Assessment of Offshore Wind Energy Leasing Areas for the BOEM Maryland Wind Energy Area

W. Musial, D. Elliott, J. Fields, Z. Parker,
G. Scott, and C. Draxl

Produced under direction of the Bureau of Ocean Energy Management (BOEM) by the National Renewable Energy Laboratory (NREL) under Interagency Agreement M13PG00002 and Task No. WFS3.1000

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Technical Report
NREL/TP-5000-58562
June 2013

Contract No. DE-AC36-08GO28308

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Executive Summary

The National Renewable Energy Laboratory (NREL), under an interagency agreement with the Bureau of Ocean Energy Management (BOEM), is providing technical assistance to identify and delineate leasing areas for offshore wind energy development within the Atlantic Coast Wind Energy Areas (WEAs) established by BOEM. This report focuses on NREL's evaluation of the Maryland (MD) WEA for the following scenarios:

- Leasing area delineation proposed by the Maryland Energy Administration (MEA)
- Two other leasing area delineation options proposed by NREL
- Leasing area delineations for two smaller WEA options proposed by BOEM in response to navigation concerns raised by the U.S. Coast Guard (USCG).

The objectives of the NREL evaluation were to assess MEA's proposed delineation of the MD WEA, perform independent analysis for the MD WEA as well as the alternative WEAs, and provide recommendations to BOEM on how the MD WEA scenarios could best be delineated.

As part of the evaluation, NREL researchers:

1. Analyzed MEA's proposed leasing areas
2. Presented a methodology for analysis and discussed NREL's preliminary recommendations of the State of Maryland's leasing area delineation with the BOEM Maryland Renewable Energy Task Force on January 29, 2013, in Annapolis, Maryland
3. Reviewed nine responses to the 2010 Maryland Request for Interest and six responses to the 2012 Maryland Call for Information and Nominations to assess any effect on the proposed development parameters
4. Conducted an independent analysis of two alternative delineations of the MD WEA
5. Proposed a preferred method of leasing area delineation for the MD WEA
6. Conducted independent analysis on two options proposed by BOEM to address navigation concerns raised by the USCG
7. Prepared this report summarizing NREL's technical approach and final recommendations to BOEM for leasing area delineations within the MD WEA, as well as the two alternative WEAs proposed by BOEM in response to the navigation concerns raised by the USCG.

In addition, NREL reviewed information from the following sources:

- Maryland Request for Interest 2010 and nine responses to the RFI
- 2012 Maryland Call for Information and Nominations (the "Call") and six responses to the Call
- The Maryland Wind Energy Area Zone Recommendation Memo (Gohn 2012)
- Verbal input received from MEA and the Maryland Department of Natural Resources during a conference call conducted on January 23, 2013

- Presentations delivered at the BOEM Maryland Renewable Energy Task Force meeting held on January 29, 2013.

The State of Maryland indicated to BOEM a preference to delineate the MD WEA into two leasing areas that would provide approximately equal potential in terms of near-term commercial development. For the MD WEA and the delineation proposed by MEA, there are two proposed leasing areas: a north (A) leasing area, with 155.52 square kilometers, and a south (B) leasing area, with 167.04 square kilometers. In addition, the state provided a list of criteria (Section 2.1) that it used to compare the relative value of each leasing area. After conducting an independent analysis using the criteria in Table ES1, NREL researchers concluded that the MEA delineation criteria included the most important aspects governing the economic value of offshore wind site development and that the final delineation of the MD WEA was logical in terms of achieving economic parity between the two leasing areas. However, some of the assumptions made by MEA and NREL were subjective, or based on hypothetical project parameters that might differ under actual development conditions. Each MEA leasing area has advantages and disadvantages and MEA presented rational arguments suggesting that the two proposed leasing areas are balanced for equal development potential. NREL's analysis, however, suggests that a more thorough analysis of certain quantitative factors (i.e., wind speed, wind direction, bathymetry, and wake effects) and informed weighting of the evaluation criteria could provide better optimization and closer balancing. NREL researchers conducted analysis to investigate the merits of the proposed Maryland delineation.

Table ES1. Evaluation Criteria Used by NREL to Assess the Maryland (MD) WEAs
(Source: NREL)

Quantitative Evaluation Criteria	Qualitative Evaluation Criteria Considered
Total area [square kilometers (km^2) and acres]	Distance from shore
Potential installed capacity [megawatts (MW)]	Fisheries and competing uses
Bathymetry [meters (m)]	Technology challenges
Annual average wind speed [meters per second (m/s)]	Development cost
Gross capacity factor (%)	Development timing
Wake losses (%)	
Annual energy production [gigawatt-hours (GWh)]	
Navigational impacts on WEA	

NREL also evaluated two additional delineation options: the NREL preferred option (a modification of the MEA delineation option), and an alternate option that sectioned the WEA using a more diagonal delineation boundary. All three delineation options of the WEA are shown below in Figure ES1. Note that each of the delineation scenarios includes a 1 nautical mile no-build setback from a potential extension of an established navigational traffic separation scheme (TSS) to the east of the WEA, depicted as a diagonal red line on the figures. NREL researchers found that the preferred option (B) is the best choice for achieving parity between the two proposed leasing areas. This option places a lower value on the deep water aliquots by moving three aliquots from the north side into the south leasing area to make leasing area B larger, and makes more efficient use of the WEA by using a straight line to delineate the leasing areas.

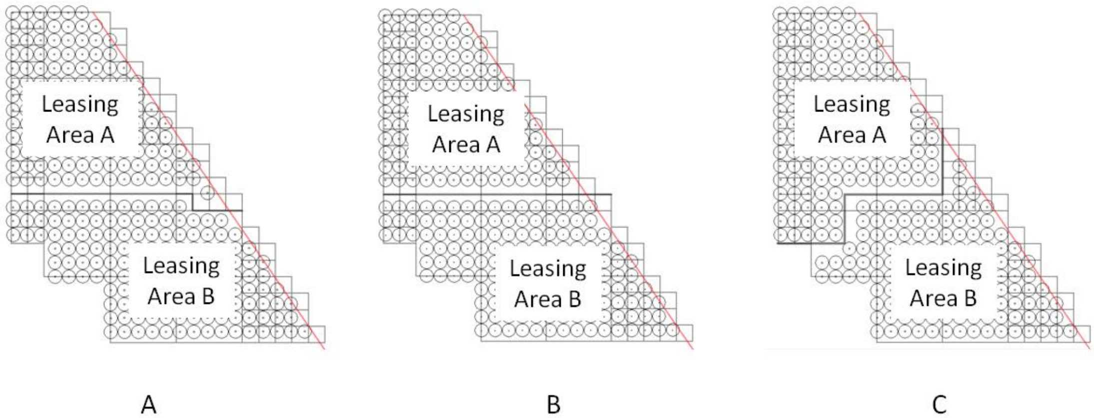

Figure ES1. Maryland Energy Administration's (MEA's) proposed delineation (A), NREL's preferred delineation (B), and NREL's diagonal optional delineation (C), provide insights on possible delineation strategies and sensitivities. NREL recommends the preferred delineation (B) as a modification to the MEA proposal.
(Source: NREL)

Table ES2 provides a comparison of the quantitative results for the three delineation options assessed for the MD WEA, as proposed by MEA and NREL, respectively. Each option was assessed (in rotor diameters, D) for both 8D x 8D and 8D x 12D turbine array spacing. All of the delineations shown in Figure ES1 represent leasing areas that are approximately equal in terms of their development potential.

Wind turbine array modeling was based on the NREL 5-megawatt (MW) reference turbine (Jonkman et al. 2009). NREL used 8D x 8D spacing to provide an estimate of wake losses that was consistent with the wind resource density used by NREL to calculate the gross resource in the United States and the practices used in current European offshore wind projects (Musial and Ram 2010). In addition, NREL assessed wider 8D x 12D spacing that was closer to the U.S. developers' proposals received by BOEM.

Using the 8D spacing criteria and the AWS Truepower OpenWind Enterprise tool, the analysis showed that wake losses were not significantly different among the delineation scenarios and therefore the wake effects were not a primary driver in setting the delineations. However, for the 8D x 8D spacing, the absolute wake losses were found to be in the range of 16%–17% (not including electrical losses), and would likely have a negative impact on the project economics, indicating that increased turbine spacing or more internal buffers may be warranted. The higher wake losses are attributed to both a relatively low average wind speed when compared to more northern Atlantic (e.g., Massachusetts and Rhode Island) and North Sea sites, and prevailing wind characteristics having an orthogonal, bimodal directional distribution with a strong component from the south southwest and a weaker prevailing component from the northwest (Figure ES2). A bimodal distribution can result in increased wake losses relative to sites with a single prevailing direction because it can hinder array optimization.

Although wake losses decrease with increased turbine spacing, the nameplate capacities of the leasing areas also decrease. NREL estimates a range of 670–760 MW per leasing area after using 8D x 8D spacing and 400–475 MW using the 8D x 12D spacing. Therefore, for all three delineation scenarios, each leasing area could support a large, commercial-scale wind power facility of at least 400 MW.

Table ES2. Maryland (MD) WEA Delineation Analysis
(Source: NREL)

Parameter	Proposed MEA Delineation		NREL Preferred Delineation		NREL Diagonal Delineation	
	Leasing Area A	Leasing Area B	Leasing Area A	Leasing Area B	Leasing Area A	Leasing Area B
Total area (km^2)	155.52	167.04	151.2	171.36	156.96	165.6
Total area (1,000 acres)	38,430	41,276	37,362	42,344	38,786	40,921
Average depth (m)	23	26	23	26	22	27
Bathymetry – depth range (m)	16–29	14–37	16–29	14–37	14–28	17–37
Average wind speed at 90 m (m/s)	8.2	8.3	8.2	8.3	8.2	8.3
8D x 8D – Zero-Degree Grid Orientation						
Wake losses (%)	17	16	17	16	17	16
Gross capacity factor (CF) (%)	44	44	44	44	44	44
Gross CF after wake losses (%)	36	37	36	37	36	37
Potential capacity (MW)	675	745	670	760	745	680
Annual energy production (GWh)	2,140	2,407	2,123	2,454	2,372	2,190
8D x 12D – 75-Degree Grid Orientation						
Wake losses (%)	13	12	13	12	12	12
Gross capacity factor (CF) (%)	44	44	44	44	44	44
Gross CF after wake losses (%)	38	39	38	39	38	39
Potential capacity (MW)	405	460	400	475	425	435
Annual energy production (GWh)	1,353	1,559	1,336	1,607	1,427	1,470

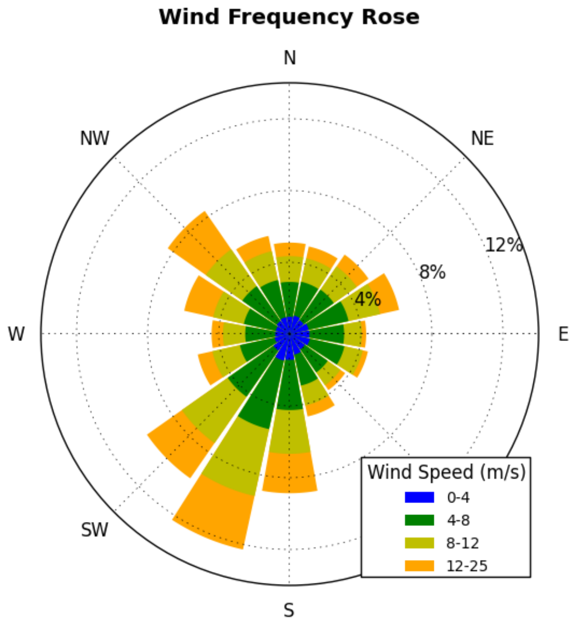

Figure ES2. Maryland (MD) WEA annual average wind frequency rose showing prevailing winds from the south southwest and northwest directions
(Source: NREL)

As shown in Table ES2, leasing area B was made larger than leasing area A, with a higher maximum development capacity (based on nameplate turbine rating) for the proposed MEA and NREL preferred delineations. This helped to offset development challenges caused by certain aliquots in leasing area B related to greater water depths. The proposed delineations made by MEA and NREL allow for a balance between these primary effects. Leasing area B is negatively impacted by water depths of up to 37 meters (m) in some aliquots in blocks 6777 and 6827 (see Figure 1). As a result, areas with these greater depths may require different support structure technology than what has typically been deployed in offshore wind projects to date (Musial and Ram 2010). Of the three options, NREL's preferred delineation of the MD WEA provides a balance for deep water development concerns while maximizing the development potential by providing a simple straight line through the WEA.

To address additional navigational safety concerns raised by the USCG, BOEM requested that NREL analyze two alternative WEA configurations that exclude portions of the more highly trafficked lease blocks to varying degrees (see Section 5). For reference, Figure ES3 shows a bathymetry map of the MD WEA with the boundaries of the two alternative WEA configurations under consideration. The two WEA alternatives are the respective areas to the left of the boundary indicated.

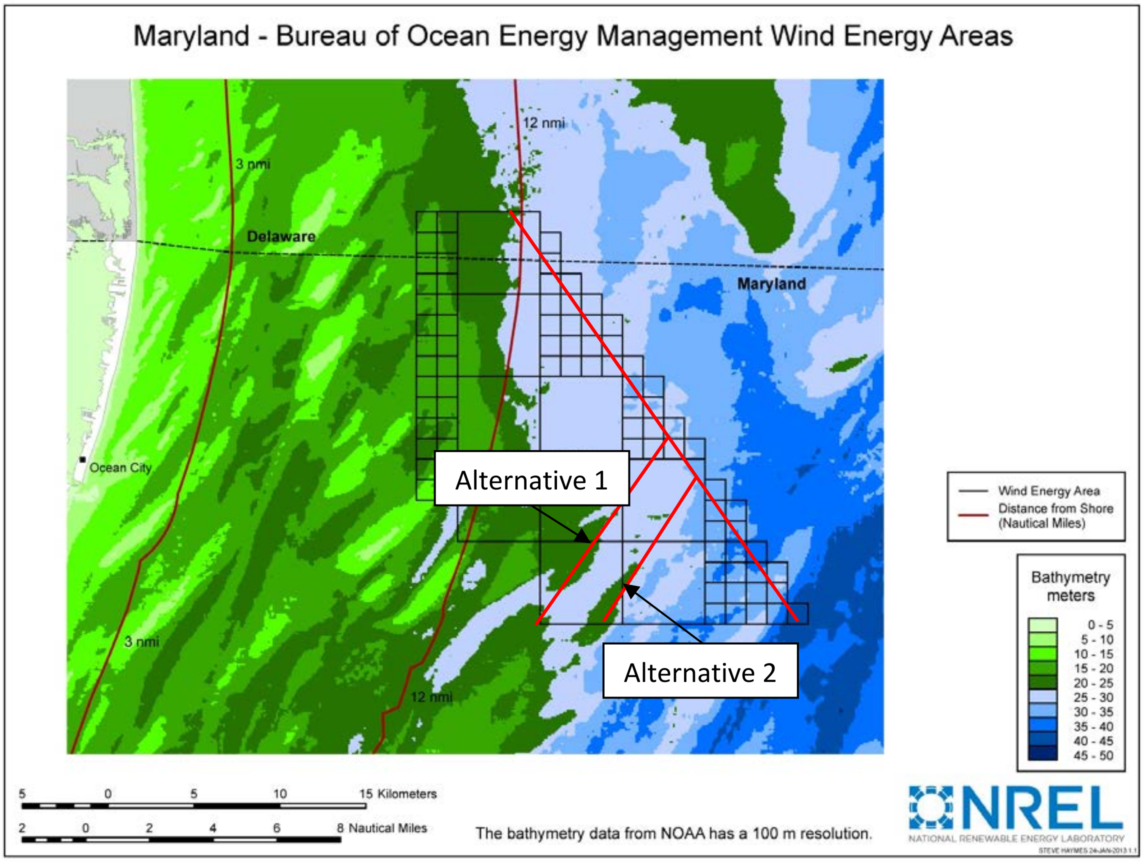

Figure ES3. Water depth map for the MD WEA alternatives
(Source: NREL)

The two alternative WEA configurations under consideration are shown in the center and right side of Figure ES4, with the original WEA shown on the left side. The focus of this analysis was to provide BOEM with information about the practical development potential of the alternate WEAs, and the possibility of subdividing these areas into economically viable leasing areas. The analysts considered the same qualitative and quantitative criteria that were used to evaluate the MD WEA in Section 4. The quantitative results of the alternatives analyses are summarized in Table ES3.

