http://www.nrel.gov/docs/fy16osti/64281.pdf</u>.

Moné, C., T. Stehly, and W. Musial. 2016. W. *Levelized Cost of Energy Analysis using a Floating Concrete Semi-submersible Foundation for the University of Maine*, Unpublished contractor report, April 24, 2016.

Musial, W. D. 2013. "Proposed Methodology for Massachusetts Wind Energy Area Delineation," Webinar presentation at BOEM Massachusetts Task Force meeting, May 15, 2013. Accessed July 2016. <u>http://www.nrel.gov/docs/fy14osti/60942.pdf</u>.

Musial, W., P. Beiter, D. Heimiller, and G. Scott. 2016. 2016 Offshore Wind Energy Resource Assessment for the United States (Technical Report). NREL/TP-5000-66599. National Renewable Energy Laboratory (NREL), Golden, CO (US). http://www.nrel.gov/docs/fy160sti/66599.pdf.

Musial, W., P. Beiter, P. Schwabe, T. Tian, T. Stehly, P. Spitsen. 2017. 2016 Offshore Wind Technologies Market Report. U.S. Department of Energy.. https://energy.gov/sites/prod/files/2017/08/f35/2016%20Offshore%20Wind%20Technologies%2 0Market%20Report.pdf.

Namovicz, C. 2013. "Assessing the Economic Value of New Utility-Scale Renewable Generation Projects." Paper presented at the EIA Energy Conference, Washington, D.C., June 17. Accessed May 2015. <u>http://www.eia.gov/conference/2013/pdf/presentations/namovicz.pdf</u>.

Navigant. 2013. "U.S. Offshore Wind Manufacturing and Supply Chain Development". Prepared for U.S. Department of Energy. www.osti.gov/scitech/servlets/purl/1087161.

Smith A., T. Stehly, W. Musial. 2015. 2014-2015 Offshore Wind Technologies Market Report (Technical Report). NREL/TP-5000-64283. NREL, Golden, CO (US). http://www.nrel.gov/docs/fy15osti/64283.pdf.

University of Maine. 2018. Aqua Ventus Home Page. Accessed January 23, 2018.http://maineaquaventus.com/

Valpy, B., P. English, A. Martínez, and E. Simonot. 2014. *Future Renewable Energy Costs: Offshore Wind* (Technical Report). Cricklade, U.K.: BVG Associates. <u>http://www.kic-innoenergy.com/wpcontent/uploads/2014/09/KIC_IE_OffshoreWind_anticipated_innovations_impact1.pdf</u>.