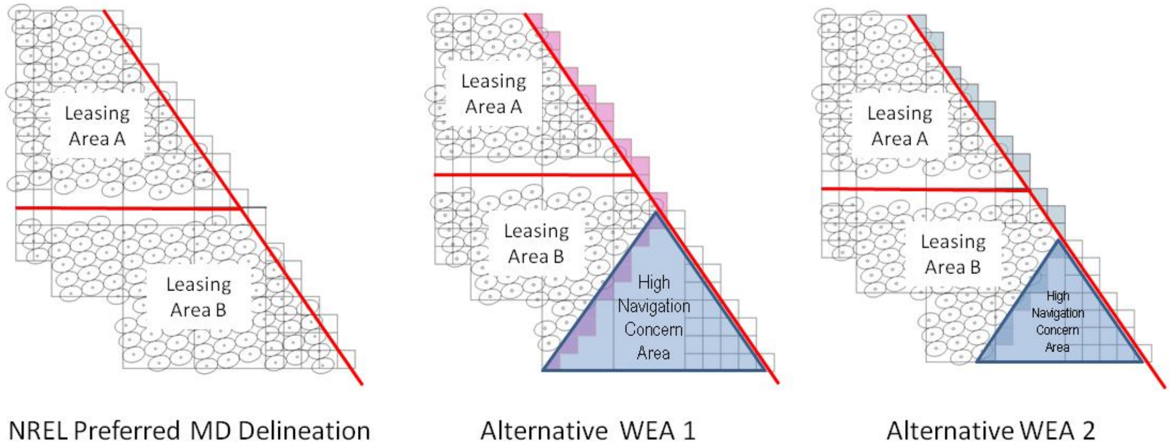

Figure ES4. Comparison of the three MD WEA delineation alternatives. Alternatives 1 and 2 remove aliquots from the southeastern end of the MD WEA, where the U.S. Coast Guard (USCG) raised concerns because of competing uses with vessel traffic.

Table ES3. Summary of Results for the MD WEA using the NREL Preferred Delineation and the Two WEA Alternatives
(Source: NREL)

	MD WEA - NREL Preferred Delineation		MD WEA Alternative 1		MD WEA Alternative 2	
Parameter	Leasing Area A	Leasing Area B	Leasing Area A	Leasing Area B	Leasing Area A	Leasing Area B
Total area (km^2)	151.2	171.4	104.5	106.4	120.8	123.5
Total area (1,000 acres)	37.4	42.3	25.8	26.3	29.8	32.0
Average depth (m)	23	26	23	23	23	24
Bathymetry – depth range (m)	16–29	14–37	16–28	14–29	16–29	14–30
Average wind speed at 90 m (m/s)	8.2	8.3	8.2	8.3	8.2	8.3
8D x 8D – Zero-Degree Grid Orientation						
Wake losses (%)	17	16	16	15	16	16
Gross capacity factor (CF) (%)	44	44	44	44	44	44
Gross CF after wake losses (%)	36	37	37	37	37	37
Potential capacity (MW)	670	760	465	525	530	610
Annual energy production (GWh)	2,123	2,454	1,496	1,720	1,698	1,983
8D x 12D – 75-Degree Grid Orientation						
Wake losses (%)	13	12	12	11	12	12
Gross capacity factor (CF) (%)	44	44	44	44	44	44
Gross CF after wake losses (%)	38	39	38	39	38	39
Potential capacity (MW)	400	475	300	315	350	370
Annual energy production (GWh)	1,336	1,607	1,010	1,079	1,173	1,258

The alternatives study required new delineation boundaries to provide approximately equal leasing areas in each of the proposed alternative WEAs. The study found that the Alternative 1 delineation could support a 300-MW wind project in leasing area A and a 315-MW project in leasing area B, and the Alternative 2 delineation could support a 350-MW project in leasing area A and a 370-MW project in leasing area B. The possible nameplate capacities that could be installed in the leasing areas in the proposed WEA alternatives are near or below what is being considered in typical commercial projects in the United States and Europe.

Key Findings

Below are the key findings of NREL's analysis and important considerations for policy makers and stakeholders involved in the Maryland offshore wind energy development process.

- The MEA analysis provided a logical approach to delineating the MD WEA, but NREL's assessment of the analysis concludes that the MEA may not have weighed the negative impacts of deep water heavily enough in balancing the leasing areas.
- Under the preferred delineation (B) in Figure ES1, leasing area A has an average depth of 23 m and leasing area B has an average depth of 26 m. Leasing area B contains 5 aliquots, with a depth greater than 35 m and a total of 140 MW of capacity in an area where the water depth is above 30 m. Installation of wind turbines in these aliquots would have higher associated costs and increased technical challenges (see Figure 6 and Figure 7).
- An optional delineation (C) in Figure ES1 of the MD WEA showed that tilting the delineation toward a more southwest-northeast diagonal direction slightly favors leasing area A, in terms of bathymetry, but produces relatively small changes in the quantitative parameters used in the other delineation options, and ultimately could result in less annual energy production in the WEA overall.
- The OpenWind project layout tool predicted that leasing area A would have higher wake losses than leasing area B (the difference is less than 1%) for both the 8D x 8D and 8D x 12D spacing, but the wake loss differences between leasing areas are small relative to the total wake losses—between 16% and 17% based on total energy for 8D x 8D spacing and 12% and 13% for the 8D x 12D spacing. The magnitude of these predicted wake losses are also comparable to the observed wake losses seen in European projects (Barthelmie et al. 2010, Jensen 2007).
- For all delineation options in Figure ES1, leasing area B is larger, the wind speeds are higher (about 0.1 m/s), and it has better exposure to dominant south-southwest winds, as shown in Figure ES2. These positive factors are expected to be offset by approximately equal negative factors because of deeper water in leasing area B.
- NREL preferred delineation (Figure ES1) consists of a straight west-east line to balance the development potential of the two leasing areas by taking into account the more challenging development caused by deeper bathymetry in leasing area B (option B in Figure ES1).

- NREL's preferred delineation utilizes the MD WEA more efficiently than the MEA proposed delination by eliminating the zigzag line that may slightly reduce the total capacity that can be installed.
- As shown in Table ES2 for the MD WEA, both leasing areas are capable of supporting at least 600 MW of potential installed capacity for the 8D x 8D spacing criteria, and 400 MW for the 8D x 12D spacing criteria.
- The prevailing winds have an orthogonal, bimodal directional distribution with a strong component from the south southwest and a weaker prevailing component from the northwest (Figure ES2). This bimodal directional distribution can result in increased wake losses relative to sites with a single prevailing direction. Also, the bimodal characteristic increases the complexity of layout optimization. As a result, increased turbine spacing and buffers may be required when compared to unidirectional wind distributions (Musial et al. 2013).
- Array density equivalent to a spacing of 8D x 12D is recommended for the MD WEA to account for higher wake losses due to lower average wind speeds and a bimodal directional distribution. At lower wind speeds, wake losses are greater because the wind turbines extract a larger percentage of the energy available in the wind than at higher wind speeds. At more energetic sites, turbines operate more often above rated power and wake losses are reduced above rated power (Barthelmie et al. 2013).
- The nameplate capacities of the two leasing areas are relatively small for both alternative WEAs (Figure ES3), and there will be little siting flexibility to account for variable bottom conditions, obstructions, and additional exclusions.
- Alternative 1 of the MD WEA, proposed to address navigational concerns raised by the USCG, will reduce the possible development potential of the two leasing areas to 300 MW and 315 MW, respectively. These project capacities are near the lower end of the project size range for typical commercial projects proposed in the United States and Europe.
- Alternative 2 of the MD WEA, proposed to address navigational concerns raised by the USCG, will reduce the possible development potential of the two leasing areas to 350 MW and 370 MW, respectively. These project capacities are near the current project size range for typical commercial projects proposed in the United States and Europe.
- The analysis in this report is coarse by industry standards and it is recommended that prospective lessees conduct more rigorous analysis on wake losses before judging the values of these leasing areas. This enhanced analysis should consider diurnal, seasonal, and annual variations as well as a full cost assessment to examine the additional cost due to added cable length. In addition, further analysis on wake losses with respect to atmospheric stability conditions is recommended.

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1 Project Background

Since 2009, the U.S. Department of Interior's Bureau of Ocean Energy Management (BOEM) has been working with intergovernmental task forces to identify the most appropriate areas for commercial wind energy leasing on the Outer Continental Shelf (OCS) off the Atlantic Coast. To date, BOEM has identified six Wind Energy Areas (WEAs) on the OCS that appear to be appropriate for commercial offshore wind energy development, with the goal of minimizing conflicts with existing uses and the environment. BOEM is currently considering issuing leases for five WEAs through a competitive process: 1) Virginia, 2) Rhode Island/Massachusetts, 3) New Jersey, 4) Maryland, and 5) Massachusetts. Except for Virginia, BOEM intends to offer more than one lease within each WEA. The WEAs that have multiple leasing areas within their boundaries (all but Virginia) require analysis, using engineering tools and available WEA site characteristics, to ensure that the leasing areas are appropriately divided.

1.1 Summary of National Renewable Energy Laboratory Task Work

The National Renewable Energy Laboratory (NREL), under an interagency agreement between the U.S. Department of Energy and BOEM, is providing technical assistance to identify and delineate offshore leasing areas for wind energy development within the Atlantic Coast WEAs.

The overarching objectives of the interagency agreement are as follows:

1. Develop a logical process by which WEAs can be subdivided into non-overlapping leasing areas for BOEM's use in developing auction processes in a renewable energy lease sale
2. Identify the appropriate number of leasing areas recommended for lease within each WEA
3. Delineate the boundaries of the leasing areas within each WEA
4. Document the methodology (i.e., variables and assumptions) by which the leasing areas are identified and delineated for each state.

The work being performed by NREL for each WEA depends on the specific site characteristics, available information provided by BOEM, and a predetermined scope of work. For Maryland (MD), the interagency agreement work scope comprises several tasks to assist BOEM in making the final determination for delineating the MD WEA into leasing areas that are capable of supporting a commercially viable project. The expectation is that the recommended delineations will provide sufficient area for modifications to the facility layout based on the results of geophysical, geological, and biological surveys that will be conducted by the developer.

First, NREL was asked to conduct a review of information that was submitted in response to applicable BOEM Federal Register notices. NREL researchers, based on their expertise, were asked to decide if any of the provided information should be incorporated into the leasing area identification and delineation methodology.

Second, NREL was asked to propose a methodology and the factors that would be used to identify the number of leasing areas and their recommended delineations. On January 29, 2013, NREL made a presentation to the BOEM Maryland Renewable Energy Task Force to fulfill this portion of the Maryland work tasks (Musial and Fields 2013). The presentation described the method for evaluating the Maryland Energy Administration (MEA) proposal and performing an independent analysis on delineation options. NREL researchers received input during the presentation from the task force to help guide the analysis and subsequently worked with BOEM to integrate the findings into this report.

NREL was also asked to review the State of Maryland's Zone Delineation Recommendation. NREL evaluated Maryland's recommendation and applied its technical methodology to determine if the proposed leasing area delineation was reasonable and technically sound (Musial and Fields 2013). NREL provided an evaluation of the Maryland recommendation (see Section 2.1) and options to Maryland's proposal that are included in this report. At BOEM's request, NREL performed additional analysis and evaluated two alternate WEA configurations. These alternate configurations were analyzed to respond to comments and concerns raised by the U.S. Coast Guard (USCG). NREL applied the methodologies described at the BOEM Maryland Renewable Energy Task Force meeting to the MD WEA and prepared this report.

Finally, NREL researchers will present the findings to the BOEM Maryland Renewable Energy Task Force at the completion of the project in the summer of 2013.

1.2 Maryland WEA and Leasing Areas

Since 2010, BOEM has been working with the BOEM Maryland Renewable Energy Task Force to identify the most appropriate area for offshore leasing in Maryland. In November 2010, BOEM published a Request for Interest (RFI) in the Federal Register to gauge specific interest in obtaining commercial wind leases in an area on the OCS offshore Maryland. In response to the RFI, BOEM received nine expressions of interest wishing to obtain a commercial lease for wind energy. In consultation with the task force, BOEM refined the area and published a Call for Information and Nominations (referred to in this document as the "Call") in the Federal Register in February 2012. In response to the Call, BOEM received six nominations of interest wishing to obtain a commercial lease for wind energy [the MD WEA comprises 79,706 acres, or 322.5 square kilometers (km^2)]. BOEM intends to hold a lease sale to auction the MD WEA and issue leases that correspond to the entire identified WEA. The results of this report and other inputs received by BOEM will help inform the final WEA boundary. The state indicated a preference for a leasing process that results in two differentiated leaseholds to increase the likelihood of multiple entities competing for state support under the Maryland Offshore Wind Energy Act of 2013. Although that legislation contains several ratepayer protection provisions and a maximum price for energy from qualifying projects, state policymakers feel that adding an additional level of price pressure through market competition may result in greater value for ratepayers (Gohn 2012). Maryland's proposed north leasing area comprises 38,430 acres (155.5 km^2) and the south leasing area comprises 41,276 acres (167.0 km^2), based on the MD WEA boundaries shown in Figure 1.

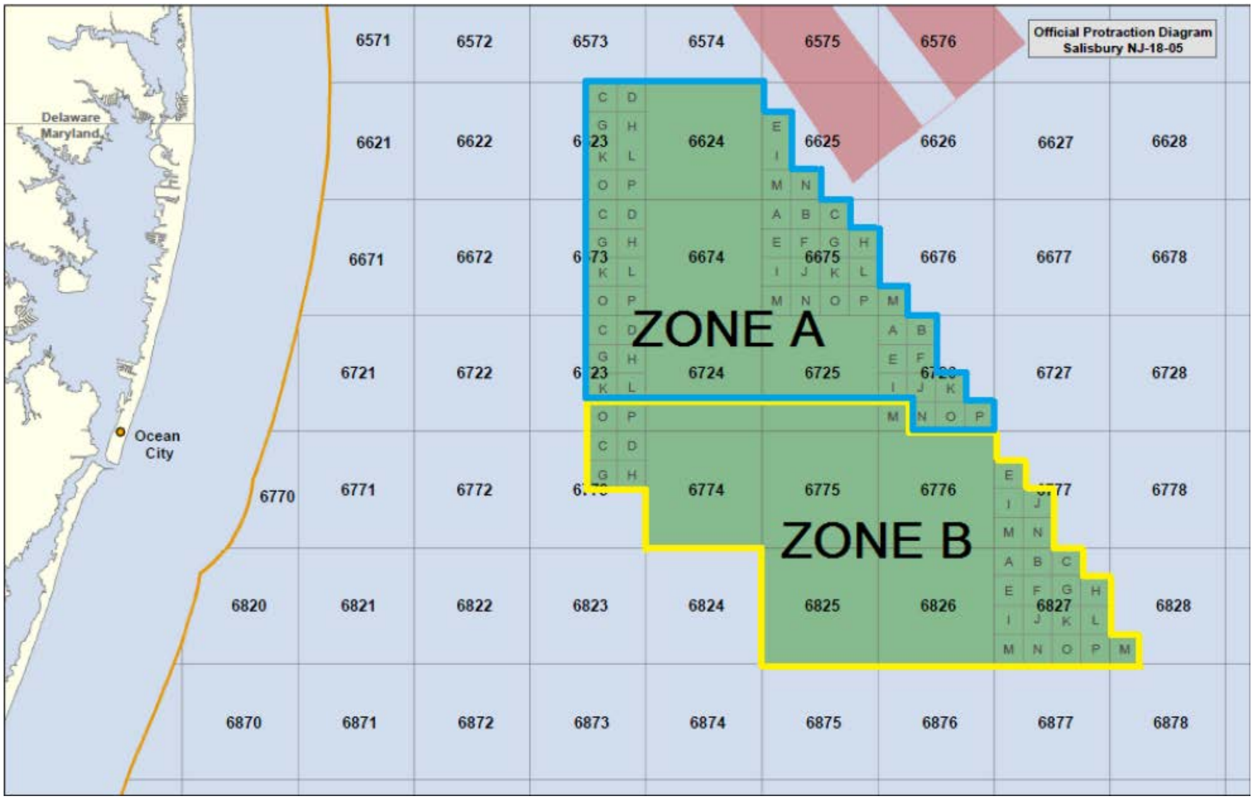

Figure 1. Maryland Energy Administration's (MEA's) proposed lease areas for the Maryland (MD) WEA (leasing areas A and B)
(Source: MEA)

MEA provided an initial delineation strategy for the MD WEA that subdivides the WEA into a north leasing area (A) and south leasing area (B). BOEM provided NREL with the MEA leasing area delineation coordinates for review and evaluation. NREL evaluated the MEA leasing area delineation on the basis of several technical criteria, including total energy production capacity, wake losses, and water depth, as well as several qualitative criteria (listed in Table 3, with further discussion in Section 4). These findings did not reveal any significant flaws in the MEA recommended approach, but determined that bathymetry might not have been given enough consideration. Further details of NREL's assessment of the MEA delineation recommendation are included in Section 2.1 and are mentioned throughout the report.

2 Literature Review

As part of the initial investigations, NREL researchers reviewed the following technical documents and communications:

- Maryland Request for Interest 2010 and nine responses to the RFI
- 2012 Maryland Call for Information and Nominations (the "Call") and six responses to the Call
- Maryland Wind Energy Area Zone Recommendation memo (Gohn 2012)
- Verbal input received from MEA and the Maryland Department of Natural Resources during a conference call conducted on January 23, 2013
- Presentations delivered at the BOEM Maryland Renewable Energy Task Force meeting held on January 29, 2013.

2.1 Maryland Proposed WEA Delineations

The MEA circulated a zone delineation recommendation on September 13, 2012. This recommendation was based on the WEA for Maryland (shown in Figure 1). The MEA had a stated goal of maximizing the available resource for the benefit of ratepayers who may be supporting offshore wind energy development through the Maryland Offshore Wind Energy Act of 2013. This included working with the Maryland Department of Natural Resources to review the available area and stakeholder interests, as well as other criteria listed below. MEA decided that a competitive lease arrangement would likely yield the best result for the ratepayers and suggested two leasing areas, as shown in Figure 1. Their aim was to create two equal leasing areas in terms of development potential and encourage a different developer for each area. Although BOEM cannot prevent a single entity from securing lease rights to both leasing areas, the State of Maryland still prefers that the MD WEA be offered for sale as two leasing areas to allow for the possibility of two different lessees.

The following MEA review criteria were used to arrive at the leasing area delineation shown in Figure 1:

- Wind speed
- Prevailing wind direction
- Bathymetry
- Distance to shore
- Transmission requirements
- Shipping lanes and potential USCG requirements
- Interproject wake effects and potential buffer requirement
- Fisheries use
- Military use
- Additional stakeholder considerations.

NREL researchers reviewed the MEA delineation for this analysis and found that leasing area (zone) B has about a 7% greater area than leasing area A, as shown in Table 4. However, leasing area B is negatively impacted by greater water depths—from 30 to 40 meters (m) in some aliquots (e.g., in blocks 6777 and 6827, as shown in Figure 1 and Figure 5). The MEA proposed line of delineation between the leasing areas is predominately a straight line from west to east, but it turns south along one aliquot north of block 6726 and then turns east again. As a result, aliquots N, O, and P of this block are incorporated into the allocated area of leasing area A until it reaches the far eastern edge of the WEA. By including the factors listed above, the MEA delineation allocates more submerged land area to leasing area B to create two approximately equal leasing areas in terms of development potential. Generally, NREL researchers found that the MEA analysis provided a logical approach to delineating the MD WEA, but suggests that MEA may not have weighed the negative impacts of deep water heavily enough when balancing the leasing areas. A preferred option is proposed later in this report.

2.2 BOEM WEA Navigational Constraints

The MD WEA is 79,706 acres (322.56 km^2) and is shown in Figure 1. The boundaries have evolved significantly over time, as BOEM received input from various stakeholder groups. Prior to publishing the Call for the MD WEA, BOEM consulted with the USCG regarding navigation issues, particularly the separation distance between offshore renewable energy facilities and shipping routes. Based on the discussions and consultation with the USCG, BOEM decided that if the traffic separation scheme (TSS) were to be extended, BOEM would not allow the installation of offshore wind turbine structures within 1 nautical mile (nm) of the TSS. This exclusion was also mentioned in the Call notice (77 FR 5558): "If the entire Call area were to be made available for leasing and development, portions of a number of sub-blocks may not be available for surface occupancy, (i.e., placement of offshore wind facilities), because of the proximity to the TSS." These blocks are shown as the hatched blocks in Figure 2. In addition, the MD WEA, along with the potential 1-nm setback, is depicted in the figure. This modification resulted in the removal of all turbines to the right of the TSS line, as shown in Figure 2. Turbines to the left of the TSS line were still included in the analysis.

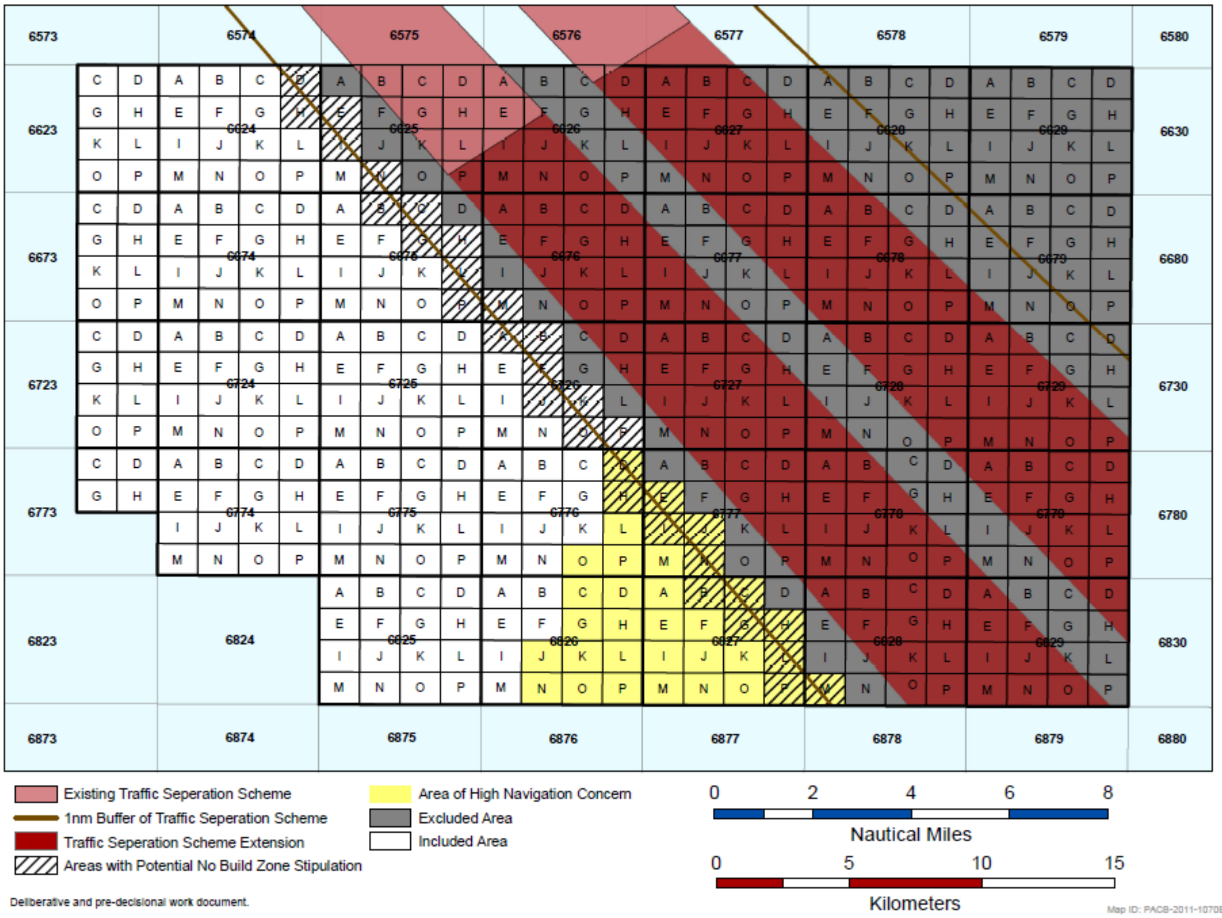

Figure 2. Maryland WEA with the traffic separation scheme (TSS) building restriction setback
(Source: Walters and Benard 2013)

2.3 NREL Review of Call for Information and Nominations and Request for Interest

BOEM made available to NREL the nominations submitted in response to its Federal Register Notices (i.e., RFI and/or Call) for use in NREL's evaluation of the MD WEA leasing area delineation. These nominations provided detailed project information such as siting constraints, project layout specifications, turbine type and size, foundation type, project capacity, development schedule, and interconnect points. NREL determined which, if any, of the provided items should be evaluated in the leasing area identification and delineation methodology. NREL researchers considered factors such as meteorological information and potential wake effects between leasing areas.

NREL was granted confidential access to the nine responses to the RFI and six responses to the 2012 Call. These nominations helped provide insight into the commercial sector considerations for offshore development and wind energy leasing area delineation—particularly with respect to array spacing and project size.

Key findings from NREL's review of the RFI and Call nominations are shown in Table 1 and Table 2. Because of confidentiality requirements, the project data from the industry responses were reduced to statistical averages, and maximum and minimum values. These values, derived from the nominations, are compared to the nominal values used in the NREL analysis in the tables.

Table 1. Summary of Nomination Statistics from Nine BOEM Maryland (MD) Wind Energy Area (WEA) Request for Interest (RFI) Responses
(Source: NREL)

	Average	Maximum	Minimum	NREL Values
Project nameplate capacity [megawatts (MW)]	865	1,500	285	875–1,430
Turbine nameplate capacity (MW)	4.43	6	3	5
Average wind speed in meters per second (m/s) at 90 meters (m)	8.46	8.75	8.15	8.3
Net capacity factor (%)	36.68	40	33	36–39
Proposed project area (km^2)	363.45	708.48	74.88	322.5
Array spacing in rotor diameters (D)	7.5D x 11D	8D x 12D	5D x 10D	8D x 8D and 8D x 12D
Array power density (MW/km^2)	3.81	6.29	3.28	5.0 and 3.28
Number of turbines	209	328	57	175–286
Maximum depth (m) after traffic separation scheme (TSS) setback	36	48	30	37
Project development time frame (years)	6	7	5	N/A

Notes:
1. NREL used the MD WEA from February 3, 2012 (http://www.boem.gov/Renewable-Energy-Program/State-Activities/Maryland.aspx) for its analysis, which differs from the earlier WEA considered by developers during the RFI.
2. The array power density computation assumes the NREL reference turbine 5-MW nameplate power capacity and 126-m rotor diameter (Jonkman et al. 2009).

Table 2. Summary of Nomination Statistics from Six BOEM MD WEA Call Responses
(Source: NREL)

	Average	Maximum	Minimum	NREL Values
Project nameplate capacity (MW)	800	1,000	350	875–1,430
Proposed project area (km^2)	287.76	322.56	213.12	322.5
Array spacing (D)	N/A	N/A	N/A	8D x 8D and 8D x 12D
Array power density (MW/km^2)	2.78	3.10	1.64	5.0 and 3.28
Project development time frame (years)	6.33	7	5	N/A

Notes:
1. NREL used the MD WEA from February 3, 2012 (http://www.boem.gov/Renewable-Energy-Program/State-Activities/Maryland.aspx) for its analysis, which differs from the earlier WEA considered by developers during the RFI.
2. The array power density computation assumes the NREL reference turbine 5-MW nameplate power capacity and 126-m rotor diameter (Jonkman et al. 2009).

In Table 1 and Table 2, the NREL values—based on a turbine array density of 5 megawatts (MW)/km^2 and 8D x 8D turbine spacing—are consistent with the gross resource estimations carried out in 2010 (Schwartz et al. 2010) and typical European wind facilities. For this investigation, NREL researchers wanted to remain consistent with this past analysis and actual industry practices, but we considered that the 8D x 8D spacing would provide a conservative estimate of array wake losses. However, the nominations reviewed for the Maryland RFI and Call used wider turbine spacing on the average that was represented better by the 8D x 12D spacing. Array densities proposed by developers under the RFI ranged from 3.28 to 6.29 MW/km^2, with an average of 3.81 MW/km^2. This wider turbine spacing tends to reflect a more cautious industry trend toward larger turbine spacing to reduce wake losses. This trend can be contrasted against early wind projects like the 80-turbine Horns Rev project in Denmark (Figure 10), which used higher array power densities (6.4 MW/km^2 and 7D x 7D turbine spacing). Although Horns Rev is not the highest density offshore array, its performance is well-documented with array losses over 10% (Hansen et al. 2012).

During the nomination evaluation, researchers also noted that some prospective developers expressed concerns about the economic and technical viability of development in deeper water. These findings are generally consistent with typical offshore project proposals, industry experience, and NREL's prior experience, and support the general conclusions of this report, which suggest that water depth may play a significant role in the overall development potential of the leasing areas.

3 NREL Methodology

3.1 Overview of Methodology

NREL's technical assessment of the delineation for leasing areas included the use of input data to model and compare key parameters, such as maximum development capacity, wind speed, capacity factor, direction and wake losses, bathymetry impacts, and energy production. To model these parameters, gridded layouts were created and evaluated in the OpenWind Enterprise tool developed by AWS Truepower (AWS Truepower 2010). The layouts were then applied to three delineation strategies for evaluation and comparison, as well as for the two alternate MD WEA boundaries.

3.2 Wind Source Data

For this investigation, NREL surveyed a variety of data sources to find a high-quality dataset that embodies best industry practices. Ultimately, the wind resource data used for the MD WEA was a high-resolution, long-term record obtained from AWS Truepower that correlated well with local empirical observations.

The mesoscale model, Mesoscale Atmospheric Simulations System, was used to simulate the atmosphere with coarse horizontal grid spacing of 20 km over the United States and immediately offshore (Manobianco et al. 1996). The Mesoscale Atmospheric Simulations System is a numerical weather model that has been developed over the past 20 years by MESO, Inc., in partnership with AWS Truepower. The mesoscale simulations were processed to produce a long-term time series of weather information called windTrends. The windTrends dataset is available from 1997 to the present and contains hourly approximations of several meteorological fields, including wind speed and direction. This data set was used to produce an annual average wind speed map at a resolution of 20,000 m (20 km) and a set of statistical files containing information about the wind resource. This information was then used as input to the microscale model, WindMap (Brower 1999), which interpolates the coarse 20-km grid data to a high-resolution grid spacing of 200 m to simulate more localized effects. The outputs of WindMap are 200-m mean annual wind speed maps and wind resource grid (WRG/B) files containing the wind speed, wind direction, and frequency distribution of the wind speed, at a hub height of 90 m. NREL researchers input these WRG/B files into the OpenWind model, where the wind speed gradients and directional distributions across the WEA were determined.

As with any analytically based modeling process, uncertainties from the model data can arise, therefore, validation with empirical data is needed to gain sufficient confidence in the modeled results. We compared the 200-m high-resolution WindMap data to the well-established Modern-Era Retrospective Analysis (MERRA) data set produced by the National Aeronautics and Space Administration (NASA) (NASA 2013). MERRA integrates a variety of observing systems with numerical models to produce a temporally and spatially consistent synthesis of observations and analyses of variables that are not easily observed. NREL researchers further compared the WRG/B files to the measurements from buoy 44009 of the National Data Buoy Center (NOAA 2013). Both comparisons confirmed the general wind speed and direction characteristics of the WRG/B data. Given the lack of measurements available offshore and the coarse resolution of other data sets, the WRG/B data files used for this study provided the best current wind climate information for the MD WEA.

3.3 Analysis Tool: OpenWind Enterprise

The OpenWind Enterprise tool is a wind energy facility design tool created by AWS Truepower and licensed to NREL. It has the capability to perform layout design, flow modeling, wake modeling, and energy assessment and is intended for commercial applications. OpenWind Enterprise was selected for its interoperability with geographic information system (GIS) data, as well as its capability to model deep array wake effects. Wake losses were evaluated using the Deep Array Fast Eddy-Viscosity Wake Model (DAWM Fast Eddy-Viscosity) in OpenWind Enterprise. The primary OpenWind components are described as follows.

3.3.1 WindMap Flow Model

The WindMap flow model within OpenWind is based on the NOABL code (Phillips 1979) and solves the conservation of mass equation to generate a three-dimensional wind flow map. The model accounts for moderate changes in terrain and surface roughness when used in conjunction with measured time series meteorological data.

3.3.2 Wake Model

Wind turbine wake modeling is an emerging science and carries a relatively high uncertainty. Uncertainties include measurement uncertainty, the effect of wake meandering, and even fundamentals, such as the correct choice of freestream wind speed profile (Barthelmie et al. 2010). As a result, it is difficult to make an accurate comparison of the different wake models that are currently available. Wake models and scientific approaches are evolving rapidly. More computationally intensive research methods that are used to calculate wakes are currently applied in research laboratories that are not yet practical for commercial use (e.g., large-eddy simulations) (Churchfield et al. 2012). Even though these methods may produce more accurate results, they are still under development and are computationally too expensive to be used for wind energy evaluations like the one conducted for this report. As of the writing of this report, the OpenWind DAWM is one of the most widely used and accepted tools in the industry. NREL's prior experience (mostly land-based) indicates that the OpenWind DAWM performs better than other models that are currently available.

The DAWM Fast-Eddy Viscosity within OpenWind (AWS Truepower 2010) is a combination of the open-source standard Eddy-Viscosity (EV) model and a roughness effect associated with each turbine.

3.3.3 Layout Design

The gridded turbine layer function within OpenWind was used to create maximum capacity layouts to fill the WEA leasing areas using the assumptions of 8D x 8D and 8D x 12D turbine spacing. Square or triangular tiling is used with manually adjusted bearing, obliquity, and offset to obtain the desired number of turbines. Where the layouts are adjacent to the line of delineation between leasing areas, the layouts force a minimum setback of 8 rotor diameters (D) from the line. This is realistic because developers in either leasing area do not have control over the adjacent layout and a setback is required to ensure minimum turbine spacing from upwind turbines that may be installed outside their respective leasing areas. This is a practical requirement of layout design to maintain turbine spacing in each leasing area and is not viewed as a buffer. Additional buffers will probably be needed to further reduce wake losses in the development of each leasing area, which could dictate more extensive setbacks.

Layouts can also be generated within OpenWind by optimizing for energy or cost, rather than using the gridded turbine layer function. This iterated optimization is commonly used for land-based projects where many development constraints, as well as road and cable layers, can be optimized to produce a layout that evolves organically into the best fit for the situation. For this assessment, NREL used the gridded turbine layer function because it is more applicable to the open offshore environment and allows for a quick comparison of different layout scenarios.

3.3.4 Energy Assessment

The energy capture function in OpenWind sums the energy produced by the turbines using 72 direction sectors and 71 wind speed steps. It calculates and stores the energy yield, capacity factor, and wake losses associated with each turbine. Losses other than those caused by the wake effects can be accounted for by directly entering assumptions or calculating from other layers.

3.4 Overview of Approach to Delineation Assessment

The primary objectives of this analysis were:

- To evaluate the Maryland Energy Administration's delineation of the MD WEA and determine if it is technically sound.
- To provide options to MEA's recommendation for the MD WEA.
- To assess two alternative WEAs proposed by BOEM to address concerns from the USCG about potential conflicts with navigation.

To meet the first two objectives, NREL evaluated three delineation options: 1) the MEA delineations (Figure 1), 2) a "preferred" delineation that is similar to the MEA delineation but that shifts three aliquots from leasing area A to leasing area B, and 3) a southwest-to-northeast zigzag delineation that was intended to demonstrate the degree of sensitivity of key delineation criteria to different divisions. The delineation strategies are shown in Figure 3.

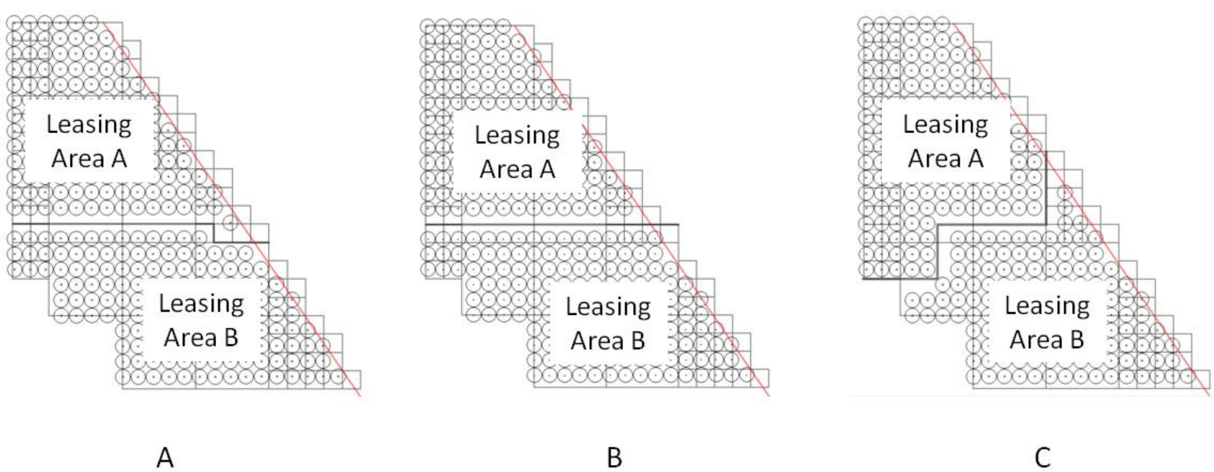

Figure 3. MEA's proposed delineation (A), NREL's preferred delineation (B), and NREL's diagonal optional delineation (C) provide insights on possible delineation strategies and their sensitivities. NREL is recommending the preferred delineation as the best option.
(Source: NREL)

NREL performed both quantitative and qualitative analysis on these three delineation strategies using the key criteria highlighted in Table 3.

Table 3. Evaluation Criteria Used by NREL to Assess the MD WEA
(Source: NREL)

Quantitative Evaluation Criteria	Qualitative Evaluation Criteria Considered
Total area (km^2 and acres)	Distance from shore
Potential installed capacity (MW)	Fisheries and competing uses
Bathymetry [meters (m)]	Technology challenges
Annual average wind speed [meters per second (m/s)]	Development cost
Gross capacity factor (%)	Development timing
Wake losses (%)	
Annual energy production [gigawatt-hours (GWh)]	
Navigational impacts on WEA	

The results of the delineation analyses conducted on the MD WEA are discussed in Section 4. Analysis to address the third objective is presented in Section 5.

4 Discussion of Results for the MD WEA

4.1 Overview of MD WEA Delineation Results

The general findings were that the Maryland recommendation (based on the criteria listed in Section 2.1) created two leasing areas that provided approximately equal development potential, with varying advantages and disadvantages that tended to balance out. While each criterion was considered by NREL, only the criteria in Table 4 were given an independent quantitative analysis.

Table 4. Maryland (MD) Delineation Analysis Criteria
(Source: NREL)

	Proposed MEA Delineation		NREL Preferred Delineation		NREL Diagonal Delineation	
Parameter	Leasing Area A	Leasing Area B	Leasing Area A	Leasing Area B	Leasing Area A	Leasing Area B
Total area (km^2)	155.52	167.04	151.2	171.36	156.96	165.6
Total area (1,000 acres)	38,430	41,276	37,362	42,344	38,786	40,921
Average depth (m)	23	26	23	26	22	27
Bathymetry – depth range (m)	16–29	14–37	16–29	14–37	14–28	17–37
Average wind speed at 90 m (m/s)	8.2	8.3	8.2	8.3	8.2	8.3
8D x 8D - Zero-Degree Grid Orientation						
Wake losses (%)	17	16	17	16	17	16
Gross capacity factor (CF) (%)	44	44	44	44	44	44
Gross CF after wake losses (%)	36	37	36	37	36	37
Potential capacity (MW)	675	745	670	760	745	680
Annual energy production (GWh)	2,140	2,407	2,123	2,454	2,372	2,190
8D x 12D – 75-Degree Grid Orientation						
Wake losses (%)	13	12	13	12	12	12
Gross capacity factor (CF) (%)	44	44	44	44	44	44
Gross CF after wake losses (%)	38	39	38	39	38	39
Potential capacity (MW)	405	460	400	475	425	435
Annual energy production (GWh)	1,353	1,559	1,336	1,607	1,427	1,470

The first two columns on the left side of Table 4 give the assessment results of the MEA delineation recommendation. Although NREL's analysis found that the MEA proposal was logical and its assumptions generally met the objectives of creating equally developable leasing areas, the delineation was probably not optimal in terms of bathymetry. The disadvantage imposed by the deeper water found in the far southeast aliquots of leasing area B were probably not weighted high enough when considering the value of the overall lease blocks. Water depths beyond 30 m will likely be a strong cost factor when deploying technology into these areas.

NREL proposes a modified delineation line that strikes a straight horizontal line across the WEA so that three additional aliquots are moved to leasing area B, as shown in the center layout of Figure 3. This is not a big change, but it increases the total area and potential deployment capacity for leasing area B incrementally, as we anticipate that leasing area B will be more challenging to develop. This analysis is shown in the two middle columns of Table 4. In addition, we noted that a straight-line delineation (option B) will allow for a greater overall capacity for the WEA because of more efficient turbine placement potential. NREL found that the zigzag in the MEA delineation reduces the maximum development capacity of leasing area B more than it increases the maximum capacity of leasing area A. The additional zigzag in the delineation boundary may also complicate the cable layout for both leasing areas in that part of the WEA because layout options may require a more circuitous routing to avoid moving into the adjacent leasing area. Given that leasing area B faces development challenges related to depth in the areas mentioned previously, it is logical to eliminate this turn in the delineation line by shifting block 6726 aliquots N, O, and P to leasing area B. Although the deeper aliquots would still be developable, this shift would help offset the imbalance in the development challenge. This modification is referred to as NREL's preferred delineation strategy in Table 4.

Using 8D x 8D spacing, there are 140 MW of nameplate capacity in leasing area B that are over 30 m in depth, with only 5 MW in leasing area A for the NREL preferred delineation. Also, at least five of these aliquots in leasing area B exceed a depth of 35 m. One of the main concerns is that some projects that may combine shallow (below 30 m) and deep water (above 30 m) over this depth range may not be feasible using a single substructure technology (e.g., monopile, jacket, and so on). Incorporating multiple support structure technologies for a single phase project would add significant cost, as it would require mobilization of redundant supply chain options, and additional engineering design and certification steps to site only a few additional turbines. A more thorough discussion of how bathymetry affects deployment cost is provided in Section 4.4.

NREL created a third delineation option, indicated as option C in Figure 3 and labeled as the diagonal delineation option in Table 4. The main purpose was to understand the sensitivity of key variables, such as energy production, bathymetry, and interproject wake effects to variations in the delineation line. In this diagonal delineation option, 12 aliquots were added to leasing area A on the western side and 12 aliquots were removed from leasing area A on the eastern side to create a more diagonal zigzag cut from southwest to northeast.[1] A southwest to northeast diagonal cut provides a higher west-facing frontage area in leasing area A, and that change illustrates the impact of increasing the exposure to the prevailing south-southwest wind component for leasing area A. Similarly, the less dominant northwest prevailing component was reduced from the leasing area B frontage. The resulting delineation analysis summarized in Table 4 shows how these modifications affected the key evaluation criteria. As expected, this delineation favored leasing area A by increasing the leasing area's energy production capacity and increasing the disparity in depth between leasing area A and B.

[1] It should be noted that, for the MD WEA, diagonal delineations introduce longer leasing area boundaries and diminish the development capacity of the respective leasing areas by creating areas near the boundaries that may make turbine placement difficult. In practice, a developer-imposed setback may alleviate this concern.

This diagonal delineation strategy appears to have exacerbated the imbalance between leasing areas A and B and therefore is not recommended, but it illustrates the impact of larger deviations from the MEA option and NREL preferred options. It also shows that relatively large changes to the delineation strategy do not have an enormous effect on the overall ability to develop the two WEA leasing areas, although these effects would probably be significant enough to affect the value of the lease areas.

4.2 Total Area

The total area of the two leasing areas is shown in Table 4 for each of the three delineation options in both square kilometers and acres (as both units are used by different stakeholders). For all three options, leasing area B has more developable area, ranging from about 7% more in the MEA proposed delineation to 13% more in the preferred (straight-line) delineation, and 5% more in the diagonal delineation using the MD WEA boundaries without the TSS setback exclusion. With the TSS setback, the percentage of area available for development does change. The northern aliquots are more severely impacted by the introduction of the TSS setback and leasing area A loses about 11% development capacity, while leasing area B loses about 5% (for options A and B in Figure 3). Therefore, the potential installed development capacity of leasing area B relative to leasing area A is significantly greater when the TSS is applied.

For each delineation option, inequalities in total area were deliberately imposed to offset the expected difference in development challenges between leasing areas A and B. The degree to which these inequalities are needed and how well these challenges can be mitigated will depend on the final WEA boundaries and the project technology specifics.

4.3 Potential Installed Development Capacity

NREL researchers evaluated the development capacity of the two leasing areas by creating turbine array layouts that maximized the nameplate capacity of installed turbines for the two leasing areas using the NREL 5-MW reference turbine (Jonkman et al. 2009) with 8D x 8D and 8D x 12D spacing. In creating these layouts, it was assumed that the developers would self-impose an internal setback buffer of 8D from the delineation line, thereby anticipating that the neighboring developer could feasibly place turbines near the delineation boundary. An example layout map with the 8-D setback buffer along the delineation line is shown in Figure 4 for the preferred delineation and 8D x 8D spacing. Note that the diameters of circular symbols in the layout are scaled to 8D.

NREL’s comparison of leasing area A and B for the MEA delineation of the MD WEA concludes that the leasing areas are similar in terms of potential development challenges and cost, but with some differing characteristics. Leasing area B, as delineated by MEA, has more favorable characteristics with respect to maximum potential project size and wake losses. Leasing area B has more favorable access to the southwesterly winds, which may result in lower wake losses for prevailing south-southwest wind directions and certain atmospheric conditions. However, the advantages of leasing area B are potentially offset by the increased costs and technical challenges associated with a water depth that is greater than 30 meters, especially in lease blocks 6777 and 6827 and some aliquots in blocks 6776 and 6826.

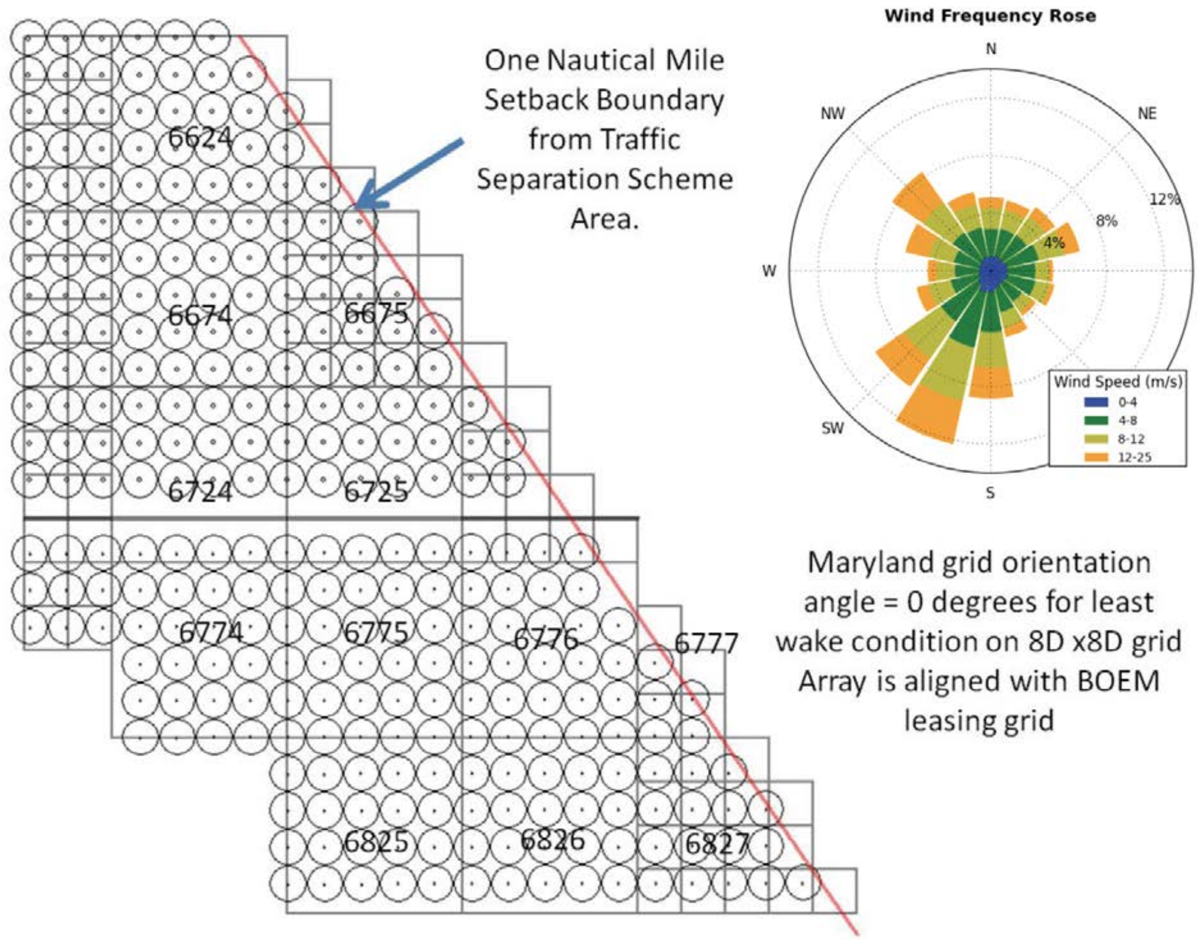

Figure 4. MD WEA (preferred option) leasing area delineation and layout map
(Source: NREL)

NREL estimated the potential installed capacity for each of the three delineation options for the MD WEA. The results shown in Table 4 indicate that the maximum installation capacities range from 670–760 MW when the TSS setbacks are imposed (during the assessment, the TSS setback resulted in a decrease in total available capacity of about 8% for the MD WEA). For the MEA delineation and NREL preferred (straight-line) delineation, leasing area B has a greater capacity than leasing area A. However, for the NREL diagonal delineation option, leasing area B has less capacity than leasing area A, even though the total area of leasing area B is still greater than leasing area A. This is the result of inefficiencies in turbine layout caused by the diagonal (zigzag) delineation and indicates that the total area alone is not a precise or reliable indicator of the potential development capacity.

4.4 Bathymetry Considerations

The water depth, or bathymetry, was an important consideration in assessing the wind development potential of the MD WEA leasing area. Figure 5 shows a bathymetry map of the MD WEA.

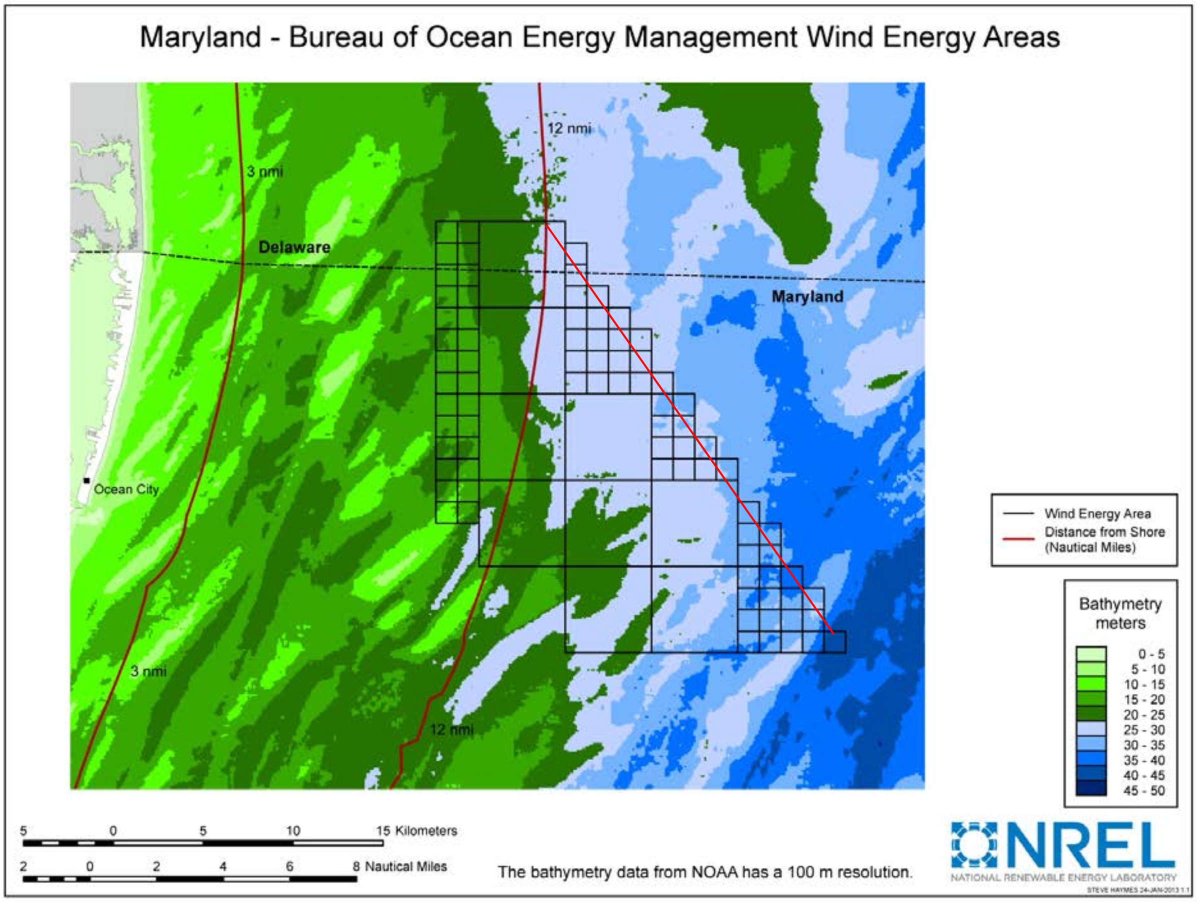

Figure 5. Water depth map for the MD WEA
(Source: NREL)

The green colors in Figure 5 represent depths below 25 m and the blue colors represent depths above 25 m. The chart shows that the deeper water areas are located in the southeastern corner of leasing area B. The approximate location of the TSS setback boundary is indicated by the red diagonal line.

Table 5 provides a breakdown of the potential installed capacity including the TSS setback and number of turbines by water depth in leasing areas A and B for the NREL preferred delineation. Although leasing area B has a maximum capacity that is 90 MW greater than leasing area A (760 MW versus 670 MW), 25 MW of the potential installed capacity in leasing area B is in water that is greater than 35 m deep, and 140 MW is in water greater than 30 m deep. (Although not presented, the depth distributions for the MEA delineation are similar to the results in Table 5.) Note, the area in the depth range of 40–45 m was east of the TSS setback and is not counted in the bathymetry tally in Table 5.

Table 5. Potential Installed Wind Capacity for the MD WEA by Leasing Area and Depth for the NREL Preferred Delineation using 8D x 8D Turbine Spacing (Including TSS Setback)
(Source: NREL)

Depth Range	Leasing Area A		Leasing Area B		Total Area	
	Capacity (MW)	Turbines	Capacity (MW)	Turbines	Capacity (MW)	Turbines
<20 m	200	40	65	13	265	53
20–25 m	190	38	240	48	430	86
25–30 m	275	55	315	63	590	118
30–35 m	5	1	115	23	120	24
35–40 m	0	0	25	5	25	5
Total	**670**	**134**	**760**	**152**	**1,430**	**286**

Depth considerations are important with respect to project risk and cost. Figure 6 shows a plot of the current projects installed, under construction, contracted, and approved in Europe, as a function of water depth and distance from shore at the end of 2012.

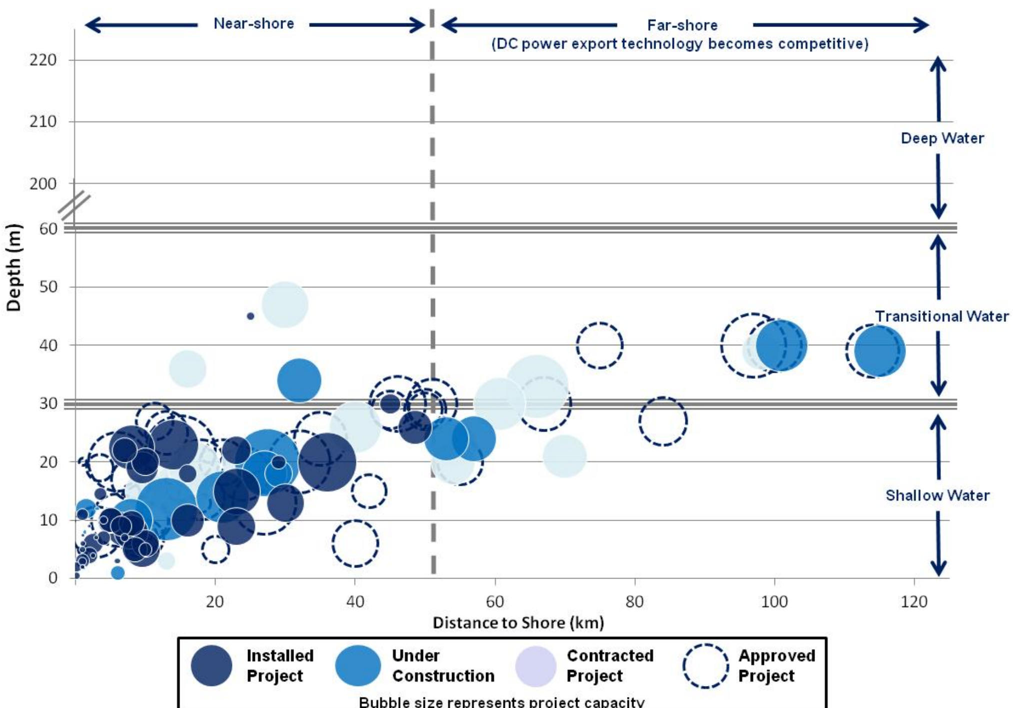

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Figure 6. Current offshore wind projects in Europe: installed, under construction, contracted, and approved, as a function of water depth and distance to shore
(Source: NREL)

The figure shows that the majority of the projects are installed in waters less than 30 meters deep, with only a few of the newer projects pushing into depths of 35 m or greater [e.g., Alpha Ventus/Germany (average depth of 30 m) and Talisman Energy/Scotland (average depth of 45 m)]. A major reason why European projects have remained in shallow water is because shallow waters are more abundant in the North Sea and European offshore wind developers have not yet had to venture into deeper waters.

Both leasing areas A and B have ample shallow water, with mean depths of about 23 m to 27 m, to support a large project of at least 400 MW using proven shallow water technology, as shown in Table 4. The minimum depths of the proposed leasing areas all range from about 14 m to 16 m. However, the maximum depths vary, from about 30 m in leasing area A to about 37 m in leasing area B. Thus, all of the leasing area A options are within the depths where the industry has the most experience, whereas some areas of leasing area B are in deeper water, where development could be more challenging.

Deeper waters could increase the amount of steel required for a given support structure and limit the feasibility of some support structure options. In addition, deeper waters limit vessel options and could increase construction and installation cost by dictating more specialized requirements. The added cost of fixed-bottom construction in deeper water is not yet fully understood because there is insufficient field data beyond 30 m to develop empirical relationships.

The U.S. Department of Energy is sponsoring NREL to model offshore cost as a function of depth by using industry experience extrapolated from existing projects. Figure 7 shows analysis done by NREL indicating a trend toward higher cost as water depth increases (Maples 2012). This analysis includes cost multipliers for structures, electrical infrastructure, ports installation, and logistics considerations. Although the figure only extends to a 30-m depth, we expect the upward trend to continue and become steeper and nonlinear at higher depths.

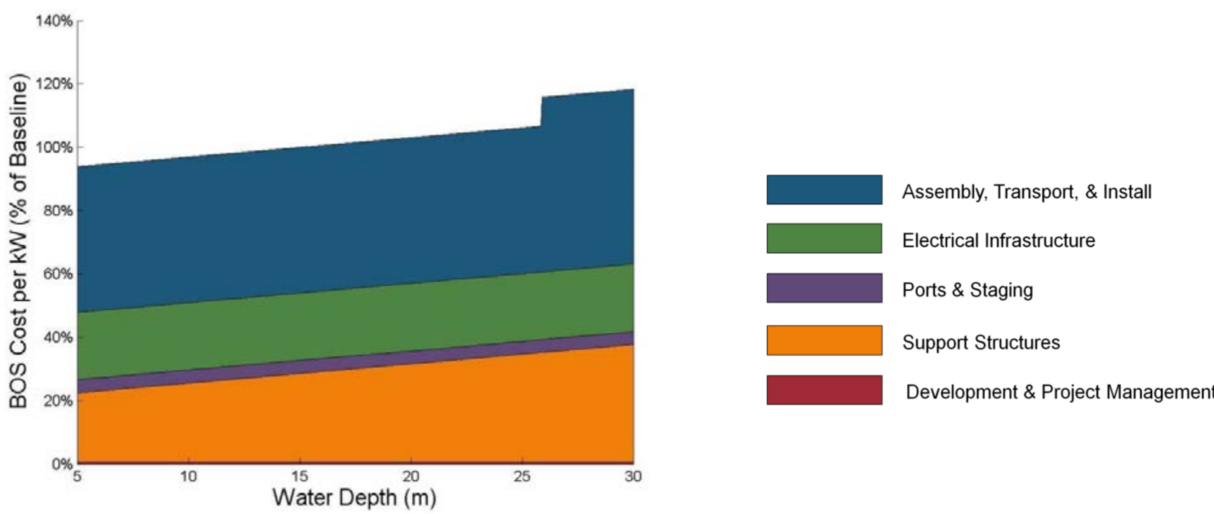

Figure 7. Balance of station (BOS) development cost by depth
(Source: NREL)

Figure 7 indicates that most of the cost increases are caused by more expensive support structures. As the depth increases, the amount of steel that is required increases at a rapid rate to maintain compliance with offshore structural reliability standards. Another factor is that, at a certain depth, the installation process requires a less common class of installation vessel that is difficult to hire. For example, commonly used jack-up barges may not be viable beyond 25–30-

m depths. This vessel scarcity and upgrade requirement is modeled as a step change in the assembly, transportation, and installation costs at an approximate depth of 25 m, as shown in Figure 7. As a result, the cost to install a small number of deeper water turbines as part of a predominately shallow water project could escalate.

4.5 Wind Resource

The annual average wind speed determined from the AWS Truepower WRG/B data described in Section 3.2 is shown in Figure 8 for the MD WEA. The figure shows that the wind speed varies from 8.1 m/s to 8.3 m/s at 90 m, with higher wind speeds in the southeast than in the northwest. This rather small wind speed gradient of about 0.2 m/s across the MD WEA is less than the typical uncertainty of about +/-0.35 m/s that is often associated with modeled wind resource data for many areas of the United States (AWS Truepower 2012).

The prevailing winds, indicated by the wind rose in Figure 9, come from the southwest and northwest directions.

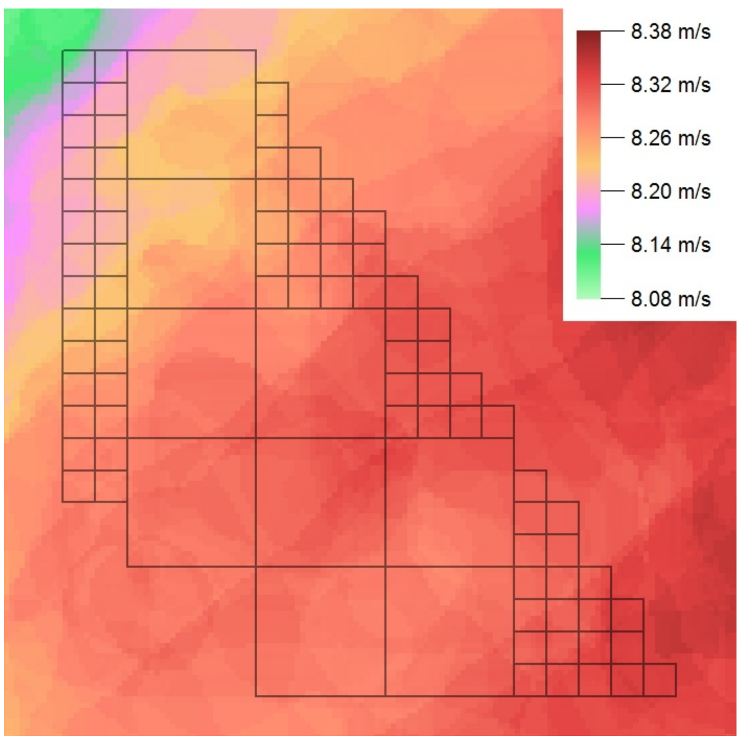

Figure 8. MD WEA showing annual average wind speed in 0.06 m/s increments
(Source: NREL)

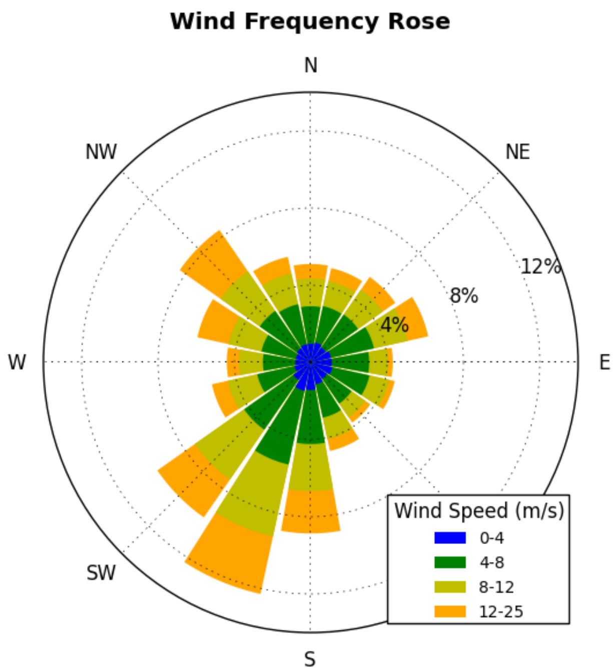

Figure 9. MD WEA annual average wind frequency rose showing prevailing winds from the southwest and northwest directions
(Source: NREL)

Note that these prevailing winds have an orthogonal, bimodal directional distribution with strong components from both the south southwest and the northwest. This type of distribution tends to increase the estimated wake losses (16% to 17% for 8D x 8D spacing) relative to sites with a single prevailing direction. In a similar study of the Rhode Island/Massachusetts (area of mutual interest), wake losses were found to be approximately 11% for the same turbine spacing in each of the leasing areas studied (Musial et al. 2013). The higher losses seen in the MD WEA are partially because turbines oriented to optimally capture wind from one direction will be compromised when winds blow from the other prevailing direction so the optimal grid alignment is a compromise between the two directions. Also, the bimodal characteristic increases the complexity of layout optimization.

Another contributor to the higher wake losses in the MD WEA is lower average wind speeds. By comparison, the average wind speeds are about 1 m/s lower in the MD WEA than the Rhode Island/Massachusetts WEA. Wind speed is one of the largest drivers of wake losses, with higher losses expected at lower average wind speed sites; approximately 2% to 3% difference in array efficiency can be attributed every 1 m/s difference in average annual wind speed (Barthelmie et al. 2013). Possible implications of these higher losses are that increased turbine spacing and buffers may be required relative to sites with unidirectional wind distributions and higher annual average wind speeds.

4.6 Capacity Factor

The gross capacity factor is the average energy output (before any losses outside the turbine itself are considered) as a percentage of the maximum possible energy output if the turbines were operating continuously at their rated power output. For each delineation option, the gross capacity factor was estimated using the analysis tools, methods, and layouts, as described in Section 3. As shown in Table 4, the gross capacity factors for all of the leasing areas and delineation options are estimated to be about 44% for the NREL 5-MW reference turbine.[2] This low variability in capacity factor indicates a fairly uniform resource distribution across the MD WEA and low sensitivity to the chosen delineation strategy. The gross capacity factor was also computed after calculating wake losses only. These values were estimated to be between 36% and 37% for the 8D x 8D spacing and between 38% and 39% for the 8D x 12D spacing for all leasing areas. A longer discussion on wake and array losses is provided in the following section.

4.7 Wake and Array Losses

4.7.1 Introduction

Wind turbine wakes within an array can result in losses in energy production and increases in structural fatigue loading. The severity of wake conditions is affected by climatic conditions, such as the ambient wind speed, ambient turbulence intensity, atmospheric stability conditions, and prevailing wind directions. Wake characteristics are also strongly influenced by the physical parameters of the wind facility including the number of turbines in operation, their spacing, and the wind plant layout.

Atmospheric stability is a measure of the wind's tendency to rise and fall vertically as it flows in the horizontal direction. When the atmosphere is stable, the thermal layers of the atmosphere are stratified, which means that heavier, cooler air is at the lowest layer and the warmer air is aloft. In this case, the flow generally stays in horizontal layers and has little tendency to mix vertically. If the temperature differential is reversed and the warmer air is below and cooler air is aloft, then the atmosphere is unstable. In this case, the two layers have a tendency to mix, with the cooler air descending and the warmer air rising. This vertical movement results in turbulence in the flow. When this type of unstable condition is present, the turbulent mixing of layers increases the available energy to the wind turbines by dissipating the wakes more rapidly and bringing more kinetic energy into the array. This is a complex condition of the atmosphere that is difficult to model and may not be fully represented by the current wind plant layout tools (including OpenWind).

Figure 10 is a photo of the Horns Rev offshore wind facility off the west coast of Denmark.

[2] Note that the NREL reference turbine (Jonkman et al. 2009) does not reflect an optimized turbine configuration and actual capacity factors may be larger because of improved technology.

Figure 10. Horns Rev I wind farm
(Source: Vattenfall, *Photo by Christian Steiness*)

The Horns Rev photo was taken on a day when fog was formed due to special atmospheric conditions resulting from a layer of cold humid air moving above a warmer sea surface (Hasager et al. 2013). The vapor trails allow wind flow visualization throughout the array and illustrate the creation of wakes downstream of the turbines. It can be seen that the wind is coming from the lower left corner of the picture and blows down the rows of the array. As the wakes propagate downstream they expand, and mix with wakes from turbines deeper in the array. This leads to increased turbulence and lower wind speeds deeper in the array and reduces power output at turbines downstream. Horns Rev uses a symmetrical array with 7D x 7D turbine spacing and a power density of 6.4 MW/km^2, compared to 5.0 MW/km^2 and 3.28 MW/km^2 for the NREL analysis in this report.

4.7.2 Effect of Array Grid Orientation

Prevailing wind directions must be considered when orienting the turbines to minimize the wake effects. NREL researchers used OpenWind to determine the grid orientation that provided the lowest wake losses for each grid array spacing scenario considered. For a gridded array, the orientation is described in OpenWind by a bearing angle, or a grid orientation angle. The grid orientation angle uses the BOEM leasing area grid as a reference frame, as illustrated in Figure 11.

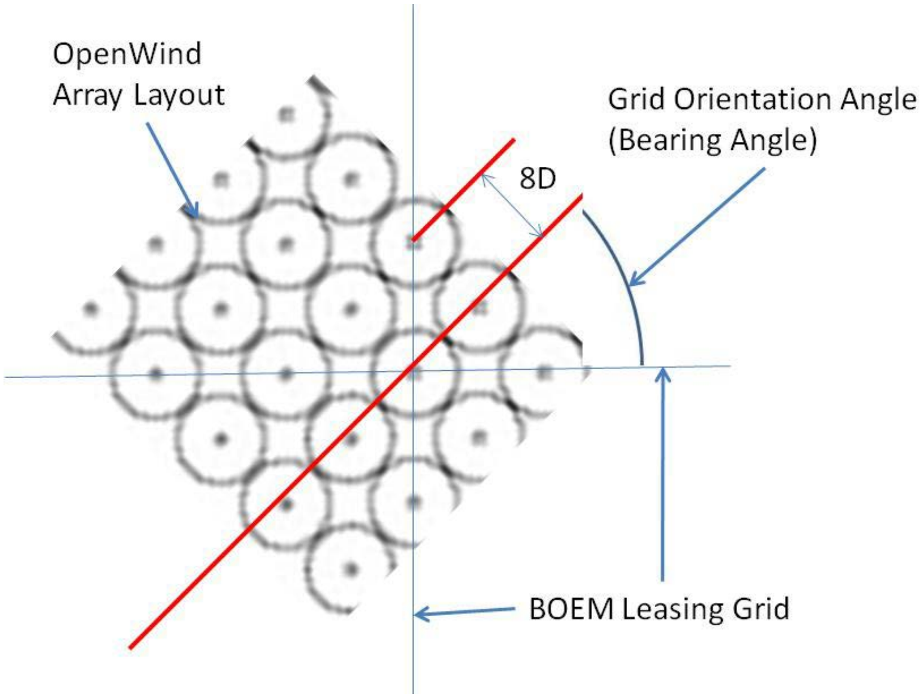

Figure 11. OpenWind uses the BOEM leasing grid as a reference frame for the grid orientation angle of the turbine array shown for 8D x 8D spacing
(Source: NREL)

NREL performed the analysis in OpenWind using the wind rose shown in Figure 9 to rotate the grid orientation at 15-degree increments to find the angle relative to the leasing grid with the lowest wake losses. The results revealed that the modeled wake losses, based on capacity factor, varied by only 0.11% over the full range of grid rotation. This variation indicated that, for the square 8D x 8D grid array spacing, the grid orientation angle was relatively unimportant in determining the total plant losses. However, we have found (see Section 5) that nonsymmetrical arrays show a more pronounced correlation with grid orientation angle.

The grid orientation angle that yielded the lowest wake losses was found to be at zero degrees for the MD WEA. This orientation is logical because the prevailing winds (southwest and northwest) occur approximately along the diagonals of a zero-degree grid. From these directions, the effective turbine separation is slightly greater because the wind does not tend to blow directly down the rows. In this case, the straight grid orientation, as shown in Figure 4, also provides the largest number of turbines within the WEA.

The 45-degree grid orientation angle results in the prevailing winds being approximately aligned with the turbine rows. Thus, the effective downwind turbine separation is almost exactly 8D under prevailing wind conditions. In the 45-degree grid orientation case, fewer turbines can be sited within the WEA because of basic geometry constraints.

One of the most important results from this analysis is that wake losses appear to be driven mostly by deep array effects that are largely independent of grid orientation. Figure 12 shows the impact of wake losses on the high-density 8D x 8D array. The two plots show array efficiency by individual turbine for grid orientation angles of 0 and 45 degrees. As indicated earlier, the total plant capacity factor varies by only 0.11% between the two grid orientations, a difference that is within the uncertainty of the model.

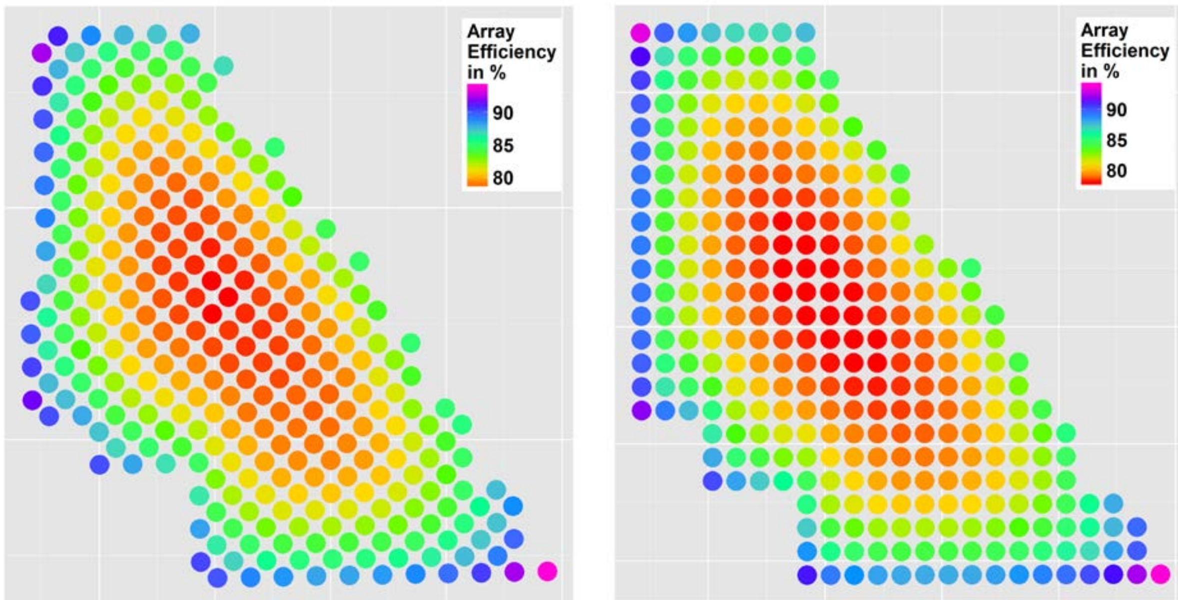

Figure 12. Deep array losses dominate for all grid orientations in the MD WEA. The array has grid orientation angles of 45 degrees (left) and 0 degrees (right).
(Source: NREL)

In Figure 12, each turbine is represented by a single dot. The colors indicate the magnitude in which the turbine is under performing in the array as compared to how it would perform in an unobstructed freestream wind. Note how the strong degradation in the wind project interior dominates the chart for both the 45- and zero-degree grid orientations.

4.7.3 Wake Losses

Measurements of annual average wake losses at offshore wind power plants in European waters are generally in the range of 10% to 20% (Barthelmie et al. 2013, Hansen et al. 2012) based on available wake measurement data. The OpenWind-derived wake loss estimates for the MD WEA are within this range, which is expected, especially considering that the assumed array density of 5 MW/km^2 (8D x 8D spacing) is similar to the operating projects providing field data.

As shown in Figure 9, the prevailing winds in the MD WEA are from the south southwest and northwest directions, with a slightly higher frequency from the south southwest than the northwest. The south southwest winds are expected to generate more stable atmospheric conditions, whereas the northwest winds are expected to generate more unstable atmospheric conditions. Unstable conditions cause more turbulent mixing and accelerated wake decay. Therefore, leasing area A is expected to experience higher wake losses if leasing area B is fully developed. The wake losses range from 16% to 17% for 8D x 8D spacing and 12% to 13% for 8D x 12D spacing, as shown in Table 4.

Wake loss findings indicate that:

- Both leasing areas will experience significant wake losses under all options investigated. Developers could mitigate these effects by implementing siting strategies that employ larger spacing and internal buffers.
- The differential wake losses between leasing area options for the MD WEA were not a significant factor in choosing a delineation boundary.
- The analysis in this report is coarse by industry standards and it is recommended that prospective lessees conduct more rigorous analysis on wake losses before judging the values of these leasing areas. This enhanced analysis should consider diurnal, seasonal, and annual variations as well as a full cost assessment to examine the additional cost due to added cable length. In addition, further analysis on wake losses with respect to atmospheric stability conditions is recommended.

4.8 Capacity Factor and Potential Annual Energy Production After Wake Losses

As shown in Table 4, gross capacity factor was also computed, including the performance losses due to wakes losses only. The wake loss calculations assumed that both leasing areas were developed fully using 8D x 8D and 8D x 12D spacing, as described in Section 4.3. Therefore, the introduction of self-regulated buffer zones could potentially decrease the impact of wake losses. After wake losses, the capacity factor is reduced to the range of about 36% to 37% (8D x 8D) and 38% to 39% (8D x 12D) for both leasing areas and all delineation options, with slightly higher capacity factors in leasing area B than leasing area A, as shown in Table 4. Additional losses from poor availability, electrical transmission, and other factors can also be expected, which may further reduce the annual energy production by 5% to 10% (the potential annual energy production is included in Table 4 for each leasing area and delineation option).

4.9 Qualitative Considerations

There are several other criteria that could influence the leasing area value and the ability to develop the MD WEA, but most of these criteria were considered to be of secondary importance, or were not understood well enough for NREL to make a valid determination, and therefore did not impact NREL's recommendation.

The distance to shore will likely add cost because of additional export cable length and longer transport times to and from the turbines for construction and service. An analysis of this factor would require a specific definition of where the land-based grid connections are made or specifics on ports and harbor staging areas. However, NREL did not conduct a full evaluation other than to acknowledge that leasing area B would be slightly more burdened by larger distances to shore. No consideration was given to the possibility that turbines located closer to the shore in leasing area A could pose a visual impact concern, and it is uncertain if this could potentially become an issue.

Additionally, MEA noted that fisheries may impose higher competing use impacts in some areas of leasing area B, which they addressed by assigning more area to leasing area B. NREL did not conduct further analysis on fisheries and the impact they might have on development. Similarly, MEA claimed that military use did not have a significant impact on the MEA delineation, therefore conflicts with military use were not considered further by NREL in its analysis of the MD WEA.

Developer inputs received through the RFI reviews were informative with respect to project size and array spacing, but only affected the NREL leasing area delineation analysis by guiding the choice of turbine spacing used in the analysis.

Finally, shipping and navigation use concerns have been raised by the USCG. The information collected from BOEM and the USCG presentation given on January 29, 2013, indicated that transportation concerns have not been fully resolved (Walters and Benard 2013). A more in-depth analysis of two alternative WEA boundaries is discussed in detail in Section 5.

5 Maryland Alternative Wind Energy Area Analysis

5.1 Overview of Alternatives

In a letter to BOEM in April 2013, USCG raised additional concerns regarding the safety of marine vessels transiting through the MD WEA. As part of its analysis, the USCG suggested that BOEM consider alternatives that would modify the WEA by removing areas of high navigational concern. As a result, two alternative WEA configurations are under consideration, as shown in Figure 13. For comparison, the original proposed WEA boundary is shown on the left side of the figure. Note that the new delineation boundaries remain oriented east-west but the line moves north to maintain approximately equal areas between leasing areas A and B. The purpose of this analysis is to provide BOEM with information about the practical development potential of the alternate WEAs and the possibility of subdividing these areas into economically viable leasing areas. During the analysis, researchers considered the same quantitative and qualitative criteria used to evaluate the original WEA in Section 4. The results of the quantitative analyses for the alternatives are shown in Table 6.

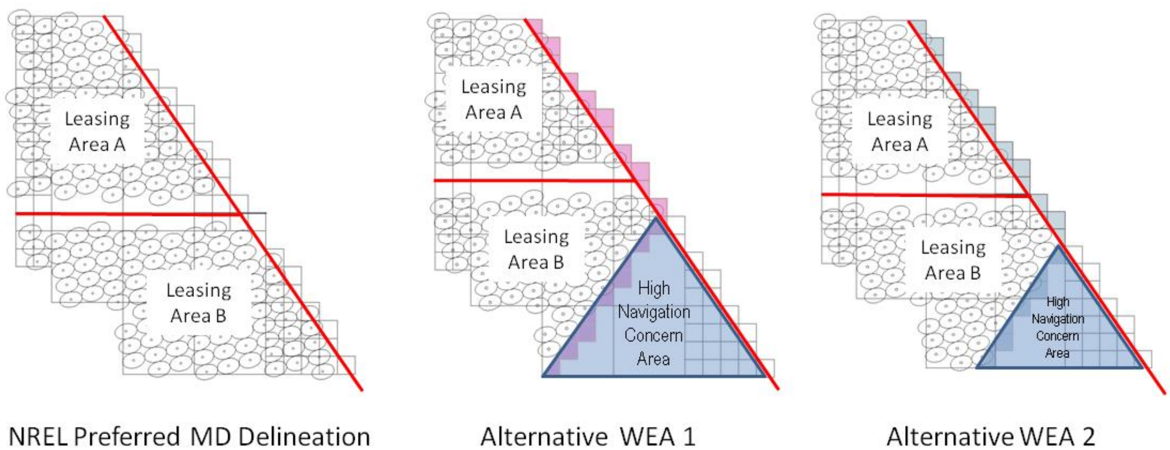

Figure 13. Comparison of three MD WEA alternatives. Alternatives 1 and 2 remove several aliquots from the southeastern end of the MD WEA, where the USCG has raised concerns because of competing uses with vessel traffic.
(Source: NREL)

Table 6. Summary of Results for the MD WEA Using the NREL Preferred Delineation and the Two WEA Alternatives
(Source: NREL)

Parameter	MD WEA - NREL Preferred Delineation		MD WEA Alternate 1		MD WEA Alternate 2	
	Leasing Area A	Leasing Area B	Leasing Area A	Leasing Area B	Leasing Area A	Leasing Area B
Total area (km^2)	151.2	171.4	104.5	106.4	120.8	123.5
Total area (1,000 acres)	37.4	42.3	25.8	26.3	29.8	32.0
Average depth (m)	23	26	23	23	23	24
Bathymetry – depth range (m)	16–29	14–37	16–28	14–29	16–29	14–30
Average wind speed at 90 m (m/s)	8.2	8.3	8.2	8.3	8.2	8.3
8D x 8D – Zero-Degree Grid Orientation						
Wake losses (%)	17	16	16	15	16	16
Gross capacity factor (CF) (%)	44	44	44	44	44	44
Gross CF after wake losses (%)	36	37	37	37	37	37
Potential capacity (MW)	670	760	465	525	530	610
Annual energy production (GWh)	2,123	2,454	1,496	1,720	1,698	1,983
8D x 12D – 75-Degree Grid Orientation						
Wake losses (%)	13	12	12	11	12	12
Gross capacity factor (CF) (%)	44	44	44	44	44	44
Gross CF after wake losses (%)	38	39	38	39	38	39
Potential capacity (MW)	400	475	300	315	350	370
Annual energy production (GWh)	1,336	1,607	1,010	1,079	1,173	1,258

5.2 Analysis of Economic Project Size

To make a project economically viable, a developer must achieve certain economies of scale that are dependent on distributing several large cost elements among a large enough number of turbines to meet overall cost requirements. These cost elements include export cable and interconnection; installation vessel mobilization; substructure fabrication and tooling; engineering design and commissioning; subcomponent testing and validation; permitting and legal fees; site assessment; maintenance equipment; and operation and maintenance contracting.

The project size that is required to achieve economic viability is not fully understood, and would vary regionally depending on state and local incentives; regional supply chain and infrastructure; and local labor and vessel rates, and additional factors. However, this report provides an analysis of some of the literature to help estimate this requirement. From the nominations provided by prospective offshore wind energy developers, many agreed that one point of optimization is the number of turbines that can be installed in a single season with a duration of approximately 6 months. Projects that are larger than this are often broken into smaller phases spanning multiple seasons or years. Depending on the turbine size used, the overall project size that can be installed in a single season (single phase) has been estimated in MD WEA nominations to be in the range of 250 MW to 500 MW. The average project nameplate capacity indicated by the nominations received by BOEM for the MD WEA was 865 MW; however, the nominations also indicated a range of 285 MW to 1,500 MW, and some of the projects assumed multi-year phases. Unfortunately, the details of this information are confidential and therefore cannot be discussed in further detail.

In Figure 14, the project size (in megawatts) is shown for European offshore wind projects by the year of commissioning. In Europe, there is a clear trend of installing larger projects. Note that in 2012, the average project size was about 325 MW.

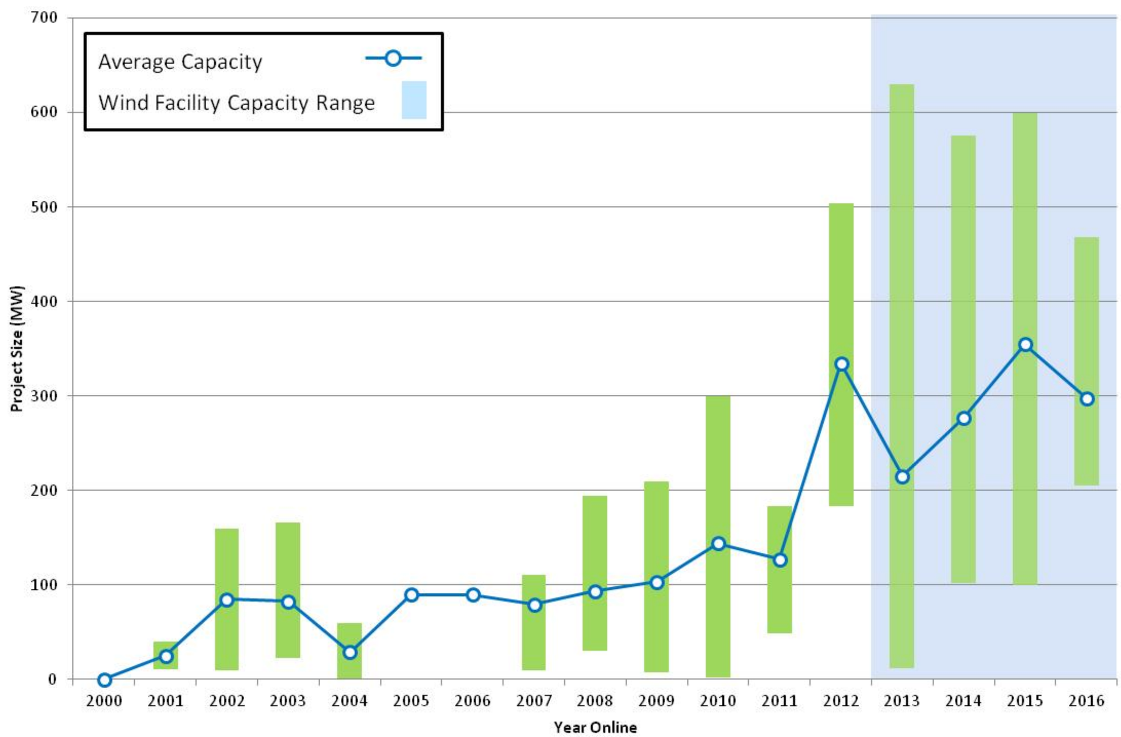

Figure 14. Trends in European offshore wind project nameplate capacity showing installed projects and projects under construction
(Source: NREL)

For the United States, the results are more speculative because no projects have been built yet. In New Jersey, a 2007/2008 state-led solicitation for preferred bidders requested that proposed project sizes be up to 350 MW (New Jersey BPU 2007). The only project in the United States that has been issued a lease by BOEM is Cape Wind, which has a nameplate capacity of 468 MW and has secured power purchase agreements totaling 365 MW. Another point of reference is that the U.S. Department of Energy's offshore wind program uses a baseline project size of 500 MW to develop current cost models and project future costs (Tegen et al. 2012).

To determine the effect of project size on the balance-of-station (BOS) costs for an offshore wind facility, NREL performed a cost analysis, which is shown in Figure 15 (Maples 2012). The figure shows that the BOS cost per installed kilowatt rises more rapidly as project size decreases from the 1-gigawatt (GW) maximum. Note that additional increases in project size beyond the 500-MW baseline seem to result in more marginal BOS cost benefits, although BOS costs do continue to decrease with project size for all project sizes up to 1 GW.

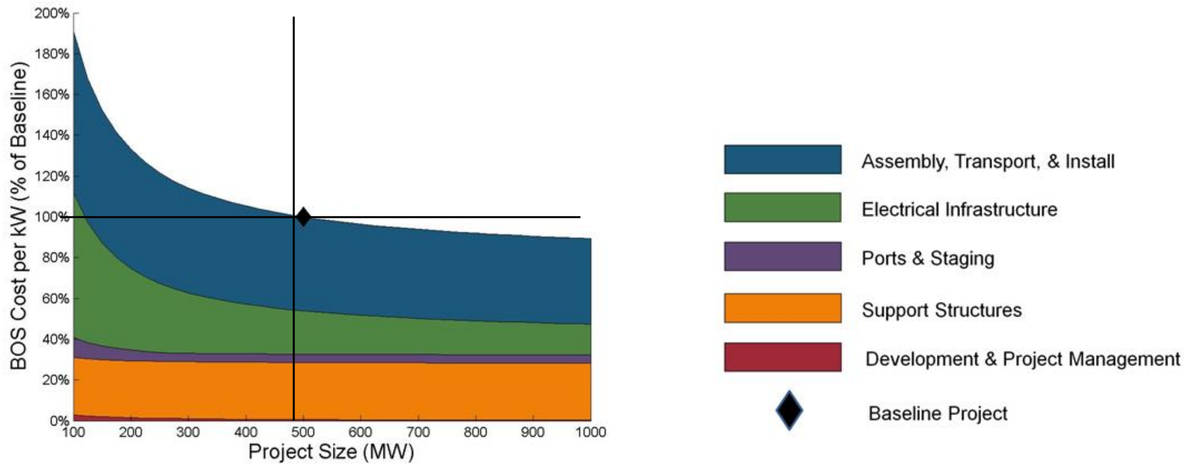

Figure 15. The effect of project size on BOS costs for an offshore wind facility
(Source: NREL)

In 2013, the State of Maryland passed the Maryland Offshore Wind Energy Act of 2013, which dedicates a portion of Maryland's Renewable Portfolio Standard to require generation from offshore wind energy. Qualifying projects must meet specific ratepayer protection standards, including maximum price. With current modeling of offshore wind energy installation costs, MEA expects that the legislation will enable a first-phase project of approximately 200 MW installed capacity. However, the 200 MW expectation should not limit project size, and larger projects are expected (Maryland 2013).

Based on the studies reviewed for this section, the average nameplate capacity for commercial offshore wind energy facilities—existing and planned for the United States and Europe—is near or above the potential installed capacity for the MD WEA alternatives with two leasing areas. The trends shown in Europe and the proposals made by developers in the United States indicate that the size of the average offshore wind energy facility will continue to grow. It is likely that this growth is largely caused by developers seeking economic viability through economies of scale. Of course the actual size needed for a project to achieve economic viability depends on many regional and global factors that will require further study.

5.3 Summary of Delineation Strategy

The delineation strategy used for the alternatives analysis focused on the creation of two feasible leasing areas within the MD WEA to address concerns from the state that a single lessee would eliminate competition from the Offshore Renewable Energy Credit process created by the Maryland Offshore Wind Energy Act of 2013. This analysis builds on the previous methodology presented in Section 4, which was to determine if the size reduction to the overall wind energy area (requested by USCG) would still allow for the development of two commercial-size projects; one in each leasing area. To make this determination, we defined the likely turbine array spacing used under a set of normal siting constraints to be 8D x 12D. For the purposes of this analysis, a setback of 8D (approximately 1 km) was assumed from the delineation boundaries, but no further buffers were imposed other than the normal grid spacing between the turbines themselves. From the analysis described in Section 4, the total area of the WEA was 322.5 km^2. This area is relatively small, and offers little siting flexibility when considering the placement of two large-scale wind plants, which are typical of those under development today. The proposed alternatives reduce the total WEA to 211 km^2 and 244.3 km^2 for Alternatives 1 and 2, respectively. A simple analysis of these areas reveals reductions of 35% and 25% (for Alternatives 1 and 2, respectively), which would reduce the nameplate capacity potential by approximately the same amount. With this in mind, NREL researchers focused on minimizing any further reductions in developable area that might be introduced by the delineation process itself. Earlier analysis (see Section 4) demonstrated that straight-line delineations were the most efficient boundaries to maximize developable area, so for the alternatives analysis, we limited the delineations to straight east-west lines. Using this method, we divided the WEAs with straight lines to come the closest to equally sized leasing areas for each alternative, as shown in Figure 13.

5.4 Development Capacity and Maximum Project Size

Most prospective developers of the MD WEA proposed array spacing greater than the 8D x 8D spacing. Therefore, to better determine the potential for practical development, NREL researchers focused the alternatives analysis on wider turbine array spacing of 8D x 12D to correspond with the typical turbine spacing and array power density proposed by developers in the MD WEA. With this spacing, the grid orientation angle was rotated to find the minimum wake losses (75 degrees). We used this approach to compute the estimated development capacity of the leasing areas.

Figure 16 illustrates the maximum project size for the three MD WEA alternatives (shown in Figure 13 and based on 8D x 12D spacing).

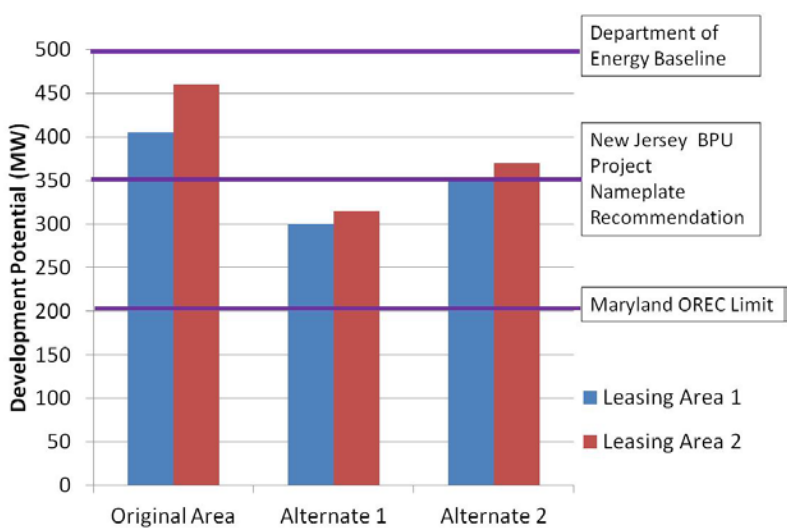

Figure 16. Comparison of development potential for the three alternative MD WEAs delineated into two leasing areas using 8D x 12D turbine array spacing
(Source: NREL)

For the 8D x 12D turbine spacing indicated in Figure 16, the MD WEA's original boundaries (with the TSS 1 nm set-back applied), would allow each leasing area to construct an offshore wind facility of about 400 MW assuming no additional buffers. Alternative 1 would allow for a project capacity of about 300 MW and Alternative 2 would allow for a project capacity of about 350 MW. Three reference lines are included in the figure to show how these project sizes compare to the 200-MW Maryland Offshore Renewable Energy Credits offering, the 350-MW baseline project size for the 2007 New Jersey BPU solicitation, and the current 500-MW baseline project size that the U.S. Department of Energy is using to develop a cost-of-energy analysis for offshore wind in the United States.

5.5 Bathymetry of Alternatives

Bathymetry was a key factor in balancing the development potential of the leasing areas in the original MD WEA. As shown in Figure 5 and Table 5, for the NREL preferred delineation, the southern leasing area comprises approximately 140 MW of capacity between 30-m and 40-m depth (for the 8D x 8D spacing), which would challenge the development in this area. These deeper aliquots are still developable, but leasing area B was made intentionally larger by delineating the MD WEA to provide better siting flexibility to offset greater technology challenges. For both alternative scenarios, most of these deeper water aliquots above 30 m (located in the far southeast aliquots) were eliminated. The remaining aliquots can be weighted equally with respect to bathymetry. Therefore, balancing the WEA alternatives using area as the primary criterion is appropriate for this analysis.

5.6 Wind Resource and Gross Capacity Factor

The analysis of the two alternative WEAs revealed no significant differences in the wind resource or gross capacity factor when compared to the MD WEA boundaries.

5.7 Wake and Array Losses

For the wake and array losses, the analysis of the alternative WEAs revealed no major changes compared to the MD WEA boundary using 8D x 8D spacing, as most of the wake losses were generated internally from within the wind plant. Overall losses were slightly lower (<1%) for the two alternatives than the original boundaries because fewer turbines could be placed inside the respective leasing areas, which resulted in fewer wakes, but the decreased wake effects were not considered to be a primary driver in the delineation analysis.

In addition, the alternatives and the original MD WEA were compared for a turbine array spacing of 8D x 12D using a grid orientation angle of 75 degrees, as shown in Figure 13 (a grid orientation angle of 75-degrees was found to have the lowest wake losses for the 8D x 12D spacing). For the wider spacing, the wake and array losses declined by about 25%, compared to the 8D x 8D spacing, for each of the leasing areas—from a range of 15% to 17% to a range of 11% to 12%. These wake losses may still be considered high by today's best practices, but the potential for further wake loss reductions would require significant reductions in overall project capacity, which could limit commercial viability. NREL's analysis did not include larger array spacing because our earlier assessment concluded that the Maryland project sizes in the alternative WEAs were already near their lower limit for commercial viability with the 8D x 12D spacing.

In general, higher array densities (such as 8D x 12D equivalent spacing) may be needed for the Maryland WEA alternatives, considering that the two leasing areas are relatively small in both cases and offer little siting flexibility. Larger spacing may also be needed to offset additional wake losses due to lower annual average wind speeds when compared to more energetic sites in the northern Atlantic or in the North Sea (Barthelmie et al. 2013).

5.8 WEA Alternatives Conclusions

Based on the comments received by the USCG, BOEM requested that NREL perform additional analysis wherein two alternatives were examined in this section. Both alternatives were proposed to eliminate potential conflicts with vessel traffic by removing some of the aliquots from the southeast end of the MD WEA, as shown in Figure 13.

The alternatives study created new delineation boundaries to provide approximately equal leasing areas in each of the proposed alternative WEAs. The new leasing areas were studied using wider turbine spacing (8D x 12D) than what was used in Section 4 to provide a more realistic assessment of the development potential using current best practices. The study found that the Alternative 1 delineation could support the development of a 300-MW wind facility in leasing area A and a 315 MW facility in leasing area B, and that the Alternative 2 delineation could support a 350-MW project in leasing area A and a 370 MW project in leasing area B. These nameplate capacities were found to be on the lower end of what may be considered an economically viable project in the United States, although no empirical data has yet been generated domestically to validate the analysis.

This analysis assumes that all of the aliquots have equal development potential for the two alternatives. For the original WEA boundary, deep water technology challenges were a major consideration in weighting the aliquots in the southeastern region that were removed for the proposed alternatives.

6 Key Findings

Below are the key findings of NREL's analysis and important considerations for policy makers and stakeholders involved in the Maryland offshore wind energy development process.

- The MEA analysis provided a logical approach to delineating the MD WEA, but NREL's assessment of the analysis concludes that the MEA may not have weighed the negative impacts of deep water heavily enough in balancing the leasing areas.
- Under the preferred delineation (B) in Figure 3, leasing area A has an average depth of 23 m and leasing area B has an average depth of 26 m. Leasing area B contains 5 aliquots, with a depth greater than 35 m and a total of 140 MW of capacity in an area where the water depth is above 30 m. Installation of wind turbines in these aliquots would have higher associated costs and increased technical challenges (see Figure 6 and Figure 7).
- An optional delineation (C) in Figure 3 of the MD WEA showed that tilting the delineation toward a more southwest-northeast diagonal direction slightly favors leasing area A, in terms of bathymetry, but produces relatively small changes in the quantitative parameters used in the other delineation options, and ultimately could result in less annual energy production in the WEA overall.
- The OpenWind project layout tool predicted that leasing area A would have higher wake losses than leasing area B (the difference is less than 1%) for both the 8D x 8D and 8D x 12D spacing, but the wake loss differences between leasing areas are small relative to the total wake losses—between 16% and 17% based on total energy for 8D x 8D spacing and 12% and 13% for the 8D x 12D spacing. The magnitude of these predicted wake losses are also comparable to the observed wake losses seen in European projects (Barthelmie et al. 2010, Jensen 2007).
- For all delineation options in Figure 3, leasing area B is larger, the wind speeds are higher (about 0.1 m/s), and it has better exposure to dominant south-southwest winds, as shown in Figure 9. These positive factors are expected to be offset by approximately equal negative factors because of deeper water in leasing area B.
- NREL's preferred delineation consists of a straight west-east line to balance the development potential of the two leasing areas by taking into account the more challenging development caused by deeper bathymetry in leasing area B (option B in Figure 3).
- NREL's preferred delineation utilizes the MD WEA more efficiently than the MEA proposed delination by eliminating the zigzag line that may slightly reduce the total capacity that can be installed.
- As shown in Table 4 for the MD WEA, both leasing areas are capable of supporting at least 600 MW of potential installed capacity for the 8D x 8D spacing criteria, and 400 MW for the 8D x 12D spacing criteria.
- The prevailing winds have an orthogonal, bimodal directional distribution with a strong component from the south southwest and a weaker prevailing component from the northwest (Figure 9). This bimodal directional distribution can result in increased wake losses relative to sites with a single prevailing direction. Also, the bimodal characteristic increases the complexity of layout optimization. As a result, increased turbine spacing and buffers may be required when compared to more unidirectional distributions (Musial et al. 2013).

- Array density equivalent to a spacing of 8D x 12D is recommended for the MD WEA to account for higher wake losses due to lower average wind speeds and a bimodal directional distribution. At lower wind speeds, wake losses are greater because the wind turbines extract a larger percentage of the energy available in the wind than at higher wind speeds. At more energetic sites, turbines operate more often above rated power and wake losses are reduced above rated power (Barthelmie et al. 2013).
- The nameplate capacities of the two leasing areas are relatively small for both alternative WEAs (Figure 13), and there will be little siting flexibility to account for variable bottom conditions, obstructions, and additional exclusions.
- Alternative 1 of the MD WEA, proposed to address navigational concerns raised by the USCG, will reduce the possible development potential of the two leasing areas to 300 MW and 315 MW, respectively. These project capacities are near the lower end of the project size range for typical commercial projects proposed in the United States and Europe.
- Alternative 2 of the MD WEA, proposed to address navigational concerns raised by the USCG, will reduce the possible development potential of the two leasing areas to 350 MW and 370 MW, respectively. These project capacities are near the current project size range for typical commercial projects proposed in the United States and Europe.
- The analysis in this report is coarse by industry standards and it is recommended that prospective lessees conduct more rigorous analysis on wake losses before judging the values of these leasing areas. This enhanced analysis should consider diurnal, seasonal, and annual variations as well as a full cost assessment to examine the additional cost due to added cable length. In addition, further analysis on wake losses with respect to atmospheric stability conditions is recommended.

7 References

AWS Truepower, LLC. (2010). OpenWind Theoretical Basis and Validation. http://www.awsopenwind.org/downloads/documentation/OpenWindTheoryAndValidation.pdf. Accessed April 6, 2013.

AWS Truepower, LLC. (2012). Wind Resource Maps and Data: Methods and Validation. : https://windnavigator.com/index.php/cms/pages/our-technology.

Barthelmie, R.J.; Pryor, S.C.; Frandsen, S.T.; Hansen, K.S.; Schepers, J.G.; Rados, K.; Schlez, W.; Neubert, A.; Jensen, L.E.; Neckelmann, S. (2010). "Quantifying the impact of wind turbine wakes on power output at offshore wind farms." *Journal of Atmospheric and Oceanic Technology*, 27(8), 1302–1317. DOI: 10.1175/2010JTECHA1398.1.

Barthelmie, R.J.; Hansen, K.S.; Pryor, S.C. (2013). "Meteorological controls on wind turbine wakes," *Proceedings of the Institute of Electrical and Electronics Engineers*. Vol. 101, No. 4, April 2013. DOI: 10.1109/JPROC.

Brower, M.C. (1999). Validation of the WindMap Model and Development of MesoMap, Proc. of Windpower 1999, American Wind Energy Association, Washington, DC.

Churchfield, M. J.; Lee, S.; Michalakes, J.; Moriarty, P. (2012). "A numerical study of the effects of atmospheric and wake turbulence on wind turbine dynamics." *Journal of Turbulence*, 13, N14. http://dx.doi.org/10.1080/14685248.2012.668191.

Gohn, A. (2012). Internal memorandum. "Maryland Wind Energy Area Zone Recommendation." September 13, 2012.

Hansen, K.S.; Barthelmie, R.J.; Jensen, L.E; Sommer. A. (2012). "The impact of turbulence intensity and atmospheric stability on power deficits due to wind turbine wakes at Horns Rev wind farm," Wind Energy, 15(1), 183–196. DOI: 10.1002/we.512.

Hasager, C.B.; Rasmussen, L.; Peña, A.; Jensen, L.E.; Réthoré, P.-E. (2013). "Wind Farm Wake: The Horns Rev Photo Case." *Energies* 6, No. 2: 696-716.

Jensen, L. (2007). Array efficiency at Horns Rev and the effect of atmospheric stability, European Wind Energy Conference Proceedings, Milan.

Jonkman, J.; Butterfield, C.P.; Musial, W.; Scott, G. (February 2009). Definition of a 5-MW Reference Wind Turbine for Offshore System Development. NREL/TP-500-38060. Golden, CO: NREL.

Manobianco, J.; Zack, J.W.; Taylor, G.E. (1996). "Workstation-based real-time mesoscale modeling designed for weather support to operations at the Kennedy Space Center and Cape Canaveral Air Station." *Bull. Amer. Meteor. Soc.*, 77, 653-672.

Maples, B. (2012). "U.S. Balance-of-Station Cost Drivers and Sensitivities," Poster presentation at AWEA Offshore Windpower Workshop 2012, Virginia Beach, VA, October 10, 2012.

Maryland. (2013). Maryland Offshore Wind Energy Act of 2013. Website for legislation. Accessed May 25, 2013. http://mgaleg.maryland.gov/webmga/frmMain.aspx?pid=billpage&tab=subject3&id=hb0226&stab=01&ys=2013RS

Musial, W.; Fields, J. (2013). "Proposed Methodology and Preliminary Findings for Maryland Offshore Leasing Zone Delineation," Presentation at BOEM Maryland Renewable Energy Task Force Meeting, Annapolis, Maryland, January 29, 2013. http://www.boem.gov/uploadedFiles/BOEM/Renewable_Energy_Program/State_Activities/NREL%20Zone%20Delineation.pdf. Accessed April 21, 2013.

Musial, W; Elliott, D.; Fields, J.; Parker, Z.; Scott, G. (2013). Analysis of Offshore Wind Energy Leasing Areas for the Rhode Island/Massachusetts Wind Energy Area; NREL Report, NREL/TP-5000-58091; http://www.nrel.gov/docs/fy13osti/58091.pdf.

Musial, W.; Ram, B. (2010). "Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers." NREL/TP-500-40745. Golden, CO: National Renewable Energy Laboratory, 240 pp.

National Aeronautics and Space Administration (NASA). (2013). MERRA: Modern-Era Retrospective Analysis for Research and Applications. http://gmao.gsfc.nasa.gov/merra. Accessed April 16, 2013.

National Oceanic and Atmospheric Administration. (NOAA). (2013). National Data Buoy Center. http://www.ndbc.noaa.gov/hmd.shtml. Accessed April 15, 2013.

New Jersey BPU. (2007). New Jersey Board of Public Utilities Press Release October 2007, Accessed May 25, 2013. http://www.state.nj.us/bpu/newsroom/news/pdf/20071004.pdf

Phillips, G.T. (1979). "A Preliminary User's Guide for the NOABL Objective Analysis Code," DOE/ET/20280-T1.

Schwartz, M.; Heimiller, D.; Haymes, S.; Musial, W. (April 2010). Assessment of Offshore Wind Energy Resources for the United States. NREL/TP-500-45889. Golden, CO: NREL.

Tegen, S.; Hand, M.; Maples, B.; Lantz, E.; Schwabe, P.; and Smith, A. (2012). "2010 Cost of Wind Energy Review," NREL Technical Report, NREL/TP-5000-52920, April 2012. http://www.nrel.gov/docs/fy12osti/52920.pdf

Walters J.; Benard, E. (2013). "BOEM State Task Force Meeting for Maryland." Presentation at BOEM Maryland Renewable Energy Task Force Meeting, Annapolis Maryland, January 29, 2013; U.S. Coast Guard. http://www.boem.gov/uploadedFiles/BOEM/Renewable_Energy_Program/State_Activities/USCG-%20MD%20State%20Task%20Force.pdf. Accessed April 17, 2013.